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FINAL REPORT

THE MORRISON FORMATION EXTINCT ECOSYSTEMS PROJECT

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LATE JURASSIC ECOSYSTEM RECONSTRUCTION DURING DEPOSITION OF THE MORRISON FORMATION AND RELATED BEDS IN THE WESTERN INTERIOR OF THE UNITED STATES

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EXECUTIVE SUMMARY

The Morrison Extinct Ecosystem Project is a joint National Park Service–U.S. Geological Survey–funded interdisciplinary study to reconstruct the Late Jurassic predominantly terrestrial ecosystem throughout the Western Interior during deposition of the Morrison Formation. This colorful formation is known worldwide for the skeletons of large dinosaurs, especially the giant sauropods, that have been recovered from it and displayed in many museums throughout the world. The formation is exposed in many National Park Service units including Arches National Park, Bighorn Canyon National Recreation Area, Black Canyon of the Gunnison National Monument, Capitol Reef National Park, Colorado National Monument, Curecanti National Recreation Area, Devils Tower National Monument, Dinosaur National Monument, Glacier National Park, Glen Canyon National Recreation Area, Grand Staircase-Escalante National Monument (under the jurisdiction of the Bureau of Land Management), Hovenweep National Monument, Wind Cave National Park, and Yellowstone National Park. The goal of the project is to improve National Park Service interpretive programs and resource management strategies by applying modern research approaches that will yield an improved understanding of the habitat that existed when the Late Jurassic dinosaurs roamed the western U.S.

The multidisciplinary approach allowed us to study various aspects of the rock and biostratigraphic record for the Morrison Formation, with various lines of evidence leading to an integrated picture. The investigations included studies of regional tectonics, regional stratigraphic framework, radiometric and paleontologic dating, sedimentology, paleosols (fossil soils), dinosaur biostratigraphy, trace fossils, taphonomy (processes that occur between the death of an organism and discovery as a fossil or trace fossil); microfossils, invertebrates, smaller vertebrates, and isotopic analysis of teeth and paleosol nodules. Integration of data from the various studies resulted in one of the most complete understandings of an ancient continental ecosystem. Although some aspects continue, most of the research has been completed and this has yielded a new and improved interpretation of the Late Jurassic ecosystem in the Western Interior of the united States.

Isotopic dating shows that the Morrison was deposited 155–148 million years ago. Deposition ceased about 7 million years before the close of the Jurassic Period, which ended approximately 141 million years ago. Paleontologic dating demonstrates that the Morrison was deposited during the Kimmeridgian and early Tithonian Ages in the Late Jurassic Epoch.

Because of continental drift, the Western Interior depositional basin was about 650 km (400 mi) farther south than today, placing the Four Corners near the latitude of the southern border of Arizona. Data from other workers that deal with climate on a global scale suggests the Earth was appreciably warmer than today (for example, polar ice caps were absent). Stable isotopes in carbonate nodules from Morrison paleosols indicate a significantly higher carbon dioxide content in the atmosphere than at present. This suggests that the Late Jurassic climate in the Western Interior was appreciably warmer than today.

During the Late Jurassic, a volcanic mountain chain somewhat similar to the present-day Andes existed along the west coast of North America more or less along the California border with Arizona and Nevada. Another highland lay farther inland roughly along the

Nevada–Utah state line. The nature of the terrain between these two areas is unclear but it probably included a small number of scattered volcanoes.

To the east of the highlands lay the vast Western Interior lowland plain on which the Morrison Formation was deposited. The inland plain extended from Arizona and New Mexico northward to Montana and into Alberta and British Columbia, Canada. The lowland may have originally extended much farther east, as some beds of possible Late Jurassic age in Iowa and Michigan suggest. Streams originating in the highlands flowed generally eastward, carrying their bedload of sand and gravel onto the aggrading Morrison alluvial plain.

Westerly to southwesterly winds left much of the inland plain in a rain shadow and were responsible for the dry climate that prevailed in most of the region. For much of the time, the climate was semiarid and perhaps arid, as indicated by deposits of bedded gypsum, which forms under highly evaporative conditions; windblown sandstone deposits; magadi-type chert; and saline, alkaline lake beds similar to strata deposited in present-day playa lakes of southeastern California. Somewhat wetter time intervals occurred, perhaps seasonally or on longer time intervals. We envision an environment where surface water was scarce much of the time and was only abundant seasonally and/or during infrequent storms. Some water entered the Western Interior basin, either as surface runoff from precipitation in the highlands farther west or through underground aquifers that were recharged from precipitation in highland source areas. Perennial streams that drained the highlands to the west traversed the Morrison alluvial plain but most likely many of the streams flowed only intermittently during most of Morrison time.

Somewhat wetter conditions probably developed throughout the region toward the end of Morrison deposition, as suggested by black mudstone beds that occur near the top of the formation at scattered localities from the Colorado Front Range foothills to Montana. Abundant carbonaceous mudstone and coal beds at the top of the Morrison in central Montana also suggest greater precipitation (or at least less evapotranspiration) and a temperate climate, at least in the northern part of the western Interior plain, toward the end of Morrison deposition.

Although eleven formally named members are recognized in the Morrison (all but two restricted to the Colorado Plateau), for simplicity the formation is divided into upper and lower parts that are separated by a conspicuous difference in clay mineralogy in the mudstone and claystone beds. Clay minerals in the lower part consist dominantly of non-swelling types whereas clay minerals in the upper part consist dominantly of swelling (smectitic) types. The vertical change in clay mineralogy can be traced as far north as northern Wyoming but has not been detected in Montana or the Black Hills of northeastern Wyoming and western South Dakota, where all the clays in the formation are of the non-swelling type. Where present, the change in clay mineralogy constitutes a valuable marker horizon for correlation purposes. About 6-15 m (20-50 ft) below the clay change is a fairly persistent paleosol (or closely spaced series of paleosols) that also is fairly widespread and appears to be another useful marker horizon near the middle of the formation. Another closely related formation that correlates with the lower part of the Morrison on the Colorado Plateau and farther north is the Ralston Creek Formation, which is only recognized in the Front Range foothills west of Denver.

The Morrison has yielded a large and varied fossil fauna and flora that appears, at first glance, to contradict the rather dry or semiarid environment that is interpreted from the rocks. For the most part, water in stream channels probably only flowed intermittently, or seasonally, but it was sufficient to allow small lakes or ponds to form in many places. The lakes and ponds probably dried up completely from time to time, as suggested by dinosaur tracks in some of the lacustrine mudstone beds and by the presence of numerous bones in mudstone beds that are interpreted as waterholes that went dry. Plant fragments, spores and pollen, charophytes, stromatolites, oncolites, sponge spicules, mollusks, and rare fish remains attest to the variety of life supported by many of these lakes, even though many of them may have been ephemeral.

Abundant trace fossils indicate that many other organisms found homes in the Morrison ecosystem. Termite nests as much as 40 m (130 ft) tall in the lower part of the formation in the southern San Juan Basin of northwestern New Mexico indicate that the water table there was at least that far beneath the surface. In the Colorado Plateau region, crayfish burrows are fairly common; most of the burrows extend less than about 5 m (15 ft) below the paleoground surface. Because crayfish burrow down to the water table, their burrows indicate a fairly shallow water table that probably could have allowed plants to survive in spite of the dry climate.

Dinosaur bones and skeletons have been recovered in many parts of the Western Interior and from much of the vertical thickness of the formation in one place or another. The bones are most commonly found in the upper part of the lower Morrison and throughout all but the uppermost part of the upper Morrison. Changes in the dinosaur fauna occur near the middle of the formation and correspond approximately with the distinct paleosol zone and also with the vertical change in clay mineralogy. This correspondence suggests that the dinosaur faunas changed in response to perturbations in the ecosystem, perhaps climatic and/or tectonic in nature. The paleosol zone indicates a decrease in depositional rate and the clay change reflects increased volcanic activity, both of which signal changes in the ecosystem that the dinosaurs were apparently sensitive to.

During the earliest stages of deposition of the lower Morrison (Windy Hill Member and correlative strata), a seaway that was an arm of the ancestral Pacific Ocean extended east across Wyoming and into adjacent parts of Montana, the Dakotas, Nebraska, northern Colorado and northern Utah. Farther south in southeastern Utah and in western and eastern Colorado, gypsum in the Tidwell Member and correlative Ralston Creek Formation was precipitated as evaporite deposits in hypersaline lagoons at the southern margin of the seaway. Elsewhere on the Colorado Plateau, the Tidwell contains lacustrine limestone and mudstone beds that contain charophytes (green algae) and ostracodes, indicating somewhat equable freshwater environments. Locally, however, these lakes were the sites of magadi-type chert accumulation, which reflects highly concentrated lake waters.

Subsequently, the seaway retreated to the northwest into Canada and streams that drained upland regions to the west of the depositional basin carried gravel, sand, and mud eastward, building an extensive alluvial plain, represented largely by the Salt Wash Member and correlative rocks. In central Colorado, scattered low hills that were remnants of the ancestral Rockies, were sufficiently high to support small streams that probably were intermittent in nature and unrelated to the Salt Wash fluvial system. Small lakes and ponds also developed locally on the alluvial plain as well as in the most distal regions in eastern Colorado and eastern Wyoming. During times when the streams went dry in the Colorado Plateau region, winds from the west and southwest removed sand from the dry stream beds and deposited it farther downwind in extensive dune fields that covered large parts of the Four Corners area. These deposits are represented today by the Bluff Sandstone Member and Junction Creek Sandstone Member, as well as the eolian sandstone facies of the Recapture Member. Smaller scattered dune fields also developed farther north in northern Utah, northwestern Colorado, Wyoming, and South Dakota (Unkpapa Sandstone Member on the east side of the Black Hills), and probably formed by deflation of previously deposited shallow marine sands.

During deposition of the upper part of the Morrison Formation, a large stream complex in the Colorado Plateau region (Westwater Canyon and Fiftymile Members) gave way to a large shallow saline, alkaline lake called Lake T'oo'dichi', which covered parts of northwestern New Mexico, northeastern Arizona, southeastern Utah, and southwestern Colorado during deposition of much of the Brushy Basin Member. Although much shallower, Lake T'oo'dichi' had about the same areal extent as Lake Michigan. Judging from similar modern saline, alkaline lakes, the alkalinity of the pore waters would at times have been high enough to cause alkaline burns to human (and possibly dinosaur?) skin. Development of the lake attests to the aridity of the time, as evaporation must greatly exceed precipitation and runoff to achieve the alkalinities and salinities recorded in the mineralogy of the ancient lake deposits. A small amount of surface water entered the lake by intermittent or perhaps perennial streams, but ground water was also an important component of lake hydrology. At times when the lake dried out to form a large pan or salina, flash floods carried sand well out into the lake basin. During times of high evaporation, the waters were too saline and alkaline for most animals to drink.

Throughout most of Morrison time, somewhat fresher water lakes developed east and north of the present-day Front Range of the Rocky Mountains where lacustrine limestone beds that contain a varied fossil assemblage attest to the availability of more potable waters.

Toward the end of Morrison deposition, large fluvial complexes, including the Jackpile Sandstone Member, were locally established as a result of renewed uplift in the highlands west and southwest of the Western Interior. Increased precipitation, especially in the highlands, probably was responsible for the renewed stream activity at this time.

Morrison deposition came to a close with development of a thick fossil soil, indicating a long cessation of deposition toward the end of the Jurassic. The fossil soil, although a useful marker for the top of the Morrison Formation, is only locally preserved because of erosion during the succeeding depositional hiatus and/or by scouring that accompanied deposition of overlying lowermost Cretaceous fluvial strata.

In summary, the habitat for the Late Jurassic dinosaurs was a broad alluvial plain in the rainshadow of highlands that bordered the plain to the west. The presence of large dunefields, evaporites, intermittent streams, and development of a large alkaline, saline lake at various times during Morrison deposition all indicate that the Morrison experienced times of considerable aridity. In spite of the semi-arid to arid climate, life-giving water was delivered to the plain by several means. These included seasonal or intermittent precipitation, perennial and intermittent streams that drained the western highlands, and shallow groundwater that was delivered by aquifers recharged by infiltration in the highlands.

Riparian vegetation was largely supported by water from perennial streams and substream flow within intermittent streambeds. Vegetation on the floodplain had to depend primarily on direct precipitation onto the floodplain (which may have been largely seasonal) and the ability to tap shallow aquifers. The large herbivorous dinosaurs could range across the plain in search of water and vegetation, whereas many of the smaller animals would have found water and shelter in riparian habitats. Scattered lakes and ponds across the alluvial plain supported a variety of aquatic life. Thus, although the Morrison climate was much drier than originally interpreted, the Morrison ecosystem supported a considerable diversity of life, including the largest herbivores that ever lived.

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INTRODUCTION

The Morrison Project began on June 1 of 1990 and lasted for three years, reaching a conclusion on May 31, 1993, when it evolved into the Morrison Formation Extinct Ecosystems Project, which extended from June 1, 1993 to May 31, 1996. Although funding ended in 1996, some of the research continues to the present (December 18, 1998). The goal of the earlier project was an endeavor to determine the fundamental stratigraphy and age of the Morrison Formation in various National Park Service units of the Western Interior, U.S., especially at Dinosaur National Monument, Utah and Colorado. Another important part of that endeavor was to place the various Late Jurassic dinosaur quarries throughout the Western Interior in their relative stratigraphic position so evolutionary aspects and biogeographic diversity of the dinosaurs could be compared, contrasted, and (or) evaluated. Building on that foundation, the Morrison Formation Extinct Ecosystems Project was designed as a multidisciplinary endeavor to determine the nature, distribution, and evolution of the ancient ecosystems that existed in the Western Interior of the United States during the Late Jurassic Epoch when the Morrison Formation and related coeval rocks, such as the Ralston Creek Formation, were deposited. The information obtained from the research can be used to suggest appropriate resource management actions. The project will also provide an improved understanding of the geological and paleontological history of these National Park Service units and better information for interpretive programs and publications.

The Morrison Formation is in the National Park Service's Rocky Mountain Region and also includes a small portion of the Southwestern Region in northwestern New Mexico and western Oklahoma largely. The formation is in the Western Interior physiographic province of the United States and is one of science's best windows onto the world of dinosaurs and Mesozoic ecosystems. Because of its varied environments, rich fossil deposits, extensive rock exposures, and broad geographic distribution, the formation offers an outstanding opportunity for a multi-park, interdisciplinary approach to the evolution of environments, habitats, communities, and climate through some 7 million years (my) of Earth history. The formation covers some 700,000 square miles in the Western Interior (Fig 1) and is world renowned for its rich concentration of dinosaur remains with more than 140 quarries identified to date and new bone accumulations continue to be discovered yearly. The formation also contains locally abundant and diverse fossil plant and other animal communities that were contemporaries of the dinosaurs and that shed light onto the nature of the Late Jurassic ecosystem.

The Morrison Formation and related beds were deposited in a variety of environments in an extensive depositional basin in the Western Interior of the United States and southwestern Canada (Fig. 1). It was deposited primarily by streams that carried their detritus eastward from the Elko Highlands farther west, and northeastward from the Mogollon Slope farther southwest (Figs. 2, 3). The precise structural nature of these highland source regions is unclear but is being studied closely by many geologists in the general scientific community. Marine strata are scarce in the Morrison, being confined to the base of the formation from northern Utah and Colorado northward. However, in northernmost Montana and southwestern Canada, marine rocks are present higher in the Morrison and in related beds in Canada. How the marine beds are related to Late Jurassic oceans is unclear, but the marine strata probably were deposited in a narrow marine embayment that connected with the paleo-oceans to the north through western Alberta and eastern British Columbia. Because the Morrison is truncated by Cretaceous strata around the periphery of the basin outlined in Figure 1, the original extent of the formation is unknown. It is clear from paleocurrent studies in fluvial sandstone beds, however, that Morrison streams in the southernmost part of the region flowed toward the southeast and therefore eventually must have entered the Late Jurassic Gulf of Mexico in central or southern Texas. Another marine embayment in the Chihuahua Trough (Figs. 2, 3) was present in westernmost Texas and adjacent Mexico. It extended into southernmost New

Mexico, but was entirely separated from the Morrison depositional basin by poorly defined lowlands slightly farther north in southern New Mexico.

Throughout most of the region, the proper stratigraphic name is Morrison Formation, but there is one important area where another formation name has been applied to strata that correlate with the lower part of the Morrison elsewhere. We apply the name Morrison Formation to all strata between the J-5 unconformity at the base to the K-1 unconformity at the top as the Morrison is usually recognized throughout a large part of the Colorado Plateau.

In a short 25 km (15 mi) north-south stretch of exposures just west of Denver, Colorado, the Ralston Creek Formation is recognized beneath the Morrison Formation. The Ralston Creek lies on the J-5 unconformity, interfingers at the top with basal beds of the Morrison, and consists largely of strata that cannot be distinguished from the Morrison where a prominent sandstone bed is missing at the base of the overlying Morrison. Because a prominent sandstone bed is not present at the base of the Morrison in many areas north and south from this rather limited part of the outcrop belt, we only recognize Ralston Creek in that limited stretch of exposures just west of Denver.

In some localities in the easternmost part of the Colorado Plateau, some of the lowermost beds of what has been mapped as the Burro Canyon Formation lie below the K-1 unconformity and are logically part of the Morrison depositional sequence. We include these beds in the Morrison Formation and restrict the Burro Canyon Formation to strata above the K-1 unconformity.

Throughout a large part of central Wyoming, many geologists place the upper Morrison contact at the prominent change in clay minerals, from non-smectitic (non-swelling) clays below to predominantly smectitic (swelling) clays above, and include the beds above the clay change in the Lower Cretaceous Cloverly Formation. By bringing the correlations north and northeastward from the Colorado Plateau and southeastward from west-central Montana, we are able to demonstrate that the clay change is within the Morrison Formation and that the proper contact with the Cloverly Formation is significantly higher (by about 30 m or 100 ft) and well within the zone of strata dominated by smectitic clay minerals. We therefore restrict the Cloverly to strata above the K-1 unconformity based on criteria that are discussed in the paper by Turner and Peterson elsewhere in this report.

Strata containing gypsum, red beds, and sandstone in central Iowa are known as the Fort Dodge Formation and are thought to be Late Jurassic in age. Because no means of dating these beds has been discovered, other than their stratigraphic position beneath Lower Cretqceous strata, they remain somewhat enigmatic. There is no physical connection in the subsurface to Jurassic strata in the Western Interior, and the possibility remains that they could be Middle Jurassic in age.

As shown in Figure 1, strata that correlate with the Morrison Formation extend into southern Canada where these rocks are known by entirely different names. From west to east in the northernmost part of Figure 1, these are the upper part of the Fernie Formation, the Morrissey Sandstone, and lower part of the Mist Mountain Formation in southeastern British Columbia and southwestern Alberta; the Swift Formation farther east in southern Alberta; and the Masefield Formation and lower part of the Success Formation in southern Saskatchewan. In southwestern Manitoba, the uppermost beds of the Waskada Formation may correlate with lowermost Morrison strata or, as seems more likely, the entire Waskada may be slightly older and correlate with the Redwater Shale Member of the Sundance Formation in the United States.

Although a study of the Canadian rocks is beyond the scope of this investigation, they are important because they are largely marine in origin and thereby provide additional information on the paleogeographic setting of the Morrison Formation in the northernmost part of the Western Interior. In northern Montana, this helps to explain an anomalous occurrence of marine sandstone beds in about the middle of the Morrison and well above the known marine strata at the base of the formation. Also in Montana, the Canadian marine strata at higher stratigraphic levels suggest that the coal beds in the uppermost part of the Morrison probably were deposited behind a marine shoreline rather than within an isolated inland coal basin.

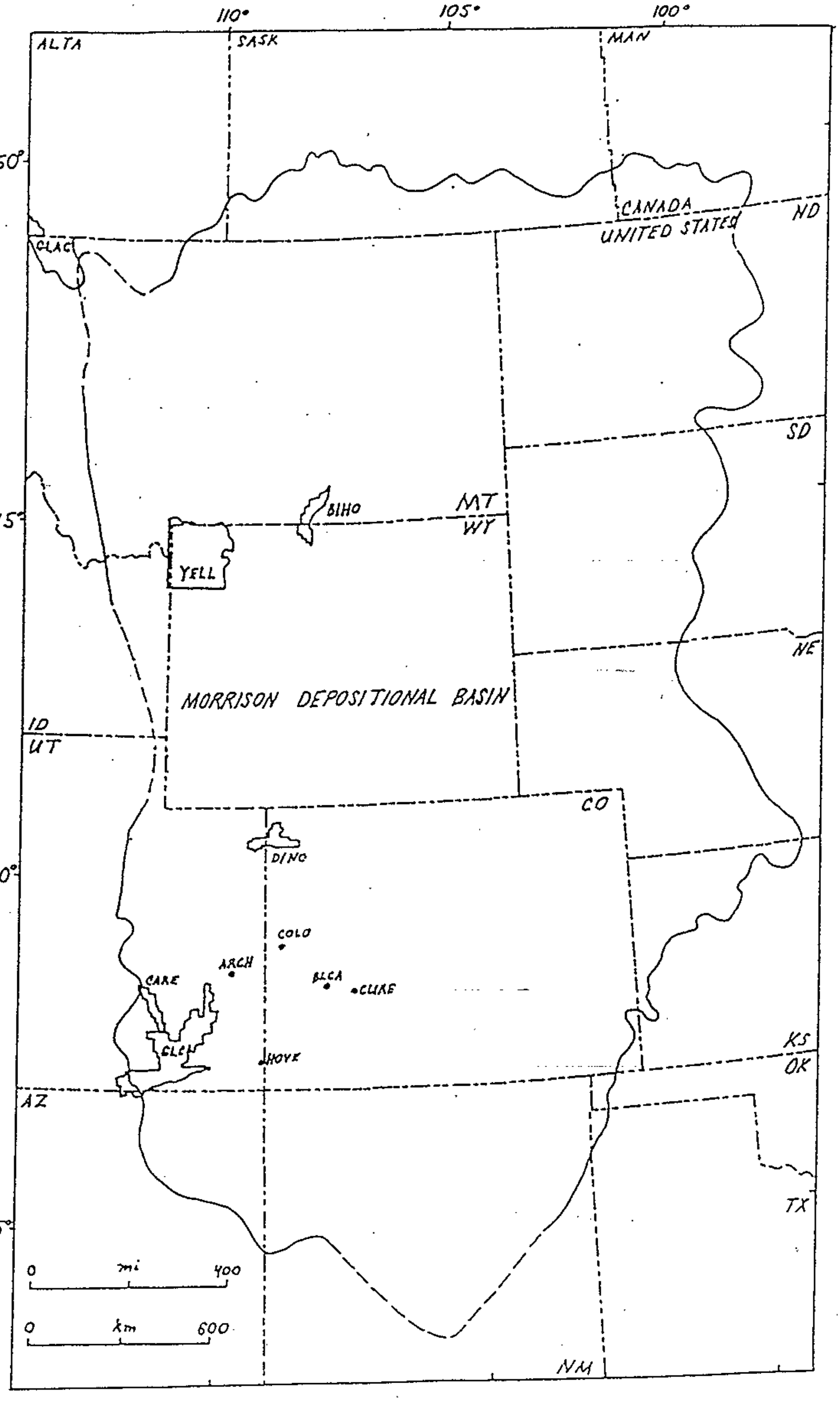
Figure 1.—The Morrison depositional basin in the Western Interior of the United States and southern Canada. Also shown are National Park Service units that contain significant exposures of the Morrison Formation.

ARCH (Arches National Park),
BIHO (Bighorn National Recreation Area),
BLCA (Black Canyon of the Gunnison National Monument),
CARE (Capitol Reef National Park),
COLO (Colorado National Monument),
CURE (Curecanti National Recreation Area),
DINO (Dinosaur National Monument),
GLAC (Glacier National Park),
GLCA (Glen Canyon National Recreation Area),
HOVE (Hovenweep National Monument),
YELL (Yellowstone National Park).

The outline of the Morrison depositional basin is modified from:

Peterson, J.A., 1972, Jurassic System; in, Mallory, W.W. (ed.), Geologic Atlas of the Rocky Mountain Region: Rocky Mountain Association of Geologists, p. 177–189 (map on p. 185).

Poulton, T.P., Christopher, J.E., Hayes, B.J.R., Losert, J., Tittemore, and J., Gilchrist, R.D., 1994, Jurassic and lowermost Cretaceous strata of the western Canada sedimentary basin; in, Mossop, G., and Shetsen, I., (compilers), Geological Atlas of the Western Canada Sedimentary Basin: Canadian Society of Petroleum Geologists and Alberta Research Council, p. 297–316 (map on p. 312).


110°
105°
100°
ALTA
SASK
MAN
50°
45°
40°
35°
CANADA
UNITED STATES
ND
GLAC
SD
BIHO
MT
WY
YELL
NE
MORRISON DEPOSITIONAL BASIN
ID
UT
CO
DINO
COLO
ARCH
CARE
BLCA
CUKE
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KS
OK
AZ
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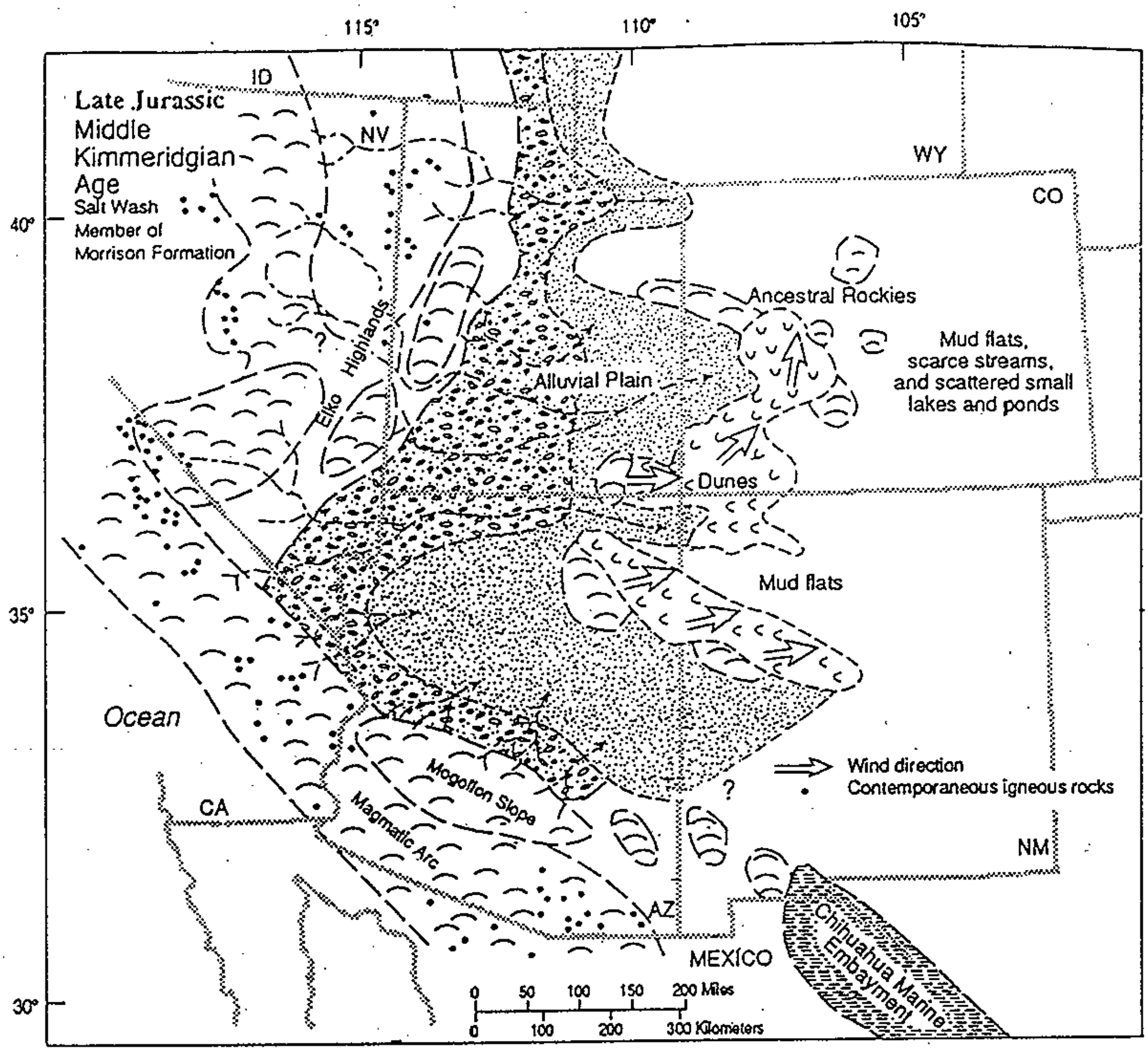
0
mi
400
0
km
600
NM

Figure 1.

Figure 2.—Paleogeography of the southern part of the Western Interior Basin during about middle Kimmeridgian time and deposition of the Salt Wash Member of the Morrison Formation and related beds. Slightly elevated regions within the depositional basin are indicated by broad concave-downward arcs, eolian dunefields are indicated by small concave eastward or northeastward arcs.



115°
110°
105°
40°
35°
30°
Late Jurassic
Middle
Kimmeridgian
Age
Salt Wash
Member of
Morrison Formation
ID
NV
WY
CO
Ancestral Rockies
Mud flats,
scarce streams,
and scattered small
lakes and ponds
Elko Highlands
Alluvial Plain
Dunes
Mud flats
Ocean
Wind direction
Contemporaneous igneous rocks
Mogollon Slope
Magmatic Arc
CA
AZ
NM
MEXICO
Chihuahua Marine Embayment
0 50 100 150 200 Miles
0 100 200 300 Kilometers

Figure 2.

Figure 3.—Paleogeography of the southern part of the Western Interior Basin during about late Kimmeridgian or early Tithonian time and deposition of the upper part of the Brushy Basin Member of the Morrison Formation and related beds. Slightly elevated regions within the depositional basin are indicated by broad concave-downward arcs.

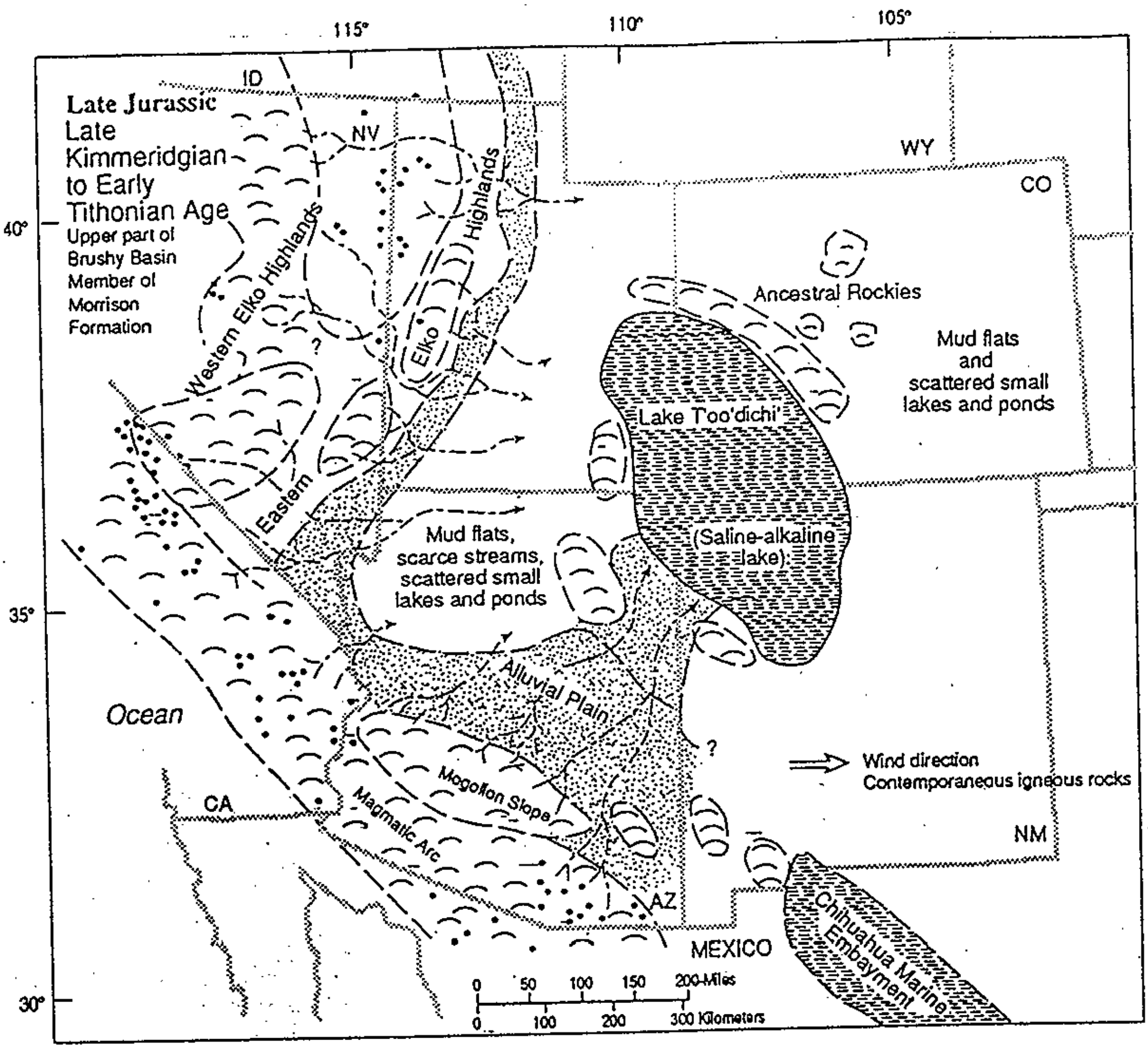

115°
110°
105°
40°
35°
30°
Late Jurassic
Late Kimmeridgian to Early Tithonian Age
Upper part of Brushy Basin Member of Morrison Formation
ID
NV
WY
CO
Western Elko Highlands
Eastern
Elko
Highlands
Ancestral Rockies
Mud flats and scattered small lakes and ponds
Lake Too'dichi'
(Saline-alkaline lake)
Mud flats, scarce streams, scattered small lakes and ponds
Alluvial Plain
Ocean
Mogollon Slope
Magmatic Arc
CA
AZ
NM
MEXICO
Chihuahua Marine Embayment
Wind direction
Contemporaneous igneous rocks
0 50 100 150 200 Miles
0 100 200 300 Kilometers

Figure 3.

STUDY AREA

The Morrison depositional basin covers much of the Western Interior of the United States. Its present-day extent ranges from northern Arizona and northern New Mexico northward to northern Montana and into southern Canada. The Morrison Formation has significant exposures in many units within the Rocky Mountain Region of the National Park Service. These include Arches National Park, Bighorn Canyon National Recreation Area, Black Canyon of the Gunnison National Monument, Capitol Reef National Park, Colorado National Monument, Curecanti National Recreation Area, Devils Tower National Monument, Dinosaur National Monument, Glacier National Park, Glen Canyon National Recreation Area, Grand Staircase-Escalante National Monument (under the jurisdiction of the Bureau of Land Management), Hovenweep National Monument, Wind Cave National Park, and Yellowstone National Park. In addition, the formation is not exposed at the surface but is present beneath approximately 10 other National Park Service units in the Western Interior.

METHODS

The methods employed by the different investigators vary considerably because of the wide variety of specialties involved. However, the overall approach has remained constant in that the investigators pursued their own research studies with the goal of integrating those pursuits with the research of the other investigators to determine various aspects of the Morrison ecosystem.

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RESULTS AND DISCUSSION

SUMMARY OF RESEARCH BY PROJECT SCIENTISTS

The following reports were submitted by the research scientists that have performed the bulk of the work on the project. The conclusions should be considered preliminary although they summarize the current status of knowledge and interpretations that have been generated thus far by the project participants.

MORRISON VERTBRATE PALEONTOLOGY; FINAL REPORT

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ACCOMPLISHMENTS

Several institutions were visited to study their vertebrate collections for comparison and contrast as well as to gain insight into faunal relationships and the evolutionary stage of Morrison vertebrates, chiefly the dinosaurs.

Dinosaur specimens were examined in various institutions in the People's Republic of China while there attending the Sixth International Symposium on Mesozoic Ecosystems and biota that was held in Beijing during late July and early August. The Jurassic theropods there are well preserved but poorly described in the scientific literature so the visit was highly useful in clarifying many concerns and uncertainties about their dinosaurs.

The Yale Peabody Museum in New Haven, Connecticut, was visited to study their collection of dinosaur bones. A new but undescribed theropod that probably came from the Bone Cabin quarry in Wyoming was found in their collections. The theropod is represented only by the proximal half of the humerus and other fragmentary material but the material is sufficient to determine that it is from an exceptionally large carnivore that may have been larger than Saurophaginax, which rivals the better known Tyrannosaurus in size. Also examined was their abundant Allosaurus material, some of which was poorly described in the literature. The skull of one specimen may turn out to be of a new species, presumably of Allosaurus. The pubis and ilium of a Marshosaurus from the Cleveland-Lloyd quarry in Utah was also studied for comparison with other specimens of the same genus elsewhere in the Western Interior.

Theropods from quarries at Como Bluff in Wyoming and now in the collections at the American Museum of Natural History were examined, measured, and photographed. They have material from a very large and undescribed Allosaurid that has a furcula, which is rarely preserved. The type specimen of Epanterias was examined and seems to be from an exceptionally large animal. Examinations were also made of other materials that have been misidentified, and specimens from Tyrannosaurus and similar dinosaurs were examined for comparison with large Jurassic dinosaurs.

The Harvard University Museum of Comparative Zoology was also visited. They have a dwarf Allosaurus(?), possibly a new species, from the Willow Spring quarry in the San Rafael Swell, Emery County, Utah. Unfortunately, the location of the site is unknown although the matrix on the bones seems unique—a light cream-colored matrix of sandstone(?) or a carbonate(?), which might be helpful in relocating the quarry. Also from the same quarry are bones of the Hypsilophodontid, Othnielia rex, plus a small theropod and sphenodonts. This is the same locality where Jensen found a small Othnielia about 2.7-3.7 m (9-12 ft) long. The collections include material of two small dinosaurs including a partial skull that is not yet identified. The museum also has important material from Douglas Draw in the western part of Dinosaur National Monument that was also examined. This consists of parts of the carnivore Deinonichus from the Lower Cretaceous Cedar Mountain Formation.

The collections at Brigham Young University that came from the Dry Mesa quarry in western Colorado were also examined. All of the material is disarticulated and difficult to deal with, but the material is very important because the collection is large and varied.

A specimen collected by John Foster from the Morrison Formation in western South Dakota was brought in and examined. It appears to be from a small Allosaurus that was about 2.1-2.7 m (7-9 ft) long. Although Allosaurus is by far the most common carnivore in the Morrison Formation, the location of this specimen so far east tends to confirm that its biogeographic range was considerable.

Collections at the Carnegie Museum in Pittsburg that originally came from the Carnegie quarry at Dinosaur National Monument were examined, as were Jurassic theropod collections that came from elsewhere.

At Dinosaur National Monument, work continued on preparing, describing, and photographing the new theropod nicknamed "Not-an-Allosaurus" that was recently found there in the Salt Wash Member of the Morrison Formation. Other studies include small teeth that are similar to Cretaceous age theropods (Troödontids?) that have been found in western Europe (England and Portugal). A tentative interpretation is that the animal that is represented by these teeth was widespread by the Late Jurassic although similar material has been found in rocks as old as the Middle Jurassic in England. Work was also done with Tom Williamson (New Mexico Museum of Natural History) on a large Allosaurid from New Mexico.

The collection of Morrison salamanders from Dinosaur National Monument was sent to specialists at the Tyrrell Museum in Canada. Their first impression is that they are rather peculiar, but they are among the first or nearly the first of good Late Jurassic salamander materials known. Tentative thoughts are that they might be "highly aquatic forms", but more study is needed to compare them with other available salamander fossils and their paleoecological preferences.

Other work includes being a co-editor for papers contributed to the forthcoming Special Paper of the Geological Society of America that will be devoted to a myriad of topics about the Morrison Formation and related beds. Most of the papers have been through technical reviews and are now either in the author's hands undergoing revisions per the reviews, or the final manuscripts have already been sent in to the editors. The editors of this important volume are Ken Carpenter (Denver Museum of Natural History), Dan Chure (National Park Service, Dinosaur National Monument), and Jim Kirkland (Dinamation International).

A symposium on the "Evolution and paleobiology of carnivorous dinosaurs" was co-organized and co-chaired by me. It was held as one of the sessions of the annual meeting of the Society of Vertebrate Paleontology and was held in Pittsburg during November, 1995.

In collaboration with other workers (Litwin, Hasiotis, Carpenter, Evanoff), a compilation was made of all known plant and animal fossils that have been recovered from the Morrison Formation anywhere in the Western Interior. The listing will be an important asset for use in analyzing Morrison life forms, associations, and population dynamics in the Morrison ecosystem.

CONCLUSIONS

Preliminary work indicates that the dominant group of theropod dinosaurs from the Morrison Formation belong to the Family Allosauridae. I have been studying a new and relatively primitive allosaurid from the Salt Wash Member of the Morrison that was recently excavated from Dinosaur National Monument. Reexamination of the original material of Saurophaginax (originally named Saurophagus) from the uppermost Morrison of western Oklahoma has established that it is genetically separate from Allosaurus. Thus, at least three genera from Family Allosauridae (the new Salt Wash primitive Allosaurid, Allosaurus, and Saurophaginax) existed during the Late Jurassic in the Western Interior of the United States. The next step is to determine how the localities of these genera correlate biostratigraphically, whether they existed contemporaneously, or if all or some of them are restricted stratigraphically.

Additional study is necessary to more accurately the nature of the vertebrate fauna that existed during deposition of the Morrison Formation in Late Jurassic time. When that is completed, we will be able to interpret the biodiversity and paleobiogeographic distribution of the fauna and relate it to the depositional framework of the formation.

FUTURE WORK

Future research endeavors will be devoted to examining important fossil collections in several institutions, mostly in the United States. Some of the goals are to obtain an understanding of the composition, distribution, variation, paleobiogeography, and biostratigraphy of the vertebrate fauna in the Morrison Formation and related beds.

PUBLICATIONS

Chure, D.J., 1995, The teeth of small theropods from the Morrison Formation (Upper Jurassic, Kimmeridgian) of Utah: Journal of Vertebrate Paleontology, v. 15, Supplement to no. 3, p. 23A.

Chure, D.J., 1995, A reassessment of the gigantic theropod Saurophagus maximus from the Morrison Formation (Upper Jurassic) of Oklahoma, USA: in, Sun, A.L., and Wang, Y.Q., (eds.), Proceedings of the Sixth International Symposium on Mesozoic Ecosystems and Biota: Short Papers, China Ocean Press, Beijing, p. 103-106.

Chure, D.J., in press, Earl Douglass and the discovery of Dinosaur National Monument; in, Gillette, D.D., (ed.), Vertebrate fossils of Utah: Utah Geological Survey publication.

Chure, D.J., in press, Dinosaur National Monument: Science and education in northeastern Utah; in, Gillette, D.D., (ed.), Vertebrate fossils of Utah: Utah Geological Survey publication.

Chure, D.J., in press, Let them eat meat: Carnivorous dinosaurs of the Late Jurassic Morrison Formation, Utah; in, Gillette, D.D., (ed.), Vertebrate fossils of Utah: Utah Geological Survey publication.

Chure, D.J., and Madsen, J.H., Jr., 1996, Variation in aspects of the tympanic pneumatic system in a population of Allosaurus fragilis from the Morrison Formation (Upper Jurassic): Journal of Vertebrate Paleontology, v. 16, p. 63-66. : Journal of Vertebrate Paleontology.

Chure, D.J., and Fiorillo, A.R., 1997, "One Big Al to go and hold the mayo": Evidence of scavenging of a specimen of Allosaurus from the Morrison Formation (Late Jurassic) of Wyoming: : Journal of Vertebrate Paleontology, v. 17, Supplement to no. 3, p. 38A.

Chure, D.J., Britt, B.B., and Madsen, J.H., 1997, A new specimen of Marshosaurus bicentesimus (Theropoda) from the Morrison Formation (Late Jurassic) of Dinosaur National Monument: Journal of Vertebrate Paleontology, v. 17, Supplement to no. 3, p. 38A.

Chure, D.J., Carpenter, K., Litwin, R., Hasiotis, S., and Evanoff, E., 1998, The flora and fauna of the Morrison Formation: Modern Geology, v. 23, nos. 1-4, p. 507-537.

Chure, D.J., and Evans, S.E., 1998, A new occurrence of Cteniogenys, with comments on its distribution and abundance: Modern Geology, v. 23, nos. 1-4, p. 49-56.

Chure, D.J., and Madsen, J.H., 1998, An unusual braincase (?Stokesosaurus clevelandi) from the Cleveland-Lloyd Dinosaur Quarry, Utah (Morrison Formation: Late Jurassic): Journal of Vertebrate Paleontology, v. 18, no. 1, p. 115-125.

Chure, D.J., Fiorillo, A.R., and McIntosh, J.S., in press, The Dinosaur National Monument Mapping Project: An educational and scientific resource; in, Gillette, D.D., (ed.), Vertebrate fossils of Utah: Utah Geological Survey publication.

Chure, D.J., and Madsen, J.H., Jr., in press, Allosaurus: The making of Utah's state fossil; in, Gillette, D.D., (ed.), Vertebrate fossils of Utah: Utah Geological Survey publication.
Chure, D.J., and Madsen, J.H., Jr., in press, On the furcula of Allosaurus: Journal of Vertebrate Paleontology.
Evans, S.E., and Chure, D.J., 1998, Morrison lizards: Structure, relationships, and biogeography: Modern Geology, v. 23, nos. 1-4, p. 35-48.
Evans, S.E., and Chure, D.J., 1998, Paramacellodid lizard skulls from the Jurassic Morrison Formation at Dinosaur National Monument, Utah: Journal of Vertebrate Paleontology, v. 18, no. 1, p. 99-114

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PALEOSOLS IN THE UPPER JURASSIC MORRISON FORMATION—IMPLICATIONS FOR PALEOCLIMATE, PALEOHYDROLOGY, AND SEQUENCE STRATIGRAPHY; FINAL REPORT

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INTRODUCTION

The Upper Jurassic Morrison Formation was deposited in an almost completely terrestrial environmental setting. Paleosols (ancient soils preserved in the sedimentary record) are a very common feature in most Morrison exposures, and, in fact, play a large role in giving the formation its distinctive color-banded appearance. Paleosols, like modern soils, were formed during times of little or no accumulation of sediment. During these times, the land surface and near-subsurface were exposed to chemical and physical weathering processes (dissolution, precipitation, wetting, drying, washing down of particles, etc.) and biological activity (rooting, burrowing, trampling, etc.). All of these processes were mediated and modulated by the local and regional paleoclimate and paleo-groundwater (paleohydrological) conditions. Features within ancient soils, which can be interpreted to have been created by these physical, chemical, and biological soil-forming (pedogenic) processes, can give important clues to what the climate and other environmental conditions were like during their formation. Environmental interpretations from paleosols are especially important given that they record average conditions over a long period of time, in contrast to those made from actively deposited sediments (stream channels, lakes, etc.) that record conditions over comparatively very short (even instantaneous) periods of time.

This study of paleosols in the Morrison Formation was undertaken in cooperation and collaboration with several other workers within the Morrison Research Initiative. Since soils are an intrinsic part of the landscape, paleosols are often found intimately associated with other types of environmentally important sedimentary rocks and with paleontological accumulations. Therefore, the study of the Morrison paleosols was intertwined with the studies of: 1) Trace fossils (behavior of soil-dwelling organisms studied by Steve Hasiotis); 2) Geochemical climatic indicators (carbonate isotope studies of soil nodules investigated by Doug Ekart and Thure Cerling); 3) Stream channels and lakes (detailed by Christine Turner and Dennis Newell); 4) Carbonate deposits in lakes (elucidated by Stan Dunagan); and 5) Large-scale packaging of the sedimentary rocks (stratigraphy by Fred Peterson.)

The following sections will summarize the activities and the type of data used in the study, and briefly relate the results and conclusions. The results are divided into two sections: 1) Floodplain and lake margin paleosols, and 2) Unconformity paleosols.

SUMMARY OF ACTIVITIES AND STUDY AREA

Exposures of the Morrison Formation were examined in the Rocky Mountain and Colorado Plateau regions during the field seasons of 1994-97. These areas in included National Park Service units (Arches National Park, Bighorn Canyon National Recreation Area, Capitol Reef National Park, Colorado National Monument, Dinosaur National Monument, Glen Canyon National Recreation Area) and surrounding areas (Front Range, Purgatoire/Picketwire Canyon, San Rafael Swell, Uinta Mountains, San Juan Basin, Como Bluff, Thermopolis, Greybull, west-central Montana). Paleosols were identified at all of the visited localities. Detailed studies were undertaken at several well-exposed areas including: Purgatoire River (Comanche National Grasslands) area, Canon City area, Fruita/Grand Junction area, San Rafael Swell area, San Juan basin area, and Four Corners area. Paleosols were identified at all stratigraphic intervals within the Morrison Formation.

FLOODPLAIN AND LAKE MARGIN PALEOSOLS

The bulk of the Morrison Formation was deposited in a fully terrestrial setting. Only the basal members of the Morrison in the Front Range, northern Utah, Wyoming, and Montana have significant marine influence (had contact with or connection with ocean environments). The overwhelming proportion of Morrison sedimentary rocks was deposited in streams, lakes, and areas marginal to these settings. Deposition of sediment on the Morrison landscape therefore occurred dominantly at the soil/atmosphere interface. After transport (mostly by rivers, some on the wind) from its source area, the sand, silt and mud that makes up the Morrison eventually reached its final resting place. However, because the Morrison landscape was fully terrestrial, the rate of deposition of this sediment was sporadic in space and time. Sand and silt built up very quickly in stream channels and lake deltas, sometimes accumulating meters of sediment in very short periods, especially during large floods. Areas closer to stream channels were built up with sediment faster than those farther away. In addition, over longer periods of time, sediment was preferentially deposited in areas of the Morrison basin that were subsiding more quickly than others. In areas where sediment is deposited quickly, physical, chemical, and biological processes that create soils (weathering, burrowing, etc.) do not have enough time to produce mature soils (well-developed horizons) because the immature soils are buried before they can be fully developed. Mature soils form in areas where sediment accumulated slowly and was subject to burrowing and mixing by plants and animals (see report by Hasiotis), and fluctuating moisture and chemical conditions, over a longer period of time. Rocks interpreted to have been deposited in floodplain and lake margin environments in the Morrison Formation are characterized by these types of immature and mature paleosols with varying degrees of development, both laterally across the ancient landscape, and vertically through geologic and stratigraphic time.

Most of the floodplain and lake margin paleosols in the Morrison have some type of calcium carbonate accumulation associated with them, either as distinct layers, nodules, or layers of nodules (Bk horizons). In the case of the floodplain paleosols, the carbonate was formed by soil-forming processes, ground-water processes or both. Carbonate accumulates in soils either above the ground-water table due to reprecipitation of dissolved limestone, in some cases biologically mediated, from dust or carbonate sediment from layers above, or at or near the ground-water table due to precipitation from the capillary fringe or upper parts of the ground-water that are saturated with calcium carbonate. In either case, these accumulations formed in the Morrison floodplains at depths less than 3 m (10 ft) below the surface. Many of the carbonate-bearing floodplain soils (calcisols) in the Morrison have layers and nodules that have a complex history of precipitation, dissolution, cracking, brecciation, and recrystallization. However, most of these processes seemed to have occurred in soil-forming or shallow ground-water environments. This is an important observation because the implication is that these carbonate accumulations were formed under geochemical conditions that had CO_2 concentrations with isotopic ratios similar to the Late Jurassic atmosphere, rather than a later deep burial (diagenetic) signature (see report by Ekart and Cerling). The occurrence and distribution of calcisols in the Morrison floodplains suggests that the paleoclimatic and paleohydrologic conditions were characterized by greater evaporation than recharge of shallow ground water, probably in an arid to seasonally dry setting. Marginal lacustrine paleosols also have Bk horizons, although the original source of this carbonate was primary deposition in shallow lacustrine settings or as palustrine carbonates in the shallow subsurface below a fringing wetland (see report of Dunagan). However, subsequent exposure, brecciation, dissolution and reprecipitation of these lake and wetland carbonates in some cases has produced a pedogenic overprint, both in the morphology and geochemistry of the carbonate (see report of Dunagan.)

The Morrison floodplain paleosols also are characterized by at least some degree of subsurface clay accumulation (argillic or Bt horizons). This accumulation occurs above the carbonate, if present, and often is reddish colored and has distinct peds (soil particles and clods) and slickensides (slide planes between soil particles or clods). These clay-rich layers form by the washing down of clay particles from overlying layers in the soil and entrapment in a less porous and permeable layer. Once clay begins to accumulate in these layers, the porosity and permeability are reduced further, and more clay accumulates. Some floodplain paleosols in the Morrison (especially the Salt Wash and lower Brushy Basin Members of the Colorado Plateau region) have distinctive sub-horizontal, slickensided fractures and vertical sand-filled fractures in their Bt horizons. These are termed vertic features and the paleosols thus vertisols. They were formed by repeated wetting and swelling, and drying and shrinkage, of the clays within the soil. The reddish colors in the Bt horizons are due to increased concentrations (Bw and Bs horizons) of iron-bearing minerals (oxides and hydroxides) trapped with the clays and adsorbed onto them. Although these red colors are distinctive, and a great aid to identifying paleosols in the Morrison, they probably are not the original colors of the Jurassic soils. The original soils were most likely brown and dark reddish brown, and burial and geologic time has changed the mineralogy (and therefore the color) of the iron compounds. However, the reddish horizons still reflect the original relative abundance of iron-bearing minerals in the soils, and the horizons they delimit are still valid and identifiable. The accumulation of clay and iron minerals in the Morrison floodplain paleosols suggests that there was significant downward movement of water and finer-grained soil material during soil-forming processes. Although the presence of carbonate in these paleosols indicates drier conditions, the clay- and iron-rich horizons also tells us that wetter conditions prevailed at some times. The co-occurrence of these two types of features in the same paleosols (argillic calcisols), in turn, is good evidence of fluctuating soil moisture conditions that we may interpret as resulting from the seasonality of precipitation (i.e., a rainy season and a dry season). The vertic features also indicate a seasonal soil moisture regime.

Floodplain paleosols in the Morrison preserve a diverse assemblage of trace fossils (see report of Hasiotis). Although plant rooting traces (rhizotubules, rhizoliths, root casts, and rhizocretions) are the most abundant paleosol traces, burrows interpreted to have been formed by insects and other arthropods are commonly found in all horizons in the floodplain paleosols. Upper horizons are characterized by back-filled and meniscate burrows whereas lower horizons have collapsed and infilled chambers. These trace fossils often occur in crudely tiered assemblages; in thick, mature cumulate soils, there is often overprinting of older traces by younger. The type of interpreted trace makers, their diversity, and their interpreted behavior (often opportunistic) support a setting characterized by fluctuating moisture conditions (see report of Hasiotis.)

Paleosols occur at all stratigraphic horizons in the Morrison Formation over the depositional basin. However, there are distinct differences in the type, degree of maturity, and lateral extent of paleosols in each interval and broad paleogeographic region. Paleosols in the lowest members of the Morrison (Tidwell and Windy Hill Members and the Ralston Creek Formation) and the lower Morrison of Wyoming and Montana are typically marginal lacustrine, palustrine calcisols, and weakly developed floodplain argillic calcisols. The carbonate horizons are dominantly ground-water-formed, although there is pervasive and sometimes complete pedogenic overprinting. Argillic horizons are locally present, although not laterally continuous or thickly developed. These paleosols were formed under conditions of relatively high, although fluctuating, ground-water conditions associated with lake levels and regional ground-water discharge. However, the paleoclimate was dominantly dry (semi-arid) and pedogenic carbonate was commonly formed in the soils due to a low precipitation to evaporation ratio (P/E ratio). Lacustrine and palustrine carbonates in marginal lacustrine and fringing wetland areas, exposed during lake-level lowstands, were pervasively pedogenically modified.

The paleosols in the Salt Wash Member and equivalent strata on the Colorado Plateau are typically floodplain argillic calcisols. They are associated with overbank fines laterally equivalent to contemporaneous large braided streams or associated with the abandonment phases of these streams. These paleosols show a range of thickness and maturity. Some paleosols are thin and weakly developed, often buried by a sandy flood deposit, crevasse splay or fluvial channel. Others are thick, mature, and have multiple, stacked Bt/Bk horizons. These simple and cumulate paleosols are distributed across the ancient landscape according to the relative rate of sedimentation on the floodplains. Areas of rapid and periodic deposition are characterized by abundant thin and simple paleosols (entisols), whereas those areas that accumulated slowly and episodically have thick, well-developed, cumulate paleosols. In large outcrops of the Salt Wash Member, a crude stratigraphic progression from braided stream sandbodies with laterally adjacent overbank deposits characterized by thin entisols to overlying muddier intervals characterized by thicker, well-developed argillic calcisols and vertic calcisols is often evident. These progressions are interpreted to be the result of the progradation of the Salt Wash braided channels and channel belts, their inevitable migration and abandonment, and the reoccupation of the area by active river deposition. These progressions, and the lake-level highstand/lowstand progressions in older and contemporaneous deposits, may be linked to larger-scale, and long-term, paleoclimatic cycles.

In the Four Corners and San Juan Basin areas, the lower Salt Wash and Tidwell Members interfinger with the Bluff Sandstone Member-Junction Creek Sandstone Member eolian deposits. In the transitional areas, where Salt Wash fluvial deposits and Tidwell playa deposits are interbedded with eolian sand sheets, paleosols in the Salt Wash and Tidwell are very weakly developed. In some outcrops, thin, deeply penetrating permineralized roots, rhizocretions and rootlets are the only visible evidence of soil formation. Thin gypsum layers (By horizons) are also common in some of the lowest intervals. These paleosols are aridosols and gypsic entisols formed in the fringing area around the dune deposits and playas in an arid paleoclimatic setting.

Paleosols in the lower Brushy Basin Member and Recapture Member in the Colorado Plateau and San Juan Basin areas are typically weakly to well-developed floodplain vertic and argillic calcisols. These paleosols are in floodplains associated with meandering and moderate sinuosity streams. They tend to be, on the whole, better developed than those in the Salt Wash Member, and are the most mature paleosols in the Morrison outside of the unconformity paleosols discussed below. Carbonate nodule horizons are common, as are well-developed Bt horizons and a distinctive, ant- and termite-nest dominated ichnofauna (see report by Hasiotis). Crayfish burrows are also common in paleosols in these intervals (see report by Hasiotis), especially in areas close to contemporaneous channels. The distinctive reddish coloration of these members is due to, among other reasons, the predominance of abundant, stacked Bw/Bs horizons that are present. The time-equivalent Westwater Canyon Member of the Four Corners and San Juan Basin regions also has these types of paleosols, although they are associated with a large braided and moderate-sinuosity stream system, less abundant, and are intercalated with thick, channel- and bar-sandstones.

Paleosols in the upper Brushy Basin Member of the Colorado Plateau region and the upper Morrison of the more eastern portions of the basin are typically weakly developed floodplain entisols and calcisols and weakly developed, non-calcareous marginal lacustrine paleosols. The floodplain paleosols in this interval are associated with thin fluvial channel sandstones deposited by straight and anastomosing streams. The overwhelming abundance of smectitic clays and other products of weathered volcanic ash in this interval suggests that during this time the Morrison basin was periodically blanketed by ash fall deposits blown in from the active volcanic arc to the west and southwest. The relative immaturity and types of paleosols, the types of stream deposits, and the common presence of both large and small lake deposits in the upper part of the Morrison suggests that at this time the landscape was characterized by sluggish, low-gradient streams and playa and perennial lakes. The ground-water tables were higher than those present during either lower Brushy Basin or Salt Wash times, and did not seem to have the same magnitude of fluctuations. However, the Fiftymile Member of the Morrison, present only in the far southwestern portion of the basin, is time-equivalent to this interval and represents a higher gradient/higher energy river system that existed more proximal to the sediment source area. The paleosols in the Fiftymile Member are similar to those associated with near channel environments in the Salt Wash Member. Overall, evidence from the paleosols suggests that conditions in the Colorado Plateau and San Juan Basin regions were wetter during upper Brushy Basin time than those of earlier Tidwell-Salt Wash-lower Brushy Basin-equivalent times.

Paleosols in the upper Morrison Formation in Montana, in and around the Belt-Great Falls coal region, and in the uppermost Morrison in Wyoming and the northern Front Range, formed in wetland environments (peat mires, clastic swamps, marginal lake wetlands). These paleosols are moderately- to well-developed, non-calcareous, and often rich in organic material (gleysols and histosols). The paleoclimatic setting was much wetter than that of any other Morrison interval, was probably humid, and in some cases, everwet.

Overall, floodplain and lake margin paleosols of the Morrison Formation record both regional and temporal paleoclimatic trends. Regional trends are evident both south to north (for example, dry—aridosols and calcisols to wet—histosols and marginal lacustrine entisols) and west to east (for example, dry—vertic calcisols to wet—palustrine and argillic calcisols) in any one stratigraphic interval. In addition, throughout Morrison deposition, evidence suggests that conditions were getting continuously wetter and possibly less seasonal through time.

UNCONFORMITY PALEOSOLS

Unconformity paleosols in the Morrison Formation developed over much longer periods of time than those represented by the floodplain and marginal lacustrine paleosols discussed above. These mature, well-developed paleosols represent relatively large breaks in the stratigraphic record and occur at boundaries between large-scale sedimentary packages in the Morrison. The strata on either side of these horizons were deposited in very different environments and, in some cases, under different paleoclimatic and paleohydrologic conditions, the Morrison world changed drastically over these boundaries. Unconformities were formed in the stratigraphic record by the processes of base-level fall and erosion, by periods of very little or no deposition of sediment, or some combination or succession of both. During these times, previously deposited sediment is either stripped away and transported during landscape degradation (drainage system incision, mass wasting, etc.) or is subject to weathering, soil formation, and the subsurface effects of fluctuating water tables. If little or no erosion takes place, over a long period of time (thousands to tens of thousands of years), under conditions where there is at least some precipitation and vegetation, a well-developed soil will form at the surface and weathering will penetrate at least to the lowest level of the water table. If the time of soil formation is long enough to span changes in climate and vegetation at the surface, the resulting soil may show a complex mixture of younger and older, relict features.

Unconformity paleosols were identified at three horizons in the Morrison Formation: 1) At the base of the formation in the far western (San Rafael Swell, UT) and southeastern (Purgatoire Canyon, CO) portions of the basin; 2) At the boundary between the Salt Wash and Brushy Basin Members on the Colorado Plateau (and equivalent horizons in the San Juan Basin, southern Wyoming, and the Cañon City area); and 3) At the top of the formation at the boundary between Upper Jurassic Morrison rocks and overlying Lower Cretaceous strata in the Colorado Plateau, Front Range, and southern Colorado. The paleosols at each of these horizons have different features that reflect the paleoclimate, biological activity, time of formation, and original parent materials.

Basal Morrison Unconformity

The paleosols at the unconformity at the base of the Morrison in the San Rafael Swell of Utah are well-developed gypsisols and calcisols formed on the underlying Middle Jurassic Summerville Formation. The Morrison Formation thins westward drastically in the San Rafael Swell, especially around Moore, I-70, and the northern portion of Capitol

Reef National Park. The thinning is at the expense of the lower members of the formation; that is, the Salt Wash and Tidwell Members lap onto a surface on the underlying Middle Jurassic strata. The paleosol at this onlap surface is in some places characterized by massive gypsum (By) horizons 0.5-4 m (1.5-13 ft) thick. This gypsum was likely dissolved, reprecipitated, and reworked from underlying gypsiferous playa mudstones in the Summerville Formation by soil formation and fluctuating and rising ground water. The regional paleoclimate shifted from arid-hyperarid during the Middle Jurassic to semi-arid during the early Late Jurassic (early Kimmeridgian), and ground-water tables must have risen enough to remobilize evaporite minerals in Middle Jurassic strata. In the northern Capitol Reef area, the unconformity paleosol exhibits multiple stacked Bk horizons superimposed on fluvial sandstones and lacustrine mudstones in the uppermost Summerville. These Bk horizons are composed of discrete carbonate nodules and continuous and brecciated carbonate layers. These horizons record a complex history of cumulate pedogenesis and ground-water fluctuations that probably occurred over a time span equivalent to that of the time of deposition of the Tidwell and Salt Wash Members to the east. The same horizon in the Purgatoire River canyon region (Comanche National Grasslands) of southeastern Colorado also has a well-developed unconformity paleosol. In this area, the Upper Jurassic Morrison Formation rests unconformably on the Middle Jurassic Bell Ranch (red siltstones and mudstones) and Entrada (thick eolian sandstone) Formations. The Bell Ranch Formation is present only as erosional remnants between areas where the unconformity has cut down to the top of the Entrada. In the areas where the unconformity at the base of the Morrison cuts through the Bell Ranch, there is a thick, very mature paleosol developed in the uppermost portions of the Entrada sandstone. This paleosol (spodosol) is characterized by distinctive red, dark reddish-brown and dark reddish-purple color mottling due to iron-mineral segregation (Bs horizon) along roots and burrows. The paleosol is not present beneath the erosional remnants of Bell Ranch Formation. In many areas in the central and northern part of the Morrison depositional basin, there is little evidence of an unconformity or soil formation at this horizon. Some of these areas (Dinosaur National Monument, northern Front Range) have evidence of marine influence, suggesting that they are regionally down the depositional dip from the paleotopographically higher areas where the unconformity is present.

Middle Morrison Unconformity

The paleosol at the unconformity between the Salt Wash and Brushy Basin Members of the Morrison on the Colorado Plateau is typically a reddish argillic calcisol similar to those in the overlying lower Brushy Basin Member in that it has the same kind of soil horizons and trace fossils. However, the degree of development and lateral extent of this paleosol is much greater than any other identified in the lower Brushy Basin Member. The most distinctive feature of this paleosol is the abundance of termite trace fossils (nests, galleries, and so forth; see report by Hasiotis). Extensive galleries and vertical shafts associated with termite nests are found in the lower portions of this paleosol and are especially well-preserved in uppermost Salt Wash sandstones. Particularly termite-trace-rich areas can be found in and around the Fruita Paleontological Area, Colorado National Monument, and Arches National Park. However, the most spectacular examples are from the equivalent horizon in the Morrison in the San Juan Basin near Fort Wingate, NM. In this area, the same unconformity paleosol is present at the boundary between the Recapture and Westwater Canyon Members of the Morrison. Giant termite nests are preserved below the unconformity in Recapture sandstones (see report by Hasiotis.) The same horizon is even traceable into the southern Front Range area, near Cañon City, CO. In the Garden Park Paleontological Area near Cañon City, a horizon rich in termite nests is present in sandstones in the uppermost lower Morrison, below a moderately-developed argillic calcisol in the lowermost upper Morrison (also the site of the Marsh-Felch dinoaurr quarry). This unconformity paleosol is probably equivalent to a distinctive, laterally continuous, pedogenically-modified, palustrine-lacustrine limestone in the Como Bluff, Casper and Thermopolis areas of southern and central Wyoming (locally called the "Great Caliche"). However, in these areas, there are no large fluvial or eolian sandstone beds in the lower Morrison and the depositional environments were dominantly lake and lake margin in both the upper and lower Morrison just above and below the unconformity. In this case, the unconformity paleosol represents a regional lake-level lowstand, exposure of lake sediments, and extensive modification due to soil-forming processes. In northern Utah and the Dinosaur National Monument area, there is large-scale incision at this horizon, where lower Morrison-Salt Wash strata are truncated, channeled, and reworked into regional paleovalleys. Undoubtedly, this horizon represents a significant change is fluvial style, ground water, and paleoclimate throughout the Morrison depositional basin. The depth, abundance, and intensity of burrowing associated with this paleosol, along with the degree of maturity of the Bt/Bk horizons, suggest that the basin underwent a long period (thousands of years?) of very low sediment deposition and local stream incision during the time of soil formation.

Uppermost Morrison Unconformity

The unconformity paleosol at the top of the Morrison Formation is a complex composite paleosol that was formed under the depositional, paleoclimatic, and paleohydrologic conditions of the latest Jurassic and then was subsequently modified by Early Cretaceous paleoclimatic and paleohydrologic processes. This thick paleosol complex is incompletely preserved due to extensive and deep erosional truncation beneath Cretaceous fluvial sandstone beds. The paleosol is only preserved on drainage divides within the Cretaceous regional drainage system. Where the paleosol is preserved (San Rafael Swell, Arches National Park, southern Front Range, Purgatoire Canyon), it is a thick (3-10 m or 10-33 ft), very distinctive, reddish and yellowish color-mottled unit. The coloration is due to extensive redistribution of iron minerals within the paleosol. These features (ferruginous nodules, iron and clay depleted zones) suggest alternating saturated and well-drained (hydroximorphic and redoximorphic) conditions during soil formation. There is no pedogenic carbonate associated with these paleosols. However, in the San Rafael Swell and surrounding Colorado Plateau exposures, there are massive and nodular carbonate horizons (calcretes) in this paleosol complex. These carbonate horizons seem to be early diagenetic and ground-water features that formed during the Early Cretaceous and have overprinted the Jurassic features (see reports of Skipp and Ekart and Cerling.) The well-developed paleosol complex (hydroximorphic gleysol) at the top the Morrison was formed under wetter conditions than any of the paleosols in the lower portions of the formation. The paleosol complex formed under dominantly saturated soil moisture conditions (with periodic drying out) and low sedimentation rates. These paleosols, along with the histosols and gleysols preserved in the uppermost Morrison in the Front Range foothills, Wyoming, and Montana record the beginning of the paleoclimatic shift from seasonally dry to semi-arid conditions that characterized most of Morrison time to the humid, wetter conditions that were soon to come in the Cretaceous.

Sedimentary Sequences

The unconformity paleosols in the Morrison Formation can be used to separate out two, large-scale sedimentary sequences. The Morrison between the lower unconformity paleosol and the middle Morrison unconformity paleosol comprises the lower of these sequences. In the central and northern Colorado Plateau region, this includes the Tidwell and Salt Wash Members; in the San Juan Basin it includes the Bluff/Junction Creek and Recapture Members, and in the Front Range foothills and Wyoming it includes the lower Morrison lacustrine units. These units represent an aggradational to progradational sequence set. Morrison strata above the unconformity paleosol in the middle of the formation comprise the second sequence. This sequence set includes the lower and upper parts of the Brushy Basin Member and the Westwater Canyon, Jackpile, and Fiftymile Members. Both of these sequence sets are capped by unconformity paleosols that represent relatively long periods of little or no deposition at the end of the aggradational/progradational episodes. Deposition of these two large-scale packages in the Morrison were probably controlled by tectonic and regional paleoclimatic changes due to the evolution of the island arc/subduction/foreland basin system that existed to the west of the depositional basin.

SUMMARY

Soils were an intrinsic part of the Morrison landscape and paleoecosystem. The paleosols exposed in outcrops of the Morrison contain excellent records of the long-term paleoclimatic and paleohydrologic conditions during the Late Jurassic. Floodplain and lake margin paleosols that formed over tens to thousands of years show evidence that most of the Morrison basin was characterized by a semi-arid paleoclimate with fluctuating ground-water conditions, a low precipitation to evaporation ratio, but with at least some seasonal precipitation. Trace fossils within these ancient soils are evidence of a diverse and opportunistic flora and fauna that took advantage of the changing conditions and existing nutrient and moisture regimes. Changes in paleosol type and degree of development over the Western Interior depositional basin indicate that the overall regional paleoclimate was drier in the western and southern portions of the basin. Changes vertically through the Morrison indicate that paleoclimatic conditions over the basin became steadily more humid through time. Finally, laterally continuous, well-developed, deeply weathered paleosols formed during times of little or no deposition and mark regional unconformities that can be traced across the basin.

APPENDIX

INTRODUCTION

The interval designations that are used here refer to subdivisions of the Morrison Formation as recognized best on the Colorado Plateau, and correlative units elsewhere. From top to bottom, these are:

9. Upper contact of the Morrison Formation. The K-1 unconformity or, in some places, the K-2 unconformity, whichever surface is present at the top of the Morrison.
8. Uppermost part of Brushy Basin Member. Includes the Jackpile Sandstone Member in the southern Colorado Plateau (San Juan Basin) and correlative but unnamed uppermost Morrison fluvial complexes elsewhere.
7. Upper part of Brushy Basin Member from the clay change to the base of the uppermost Morrison fluvial sandstone beds. Includes the middle and upper fluvial sandstone parts of the Westwater Canyon Member in the eastern Colorado Plateau and upper fluvial sandstone beds of the Fiftymile Member in south-central Utah (Kaiparowits Plateau).
6. Lower part of the Brushy Basin Member. Extends from the top of the Salt Wash Member to the clay change. At the top, includes the lowermost fluvial sandstone beds of the Westwater Canyon Member in the eastern Colorado Plateau, the lower mudstone and fluvial sandstone beds of the Fiftymile Member in south-central Utah (Kaiparowits Plateau), and the uppermost part of the Recapture Member in the southern Colorado Plateau.
5. Upper fluvial complex of the Salt Wash Member in the western Colorado Plateau or the upper "rim" of the Salt Wash in the eastern Colorado Plateau. Includes correlative beds of the uppermost Tidwell, Bluff Sandstone, and Junction Creek Sandstone Members where some lower strata of the upper fluvial complex pinch out. Includes correlative strata in the Recapture Member in the southern Colorado Plateau.
4. Middle fluvial sandstone and mudstone complex of the Salt Wash Member in the western Colorado Plateau or the middle dominantly mudstone unit in the eastern Colorado Plateau. Includes correlative beds in the Tidwell Member where the lower beds of the Salt Wash pinch out. Includes correlative beds in the Tidwell, Bluff Sandstone, and Junction Creek Sandstone Members where the fluvial sandstone beds in the lower Salt Wash fluvial complex pinch out. Includes correlative strata in the Recapture Member in the southern Colorado Plateau.
3. Lower fluvial complex of the Salt Wash Member in the western Colorado Plateau or the lower "rim" of the Salt Wash in the eastern Colorado Plateau. Includes correlative beds in the Tidwell, Bluff Sandstone, and Junction Creek Sandstone Members where the fluvial sandstone beds in the lower Salt Wash fluvial complex pinch out. Includes correlative strata in the Recapture Member in the southern Colorado Plateau.
2. Tidwell Member where it is beneath the lower fluvial complex or lower rim of the Salt Wash Member. Includes lowermost fluvial sandstone beds of the Salt Wash where those strata lie directly on the J-5 surface in south-central Utah (Kaiparowits Plateau). Includes lowermost beds of the Bluff Sandstone and Junction Creek Sandstone Members on the Colorado Plateau and the Swift Formation in northern Wyoming and Montana. Includes correlative strata in the lowermost part of the Recapture Member in the southern Colorado Plateau.
1. The basal contact surface of the Morrison Formation and correlative rocks, also known as the J-5 surface.

LOCALITY: CHURCH ROCK (CR), NEW MEXICO

Intervals 5-6

Data: Paleosol between Westwater Canyon and Recapture Members.
Interpretation: Deep (thick) weathering horizon developed on Recapture eolian deposits marked by termite nests and deeply penetrating complete bioturbation. Equivalent unconformity paleosol to top Salt Wash sequence boundary in UT/CO; climate below was arid, wetter but seasonal above.

LOCALITY: CAÑON CITY (CC), COLORADO

Intervals 5-6

Data: Paleosol between upper and lower Morrison; at level of Felch Stego Quarry.
Interpretation: calcic vertisol with deep penetrating termite and crayfish burrows. Possibly equivalent unconformity paleosol to top Salt Wash sequence boundary in UT/CO; semi-arid to seasonal climate

Intervals 7-8

Data: Lacustrine facies at Cope Quarry sites; lacustrine mudstones capped by small deltas and terminal splay facies (formerly interpreted as channels).
Interpretation: Upper Morrison (especially dino quarry facies) characterized by shallow lacustrine systems; wetter but still seasonal climate.

Interval 9

Data: Thick weathering horizon below Lytle Formation.
Interpretation: Very mature hydroximorphic paleosol (gleysol); incipient laterization; wet climate

LOCALITY: FRUITA (F) AND GRAND JUNCTION (GJ), COLORADO

Interval 2

Data: Interbedded lacustrine mudstones, limestones, sandstone.
Interpretation: Shallow lake system, flucuating lake level, small deltas, terminal splays; semi-arid climate

Intervals 3, 4, 5

Data: Bar-dominated and channel-dominated fluvial sandstones interbedded with floodplain and lacustrine mudstones, lacustrine limestones.
Interpretation: Braided stream system interacting with lacustrine system, fluctuating lake levels and sediment supply; semi-arid to seasonal climate.

Intervals 5-6

Data: Paleosol at top of Salt Wash Member-base of Brushy Basin Member.
Interpretation: Calcic vertisol with deep penetrating termite nests; unconformity/sequence-bounding paleosol; semi-arid to seasonal climate.

Interval 6

Data: Thin fluvial sandstone beds interbedded with floodplain paleosols.
Interpretation: High-sinuosity streams, well-drained floodplains (calcic vertisols); seasonal climate.

Interval 7

Data: Thin ribbon sandstone beds interbedded with lacustrine mudstone, entisols.
Interpretation: Straight-anastomosing streams, poorly-drained floodplains, abandoned channel ponds, lacustrine margin; semi-arid to seasonal climate.

Intervals 8-9

Data: Stacked paleosols.
Interpretation: Low-sedimentation rate, composite paleosols, increasing hydroximorphism; increasingly wetter climate.

LOCALITY: MORRISON (M), COLORADO (INCLUDING HIGHWAY I-70 AND WEST ALAMEDA PARKWAY ROADCUTS)

Intervals 2-3

Data: Lacustrine mudstones and thin sandstones.
Interpretation: Lake, lake margin, small deltas, terminal splays; high ground-water table/fluctuating lake levels; seasonal, possibly semi-arid climate.

Intervals 4,5,6

Data: Fluvial sandstones, floodplain mudstones.
Interpretation: High-sinuosity streams, well-drained floodplain (calcic vertisols); seasonal climate.

Interval 9

Data: Weathering horizon below Lytle Formation.
Interpretation: Mature vertisol with hydroximorphic overprint; unconformity/sequence-bounding paleosol; wet climate.

LOCALITY: PARK CREEK RESERVOIR (PCR), COLORADO

Intervals 2,3,4

Data: Interbedded lacustrine limestones, mudstones; thin marginal marine/marine mudstones (rare Gryphea sp.).
Interpretation: Shallow lake system with some sporadic marine/brackish-water connection; semi-arid climate

LOCALITY: PICKETWIRE CANYON (PW), COLORADO

Interval 1

Data: Thick weathering horizon on top of Entrada Sansdtone at base of Morrison Formation.
Interpretation: Very mature spodosol with intense hydroximorphic alteration; unconformity/sequence bounding paleosol; evidence of erosional truncation of Middle Jurassic Bell Ranch Formation; semi-arid to possibly seasonal climate, shows effect of positive relief/better drainage though.

Intervals 8-9

Data: Stacked lacustrine mudstones, limestones, well-developed paleosols capped by thick weathering horizon below Lytle Formation.
Interpretation: Low-sedimentation rate, fluctuating lake levels, capped by unconformity/sequence-bounding paleosol; increasingly wetter climate.

LOCALITY: BLUFF (BL), UTAH

Intervals 5-6

Data: Interbedded fluvial/eolian sandstones, floodplain mudstones.
Interpretation: Marginal eolian-fluvial system, fluctuating ground-water table, well-drained floodplain (calcic vertisols, aridosols); semi-arid to possibly seasonal climate, evidence of possibly extreme climatic swings (drier/wetter)

LOCALITY: CLEVELAND-LLOYD QUARRY CL), UTAH

Intervals 8-9

Data: Stacked mature paleosols, interbedded conglomeratic sandstones.
Interpretation: Decreasing sedimentation rates, some incision and backfilling of fluvial channels, capped by very mature hydroximorphic paleosol at unconformity/sequence boundary with Lower Cretaceous Buckhorn Conglomerate of the Cedar Mountain Formation; increasingly wetter climate.

LOCALITY: (H) HANNA, UTAH

Intervals 2,3,4,5

Data: Lacustrine to marginal marine mudstones, thin ripple cross-laminated sandstones.
Interpretation: Regressive sequence from tidal flat to lake, lake margin, terminal splays/deltas; soils increasingly mature and well-drained (possibly capped by Sequence Boundary paleosol?); seasonal but possibly semi-arid climate.

Intervals 6-7, 8?

Data: Floodplain and lacustrine mudstones, ribbon and thin sheet sandstones.
Interpretation: Mixed high to low sinuosity (and possibly anastomosed) streams and marginal lacustrine system; both well-drained and poorly-drained paleosols (vertisols, gleysols, and entisols); seasonal to possibly wetter climate.

LOCALITY: HATT RANCH (HR), UTAH

Intervals 8-9

Data: Stacked well-developed paleosols overprinted by massive but local calcrete/silcrete.
Interpretation: Slow and decreasing sedimentation rates, vertic to hydroximorphic paleosols, subsequent alteration by Latest Jurassic/Early Createaceous soil-forming processes; last Morrison paleosol is unconformity/SB; increasingly wetter climate.

LOCALITY: MOORE CUTOFF (MC), UTAH

Intervals 2,3,4,5

Data: Braided-stream sandstones, floodplain/lacustrine mudstones and limestones.
Interpretation: Condensed (onlapped?) Salt Wash/Tidwell interval marginal to main clastic pathways; semi-arid to seasonal climate.

Interval 6

Data: Point bar, levee, crevasse splay sandstones and weak to moderately developed floodplain paleosols with deeply penetrating termite and ant nests.
Interpretation: High-sinuosity streams, mostly well-drained floodplains, fluctuating ground-water table; seasonal climate.

Intervals 8-9

Data: Stacked moderately- to well-developed paleosols capped by very mature weathering horizon overprinted by patchy calcrete/silcrete below Lower Cretacceous Buckhorn Conglomerate Member of the Cedar Mountain Formation.
Interpretation: Composite paleosols in uppermost part of Brushy Basin (mostly floodplain mudstones) capped by mature hydroximorphic gleysol, subsequent alteration by Latest Jurassic/Early Cretaceous soil and ground-water processes; increasingly wetter climate.

LOCALITY: SHOOTARING CANYON (SC), UTAH

Intervals 3,4,5

Data: Stacked, broad, braided stream channels with thin overbank/floodplain splays and paleosols.
Interpretation: Proximal braided stream system, flashy discharge, well-drained paleosols with diverse rooting and burrowing (termites, crayfish), moderately fluctuating water tables, constructive but low floodplain sedimentation rates, avulsion-dominated; semi-arid to seasonal climate.

LOCALITY: ARMINTO (AR), ALSO CALLED BAKER CABIN, WYOMING

Intervals 2-7

Data: Interbedded mudstones and sandstones, thin limestones, poorly- to moderately-developed paleosols and palustrine limestones.
Interpretation: Dominantly lacustrine deposition, fluctuating lake levels with small low-stand fluvial and deltaic/splay complexes; seasonal climate.

Intervals 8-9?

Data: Organic-rich mudstones.
Interpretation: Shallow lake and wetlands, histosols; wet climate.

LOCALITY: COMO BLUFF (CB), WYOMING

Intervals 2-5?

Data: Interbedded lacustrine mudstones, limestones, thin sandstones.
Interpretation: Dominantly lacustrine deposition with fluctuating lake levels, subsequent exposure surfaces, palustrine and wetland paleosols, and thin low-stand splays and fluvial complexes; the "great caliche" is an extensive, pedogenically-modified lacustrine exposure surface possibly equivalent to the top of the Salt Wash Sequence Boundary unconformity paleosol in Colorado and Utah; seasonal climate, but with cyclic/episodic drier intervals.

Intervals 6-8

Data: Mostly lacustrine and some floodplain mudstones.
Interpretation: Dominantly clastic lacustrine deposition with minor low-stand splays and fluvial systems; Nail Quarry etc. are in marginal/shallow lacustrine settings, possibly associated with low-stand exposure surfaces; seasonal climate, possibly increasingly wetter.

LOCALITY: GREYBULL (GB), WYOMING

Intervals 2-5

Data: Thin sandstones, lacustrine and floodplain mudstones.
Interpretation: Low gradient fluvial system, mixed high and low sinuosity streams, well-drained soils; seasonal climate, but sporadic calcrete/silcrete horizons indicate episodic drier intervals.

Intervals 6-8

Data: Lacustrine and floodplain mudstones, thin sandstones.
Interpretation: Lacustrine and low-stand fluvial/deltaic splays; poorly drained soils and wetlands; seasonal but increasingly wetter climate.

LOCALITY: SYKES MOUNTAIN (SM), WYOMING

Intervals 2-5

Data: Interbedded sandstones, floodplain mudstones, organic-rich lacustrine mudstones.
Interpretation: Low-gradient fluvial system, poorly- to moderately-drained floodplains, abandoned channel ponds; seasonal climate.

Intervals 6-8

Data: Floodplain and lacustrine mudstones, thin sheet and ribbon sandstones.
Interpretation: Moderately- to poorly-developed soils and marginal lacustrine exposure surfaces (palustrine deposits); increasingly wetter climate.

LOCALITY: THERMOPOLIS (TP), WYOMING

Intervals 6-8

Data: Lacustrine mudstones, thin splay sandstones.
Interpretation: Lake and lake margin environments; seasonal to increasingly wetter climate.

LOCALITY: BRIDGER (B), MONTANA (ALSO CALLED MOTHER'S DAY QUARRY)

Intervals 2-5

Data: Interbedded thin sandstones, lacustrine mudstones, rippled silty sandstones.
Interpretation: Marginal lacustrine to brackish/marine mudflat/sandflat; semi-arid to seasonal climate.

Intervals 6-8

Data: Fluvial sandstones, floodplain and lacustrine mudstones.
Interpretation: Low-gradient fluvial system controlled by fluctuating but shallow lakes; lacustrine margin splays, palustrine limestones and wetland deposits; seasonal but increasingly wetter climate.

LOCALITY: BOULDER RIVER (BR), MONTANA

Intervals 6-8

Data: Lacustrine and palustrine limestones and mudstones.
Interpretation: Grouond-water-fed lake system, extensive exposure alteration; seasonal to possibly wetter climate.

LOCALITY: BELT (BT), MONTANA
Intervals 6-8

Data: Thick coal seams, organic-rich lacustrine mudstones.
Interpretation: Mire and everwet swamp and lake system; very wet climate or perennially high water table

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LACUSTRINE CARBONATE DEPOSITS IN THE UPPER JURASSIC MORRISON FORMATION OF THE WESTERN INTERIOR; FINAL REPORT

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INTRODUCTION

Lacustrine deposits serve as valuable archives of continental paleoecology, paleohydrology, and paleoclimatology on a fine temporal scale; however, this is one aspect of the Upper Jurassic Morrison Formation which has yet to be utilized. This study represents the first systematic, regional-scale investigation of lacustrine carbonate deposits in the Morrison Formation, focusing on the well-developed lacustrine complex in east-central Colorado. The results of this investigation will provide a framework for future studies and interpretations of the Morrison Formation throughout the Western Interior, wherever lacustrine carbonate deposits occur.

SUMMARY OF ACTIVITIES

Ten detailed stratigraphic sections of the Morrison Formation were measured and described over the 1996 and 1997 field seasons in east-central Colorado along the Colorado Front Range. In the primary study, the lacustrine strata corresponds to stratigraphic intervals 3-7. Reconnaissance sections were also examined in selected National Park Service (NPS) units including Bighorn Canyon National Recreation Area, Colorado National Monument, Curecanti National Recreation Area, Dinosaur National Monument, and Dinosaur Ridge National Historic Site. Other Morrison exposures were examined in portions of Colorado (Fruita, Glenwood Springs), Wyoming (Arminto, Como Bluff, Greybull, Thermopolis), Montana (Bridger, Belt, Gibson Reservoir), and Utah

(Cleveland-Lloyd Quarry, Hanna, Moore Cutoff). The lacustrine strata from these additional localities correspond to stratigraphic intervals 2-7.

RESULTS

Lacustrine Depositional Environments

The Morrison lacustrine succession represents a complex vertical sequence of complete and incomplete cycles of multiple lake formation and filling, with the marginal lacustrine deposits reflecting the dynamic interplay between open lacustrine and adjacent alluvial sedimentation (Figure 1). An idealized Morrison lake was characterized by a relatively ìdeeperî open lacustrine setting surrounded by a wide marginal lacustrine zone that laterally passed into adjacent alluvial environments. The lacustrine depositional facies in the Morrison Formation are subdivided into two facies associations - open lacustrine and marginal lacustrine. These lacustrine facies associations are further subdivided into 11 microfacies based on field observations and detailed petrographic observations (Table 1).

The abundance of shallow-water carbonate deposits with low detrital contents and extensive lake margin facies is consistent with lakes dominated by low-energy, low-gradient ërampí-type margin settings (sensu Platt and Wright, 1991); ooid grainstone and cross-stratified peloid-skeletal packstone to grainstone facies were locally present along wave-influenced margins. Oscillations in lake level resulted in the exposure of large areas of the lake margin. This marginal lake area is subdivided into an inner and outer zone. The inner marginal area was characterized by higher clastic contents, an abundance of packstone to grainstone carbonate facies, and locally high-energy regimes. Pedogenic activity, vegetative reworking, and meteoric diagenesis modified lacustrine fabrics through processes such as rooting, mottling, pseudomicrokarst, desiccation and pedogenic crack formation, and microkarst on carbonate substrates in both the inner and outer marginal lacustrine zones. Modification was more intense in the inner zone. The outer marginal lake setting had lower clastic inputs and low-energy regimes with associated carbonate microfacies.

The presence of open lacustrine facies does not imply deposition in a deep-water body with a permanently stratified water column even though this facies association occupied the most distal portion of the lacustrine system. On the contrary, these lacustrine deposits locally display pseudomicrokarst and desiccation cracks suggesting deposition in a lake that was shallow even in its open areas. The paucity of well-defined laminations with significant bioturbation suggests oxygenated bottom waters and indicates that the lakes were probably polymictic to holomictic. The general absence of well-preserved fish remains is also a good indicator of holomictic lakes (Freytet and Plaziat, 1982; Elder and Smith, 1986). The mudstone and wackestone textures suggest predominantly low-energy sedimentation.

Paleoecology

A diverse biota was present in Morrison carbonate lakes and ponds. Body fossils include charophytes (calcified stems and gyrogonites), ostracodes, spongillids, unionid bivalves, gastropods (prosobranch and pulmonate), microbialites, and conchostracans; bone fragments indicate crocodiles, dinosaurs and fish were present. Trace fossil evidence also suggests the presence of insects, crustaceans, plants, and dinosaurs.

Based on paleontologic evidence, east-central Colorado contained numerous perennial to ephemeral lakes and ponds that were predominately freshwater. Perennial lacustrine conditions are suggested by the presence of prosobranch gastropods, unionid bivalves, and fish remains, where restricted faunas such as conchostracans and pulmonate gastropods dominate, ephemeral conditions are indicated. Mild currents, probably driven by winds over the shallow lakes, are also suggested due to the presence of unionid bivalves and spongillids in Morrison lakes.

The freshwater nature of Morrison lakes and ponds is demonstrated by the abundance of freshwater ostracodes and charophytes, with salinity ranges typically <9 ‰ (Schudack et al., in press). Magadi-type cherts indicated that the lakes experienced periods of high alkalinity (high pH > 9.0-9.5; Eugster and Jones, 1968; Hay, 1968; Eugster, 1969), which was probably due to high productivity associated with charophyte photosynthesis. These cherts are, however, restricted to the lower Morrison Formation and their association with microbialites and freshwater ostracodes and charophytes indicates highly alkaline but not necessarily saline conditions.

The presence of unionid bivalves, prosobranch gastropods, and fish remains suggest that Morrison lake deposits experienced at least temporary periods where the lakes were hydrologically-open. However, as lake systems develop, changes in extrinsic and intrinsic factors such as climate, morphology, tectonics, and drainage systems may result in an evolution of their hydrologic balance.

Paleohydrology

The three potential water sources for Morrison lakes and ponds were meteoric water, spring discharge, and groundwater. Direct precipitation onto lake surfaces and runoff from streams comprised the majority of the meteoric input into Morrison lakes. The paucity of lacustrine deltaic deposits suggests that these streams were probably ephemeral due to dry climatic conditions. Climate models for the Western Interior during the Late Jurassic also suggest dry conditions with yearly precipitation rates of <500 mm and net precipitation minus evaporation (P–E) near zero (Moore et al., 1992; Valdes and Sellwood, 1992). These climatic conditions resulted from the probable rainshadow associated with the Mesocordilleran high and the breakdown of the Pangean monsoon (Parrish, 1993a, b). Based on paleontological evidence, many Morrison lakes apparently experienced hydrologically-open conditions, at least periodically; hence, a meteoric source would have contributed only a relatively modest amount to the water budget of Morrison lakes and not enough to maintain the necessary perennial lacustrine conditions.

Spring water discharge into lakes is typically associated with travertine or tufa deposits and coated grains. Coated grains and travertine deposits were observed in the Morrison Formation near Belt, Montana; hence, in the northern portion of the Morrison depositional system such spring discharges may have influenced lacustrine hydrology and carbonate sedimentation. However, tufas and other spring-related deposits were not observed in the primary study area and spring discharge is not considered as a factor in the hydrological budget of Morrison lakes.

Groundwater seepage from paleoaquifers (i.e., the Navajo Sandstone, Entrada Formation, or the Salt Wash Member of the Morrison Formation) and/or from a high groundwater table into topographic lows, represents an important potential water source. In the westernmost Colorado Plateau, recharging paleoaquifers would have had a greater hydraulic head due to tectonic uplift and these paleoaquifers would have transported groundwater 100ís of kilometers, potentially elevating the water table east of the Ancestral Rockies and seeping into paleotopographic lows. Evidence for a high groundwater table is present in the abundance of gleyed open- and marginal-lacustrine deposits; burrow depths for some trace fossils are shallower in east-central Colorado as opposed to the Colorado Plateau, also suggesting a higher water table. The presence of fossil wood and rhizoliths from siliciclastic and carbonate deposits also indicates a water table high enough to permit plant growth despite prevailing aridity. Based on the low meteoric input and the lack evidence for springs, prevailing climatic conditions, and biotic requirements, Morrison lakes appear to have been primarily groundwater-fed.

Paleoclimate

Climate models and sedimentologic evidence from the Colorado Plateau suggest that the Late Jurassic Morrison paleoecosystem was dominated by semi-arid to arid conditions.

Controversy over these climatic interpretations has arisen due to apparently conflicting paleofloral interpretations, which suggest a humid and subtropical climate for the same area. While climatically sensitive lacustrine carbonates are not volumetrically significant, they are present throughout the Morrison deposystem and they provide a high resolution record of subtle Late Jurassic climatic and hydrologic changes. Marginal lacustrine carbonates are characterized by numerous indicators suggesting that lake margins were repeatedly subjected to exposure. These features include: abundant pseudomicrokarst and microkarst features with vadose and internal sediment fills; root traces, columnar and stacked rhizoconcretions, and Microcodium; circumgranular, desiccation, horizontal, and septarian cracks; brecciation and grainification; and rare blackened pebbles. Pedogenic carbonate commonly displays evidence of multiple cycles of nodule breaking, healing and re-cracking. Minor pseudomorphs after evaporites (gypsum and ?trona) and evaporite nodules (gypsum) are present in lacustrine and palustrine carbonates; bedded evaporite deposits are restricted to the lower Morrison in the southeastern Colorado.

Overall, the terrestrial carbonate record suggests that the Morrison paleoecosystem east of the Ancestral Rocky mountains was dominated by semi-arid conditions during deposition of the lowermost Morrison, with evaporitic playas in the southeast and freshwater to alkaline lakes to the north. Exposure indicators in palustrine deposits indicate that the majority of the lacustrine complex was deposited under a climate transitional between semi-arid and semi-humid, with distinct dry and wet periods (seasonal?). Lake hydroperiods estimated using a freshwater exposure index ranged from approximately 80-320 days (Figure 2).

Stable Isotope Geochemistry

To date 61 stable oxygen and carbon isotope analyses have been performed on primary lacustrine (micrite) and pedogenic carbonate phases (Figure 3A), with the values are reported relative to the PDB standard. The open lacustrine carbonates range in $\delta^{13}C$ from –

2.5 to –4.3 ‰ and in $\delta^{18}O$ from –8.3 to –9.9 ‰. Pedogenic carbonates also display a homogeneous isotopic composition ($\delta^{13}C$ = –4.6 to –5.7 ‰; $\delta^{18}O$ = –9.2 to –11.0 ‰). The marginal (palustrine) carbonates ($\delta^{13}C$ = –2.5 to –8.8 ‰; $\delta^{18}O$ = –8.2 to –12.9 ‰) show an increase in isotopic heterogeneity as compared to the open lacustrine and pedogenic carbonate.

Primary carbonate from hydrologically-open lakes display little to no covariance between $\delta^{13}C$ and $\delta^{18}O$, whereas covariance is common in hydrologically-closed lakes ($r \geq 0.7$; Talbot and Kelts, 1990; Talbot, 1990). Morrison primary carbonates from open and marginal lacustrine facies display no covariance ($r < 0.2$-0.3), suggesting hydrologically-open lakes. The wide range of $\delta^{13}C$ values of Morrison primary carbonate is a function of organic productivity in the lake waters (McKenzie, 1985), with more positive $\delta^{13}C$ values for lake carbonates deposited during periods or in areas of high productivity and more negative values when or where productivity is lower. A plot of the spatial distribution of lacustrine isotopic compositions suggests organic productivity varied geographically (Figure 3B), with higher organic productivity in lakes from the northern and southern exposures. The presence of pseudomicrokarst in marginal lacustrine carbonates also suggests pedogenic processes may have played a critical role in altering the isotopic composition due to contact with isotopically light soil-derived CO_2.

SUMMARY

The Morrison paleoecosystem was characterized by numerous low-gradient and low-energy, shallow-water, perennial and ephemeral carbonate lakes and ponds. The paleolakes were holomictic to polymictic conditions and were fed by high groundwater tables that discharged into paleotopographic lows. A diverse invertebrate biota was present in the carbonate lakes and ponds of the Morrison paleoecosystem, including charophytes, ostracodes, sponges, unionid bivalves, gastropods, microbialites, conchostracans; insects, crayfish, plants, fish, crocodiles, and dinosaurs. Overall, the lacustrine carbonate record suggests that the Morrison paleoecosystem in Colorado was dominated by semi-arid conditions during deposition of the lowermost Morrison (stratigraphic intervals 3-7), with evaporitic playas in the southeast and freshwater to alkaline-saline lakes to the north. Exposure indicators in palustrine deposits indicate that the majority of the lacustrine complex was deposited under a climate transitional between semi-arid and semi-humid, with distinct dry and wet periods (seasonal?) and lake hydroperiods that ranged from approximately 75-320 days.

PUBLICATIONS

Dunagan, S.P., In preparation, Controls on lacustrine and palustrine carbonate deposition within a Late Jurassic paleoecosystem, the Morrison Formation (Colorado, USA): Journal of Sedimentary Research, 49 pages, 8 figures, 4 tables.

Dunagan, S.P., In preparation, Constraining paleoclimate and paleohydrology within a Late Jurassic paleoecosystem: Insights from the terrestrial carbonate record (Morrison Formation, USA): Sedimentology, 20 pages, 4 figures, 1 table.

Dunagan, S.P., In preparation, Late Jurassic Magadi-type cherts from the Morrison Formation (Colorado): Implications for paleolimnology and hydrogeochemistry: Journal of Sedimentary Research, 22 pages, 9 figures, 1 table.

Dunagan, S.P., In preparation, Paleosynecology and paleolimnology of perennial to ephemeral carbonate lakes and ponds from the Morrison Formation (Upper Jurassic, Colorado, USA): Palaeogeography, Palaeoclimatology, Palaeoecology, 36 pages, 5 figures, 1 table.

Dunagan, S.P., 1998, Insights into Late Jurassic paleohydrology and paleoclimatology from palustrine and lacustrine carbonates of the Morrison Formation, Colorado, USA: Fifth International Symposium on the Jurassic System, Vancouver, British Columbia, 1 p.

Dunagan, S.P., In review, A North American freshwater sponge (Eospongilla morrisonensis, new genus and species) from the Morrison Formation (Upper Jurassic): Journal of Paleontology, 18 pages, 5 figures.

Dunagan, S.P., In review, Lacustrine carbonates of the Morrison Formation (Upper Jurassic), Western Interior, USA; in, Gierlowski-Kordesch, E., and Kelts, K., (eds.), Global Geological Record of Lake Basins: American Association of Petroleum Geologists Memoir, v. 2, 10 pages, 3 figures.

Dunagan, S.P., 1997, Jurassic freshwater sponges from the Morrison Formation, U.S.A.: Southeastern Section, Geological Society of America, Abstracts with Program, v. 29, no. 3, p. 14-15.

Dunagan, S.P., Demko, T.M., Driese, S.G., and Walker, K.R., 1996, Lacustrine and palustrine carbonate facies of the Morrison Formation (Upper Jurassic): Implications for paleoenvironmental reconstructions: Geological Society of America, Abstracts with Programs, v. 28, no. 6, p. 336.

Dunagan, S.P., Driese, S.G., and Walker, K.R., 1997, Paleolimnological implications of Magadi-type cherts from lacustrine carbonate in the Morrison Formation (Upper Jurassic), Colorado, U.S.A.: Geological Society of America, Abstracts with Program, v. 29, no. 6, p. 270.

REFERENCES CITED

Eugster, H.P., 1969, Inorganic bedded cherts from the Magadi area, Kenya: Contributions to Mineralogy and Petrology, v. 22, p. 1-31.

Freytet, P, and Plaziat, J.-C., 1982, Continental Carbonate Sedimentation and Pedogenesis—Late Cretaceous and Early Tertiary of Southern France: Contributions to Sedimentology No. 12, p. 213.

Hay, R.L., 1968, Chert and its sodium-silicate precursors in sodium-carbonate lakes of East Africa: Contributions to Mineralogy and Petrology, v. 17, p. 255-274.

Moore, G.T., Hayashida, D.N., Ross, C.A., and Jacobson, S.R., 1992, Paleoclimate of the Kimmeridgian/Titonian (Late Jurassic) world: I. Results using a general circulation model: Palaeogeography, palaeoclimatology, and palaeoecology, v. 93, p. 113-150.

Parrish, J.T., 1993a, Climate of the supercontinent Pangea: Journal of Geology, v. 101, p. 215-233.

Parrish, J.T., 1993b, Mesozoic climates of the Colorado Plateau; in, Morales, M., (ed.), Aspects of Mesozoic Geology and Paleontology of the Colorado Plateau: Museum of Northern Arizona Bulletin 59, p. 1-11.

Platt, N.H., and Wright, V.P., 1991, Lacustrine carbonates: Facies models, facies distribution, and hydrocarbon aspects; in, Anadon, P., Cabrera , Ll., and Kelts, K., (eds.), Lacustrine Facies Analysis: International Association of Sedimentologists, Special Publication No. 13, p. 57-74.

Schudack, M.E., Turner, C.E., and Peterson, F., in press, Biostratigraphy, paleoecology, and biogeography of charophytes and ostracodes from the Upper Jurassic Morrison Formation, Western Interior, USA: Modern Geology, v. 22, nos. 1-4, p. 379-414. .

Talbot, M.R., and Kelts, K., 1990, Paleolimnological signatures from Carbon and Oxygen isotopic ratios in carbonates from organic carbon-rich lacustrine sediments; in, Katz, B.J., (ed.), Lacustrine Basin Exploration—Case Studies and Modern Analogs: p. 99-112.

Talbot, M.R., 1990, A review of the paleohydrological interpretation of carbon and oxygen isotopic ratios in primary lacustrine carbonates: Chemical Geology, v. 80, p. 261-279.

Valdes, P.J., and Sellwood, B.W., 1992, A palaeoclimate model for the Kimmeridgian: Palaeogeography, Palaeoclimatology, and Palaeoecology, v. 95, p. 47-72.

APPENDIX

INTRODUCTION

The interval designations that are used here refer to subdivisions of the Morrison Formation as recognized best on the Colorado Plateau, and correlative units elsewhere. From top to bottom, these are:

9. Upper contact of the Morrison Formation. The K-1 unconformity or, in some places, the K-2 unconformity, whichever surface is present at the top of the Morrison.
8. Uppermost part of Brushy Basin Member. Includes the Jackpile Sandstone Member in the southern Colorado Plateau (San Juan Basin) and correlative but unnamed uppermost Morrison fluvial complexes elsewhere.
7. Upper part of Brushy Basin Member from the clay change to the base of the uppermost Morrison fluvial sandstone beds. Includes the middle and upper fluvial sandstone parts of the Westwater Canyon Member in the eastern Colorado Plateau and upper fluvial sandstone beds of the Fiftymile Member in south-central Utah (Kaiparowits Plateau).
6. Lower part of the Brushy Basin Member. Extends from the top of the Salt Wash Member to the clay change. At the top, includes the lowermost fluvial sandstone beds of the Westwater Canyon Member in the eastern Colorado Plateau, the lower mudstone and fluvial sandstone beds of the Fiftymile Member in south-central Utah (Kaiparowits Plateau), and the uppermost part of the Recapture Member in the southern Colorado Plateau.
5. Upper fluvial complex of the Salt Wash Member in the western Colorado Plateau or the upper "rim" of the Salt Wash in the eastern Colorado Plateau. Includes correlative beds of the uppermost Tidwell, Bluff Sandstone, and Junction Creek Sandstone Members where some lower strata of the upper fluvial complex pinch out. Includes correlative strata in the Recapture Member in the southern Colorado Plateau.
4. Middle fluvial sandstone and mudstone complex of the Salt Wash Member in the western Colorado Plateau or the middle dominantly mudstone unit in the eastern Colorado Plateau. Includes correlative beds in the Tidwell Member where the lower beds of the Salt Wash pinch out. Includes correlative beds in the Tidwell, Bluff Sandstone, and Junction Creek Sandstone Members where the fluvial sandstone beds in the lower Salt Wash fluvial complex pinch out. Includes correlative strata in the Recapture Member in the southern Colorado Plateau.
3. Lower fluvial complex of the Salt Wash Member in the western Colorado Plateau or the lower "rim" of the Salt Wash in the eastern Colorado Plateau. Includes correlative beds in the Tidwell, Bluff Sandstone, and Junction Creek Sandstone Members where the fluvial sandstone beds in the lower Salt Wash fluvial complex pinch out. Includes correlative strata in the Recapture Member in the southern Colorado Plateau.
2. Tidwell Member where it is beneath the lower fluvial complex or lower rim of the Salt Wash Member. Includes lowermost fluvial sandstone beds of the Salt Wash where those strata lie directly on the J-5 surface in south-central Utah (Kaiparowits Plateau). Includes lowermost beds of the Bluff Sandstone and Junction Creek Sandstone Members on the Colorado Plateau and the Swift Formation in northern Wyoming and Montana. Includes correlative strata in the lowermost part of the Recapture Member in the southern Colorado Plateau.
1. The basal contact surface of the Morrison Formation and correlative rocks, also known as the J-5 surface.

LOCALITY: PARK CREEK RESERVOIR (PCR)

Intervals 3-7

Just above the Windy Hill Member to about 27 m below the top of the formation.

Data

Centimeter to meter-scale interbeds of limestones, green mudstone and "clean" massive sandstones; the limestones have microbialite (i.e. stromatolite) biostromes to bioherms (30-50 diameter; up to 30 cm thick; 7-14 cm of relief) and microbial laminates; magadi-type cherts are associated with the stromatolites; limestone skeletal components include ostracodes, gyrogonites, charophyte stems, unionid bivalves, rare gastropods; a crocodile jaw (sandstone), probable fish remains (limestone), and other vertebrate remains (limestone & sandstone) are also present; limestones display rare diffuse laminations (of physical origin) and abundant 'intermediate-type' pseudomicrokarst (sensu Platt and Wright, 1992); pseudomicrokarst increases upsection.

Interpretation

Well-developed lacustrine succession is present that is characterized by relatively shallow open lacustrine limestones (microbialites and laminated skeletal mudstone-packstone) and marginal lacustrine deposits (limestones with abundant pseudomicrokarst, massive green mudstones, and siltstones/sandstones). The lake had a low-energy, low gradient 'ramp'-type geometry (sensu, Platt and Wright, 1991), whereby minor lake level fluctuations resulted in extensive exposure of the marginal lacustrine deposits to reworking from vegetation and pedogenic activity. The presence of magadi-type cherts in intervals 3-4 indicates alkaline lake waters; a relative increase in the abundance and intensity of pseudomicrokarst up-section may indicate decreasing production of accommodation space within the basin; open lacustrine facies (lakes) are present only in the lower intervals; carbonate and clastic ponds dominated the upper intervals. Best constrained lake depth estimate = <10m; best gut-feeling = 3-5 m (tops!) because even the open lacustrine deposits show minor signs of storm reworking and minor exposure features/pseudomicrokarst. The 'intermediate-type' pseudomicrokarst is typical of a climate transitional between semi-arid and semi-humid.

LOCALITY: MORRISON (M)

Intervals 6-7

Non-smectitic, lower part of Brushy Basin Member and equivalent rocks.

Data

Centimeter to meter-scale interbeds of limestones, green mudstone and massive sandstones; skeletal components in the limestones include ostracodes, gyrogonites, charophyte stems, unionid bivalves, gastropods (prosobranchs), and rare conchostracans; rare bone fragments (dinosaur vs. fish???), plant tissue fragments, mm-scale meniscate burrows and Microcodium in the limestones; limestones display abundant 'intermediate-type' pseudomicrokarst (sensu Platt and Wright, 1992).

Interpretation

Well-developed lacustrine succession displaying relatively shallow open lacustrine limestones (microbialites) to marginal lacustrine limestones with abundant pseudomicrokarst, massive green mudstones, and sandstones. Lake was characterized by a low-energy, low gradient 'ramp' geometry, whereby minor lake level fluctuations resulted in extensive exposure of the marginal lacustrine deposits to reworking from vegetation and pedogenic activity. Minor open lacustrine facies (small lakes) are present only in the lower intervals; carbonate and clastic ponds dominated the upper intervals.. The carbonate lake sequence is capped by dinosaur-bearing fluvial sandstones and red to olive overbank mudstones.

LOCALITY: CAÑON CITY (CC)

Intervals 3-7

Depending on where you are, Skyline Drive, Marsh-Felch quarry, or Cope's Nipple, this interval includes the lower unit of Salt Wash Member up to about the smectitic upper part of the Brushy Basin Member.

Data

Centimeter to meter-scale interbeds of limestones, green mudstone, and sandstones; the limestones locally display diffuse bioturbated laminations; Magadi-type cherts are present in limestones in intervals 3-5; ostracodes, gyrogonites, charophyte stems, unionid bivalves, gastropods (prosobranchs and pulmonates); fish remains (limestone), other vertebrate remains (limestone & sandstone); limestones display 'intermediate-type' pseudomicrokarst (sensu Platt and Wright, 1992), which increases in abundance and intensity upsection; the clay or marl content of the limestones also increases upsection; ripple marked sandstones occur interbedded with mm-cm scale gypsum beds, which infill teepee structures; calcareous siltstones contain fern and other plant fragments and conchostracans.

Interpretation

Well-developed lacustrine succession with a relatively shallow open lacustrine limestones to marginal lacustrine limestones, massive green mudstones, and sandstones; meandering fluvial channels were present. The lake was, like the others, characterized by a low-energy, low gradient 'ramp' geometry, where minor lake level fluctuations exposed the margin to vegetative and pedogenic reworking. The presence of Magadi-type cherts in intervals 3-4 indicates alkaline lake waters; open lacustrine facies (lakes) are present only in the lower intervals; carbonate and clastic ponds dominated the upper intervals. 'Intermediate-type' pseudomicrokarst is typical of a climate transitional between semi-arid and semi-humid. Same paleobathymetry as PCR.

LOCALITY: PICKETWIRE CANYON (PW)

Intervals 3/4-7

Lower to middle Salt Wash to about upper smectitic Brushy Basin Member.

Data

A 25 m thick gypsum-red mudstone complex is capped by a "silicified limestone" and is overlain by centimeter to meter-scale interbeds of limestones, green mudstones, and sandstones; the limestones locally exhibit diffuse to bioturbated laminations; Magadi-type cherts are also present in limestones in intervals 3-4; ostracodes, gyrogonites, charophyte stems, unionid bivalves, gastropods (prosobranchs and pulmonates); minor ooids; possible fish and other vertebrate remains present; limestones display 'intermediate-type' pseudomicrokarst (sensu Platt and Wright, 1992).

Interpretation

Well-developed lacustrine sequence with a relatively shallow open lacustrine limestones to marginal lacustrine limestones, massive green mudstones, and sandstones; meandering fluvial channels were present. The lake was, like the others, characterized by a low-energy, low gradient 'ramp' geometry, where minor lake level fluctuations exposed the margin to vegetative and pedogenic reworking. The presence of Magadi-type cherts in intervals 3-4 indicates alkaline lake waters; open lacustrine facies (lakes) are present only in the lower intervals; carbonate and clastic ponds dominated the upper intervals. Ooids are rare and were likely transported from the "nearby" ooid shoal at the Purgatoire Trackway. 'Intermediate-type' pseudomicrokarst is typical of a climate transitional between semi-arid and semi-humid. Same basic paleobathymetry as PCR.

LOCALITY: FRUITA (F)

Intervals 3-4 (?)

Lower to middle unit of the Salt Wash Member and equivalent rocks.

Data

Limestone with Magadi-type chert, ostracodes, and gyrogonites; 'intermediate-type' pseudomicrokarst (sensu Platt and Wright, 1992) present.

Interpretation

Magadi-type cherts indicate alkaline lacustrine setting while the presence of ostracodes and gyrogonites suggest that hydrogeochemistry did not evolve into saline conditions. The presence of pseudomicrokarst suggests frequent exposure of lacustrine margins with subsequent modification by vegetation and pedogenic activity. 'Intermediate-type' pseudomicrokarst is typical of a climate transitional between semi-arid and semi-humid.

LOCALITIES: AR, B, CB, CL, DNM, GR, GW, AND MC

AR Arminto-Baker Cabin (not Alcova Reservoir)
B Bridger-Mother's Day Quarry
CB Como Bluff
CL Cleveland-Lloyd Quarry
DNM Dinosaur National Monument
GR Gibson Reservoir
GW Glenwood Springs
MC Moore Cutoff (not Montezuma Canyon)

Data

Limestones with various charophytes fragments ± microbial laminates, plant fragments, and ostracodes; many limestones are characterized by significant pseudomicrokarst and other exposure features.

Interpretation

Numerous "freshwater" lakes and ponds were presence across the Morrison depositional plain. It appears that the greatest concentration of these carbonate lakes and ponds occupied present-day east-central Colorado, northeastern New Mexico, western Oklahoma, and southern Wyoming.

REFERENCES CITED

Platt, N.H., and Wright, V.P., 1991, Lacustrine carbonates: Facies models, facies distribution, and hydrocarbon aspects; in, Anadon, P., Cabrera , Ll., and Kelts, K., (eds.), Lacustrine Facies Analysis: International Association of Sedimentologists, Special Publication No. 13, p. 57-74.

Platt, N.H., and Wright, V.P., 1992, Palustrine carbonates and the Florida Everglades: Towards an exposure index for the fresh-water environment?: Journal of Sedimentary Petrology, v. 62, no. 6, p. 1058-1071.

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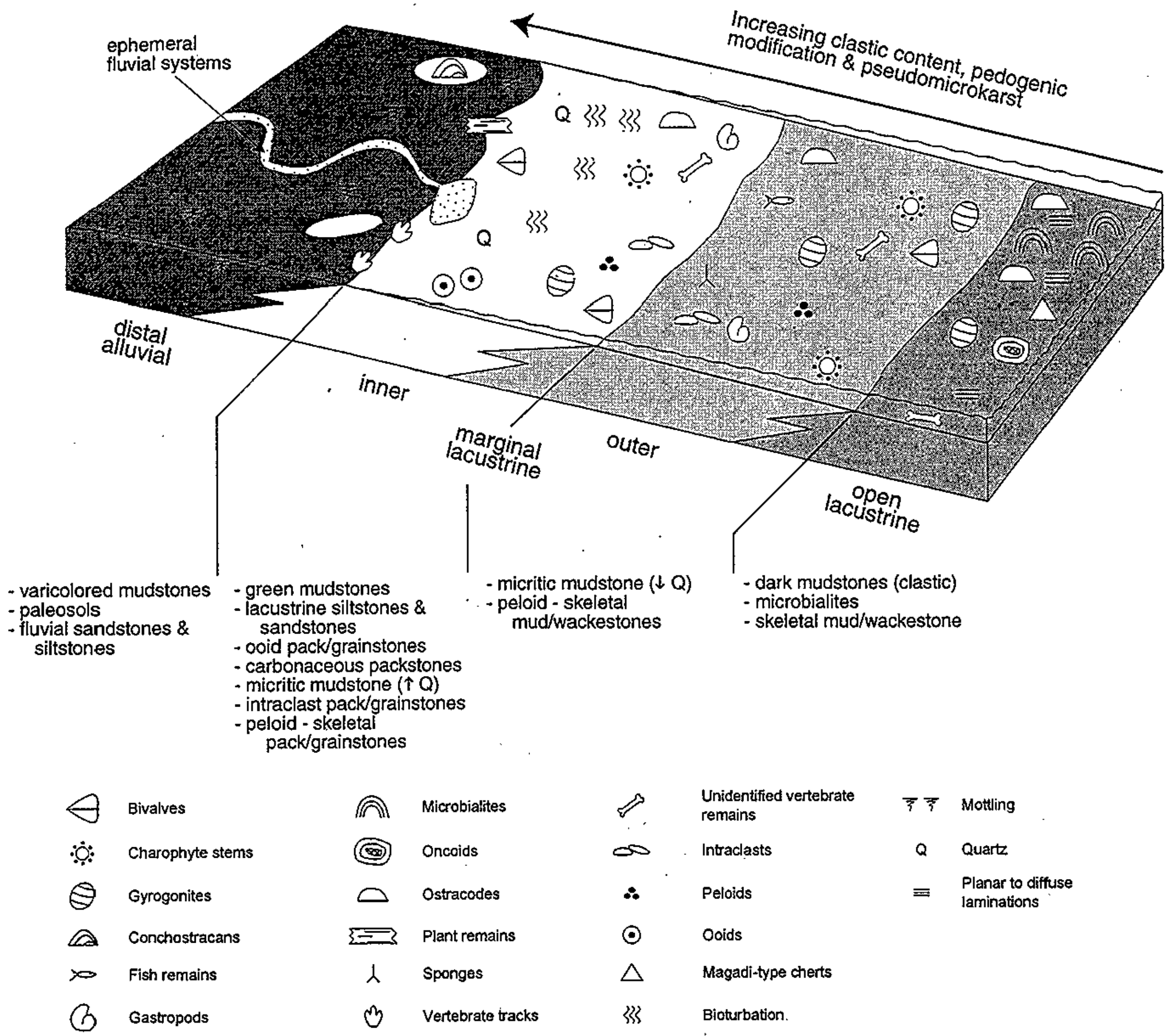


Figure 1. Schematic block diagram of the lacustrine facies relations for the Morrison Formation. The hypothesized vertical relationships for the open lacustrine, marginal lacustrine, and distal alluvial facies are also shown. Not to scale.

Table 1.—Microfacies from the open and marginal lacustrine facies associations. Note that the presence of pseudomicrokarst as an exposure indicator indicates complex fills of vadose silt, micritic clasts, and calcite cement.

Lacustrine Facies Associations	Microfacies	Biota	Exposure Indicators	Other depositional Features
Open	skeletal mudstone-wackestone	gyrogonites, ostracodes, gastropods (prosobranch and pulmonate), fish bone, algal & microbial filaments	minor to moderate pseudomicrokarst	minor intraclasts and detrital quartz; Magadi-type cherts; diffuse to bioturbated laminations
	microbialites	stromatolites, algal and cyanobacterial filaments, oncoids, gyrogonites, ostracodes, fish bone	minor to moderate pseudomicrokarst; minor desiccation cracks	minor intraclasts and detrital quartz; Magadi-type cherts; diffuse to bioturbated laminations; composite microbial biostromes (planar, wrinkled, laterally-linked, and columnar stromatolites
	mudstone (clastic)		rare desiccation crack (?)	dark with laminations and minor detrital quartz silt
Marginal	carbonaceous packstone	plant fragments (xylem and cortical vascular tissue), minor gastropods	minor pseudomicrokarst	diffuse laminations, pyrite
	intraclast wackestone - grainstone	gyrogonites, ostracodes	pseudomicrokarst (moderate to intense); brecciation, grainification, & circumgranular cracks; illuviated clays	peloids and green mudstone rip-up clasts; rare dark intraclasts; minor ooids and volcanic shards; chert; detrital quartz; pyrite
	micritic mudstone	rare unionid bivalves, ostracodes, gyrogonites	pseudomicrokarst (moderate to intense); root traces; brecciation, grainification, & circumgranular cracks; calcrete	starved ripples of detrital quartz & peloids; pseudomorphs after gypsum and trona; plant fragments, detrital quartz, volcanic shards, & pyrite
	ooid packstone - grainstone	unionid bivalves, ostracodes, & bone	microkarst	minor ripples marks; dinoturbation & trackways; nuclei composed of quartz, bone, ooids, and bioclasts
	peloid skeletal mudstone - wackestone	charophytes (stems & gyrogonites), ostracodes, unionid bivalves, sponges, gastropods	pseudomicrokarst (moderate to intense); root traces, alveolar texture, & circumgranular cracks; subaerial exposure surfaces	rare plant fragments, oncoids, & bone debris (fish & reptile); blackened intraclasts; minor green mudstone rip-up clasts; Magadi-type cherts; pseudomorphs after gypsum; pyrite; detrital quartz
	peloid skeletal packstone - grainstone	charophyte stems & gyrogonites, unionid bivalves, ostracodes	pseudomicrokarst (moderate to intense), illuviated clays	minor cross-laminations; alternating grainstone and packstone laminae; pseudomorphs after gypsum; Magadi-type cherts; intraclasts; pyrite; detrital quartz
	green mudstone	gyrogonites & gastropods; rare unionid bivalve, bone, & ostracode fragments	red to purple mottles; carbonate nodules with septarian and circumgranular cracks	structureless to massive; detrital quartz silt and sand with rare lithic fragments; carbonate nodules
	siltstone	plant debris, ostracodes conchostracans, & bone fragments		laminations; detrital quartz sand
	sandstone	plant & bone fragments (crocodile jaw)	teepee structures	bioturbated; traces infilled with green mudstone; rare gypsum interbeds (<4 cm thick) & symmetrical ripple marks

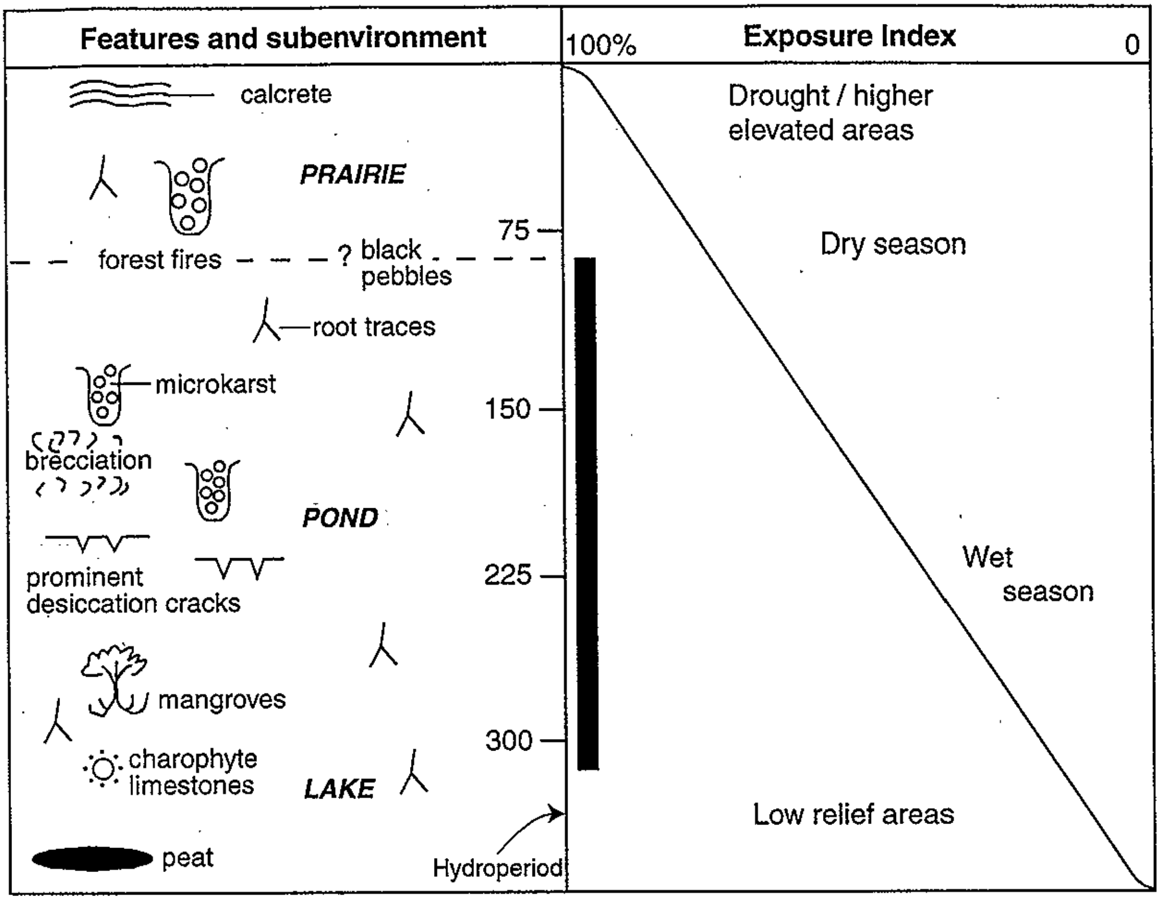


Figure 2. Estimated hydroperiod for Morrison carbonate ponds and lakes. Based upon features observed from Morrison palustrine carbonate deposits, which provide an estimate of the hydroperiod and exposure index (black box). The hydroperiod represents the number of days the sediment surface is inundated over the course of the year. The exposure index is the percentage of time the sediment surface is exposed. The freshwater exposure index is based on Platt and Wright (1992).

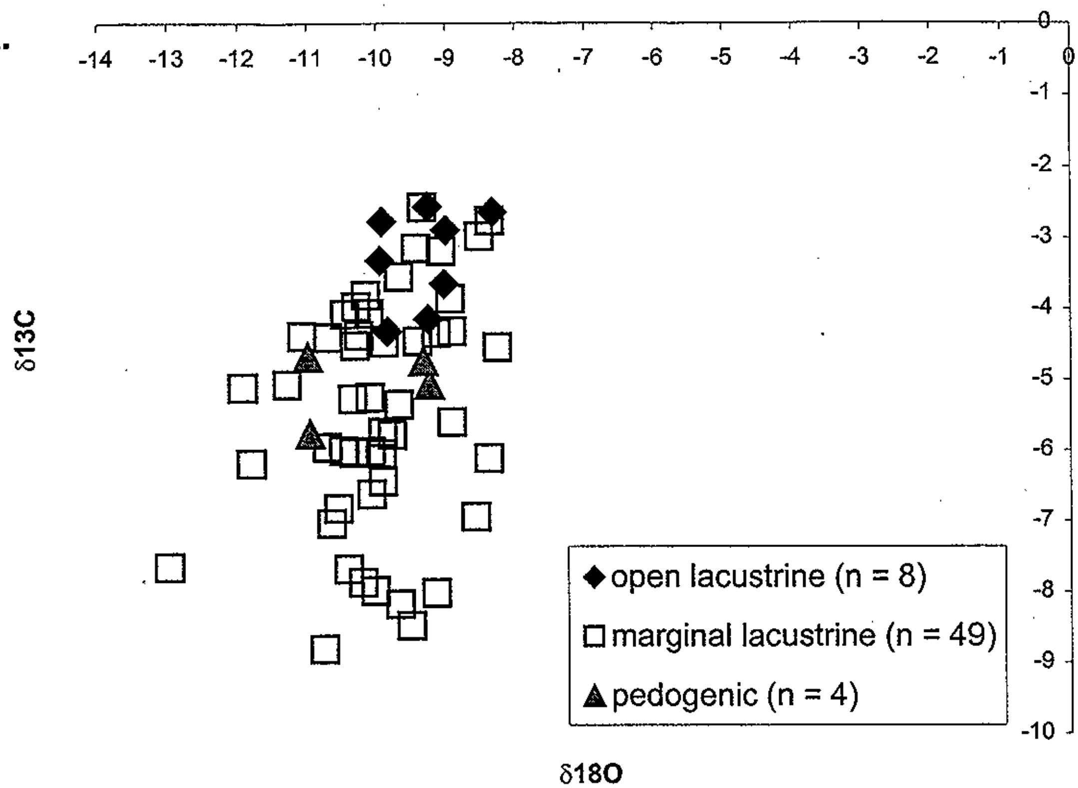
Figure 3.—Plot of stable carbon and oxygen isotope compositions from the Morrison Formation.

A, Cross-plot of primary depositional (open and marginal lacustrine) and pedogenic phases in east-central Colorado.

B, Geographic distribution of primary depositional phases. Abbrevations refer to localities in east-central Colorado:

PCR=Park Creek Reservoir
H=Highway 287
HR=Horsetooth Reservoir
I70=Highway I-70 road cuts west of Denver
WAP=West Alameda Parkway
CN=Cope's Nipple
MFQ=Marsh-Felch Quarry
SD=Skyline Drive

A.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-2
-3
-4
-5
-6
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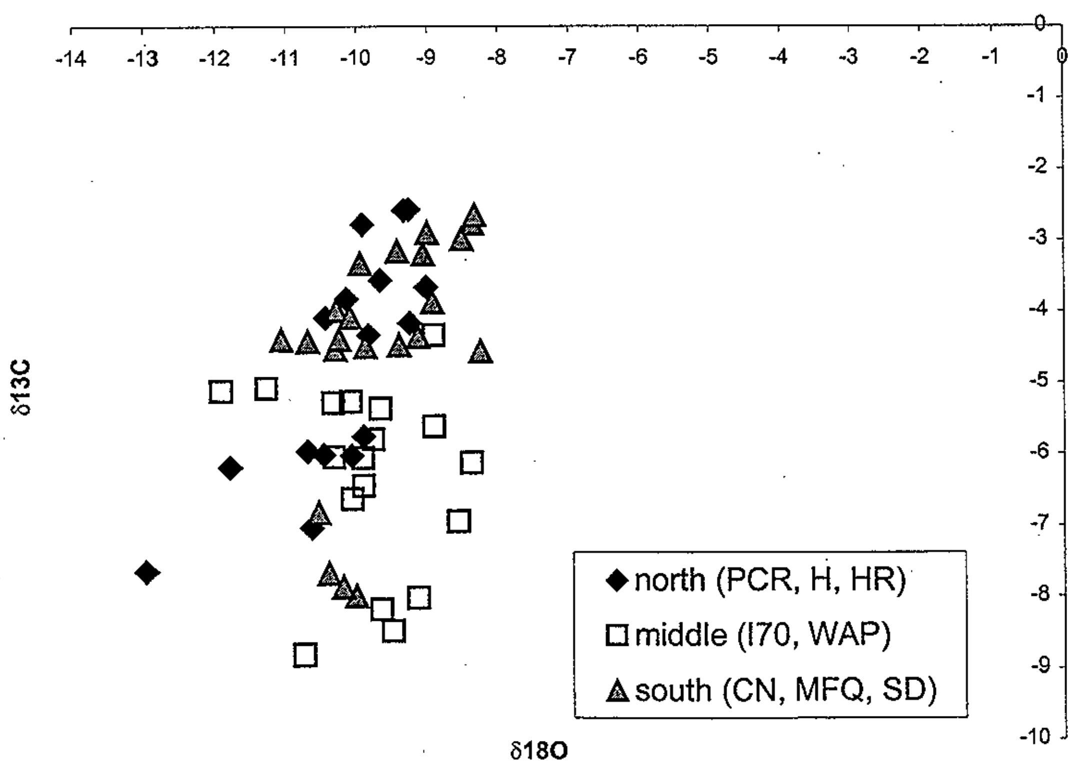
δ13C
δ18O
open lacustrine (n = 8)
marginal lacustrine (n = 49)
pedogenic (n = 4)

B.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-3
-4
-5
-6
-7
-8
-9
-10
δ13C
δ18O
north (PCR, H, HR)
middle (I70, WAP)
south (CN, MFQ, SD)

STABLE ISOTOPE STUDIES IN THE UPPER JURASSIC MORRISON FORMATION OF THE WESTERN INTERIOR; FINAL REPORT

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SUMMARY OF ACTIVITIES

Studies over the last fifty years have shown that systematic variations exist in carbon and oxygen isotope compositions of materials formed by plants, animals, and abiotic processes in modern ecosystems. Extension of this knowledge to the past has made possible inferences of past conditions from the isotopic compositions of fossil materials. The Morrison formation has preserved several materials appropriate for this type of study. For the purpose of paleoecological reconstruction, we have analyzed paleosols (fossil soils), fresh water limestones, fossil teeth, and dinosaur eggshells from the Morrison formation.

Fossil Soils

The Morrison formation has abundant paleosols with caliche ($CaCO_3$) horizons. Approximately 65 separate paleosol horizons (collected from Montana, Wyoming, Utah, Colorado, New Mexico and Arizona) were analyzed for this study. The carbon isotope compositions yield information on the CO_2 content of the paleoatmosphere under which the soils formed. The oxygen isotope compositions of the soil carbonates relate to the isotopic composition of the rainwater during formation of the soil, which varies with paleoclimate and paleogeographic position.

The fossil soils of the Morrison formation have been an important addition of a separate study measuring the CO_2 concentrations of the atmosphere over the last 400 million years. This is accomplished according to the isotope paleobarometer developed by Cerling (1984).

The results indicate very high carbon dioxide levels during deposition of the Morrison formation as shown in Figure 1.

At approximately 2000 parts per million carbon dioxide, the Morrison formation had some of the highest CO_2 levels measured during the last 400 million years. The modern atmosphere has 350 ppm, only 1/6th of the level measured for these Late Jurassic soils. Such high CO_2 levels would have contributed to a hothouse climate, and probably energized massive weather systems to redistribute the sun's heat over the surface of the Earth.

The oxygen isotope composition of soil caliche records the oxygen isotope composition of the precipitation under which it formed. Because the isotopic composition of rainwater is related to environment, we can infer paleoenvironmental conditions from the fossil caliche in Morrison paleosols.

Generally, coastal areas have precipitation with oxygen isotope values around 0‰. As rainclouds move inland and continue to lose moisture to precipitation, they preferentially lose the heavy isotopes first. Therefore, maritime environments have relatively postive values (around 0‰) while inland areas have more negative values. The most negative values are found in dry, continental interiors where much of the cloud vapor has been lost.

Figure 2 shows the isotopic composition of the Morrison palosols compared to a suite of modern soils. The Morrison paleosols are highly depleted in ^{18}O and compare with modern soils developed in rain shadows and continental interiors where the air is dry. In such situations, it is usual to have pronounced seasons with hot days and cold nights since there is little moisture in the air to buffer temperatures.

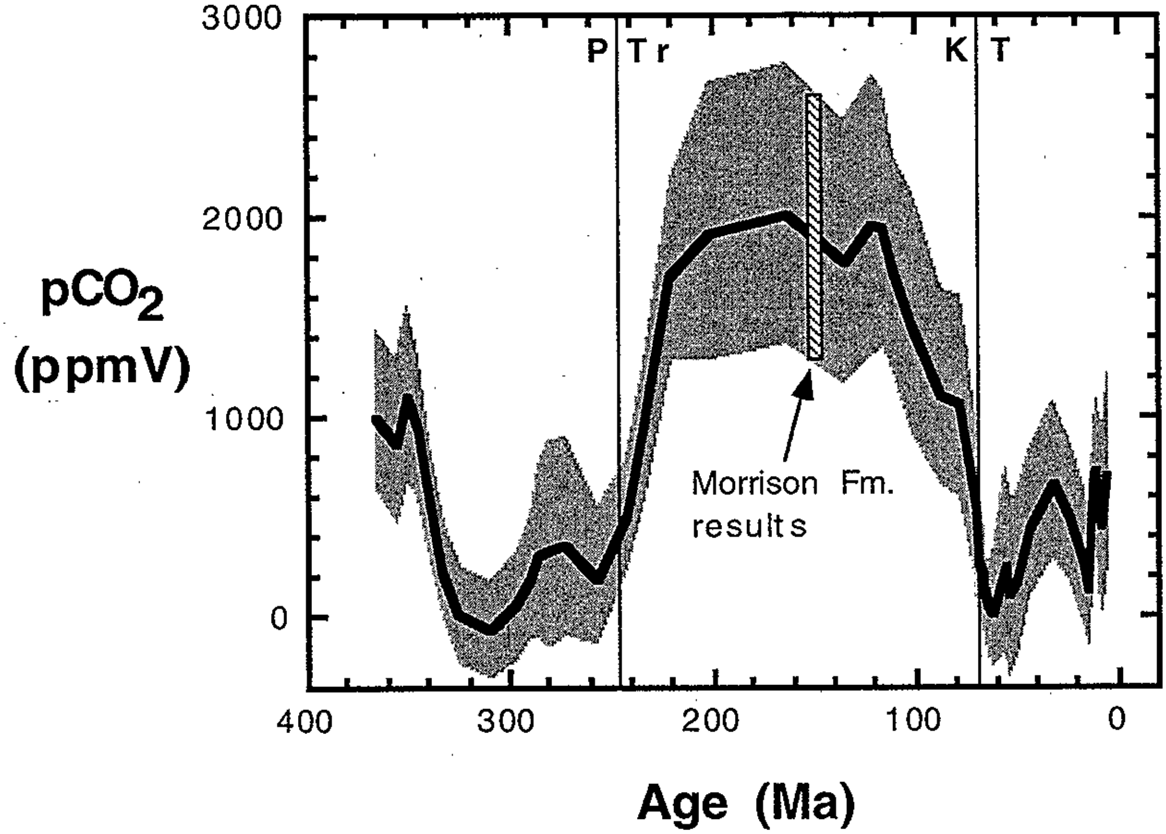

Figure 1.—Results of the fossil soil CO_2 paleobarometer (unpublished results of >700 fossil soils). The plot is a 5 point weighted average of individual measurements.

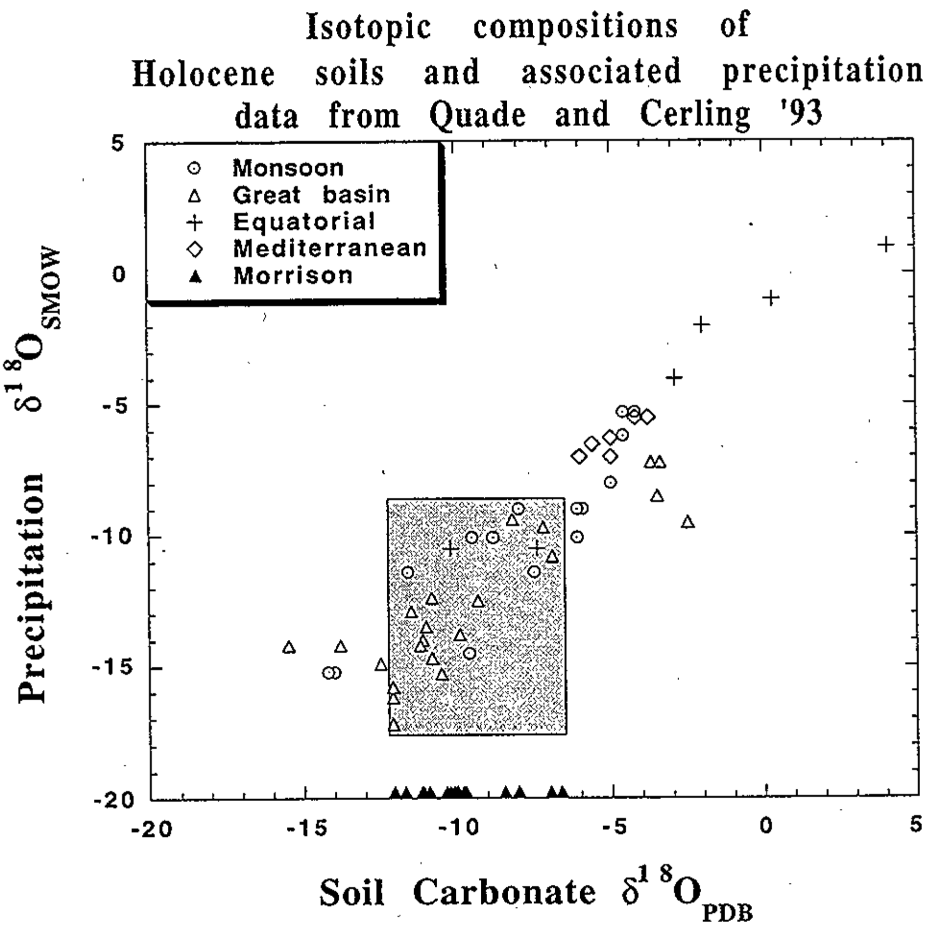

Figure 2.—Comparison of the isotopic compositions of rainwater and soil carbonates. The isotopic composition of Morrison rainwater can be inferred by reference to this suite of modern rain/soil carbonate data pairs.

Lacustrine Carbonates

Carbonate minerals precipitated in lakes can be used to infer the isotopic composition of lake water. A collection of lacustrine carbonates was analyzed and is shown in Figure 3. The values substantiate rainwater highly depleted in the heavy oxygen isotopes such as are found in modern rain shadows. The trend toward more negative values at high latitudes is a trend seen on the modern landscapes and is correlated with lower average temperatures at the higher latitudes.

Teeth and Eggshells

Similar to the manner in which the soil carbonates can be used to infer the isotopic composition of the paleorainwater, the isotopic composition of some fossil materials can be used to infer the isotopic composition of ingested water. There are two primary sources of water for animals. Environmental water in streams, lakes and springs and water contained in food. Leaf water is a commonly a significant source of water for herbivores. Evaporation of water from leaves produces an enrichment in the heavy isotopes of oxygen in the remaining water, since the lighter isotopes require less energy to enter the gaseous phase. This effect typical causes water in leaves to be 10‰ more positive in oxygen isotopes than the local rainwater. Comparisons of oxygen isotopes preserved in teeth and eggshells allows us to infer the behavior of the animal with regards to its water source.

The isotopic composition of three fossil teeth from the Morrison formation are shown in Figure 4, compared with a large database of many fossil mammal teeth. The oxygen isotope compositions of the teeth vary over approximately the same range as the soil carbonates (Fig. 2). The carbon isotopes are relatively positive for C3 vegetation, suggesting the possibility that the vegetation was water stressed.

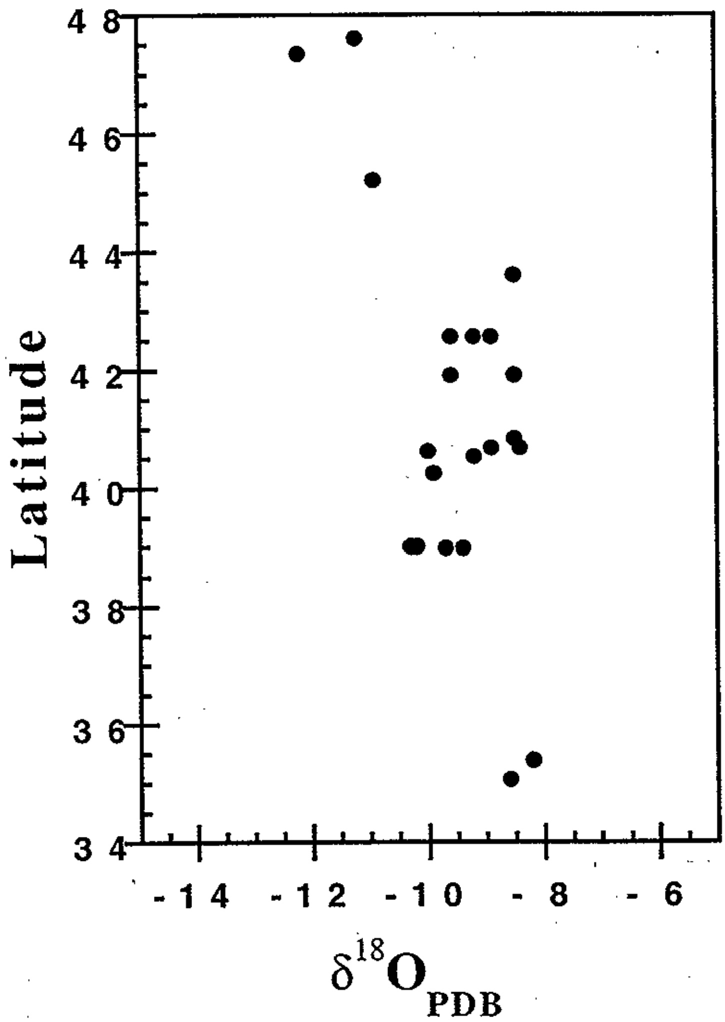

Figure 3.—Isotopic composition of Morrison lake carbonates by degrees of latitude.

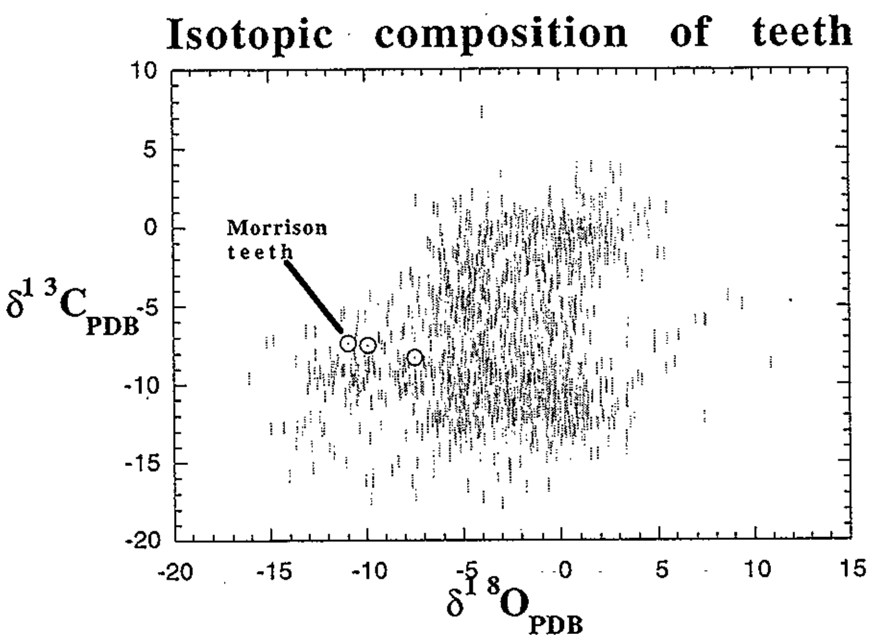

Figure 4.—Isotopic composition of Morrison teeth compared with a large fossil tooth database.

The Morrison formation eggshell carbonates are shown in Figure 5, compared with a collection of other dinosaur eggshells from Sarkar (1991), Folinsbee (1970) and unpublished data. The Morrison eggshells are more enriched in ^{13}C than most of the other shells, suggesting that the organic matter consumed by the dinosaurs was more enriched in ^{13}C. Isotopic compositions such as these occur in water stressed plants, such as found in rain shadows and continental interiors. Oxygen isotopes in the eggshells are generally more positive than the soil carbonates, suggesting that leaf water is a significant source of water for these dinosaurs.

CONCLUSIONS

The isotopic work on the Morrison formation suggests that the atmosphere had high levels of CO_2 and that the climate was dominated by a rain shadow or continental climate. This is substantiated by the highly depleted oxygen isotope values in all the materials and by the relatively positive carbon isotope compositions in the teeth and eggshells. Due to the low moisture content of the air, relatively large shifts in temperature would be likely on daily and seasonal cycles.

REFERENCES CITED

Cerling, T. E., and Quade, J., 1993, Stable carbon and oxygen isotopes in soil carbonates: Geophysical Monograph 78, Climate Change in Continental Isotopic Records, American Geophysical Union, p. 217-231.

Cerling, T. E. 1984, The stable isotopic composition of modern soil carbonate and its relationship to climate: Earth and Planetary Science Letters, v. 71, p. 229-240.

Folinsbee, R. E., Fritz, P., Krouse, H.R., and Robblee, A.R., 1970, Carbon-13 and Oxygen-18 in dinosaur, crocodile, and bird eggshells indicate environmental conditions: Science, v. 168, p. 1353-1355.

Sarkar, A., Bhattacharya, S.K., and Mohabey, D.M., 1991, Stable-isotope analyses of dinosaur eggshell: Paleoenvironmental implications: Geology, v. 19, p. 1068-1071.

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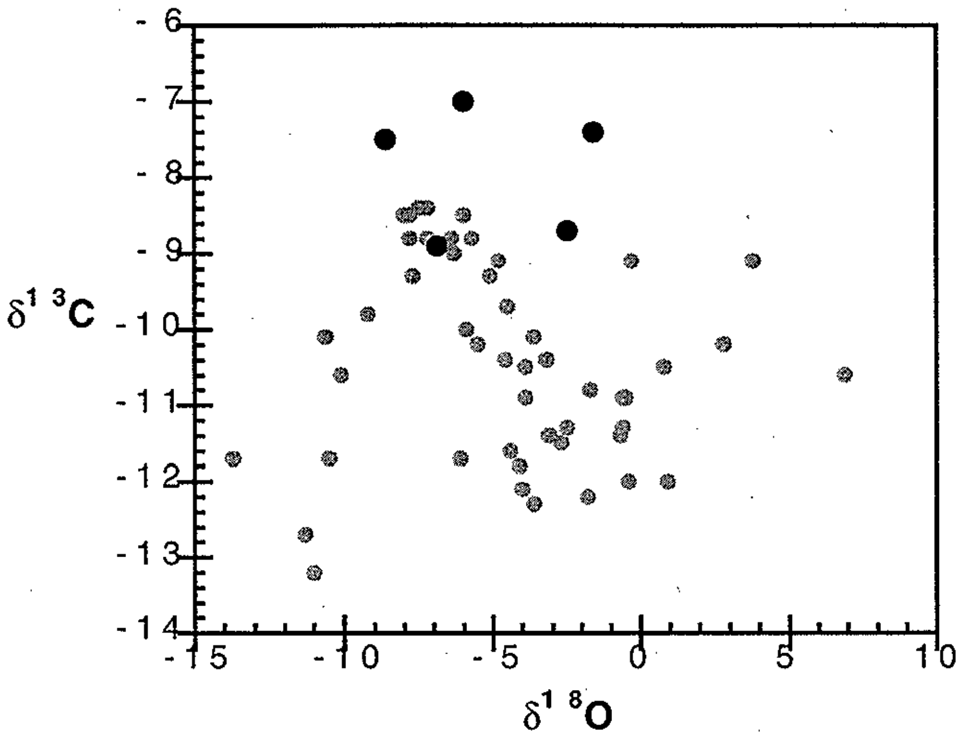

Figure 5.—Isotopic composition of dinosaur eggshell carbonates. Morrison eggshells are represented by the large black points.

A SURVEY OF PALEONTOLOGIC RESOURCES IN THE UPPER JURASSIC MORRISON FORMATION IN NATIONAL PARK SERVICE UNITS OF THE WESTERN INTERIOR; FINAL REPORT

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SUMMARY OF ACTIVITIES

During the three field seasons of the Morrison Ecosystem research project, I have explored Morrison exposures in and adjacent to Arches National Park, Colorado National Monument, Bighorn Can yon National Recreation Area, Yellowstone National Park, Glen Canyon National Recreation Area, and Capitol Reef National Park in that order. In addition, several other sites in Utah, Colorado, Wyoming and Montana were visited briefly in the course of field conferences with other colleagues on the Morrison project.

The primary objective of this fieldwork has been to survey the formation to locate and document fossil occurrences. Accordingly, fossil occurrences were sought by careful examination of available Morrison outcrops. When fossils were found, each site was documented photographically, by verbal description in field notes, by marking on standard USGS topographic maps (7.5 minute quadrangles), and by recording GPS files. Information recorded in notes taken in the field include: geographic location, stratigraphic position, nature of the occurrence, identification of fossils present, an assessment of the potential of the site to produce scientifically useful specimens, and evidence indicating collection or attempted collection of fossils in the survey area.

SUMMARY OF RESEARCH

The results of this survey can be combined with the results of a similar survey carried out at Dinosaur National Monument. Together, they provide data for nearly 600 paleontological sites throughout the Morrison Formation. They reveal useful information about the nature of the fossil occurrences, the geographic and stratigraphic distribution of the fossils, and the potential of and threats to the paleontological resource. The data provide new insights into the taphonomy of the Morrison that can constrain paleoecological interpretations. It can also prove to be a valuable tool for management of the paleontological resources within the parks.

Dinosaur National Monument (DINO)

The survey of the Morrison Formation within DINO was conducted during the summers of 1990, 91, and 92. Unlike the surveys conducted during the Morrison Ecosystem project, which had a much broader scope, the survey of the Morrison at DINO was exhaustive. Every area of available outcrop was closely inspected. Because of this close scrutiny and the fact that the Morrison was relatively fossiliferous throughout its area of exposure at DINO, 360 localities were documented during the three years of the survey. The method of documenting localities used in the later surveys was developed during the survey of DINO, making the data directly comparable for all sites.

The results from DINO are, in many ways, characteristic of the general findings of the study. New information concerning the stratigraphic distribution of fossils within the Morrison, the relative abundance of different kinds of fossils, the lithologies within which the fossils are commonly preserved, and the nature of the fossils occurrences are revealed by the DINO survey and corroborated by the more recent work.

	Localities	%
Windy Hill	1	.283%
Tidwell	2	.567%
Salt Wash : Lower	23	6.516%
Salt Wash : Middle	108	30.595%
Salt Wash : Upper	91	25.779%
Lower Brushy Basin	16	4.533%
Upper Brushy : Low...	98	27.762%
Upper Brushy : Upper	14	3.966%

Table 1: Stratigraphic distribution of localities at DINO

The stratigraphic distribution of fossil localities within the Morrison is represented in Table 1. Stratigraphic position of each locality was recorded to within one of the component members of the formation or smaller, distinctive subdivisions of the members. One of the most remarkable discoveries about the fossil distribution is the abundance of localities within the Salt Wash Member, particularly the middle and upper parts. Because most of the classic dinosaur localities have been found in the upper Brushy Basin Member, the Salt Wash has been thought of as relatively unfossiliferous. But there are comparable numbers of localities in each of the middle part of the Salt Wash, the upper Salt Wash, and the upper Brushy Basin. There are a number of reasons for this. In the first place, dinosaur bones, the commonest fossil in the Morrison, are approximately as abundant in the Salt Wash as they are in the Brushy Basin. In addition, the second most abundant fossils, silicified wood logs, are much more common in the Salt Wash than in the Brushy Basin.

	Localities	%
Dinosaur bone	222	63.61%
Small bone	16	4.585%
Potential microsite	8	2.292%
Silicified wood	77	22.063%
Coalified wood	3	.86%
Organic material	3	.86%
Invertebrate fossil	10	2.865%
Invertebrate trace	10	2.865%

Table 2: Fossil material at DINO

The relative abundance of different types of fossil materials represented in Table 2 bears out the casual observation that dinosaur bone is particularly common in the Morrison Formation. It is the single most abundant category of fossil material. Dinosaur bone occurs as everything from nearly unrecognizable, unidentifiable fragments to a complete articulated skeleton, with every degree of preservation in between represented. After dinosaur bone, silicified wood is the next most common fossil. The wood occurs most often as small logs or pieces of logs, but large logs are found. In most cases, the silicification does not preserve the cellular structure of the wood. Other fossils occur with much lower frequency but are indicative of a diverse biota that includes small mammals, reptiles and amphibians, freshwater and terrestrial invertebrates, and smaller plants.

	Localities	%
Sandstone	279	79.261%
Mudstone	64	18.182%
Carbonate	9	2.557%

Table 3: Lithologies at DINO

The record of lithologies within which the fossils occur, represented in Table 3, reveals that fossils are most often found in sandstones. This may be attributed in part to the fact that sandstones are the dominant lithology of the Salt Wash. However, even in the Brushy

Basin where mudstones make up a greater part of the section, the fossils still occur more often in sandstones. An important exception to this rule is the microvertebrate fauna, which has so far been found only in the mudstones.

Although we did observe evidence that someone had been prospecting for fossils in the Morrison in a remote area of the park, there was no evidence of significant illegal collecting within park boundaries.

Arches National Park (ARCH)

Occurrences at ARCH are similar in many respects to those at DINO, but there are some important differences in the pattern, both in the stratigraphic distribution and the relative abundance of different types of fossils.

	Localities	%
Windy Hill	0	0%
Tidwell	0	0%
Salt Wash: Lower	3	5.455%
Salt Wash: Middle	4	7.273%
Salt Wash: Upper	10	18.182%
Lower Brushy Basin	21	38.182%
Upper Brushy: Low...	11	20%
Upper Brushy: Upper	6	10.909%

Table 4: Stratigraphic distribution of localities at ARCH

As can be seen from Table 4, fossils occur with comparable abundance in the upper part of the Salt Wash and the lower part of the Upper Brushy Basin. But while fossils were relatively sparse in the Lower Brushy Basin at DINO, this appears to be the most fossiliferous unit at ARCH. This is partially explained by the common presence of invertebrate traces at this level at ARCH that were not observed at DINO. But this is not the entire explanation, as these invertebrate trace localities do not account for the entire difference. A somewhat lower proportion of localities in the lower and middle parts of the

Salt Wash is also noticeable. The lower number of fossil wood occurrences at ARCH may account for this.

	Localities	%
Dinosaur bone	45	69.231%
Small bone	3	4.615%
Potential microsite	0	0%
Silicified wood	3	4.615%
Coalified wood	1	1.538%
Organic material	0	0%
Invertebrate fossil	0	0%
Invertebrate trace	13	20%

Table 5: Fossil material at ARCH

As at DINO and throughout the Morrison, dinosaur bone is the most abundant fossil. A marked difference can be seen in the abundance of invertebrate trace fossil occurrences. These consist largely of termite nests and vertical burrows attributable to some kind of insect. In fact, the locality records may underrepresent such fossils, because some localities were actually horizons that were laterally extensive at outcrop scale. The greater scarcity of fossil wood at ARCH may be biased by long-term, intensive collecting of this area by amateurs. On the other hand, even within the park little wood was found that could definitely be attributed to the Morrison Formation.

	Localities	%
Sandstone	43	70.492%
Mudstone	18	29.508%
Carbonate	0	0%

Table 6: Lithologies at ARCH

As elsewhere in the Morrison, fossils occur primarily in sandstones. However, the Salt Wash at ARCH is dominated by sandstones to an even greater extent than in other areas of the study, and, although it cannot be seen in Table 6, most of the fossil sites in the lower part of the Upper Brushy Basin were found in mudstones.

There was clear evidence of collecting activity in the Morrison within and around ARCH. However, it is not clear whether the attempts to collect specimens now within the park occurred before or since that area was incorporated into the park. There is much amateur and commercial collecting activity in the area surrounding the park which consists of a mix of state and federal lands.

Colorado National Monument (COLM)

COLM is located in an area that has been very productive of fossils from the Morrison. The Fruita Paleontological Area, which has yielded an important microvertebrate fauna, as well as dinosaur fossils, and several excavation sites where dinosaurs have been collected are just a short distance beyond the boundaries of the park. Similar concentrations of fossils were not found within the park, but many localities, exhibiting a diverse fossil biota, occur in and adjacent to COLM.

	Localities	%
Windy Hill	0	0%
Tidwell	1	1.282%
Salt Wash : Lower	4	5.128%
Salt Wash : Middle	28	35.897%
Salt Wash : Upper	7	8.974%
Lower Brushy Basin	7	8.974%
Upper Brushy : Low...	10	12.821%
Upper Brushy : Upper	21	26.923%

Table 7: Stratigraphic distribution of localities at COLM

Two observations on the distribution of localities at COLM (Table 7) stand out as different from other study areas; the relatively high number of localities within the middle part of the Salt Wash and within the uppermost part of the Brushy Basin. At COLM, more than at any other area studied, fine-grained sediments dominate the middle part of the Salt Wash. Many of the localities within this interval produce fossil invertebrates, which are much more common here than elsewhere in the Morrison. There is no obvious explanation for the relatively high proportion of fossil localities within the uppermost Brushy Basin.

	Localities	%
Dinosaur bone	35	48.611%
Small bone	10	13.889%
Potential microsite	0	0%
Silicified wood	0	0%
Coalified wood	0	0%
Organic material	0	0%
Invertebrate fossil	16	22.222%
Invertebrate trace	11	15.278%

Table 8: Fossil material at COLM

Although dinosaur bone is still the most abundant fossil at COLM, there seems to be proportionately less than at either DINO or ARCH. This is undoubtedly the result of the much greater number of invertebrate fossil localities at COLM. As noted above, the distinctive lithologic character of the middle part of the Salt Wash, where most of these localities occur, is probably responsible for this peculiarity. As at ARCH, a distinctive invertebrate trace fossil horizon in the upper Salt Wash and lower Brushy Basin, characterized by termite nests, ant nests, and other insect burrows, accounts for many localities that diminish the proportion of dinosaur-bearing sites. The general absence of fossil wood from this area is remarkable. Anecdotal reports of logs collected from the Morrison in this area by local amateurs raise the possibility that such localities have been collected out. But, one would expect at least some scrappy indications if fossil wood were as abundant as it is at DINO.

	Localities	%
Sandstone	36	49.315%
Mudstone	24	32.877%
Carbonate	13	17.808%

Table 9: Lithologies at COLM

For the same reasons discussed above, a much higher proportion of localities at COLM occurs within mudstones than at other study areas. Most of these are unionid clam sites in gray mudstones of the middle Salt Wash. The middle part of the Salt Wash is also responsible for the high number of localities in carbonates. Thin, discontinuous limestones are common in the lower part of this interval and may contain gastropods and charophytes.

No evidence of recent illegal fossil collecting was observed within the park. In Morrison exposures adjacent to the park, on federal lands, however, there were clear indications of substantial collecting efforts. This included excavations and the probable removal of large bones.

Bighorn Canyon National Recreation Area (BIHO)

As far north as BIHO, the Morrison Formation is very different in character from the section in the Colorado Plateau, where most of the study areas are located, and much thinner. All of the Morrison within the park occurs around Sykes Mountain, much of it high on steep slopes and therefore relatively inaccessible. Even so, a brief survey of accessible outcrops yielded five localities with dinosaur bone, two with invertebrate burrows, one with coalified wood, and a dinosaur track horizon.

The formation is undifferentiated at BIHO, and it is difficult to determine what parts of the section correspond with stratigraphic units recognized elsewhere. Based on their relative position in the section, most of the localities appear to fall within a part of the section corresponding to the uppermost Brushy Basin. The wood locality is a bit lower in the section but still within sediments that probably are equivalent to the Brushy Basin. The section is very sandy, with little mudstone, and all localities are within sandstones. No evidence of significant collecting activity was observed.

Yellowstone National Park (YELL)

A brief, unsuccessful attempt was made to locate Morrison exposures within the park, but a good exposure was examined at Devil,s Slide just north of the park. No sign of fossils was found in the Morrison at this locality where it has been deformed and slightly metamorphosed.

Glen Canyon National Recreation Area (GLCA)

The upper part of the Morrison appears to be truncated by erosion at the south end of its outcrop within GLCA and it becomes more complete to the north. In this southern outcrop area, massive sandstones are the dominat lithology of the Salt Wash and lower Brushy Basin. Only a single dinosaur bone was found in the base of the Salt Wash there. The massive sandstones of the Salt Wash are also exposed as steep cliffs near Bullfrog to the north. The Brushy Basin, though present, has been stripped from the more resistant Salt Wash and is only preserved outside the park. Two trace fossil horizons characterized by termite nests were found at the top of the Salt Wash near the northern boundary of the park.

Capitol Reef National Park (CARE)

The Morrison is extensively exposed within and adjacent to CARE. Both the Salt Wash and Brushy Basin are well exposed, although the Brushy Basin may be truncated at the top by erosion. The survey of CARE was not exhaustive, but examined segments of the outcrop area that were taken to be representative of the whole.

	Localities	%
Windy Hill	0	0%
Tidwell	1	1.923%
Salt Wash: Lower	8	15.385%
Salt Wash: Middle	12	23.077%
Salt Wash: Upper	18	34.615%
Lower Brushy Basin	4	7.692%
Upper Brushy : Low...	8	15.385%
Upper Brushy : Upper	1	1.923%

Table 10: Stratigraphic distribution of localities at CARE

The summary data presented in Table 10 show that the fossil localities are distributed among the stratigraphic intervals recognized, with the heaviest representation in the middle and upper parts of the Salt Wash. The large numbers of Salt Wash localities are accounted for in large part by fossil log localities, which are abundant here. But dinosaurs are well represented as well. The distribution of fossils at CARE would resemble that at DINO but that fossils are much sparser in the Brushy Basin, which is dominated by mudstone to a much greater extent than other study areas.

	Localities	%
Dinosaur bone	24	47.059%
Small bone	0	0%
Potential microsite	0	0%
Silicified wood	20	39.216%
Coalified wood	0	0%
Organic material	0	0%
Invertebrate fossil	0	0%
Invertebrate trace	7	13.725%

Table 11: Fossil material at CARE

As at DINO, dinosaur bone and fossil wood are the first and second most abundant fossils at CARE. The absence of small bone may reflect the relatively small number of localities sampled, but may also be attributed to the scarcity of fossils from the Brushy

Basin, which usually produces such fossils. Although no invertebrate fossils appear in the chart, some unionid clams were found at one site, which was primarily a dinosaur locality.

	Localities	%
Sandstone	48	96%
Mudstone	2	4%
Carbonate	0	0%

Table 12: Lithologies at CARE

Table 12 shows that the mudstones were largely unfossiliferous. This undoubtedly accounts for the low number of fossil localities within the Brushy Basin. Most fossil localities within the Brushy Basin were within the few sandstones.

Although there was no evidence of significant collecting activity within the park, there were many examples of collecting or attempts to collect fossils in the Morrison exposures immediately outside the park. Within a small area outside the east entrance to the park, many dinosaur bone localities had been vandalized. Large bones had been collected piecemeal by breaking off chunks that protruded from the sandstone or that could be hammered free. Similar sites were found in another area to the north, and at two localities in the mudstones, there was clear evidence of digging, with scattered bone fragments surrounding the excavation. Some of the activity was undoubtedly quite recent, but growth of vegetation at other sites indicated that the disturbance had occurred years ago. This suggests that amateur and commercial collecting in this general area is fairly active and is long established. At the same time, the park boundaries appear to have been respected. However, this may be explained by the fact that exposures within the park are less productive than the surrounding area.

CONCLUSIONS

The data from this survey may be useful for several purposes including reassessment of the taphonomy of the Morrison Formation and as a guide to resource management. Initial analyses have attempted to draw some conclusions in these areas.

In many respects dinosaurs provide the most useful taphonomic evidence for the Morrison Formation. They are abundant and widespread, and the nature of their preservation tells us something about the nature of the environment. Why is dinosaur bone the commonest fossil? It could be that dinosaurs were abundant in the environment; but whether they were or not, their abundance as fossils probably has more to do with the survivability of large, massive bones in the face of weathering processes, before burial.

The fossil remains of smaller, more lightly built organisms would be reduced to unrecognizable constituents in a much shorter time than would those of the large dinosaurs. In general, the fossil record of the Morrison is an attritional sample of the remains of organisms that accumulated on the substrate over some time and were buried by a depositional event or events that may also have concentrated the remains in drainages. This interpretation is also supported by the observation that dinosaur occurrences encompass the complete range of decomposition of the remains. Complete articulated skeletons occur rarely. Articulated and disarticulated partial skeletons are more common, and isolated elements or fragments are abundant. In some channel deposits well-worn pebbles of bone may be found. Of identifiable fragmentary remains, many appear to be sauropods. This may reflect the massive nature of the sauropod skeleton rather than relative abundance of living sauropods.

The abundance of fossil wood, sometimes occurring as large logs, implies the existence of large trees either at or near the locality, or in the upper reaches of the drainage basin of the streams. In most cases, it is logs that are preserved, not stumps in situ (The only stump observed in the course of this survey was in eolian deposits in central Wyoming). This implies that there was some transport, but one should consider how far upstream the depositing stream would have remained competent to transport large logs.

The predominance of sandstones as the lithology within which fossils are found may be explained by several hypotheses, which are not mutually exclusive. Although there are eolian sandstones in the Morrison, those at the fossil localities documented here are all fluvial sandstones. One possible explanation is that the streams that deposited the sandstones may have concentrated the organic remains. This explanation would be quite consistent with the nature of the occurrences of many of the dinosaur fossils and most of the fossil wood. Organic remains could have been swept from the surface into streams in flood, or, perhaps more likely, incorporated into channel sands as the channel cut laterally into floodplain sediments.

Another possible explanation is that the living organisms were concentrated along the streams. One observation that argues for this interpretation is the fact that, while fossils are found in the mudstones, in most cases the mudstones are closely associated with fluvial sandstones. In parts of CARE where sandstones are extremely sparse in the mudstone-dominated upper Brushy Basin, the mudstones are devoid of fossils.

A third explanation that may account for the sandstone dominance is collection bias. The mudstones are, in many parts of the Morrison, heavily bentonitic. These sediments are often deeply weathered, and the repeated shrinking and swelling of the muds in the weathering zone are not kind to fossils. In addition, the characteristic popcorn surface of weathered bentonitic muds is extremely irregular with many cracks to hide broken fragments of fossils. Therefore, fossils in mudstone are likely to have poor or no surface expression and may be more easily overlooked in prospecting. Sandstones, on the other hand, are more likely to present a clean exposure that is little weathered, and do not subject the contained fossils to such great stresses on weathering.

Contrary to this pattern, certain types of fossils are found primarily or exclusively in mudstone. The microvertebrate faunas including amphibians, lizards, and mammals have been found only in the mudstones. It appears that their occurrence in the fine grained sediments is a function of their life habitats in and around ponds and other subenvironments of the floodplain. The absence of these small vertebrates from the sandstones is a bit puzzling. Throughout the Cretaceous and Tertiary, small vertebrate remains are often concentrated as a small lag deposit within fluvial sands, and are an important source of small mammal samples. No such small fossil concentrations have been found in the Morrison although similar sedimentologic environments do occur. Although it is true that later mammals are on average much large than Morrison mammals, some very tiny specimens have been found in such deposits. It seems unlikely that the small size and delicacy of the mammals and other microvertebrates can alone account for these observations.

Another type of fossil that occurs predominantly in the mudstones is the unionid clams. Most of the localities for these invertebrates were in the middle shaly part of the Salt Wash at COLM. This seems likely to be an indication of habitat preference by these clams.

The results of the survey can be used for management of the paleontologic resource and for interpretation within the parks involved in the study. The documentation for the localities found will be archived in the parks and can be utilized by appropriate personnel or future researchers in the parks. In addition, additional interpretive material is planned for the parks involved in the study and for popular consumption.

RECOMMENDATIONS

The Morrison Formation may contain fossils wherever it occurs. Fossils are likely to occur in both the Salt Wash and Brushy Basin members of the formation. It is more likely that fossils will be found in the sandstones, although the mudstones may contain fossils, and some very important fossils, notably fossil mammals, have been found only in the mudstones. Therefore, park personnel should become familiar with known fossil occurrences, especially where they may be useful for interpretation or vulnerable to loss or destruction, and should be alert to the possibility that new fossils may be found in the course of park development or by visitors. It would be helpful if park personnel (at least one appropriate person) would establish and maintain communication with a qualified paleontologist, such as the Park Paleontologist at DINO, for consultation as matters requiring paleontological expertise arise. This can be accomplished easily using e-mail.

There is no clear evidence of extensive, current vandalism or collecting of fossils within the boundaries of any of the parks studied. However, there is much evidence of longstanding and ongoing vandalism and collecting at localities in areas adjacent to the parks, especially at ARCH, COLM, and CARE. Much of this occurs on federal lands, and is illegal. Park personnel may wish to be aware of such activity where there is the possibility that it might extend into the park in boundary areas, or in the event that there would be sufficient motivation for some to attempt collecting within the park.

PUBLICATIONS AND REPORTS

Engelmann, G.F., and Fiorillo, A., in preparation, The taphonomy and paleoecology of the Morrison Formation.

Bradley, LW., Callison, G., and Engelmann, G.F., in preparation, Jaw musculature of a Late Jurassic multituberculate from North America.

Engelmann, G.F., in press, Stratigraphic and geographic distribution of fossils in the upper part of the Upper Jurassic Morrison Formation of the Rocky Mountain region; in, Gillette, D.D., (ed.),Vertebrate Fossils of Utah: Utah Geological Survey.

Engelmann, G.F. and Callison, G., in press, Glirodon grandis, a new multituberculate mammal from the Jurassic Morrison Formation; in, Gillette, D.D., (ed.), Vertebrate Fossils of Utah: Utah Geological Survey.

Engelmann, G.F. and Hasiotis, S.T., in press, Deep dinosaur tracks in the Morrison: Sole marks that are really sole marks; in, Gillette, D.D., (ed.), Vertebrate Fossils of Utah: Utah Geological Survey.

Engelmann, G.F. and Callison, G., 1998, Mammalian Faunas of the Morrison Formation: Modern Geology, v. 23, nos. 1-4, p. 343-380.

Bradley, L. W., Callison, G., and Engelmann, G.F., 1997, Jaw musculature of a Late Jurassic multituberculate from North America: Society of Vertebrate Paleontology, (abstract).

Engelmann, G.F., 1996, Distribution of fossils within the Jurassic Morrison Formation in the Rocky Mountain region: Presentation at the Morrison Extinct Ecosystem Workshop, 1996 Annual Meeting of the Geological Society of America, Denver CO.

PALEOENVIRONMENTAL IMPLICATIONS OF FRESHWATER GASTROPOD FAUNAS IN THE UPPER JURASSIC MORRISON FORMATION OF THE WESTERN INTERIOR—AN ENIGMA BETWEEN GEOLOGIC AND BIOLOGIC EVIDENCE; FINAL REPORT

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SUMMARY

The Morrison Formation contains the shells of two major groups of freshwater gastropods, the prosobranchs and pulmonates. Freshwater prosobranchs are gill-bearing snails that live in perennial waters that are well oxygenated and have low turbidity. The freshwater pulmonates are lung-bearing snails that live in a wide variety of habitats that range from perennial to intermittent waters, high to low oxygenated waters, and moderate to low turbidity. The Morrison freshwater gastropods are remarkably similar to modern taxa and many can be assigned to modern genera. The environmental limits of modern snails can be extrapolated to the Morrison snails.

The shells of prosobranchs and pulmonates occur together in most Morrison assemblages but the dominance of the two groups changes vertically in the section. The lower part of the Morrison, below the illite/smectite clay change, contains assemblages dominated by pulmonate snails. Above the clay change, the assemblages are dominated by prosobranch snails. Based on modern analogues, the snails suggest that the lower assemblages accumulated in more stressful aquatic environments, possibly more intermittent waters with low oxygen or moderate turbidity. The upper assemblages suggest the presence of more perennial waters with high oxygen and low turbidity. However, both faunas contain numerous prosobranch snails that indicate the presence of well-oxygenated perennial waters before and after the time of the clay change. The enigma comes from evidence of the associated clays. The clays below the clay change were derived from the

weathering of materials at the margins of the Morrison depositional basin and the waters may have been relatively clear of sediment. The clays above the clay change are smectitic and were derived from the large input of volcanic ash that presumably would have made the water bodies relatively turbid, conditions that would not have been favorable to the prosobranchs.

By way of comparison, the combination of increased seasonality of freshwater environments and the massive input of fine-grained volcanic ash during the late Eocene in the Central Rocky Mountains and Great Plains resulted in a decrease in prosobranch freshwater mollusk populations to near extinction. The answer to the Morrison gastropod problem may lie in geochemical differences between the aquatic environments above and below the clay change. The turbidity effects of increased volcanic ash apparently did not affect the prosobranch snails in the upper part of the Morrison Formation.

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PALEONTOLOGIC RESOURCES IN THE UPPER JURASSIC MORRISON FORMATION OF CURECANTI NATIONAL RECREATION AREA AND BLACK CANYON OF THE GUNNISON NATIONAL MONUMENT, COLORADO; FINAL REPORT

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SUMMARY

A detailed paleontologic reconnaissance of the Upper Jurassic Morrison Formation of Curecanti National Recreation Area (CURE) and Black Canyon of the Gunnison National Monument was sponsored by the National Park Service from 1994-1996. Results of this study have shown these park units, particularly the former unit, to contain a wide diversity of fossil remains. Seventeen fossil localities were discovered during the course of this survey. The most spectacular of these finds is a sauropod dinosaur skeleton and associated meat-eating theropod dinosaur teeth. In addition to this find, other remains discovered include various plant fossils (both leaves and roots), termite nests, worm tubes, crayfish burrows, clam burrows, and bee nests (Fig. 1).

Stratigraphic sections have been made through pertinent areas that provide insights into the relationships of these various fossil finds. Also, in areas of specific interest, samples were collected for analysis of clay minerals. This work has shown that the base of the Morrison Formation in CURE was deposited under humid conditions.

The Morrison Formation of the western United States has produced the vast majority of the Jurassic dinosaurs from North America. However, most of these remains have been derived from only a few major localities. Given the large geographic extent of the Morrison Formation, many gaps still exist in understanding the distribution of dinosaurian taxa from this interval of time. The results of this study have provided valuable scientific insights into the distribution and paleoecology of the ancient fauna of the Morrison Formation.

INTRODUCTION

Curecanti National Recreation Area (CURE) encompasses the eastern portion of the Black Canyon of the Gunnison, and shares a common boundary with the Black Canyon of the Gunnison National Monument. The park contains three dams which comprise the Wayne N. Aspinall Unit of the Upper Colorado River Storage Project. The largest reservoir created by the dams, Blue Mesa Reservoir, serves as a major recreational resource for fishermen and boating enthusiasts.

Geologically, the park is recognized for having exposures of rocks that date to over 1.7 billion years in age, making these rocks among the oldest in western North America. In addition to these well-recognized resources, CURE also contains fossil resources that have significant scientific and educational value (Table 1). The most important of these fossil finds is in the Upper Jurassic Morrison Formation in the park.

The paleontological sites discussed in this report are noteworthy for several reasons. First, these sites include the second major dinosaur discovery in the Morrison Formation between the historically important Canon City area of the southern Front Range and the Uncompaghre uplift in western Colorado. Second, the discovery of these fossil sites in a park not previously recognized for its paleontologic resources, emphasizes the point that important management issues may include resources not traditionally recognized within individual parks. Further, like the great diversity in the types of remains found in the fossil record, there is also diversity in management techniques that can be employed to document these occurrences. Finally, in his recent report on public use in Yellowstone National Park, Schullery (1997) showed that 72% of the visitors went to visitor centers or museums, in contrast to only 7% of visitors using the backcountry. This would suggest that although direct backcountry use may not be a priority, the public is interested in learning about all aspects of a particular park.

TABLE 1

Type of Fossil Localities	BLCA	CURE	Totals
Vertebrate Localities	1	9	10
Invertebrate Localities	0	4	4
Plant Localities	0	3	3
Totals	1	16	17

Table 1.—Summary of the distribution and type of fossil localities identified in this survey.
BLCA = Black Canyon of the Gunnison National Monument,.
CURE = Curecanti National Recreation Area.

VERTEBRATE FOSSILS

In the area surrounding the town of Gunnison only one significant dinosaur find had been reported previously (Bartleson and Jensen, 1988). A new dinosaur locality was discovered in the Morrison Formation during recent paleontological fieldwork Curecanti National Recreation Area and Black Canyon of the Gunnison National Monument, of west-central Colorado. This site has thus far yielded the remains of two dinosaur taxa, a sauropod (cf. Apatosaurus) and the theropod Allosaurus (Fiorillo and May, 1996).

The quarry is at the edge of a lense-shaped, fine- to medium-grained sandstone that thickens to 1.5m and is a least 30m in lateral extent along the outcrop exposure. Sedimentary structures within this sandstone suggest a flood event with rapidly decreasing flow velocity.

The remains of two dinosaur taxa have been found at this quarry: an articulated partial sauropod skeleton consisting of several posterior cervical and anterior thoracic vertebrae, ribs, and fragmentary limb material, and an isolated theropod tooth. The sauropod has been referred to the genus Apatosaurus (Fiorillo and May, 1996) and the theropod tooth assigned to the genus Allosaurus (Fiorillo and May, 1996).

Isolated predatory dinosaur teeth are commonly found at sites where there are articulated or associated dinosaur skeletons (Fiorillo, 1991). These occurrences are typically interpreted as the shed teeth of predators as the predators fed on the carcass.

Sediment grain size is an estimator of flow velocity in stream deposits. A good deal of experimental work has been done to provide a means to estimate the relationship between sediments of a given size and the corresponding bones that would have been carried by those stream flows. A large disparity between sediment size and the fossil bone size probably indicates that the fossil bones were not transported to the site as part of the bedload of the stream. Such is the case at the CURE dinosaur site. The articulated nature of the skeleton suggests that the sauropod was transported to the site as a bloated carcass. Subsequent to final burial of the skeleton, based on the co-occurrence of isolated theropod teeth, this specimen was probably scavenged by at least one Allosaurus.

Management Issues for Vertebrates

When the site was discovered, the global scientific importance, as well as the regional educational potential, were immediately recognized. This site is located along the shores of the Blue Mesa Reservoir in Curecanti National Recreation Area. Previous destruction of bone material at the site was due to exposure to the weather and wave action during periods of high lake level. Excavation was deemed the only viable alternative to preserving this resource.

A carefully coordinated excavation project involving the National Park Service, the Dallas Museum of Natural History, the United States Forest Service, and the Academy of Natural Sciences of Philadelphia is currently ongoing. The National Park Service has provided the logistical support and framework for the excavation while the Dallas Museum of Natural History and the Academy of Natural Sciences of Philadelphia have provided the technical expertise for the fine-scale excavation. The first large jacket containing several sauropod vertebrae was removed during the summer of 1995 and is currently being prepared for detailed study.

INVERTEBRATES

Continued survey of this park unit has provided new insights on the trace fossils within the fluvial, or stream channel and floodplain, facies of the Morrison Formation, and the overall Jurassic paleoecosystem within this park. Trace fossils are typically defined as fossilized equivalents of the structures produced in rocks, sediments and grains by the life processes of organisms, with the study of these features referred to as ichnology (Bromley, 1996). The most common trace fossils include burrows and footprints.

Several types of invertebrate (an animal without a backbone) trace fossils have now been identified in the upper part of the Morrison Formation of Curecanti National Recreation Area. These trace fossils record important information regarding the paleohydrologic and paleoecologic setting of this unit in this park. Hundreds of traces occur in fluvial sandstone and mudstone deposits. The traces include crayfish burrows, termite nests, homopteran burrows, bee cells, and earthworm burrows (Fiorillo and Hasiotis, 1996). Also present are various sizes of rhizoliths, or plant root traces (Fiorillo and Hasiotis, 1996). The invertebrate trace fossils predominantly occur in sandstones, whereas the plant root traces can occur in either the mudstones or the sandstones. Stratigraphically, these fossil traces appear to be confined to the lower part of the Brushy Basin Member or the upper part of the Salt Wash Member of the Morrison Formation. Perhaps most spectacular of these fossil traces are the remains of ancient termite nests.

The distribution and shape of these traces are related to paleoenvironmental conditions such as variations in water table and soil moisture levels that these burrowing organisms experienced during the Late Jurassic. For example, the length of the crayfish burrows delineates the depth of the water table level. The traces in Curecanti National Recreation Area with the greatest vertical component are the termite nests, which occur within the confines of large fossil root traces. The restriction of this ichnofossil to within a few meters of the Salt Wash/Brushy Basin contact suggests that this zone was a time of greater aridity during the highly seasonal climate than in other portions of the Morrison Formation in the park. This pattern has been observed by workers in other park units studied.

Management Issues for Invertebrates

The occurrence and distribution of these trace fossils has scientific importance, as well as public education potential. These fossils are largely located along the shores of the Blue Mesa Reservoir in Curecanti National Recreation Area, in large sandstone blocks that weigh in excess of 450 kg (1000 lbs) each. Given the logistical difficulty in moving such large blocks, or alternatively, attempting to utilize diamond-bladed rock saws to cut the fossils of interest out of the sandstone, it was deemed most appropriate to follow a third alternative. This third alternative was to produce latex peels of select fossil features. These peels would then be used as molds for making plaster casts that can be used for educational and exhibit needs. One peel was subsequently cast in plaster, painted and was used as part of a highy successful temporary exhibit entitled "Six Legs Over Texas: the infestation continues" at the Dallas Museum of Natural History.

Similarly, casts are available to the National Park Service for its educational and exhibit needs. Further these casts provide researchers the opportunity to study accurate reproductions of these fossil features, features which would otherwise be lost due to erosion. The National Park Service has provided the logistical support and framework for the excavation while the Dallas Museum of Natural History has provided the technical expertise for the molding and casting. This partnership has produced a successful model of cooperation, between the Park Service and a private institution, that has yielded important scientific, preservation, and educational results from a previously unrecognized resource.

CLAY MINERALOGY

A 16.5 m section was examined in the lower part of the Brushy Basin Member of the Morrison Formation, along Red Creek in CURE. This section begins with a 1.5 m thick, fine-grained, trough cross-bedded sandstone bed containing numerous invertebrate burrows (Fiorillo and Hasiotis, 1996). Above this unit is a dominantly maroon mudstone sequence, approximately 7 m thick described in more detail elsewhere (Fiorillo and McCarty, 1996). Overlying the mudstone sequence is another fine-grained sandstone bed 1 m thick containing clam burrows (Fiorillo and Hasiotis, 1996). Overlying this sandstone bed is a second, 5 m thick mudstone unit similar to the 7 m thick sequence described below. Capping this section is a 2 m thick sandstone bed containing termite burrows (Fiorillo and Hasiotis, 1996). The section is described in stratigraphic order below.

2.0 m	Sandstone, termite burrows (top of interval)
5.0 m	Mudstone, maroon
1.0 m	Sandstone, clam burrows
7.0 m	Mudstone, maroon
1.5 m	Sandstone, cross-bedded, invertebrate burrows(bottom of interval)
16.5 m	Total of unit studied

Diffraction data were collected from this 7 m mudstone unit using a Scintag XGEN 4000 diffractometer. Clay mineral identification was made from the diagnostic basal reflections of non-expandable clay minerals (Moore and Reynolds, 1989) and model calculations with the NEWMOD computer program (Reynolds, 1985). Mixed-layered illite/smectite (I/S) clay minerals were identified using the Δ °2θ (Moore and Reynolds, 1989) and by model calculations using NEWMOD (Reynolds, 1985). The proportion of kaolinite in each sample was based on the intensity ratio of the kaolinite 002 reflection to that of the I/S* 003 reflection (I/S* 003 = $illite_{002}/smectite_{003}$). A regression analysis was made between the K_{002}:I/S^*_{003} intensity ratios from calculated patterns of I/S and kaolinite mixed together in definite proportions using the MIXER option in NEWMOD. The K_{002}:I/S^*_{003} intensity ratio from the experimental diffraction patterns was then measured and the percentage of kaolinite was calculated with the regression equation. Table 2 summarizes the mineralogical results.

At Red Creek, the combination of root traces, clay slickensides, and blocky peds are all indicative of a paleosol (Van Houten, 1982; Retallack, 1988; 1990). The presence of clay slickensides in diffuse zones with lateral extent indicates a clay enhancement of at least one B, or Bt, horizon. These horizons are associated with typically fine (<1 cm) blocky peds, a pattern consistent with Bt horizons (Retallack, 1988). Further, the diffuse nature of these horizons and their distribution through at least a one meter interval, and the enhancement of kaolinite suggest that this paleosol formed under humid conditions (Retallack, 1990:89).

Thompson et al. (1982) found that in nonmarine Tertiary basin samples underlying unconformities, kaolinite-rich mineralogy and saprolitic texture strongly suggested a paleosurface formed during high rainfall intervals. McCarty and Thompson (1991) found that abrupt discontinuities in clay mineralogy correlate with regional unconformities. Strong correlation between rainfall and soil clay mineralogy have been made by Keller (1965) and Barshad (1966). Barshad (1966) found that in soils, the frequency and distribution patterns of the clay minerals was controlled more by precipitation than by parent material, and the chemical environment that exists during clay mineral formation determines their nature. Kaolinite was associated with mean annual rainfall > 40 inches, and montmorillonite with mean annual rainfall <20 inches (Barshad, 1966).

TABLE 2

Sample ID	Unit	Clay Minerals	I/S R & %exp.	Other Minerals	%K
RCU3	1	I/S, K	R3, 5-10	Q, C	1-2
RCU4	2	I/S, K	R3, 5-10	Q, C	t
RCU5	3	I/S, K	R3, 5-10	Q, C	t
RCU10	8	I/S, K	R3, 5-10	Q, C	24
RCU11	9	I/S	R3, 5-10	Q, C	0
RCU12	9	I/S	R3, 5-10	Q, C	0
RCU13	10	I/S	R3, 5-10	Q, C	t

Table 2.—Results of the clay mineralogy study of the Red Creek mudstone sequence. Abbreviations: I/S = illite/smectite, K = kaolinite, I = illite, t = trace, Q = quartz, C = calcite, exp. = % expandability in I/S (i.e. % smectite layers), and R = reichweite.

Reichweite (the "reach back") refers to the probability, given a layer A, of finding the next layer to be B. Flipping a coin is R = 0 (R0), there is no influence at all of one flip on another. In illite/smectite, there is a transition series from pure smectite to pure illite, through stages of increasing illite layers (decreasing expandability). Not only do the amount of illite layers increase, but ordering increases as well. R1 means that given a smectite layer, the next layer must be an illite. No two smectite layers can be found next to each other, but illite layers can if there are more than 50%. R3, or greater, means that for a smectite layer one must reach back over 3 or more illite layers to find another smectite layer. Error in proportion of kaolinite is ± 5-10%. The samples are listed in stratigraphically ascending order.

Clay minerals in the <1μm size fraction of the Red Creek samples are dominated by 10% expandable I/S with R3 ordering (Table 1). However, the sample RCU10 also contains approximately 25% kaolinite with the I/S (Table 1). Given the hand specimen characteristics observed in the field that highlight the paleopedogenic nature of this interval, the difference in clay mineralogy of the RCU10 sample is interpreted as resulting from the development of a fossil soil. The significant kaolinite content in the RCU10 sample is consistent with soil formation during humid conditions. The R3 I/S clays in the Red Creek samples are interpreted to be of detrital origin because other I/S group clay mineral samples in the area, subjected to comparable diagenetic conditions, are highly expandable random ordered illite/smectites typical of low temperature environments. In light of the above discussion, this kaolinite spike likely also represents a discontinuity, a feature observed throughout much of the Morrison Formation studied for this summary report.

Given the combination of field and mineralogical characteristics observed at Red Creek, the paleosols within this sequence, best exemplified by the upper units in the sequence, would be classified as either ultisols (*sensu* Retallack, 1988, 1990) or argillisols (*sensu* Mack et al., 1993). Further the characteristics observed are consistent with a paleosol forming under humid conditions. Additional work is needed in the park to explore the lateral variability of the results found in the Red Creek section.

SUMMARY

A summary of the stratigraphic relationships is presented in Figure 1. Clearly most of the paleontologically significant resources for both park units is in the lower part of the Brushy Basin Member of the Morrison Formation. Although vertebrate, invertebrate and plant remains were found in this study, megafloral remains (i.e., leaves, stems, etc.) are rare.

Given the diversity of fossil types, management techniques vary from fossil excavation to making latex peels of fossil features. The results of this study have been a valuable tool for these park units. These spatial data have been incorporated in a GIS for manipulation. These data were then used in resource planning and park budgeting.

REFERENCES CITED

Barshad, I., 1966, The effect of a variation in precipitation on the nature of clay mineral formation in soils from acid and basic igneous rocks; in, Proceedings, International Clay Conference, Jerusalem: Clay Minerals Society, v. I, p. 167-172.

Bartleson, B.L., and J.A. Jensen, 1988, The Oldest(?) Morrison Formation dinosaur, Gunnison, Colorado: The Mountain Geologist, v. 25, p. 129-139.

Bromley, R.G., 1996, Trace Fossils: Biology, Taphonomy and Applications: Chapman and Hall, London, 2nd ed., 361 p.

Fiorillo, A.R., 1991, Prey bone utilization by predatory dinosaurs: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 88, p. 157-166.

Fiorillo, A.R., and Hasiotis, S.T., 1996, Preliminary report on the continental ichnofossils from the Upper Jurassic Morrison Formation of Curecanti National Recreation Area, Colorado: Geological Society of America, Rocky Mountain Section, Abstracts With Programs, v. 24, no. 4, p. 7-8.

Fiorillo, A.R., and May, C.L., 1996, Preliminary report on the taphonomy and depositional setting of a new dinosaur locality in the Morrison Formation (Brushy Basin Member) of Curecanti National Recreation Area, Colorado; in, The Continental Jurassic: Morales, M. (ed.), Museum of Northern Arizona Bulletin 60, p. 555-561.

Fiorillo, A.R., and McCarty, D.K., 1996, Paleopedological evidence for a humid environment in the lower part of the Brushy Basin Member, Morrison Formation, of Curecanti National Recreation Area, Colorado; in, The Continental Jurassic: Morales, M. (ed.), Museum of Northern Arizona Bulletin 60, p. 575-580.

Fiorillo, A.R., May, C.L., and Harris, R, 1997, Comparison of paleontological resource management in the Rocky Mountain Region by the National Park Service and the U.S. Forest Service; in, Making Protection Work: Harmon, D. (ed.), The George Wright Society Biennial Conference, The George Wright Society, Hancock, Michigan, p. 308-311.

Keller, W.D., 1965, The principles of chemical weathering: Lucas Brothers Publishers, Columbia, Missouri, 111p.

Mack, G.H., James, W.C. and Curtis, H.C. 1993, Classification of paleosols: Geological Society of America Bulletin, v. 105, p. 129-136.

McCarty, D.K., and Thompson, G.R. 1991, Burial diagenesis in two Montana Tertiary basins: Clays and Clay Minerals, v. 39, p. 293-305.

Moore, D.M., and Reynolds, R.C., Jr., 1989, X-Ray diffraction and the identification and analysis of clay minerals: Oxford University Press, New York, 332 p.

Retallack, G.J., 1988, Field recognition of paleosols; in, Reinhardt, J., and Sigleo, W.R., (eds.), Paleosols and weathering through geologic time: Principles and applications: Geological Society of America Special Paper 216, p. 1-20.

Retallack, G.J., 1990, Soils of the past: An introduction to paleopedology: Unwin Hyman, Boston 520 p.

Reynolds, R.C., Jr., 1985, NEWMOD*, A computer program for the calculation of one-dimensional diffraction patterns of mixed-layered clays: R.C. Reynolds, Jr., 8 Brook Road, Hanover, New Hampshire.

Schullery, P., 1997, Searching for Yellowstone: Houghton Mifflin Co., Boston, 338 p.
Thompson, G.R., Fields, R.W. and Alt, D., 1982, Land-based evidence for Tertiary climatic variations, Northern Rockies: Geology, v. 10, p. 413-417.
Van Houten, F.B., 1982, Ancient soils and ancient climates; in, Climate and Earth History: Studies in Geophysics, National Academy Press, Washington, D.C., p. 112-117.

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Figure 1.—Generalized measured section for the Morrison Formation at Curecanti National Recreation Area with key sandstone units highlighted. The section illustrates the stratigraphic relationships of the key features mentioned in the report. The figure also includes a qualitative boundary between dominantly green and maroon mudstone units that was observed in the field.

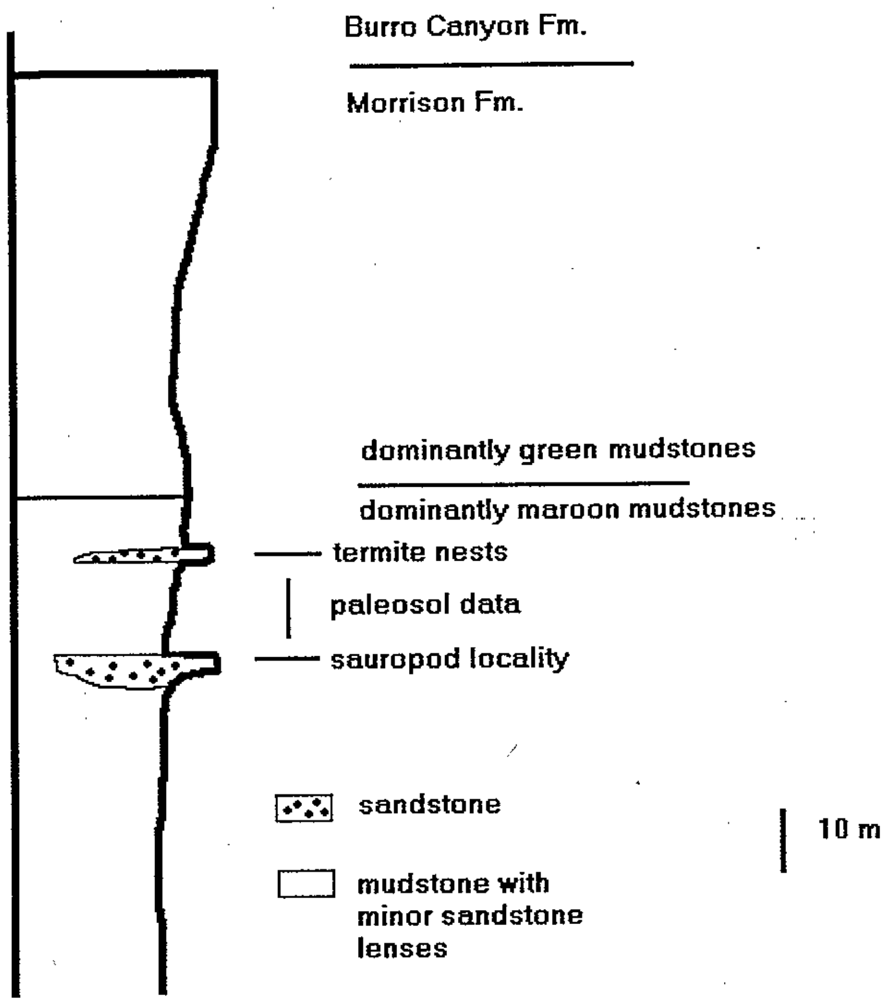
Burro Canyon Fm.
Morrison Fm.
dominantly green mudstones
dominantly maroon mudstones
termite nests
paleosol data
sauropod locality
sandstone
mudstone with minor sandstone lenses
10 m

Figure 1.

BIVALVES AS TOOLS FOR PALEOENVIRONMENTAL ANALYSIS—UPPER JURASSIC MORRISON FORMATION OF THE WESTERN INTERIOR; FINAL REPORT

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INTRODUCTION

Non-marine molluscs often dominate the biomass of meandering fluvial and marginal lacustrine depositional environments. The high density of bivalve resting traces at Alcova, WY and at Cleveland Lloyd Quarry, UT, demonstrate unionid bivalves were dominant members of aquatic communities of the Morrison Formation. Bivalve fossils are geographically and stratigraphically distributed throughout the Morrison basin (in Appendix 1).

The scientific literature has been searched for references to occurrences of molluscs from Morrison Formation strata. Thirty-five bivalve localities have been identified, that range geographically throughout the entire latitudinal extent of the basin and stratigraphically from all ages of strata that compose the Morrison Formation (documented in database constructed and summarized in Hanley, Evanoff and Good, 1986; and Evanoff, Good and Hanley, in press).

METHOD OF RESEARCH

Interpretations of the paleoecological significance of Morrison bivalves are formulated in this report from three levels of analysis. First, previously reported fossil bivalve occurrences have been analyzed. This analysis is limited by the variable quality of geographic and stratigraphic information available in the literature, and by the need of taxonomic revision of the bivalve faunas of the Morrison. Second, eight localities have been examined by the investigator in the past three field seasons. Samples and biostratinomic observations have been collected at the field sites. These sites have the value of being studied by the NPS-Jurassic Ecosystem Reconstruction research team (allowing collaboration at the field sites with other scientists, and precise geographic and stratigraphic positions are available for all field sites). Third, preliminary study of Morrison bivalve shell ultrastructure have been conducted to identify shell growth banding patterns.

REPORTS OF MOLLUSC OCCURRENCES

The bivalve fauna of the Morrison Formation currently consists of seventeen species (Hanley, Evanoff and Good, 1986; Evanoff, Good and Hanley, in press). See Table 1 for the faunal list of bivalve species of the Morrison Formation. The earliest publications on the Morrison molluscs were published over 100 years ago (White, 1987, 1886, 1905, but research on this fauna has been sporadic and primarily concerned with taxonomies (Logan, 1900, Branson, 1935, 1964; Holt, 1942). The last major publication on the Morrison molluscs was by T.C. Yen, (1952). The taxonomy of all mollusc groups of the Morrison are in need of revision. Despite the problems with the taxonomy of the molluscs, some interesting paleogeographic and paleoenvironmental interpretations can be drawn. Unionids are taxonomically conservative, which allows for paleoecologic interpretations by analogy, or taxonomic uniformitarinism of Dodd and Stanton (1981). Optimal environmental conditions for unionid bivalves are presented in Table 2(A).

Unio and Vetulonaia spp. of bivalves are widely distributed geographically and stratigraphically. Where present, they are usually abundant and are characteristic of many Morrison faunas. Hadrodon spp. are geographically and stratigraphically restricted (occurring only in the Salt Wash Member in the west-central Colorado part of the Colorado Plateau region). Summary information of previously reported Morrison mollusc occurrences is presented in Tables 3 and 4.

Paleobiogeography of Morrison basin unionid faunas drawn from bivalve distributions have been used to interpret histories of drainage interconnections. Unionacean bivalves are very efficiently dispersed within the drainage basin by the glochidial parasitic larvae that attaches to fish (Kat, 1984). Partial faunas of unionaceans may be transferred between drainage basin during stream capture events in the headland regions (Van der Schalie, 1944). Modern unionacean faunas of the Atlantic coastal plain rivers indicate "island biogeography" concepts that effectively explain the observed distributions of modern unionacean species (Sepkoski and Rex, 1974). Application of such paleobiogeographic analyses of fossil unionacean bivalves indicated no barriers to dispersal between the Late Triassic basin of the American Southwest, with flow-through drainage from the Dockum Basin into the Chinle Basin (Good, 1992, 1993a). Unionacean paleobiogeographic distribution patterns within the Morrison basin may provide evidence of fluvial confluence patterns and determination of dispersal pathways and barriers within the basin. Fluvial confluence pattern interpretations for the Morrison basin are not possible until taxonomy of previous collections are verified and stratigraphic position of each locality are constrained. The investigator hopes to pursue this avenue of research in the future.

LOCALITIES EXAMINED IN THIS STUDY

Paleoecologic Analysis and Refinement of Depositional Environment Interpretations

A wide range of depositional environments have been recognized in the Morrison basin, including fluvial channel, overbank floodplain, eolian, lake margin, lacustrine, and coal swamps. Fossil molluscs have been reported from the freshwater aquatic depositional environments of the Morrison. As shown in this preliminary report, bivalves have the potential to considerably enhance paleoecological interpretations. Freshwater bivalve assemblages can be analyzed to identify ecological associations that can be used to refine interpretations of depositional environments. The paleoautecology of individual species can be constrained from the application of taxonomic uniformitarianism (Dodd and Stanton, 1981). This analysis transfers the ecologic tolerances of extant taxonomic relatives to the paleoecologic tolerances of extinct species; but must be evaluated for shifting ecologic tolerances through geologic time within the taxonomic group. Assemblages of molluscs and co-occurring taxa; such as vertebrates (Chure, Englemann, McIntosh), ostracodes, charaphytes (Schudack), plants (Demko, Ash, and Tidwell), and trace fossils (Hasiotis) can be taphonomically analyzed to identify biostratinomic mixing of fossils from disparate ecologic units. The goal of the taphonomic analysis is to discriminate ecological associations of taxa and to interpret the taphonomic history of an assemblage. Then, the depositional environment can be further constrained by the paleosynecology of the ecologic associations of molluscs and co-occurring taxa. The specific conditions of the depositional environment are restricted to the range of overlapping tolerances of individual taxa that compose the association. This approach has generated refined interpretations of the Late Triassic Chinle Formation mollusc assemblages (Good and others, 1986; Parrish and Good, 1986; Good, 1989a, 1989b, 1991, 1993a, 1993d; Dubiel and others, 1989, 1991), and Paleogene mollusc faunas of the Western Interior (Hanley, 1976; Good, 1986a, 1987; Dubiel and others, in press).

The paleoecological tolerances for Morrison bivalves are drawn from the ecological tolerances of modern unionid bivalves. This is a family-level transfer ecology interpretation. The tolerances of modern unionids define habitats where unionids are able to thrive at abundances similar to those observed in Morrison unionid localities. Those tolerances are summarized in Table 2(A). Unionids are noted for their ecophenotypic plasticity (the shell form is modified to adapt to a particular habitat). Shell obesity is positively correlated with increasing size of the fluvial system and inversely correlated to flow velocity (less obese shelled individuals are able to burrow more quickly and prevent potential entrainment in the flow during fluvial bed scouring). Size is positively correlated with size of the fluvial system and protected benthic habitats of lacustrine systems. Shell height is negatively correlated with flow velocity (with greatest heights of shell developed in large sluggish fluvial systems and protected lacustrine environments. These parameters were used to identify three ecophenotypic subpopulations within species of Chinle unionids (Good, 1993). Similar analyses have been conducted on the Morrison unionid species.

Paleosynecological analyses (see Table 2(A) for biotic requirements of unionids) indicate a relatively short food chain exists. The lack of significant predators in combination with their "reclusive", infaunal lifestyle has been a successful habitat selection, as indicated by the success of modern unionids. The principal biotic ecological requirement for success is the development of the glochidial parasitic larvae that provides a dispersal mechanism for distributing these bivalves upstream. The abiotic factors are more significant in controlling the distributions of unionid bivalves.

Bivalve Assemblages Preserved Within Channels

Localities 1, 2 (DNM, UT), 6 (Alcova, WY)

Taphonomic analysis was conducted on the bivalve assemblage at the Carnegie Dinosaur Quarry sandstone bed (Localities 1 and 2), the results of which were presented by Kozlowski and Good (1995). This study recognized that the bivalvesthere represent a death assemblage of disarticulated unionid bivalve shells. The shells occur in current stable orientations that locally have imbricated stacking, and in troughs of mid-channel bars within the thalweg. The shells are well sorted by size; however, fragmentation and abrasion are minor. These features indicate a transported assemblage that has not been transported very far from the original life habitat of the bivalves (probably less than a few kilometers or miles, at most). The shell form of the bivalves indicates they inhabited a relatively high velocity, small fluvial system. The abundance of the specimens suggests a nearby upstream optimum habitat for the unionids that provided shells from the dead and decayed members of the population. Only a few articulated specimens have been found and they are generally not in life position, suggesting they were transported, buried, and unable to reestablish life functions; the predominant disarticulated valves require days to weeks of post-death decay of the ligament to disjoin the valves, suggesting the fauna represents a transported death assemblage. The shells are often replaced by silica. Insect trace fossil marks on the dinosaur bone from the quarry bed indicate subaerial exposure of the bone. The bones occur also in the thalweg deposits of the same fluvial channels as the bivalves. Optimum habitats for unionids require perennial aquatic habitats, suggesting a possible conflict in the paleoenvironmental interpretations. That is, a nearby upstream perennial habitat is required for the observed bivalve abundances whereas an ephemeral water habitat is indicated by the beetle-bored dinosaur bones in the stream bed, which requires that the stream dried up. Possible explanations are that the quarry sandstone bed was deposited during a climatic transition from higher to lower moisture regimes. The bivalves probably represent individuals of approximately 5-10 years of age (by comparison to comparable-sized, similar morphotypes from the Chinle Formation that preserve annual growth bands). This indicates development of a large unionid colony within a perennial aquatic, high velocity stream-flow habitat in a nearby upstream direction. Dead shells from this colony were transported a short distance downstream as part of the bedload and became part of the bedload deposit when the fluvial system dried up. Bones exposed in the thalweg were subsequently bored by beetles. Note that this is a hypothetical sequence of events that could have produced the seemingly disparate observations in the quarry sandstone.

The bivalve localities (Locality 6) at Alcova, WY, include six stacked beds of bivalve resting traces and internal molds (Unio sp.) from an overlying sandstone. The resting traces of bivalves are preserved in a channel sandstone bed that is composed of alternating sandstone beds and thin mudstone units. The bivalve resting traces were formed in the upper surfaces of the mudstone units. After the shells were removed, the indentions in the mudstone were filled by sand, creating the resting traces. The abundance of unionids is notable, indicating they were the dominant biomass within the fluvial system. Body fossils of bivalves are preserved in an overlying sandstone. The shells have experienced significant dissolution, producing internal molds of the bivalves. The geometry and sedimentary structures of the sandstone bed that contains the bivalves indicate it was deposited as a crevasse splay. The bivalves are predominately articulated but in random orientation. The shells most likely were entrained during a storm or flood event by high energy flow within the channel and then transported out of the channel and deposited within proximal overbank sediments.

Bivalve Assemblages Preserved Within Floodplain Ponds

Localities 3 (Cleveland-Lloyd Quarry, UT),
4 (Green River UT),
5 (Como Bluff, WY), and
8 (CNM, CO)

These assemblages are similar in their preservation within a fine-grained matrix,. The faunal characteristics that indicate lotic aquatic conditions include the shell morphology of large size and typically obese shell form. These faunas are interpreted as disturbed neighborhood assemblages (preserved in sediments inhabited during life, but out of life postion. Biostratinomic features that indicate a disturbed neighborhood assemblage are the wide range in sizes of specimens, excellent preservation (due to lack of transport), and high proportion of articulated specimens. All these features suggest an ecological association.

PALEOCLIMATIC SEASONALITY FROM GROWTH BANDS

Bivalves produce new shell material along the inner surface of the shell by the mantle. This results in the shell preserving a record of the conditions of the paleoenvironment through the life of the bivalve. New shell material is continuously deposited while conditions are favorable for the individual bivalve to pump water from the overlying aquatic habitat. Pumping is accomplished by the gill, which draws water into the mantle cavity through a short incurrent siphon tube. The gill extracts oxygen and filters food particles for consumption. Waste gases and products are removed from the mantle cavity in water that exits the mantle cavity though the excurrent siphon tube. Dark-colored, concentric growth bands are produced when the unionid bivalve is forced to close the valves and suspend water exchange (Coker and others, 1921). Two types of growth bands are recognized: pseudoannual bands that are faint and irregularly spaced and annual bands that are darker and regularly spaced. Pseudoannual bands are produced by short-term closure of valves, and can be produced by predation attacks or isolated storm flood runoff with high turbidity. Annual bands are produced when long-term closure of valves is forced by near freezing, cold temperatures (hibernation), or desiccation of habitat (aestivation). Bivalve growth band patterns have been used to interpret the paleoclimate of the Upper Triassic Chinle Formation (Dubiel and others, 1991; Good, 1993).

Bivalve shells from five localities were thin-sectioned for growth band analysis (Shultz, Steinhardt and Good, 1997). Three specimens from each of the localities were thin-sectioned, photographed, and quantitatively analyzed. The following interpretations are drawn from five localities, but more work is needed to verify the pattern in the stratigraphic record of changing growth banding and possible causal climate change. Data is presented in Appendix 2.

Bivalves from the Tidwell Member (Green River, UT) and Tidwell Member equivalent beds (Como Bluff, WY) both exhibited continuous growth with an absence of layering within the shells. The absence of layering indicates continuous favorable habitat for filter feeding, suggesting uniform temperature and precipitation climatic conditions.

Bivalve shells from the Salt Wash Member (CNM, CO) exhibited strongly developed annual growth bands. This indicates a strong annual precipitation cyclicity. Temperature cyclicity is eliminated from consideration due to the low paleo-latitudinal position of the locality.

Bivalves from the Brushy Basin Member were examined from Dinosaur National Monument, UT, and from the Cleveland-Lloyd Quarry, UT. The DNM specimens were silicified, and the diagenetic replacement destroyed the ultrastructure. This precluded the study of these specimens. The Cleveland-Lloyd Quarry specimens exhibited an irregular banding pattern. This pattern typically indicates a combination of annual and pseudoannual growth bands. The band pattern suggests the annual precipitation cyclicity may have decreased in strength.

SUMMARY

Although preliminary in scope, this study of the mollusc faunas of the Morrison Formation provides an enhanced understanding of the paleogeography and paleoenvironments of the large basin in which it was deposited. With further study, the unique dispersal mechanism employed by unionacean bivalves can allow documentation of paleodrainage confluence patterns, which can enhance an understanding of the paleogeography of the basin. Additionally, molluscan biostratigraphy has the potential to enhance correlations across the broad distances within the Morrison basin.

Preliminary growth band studies suggest changes from the lower to upper parts of the Morrison Formation. Bivalves in the Tidwell Member suggest a ubiquitous optimum habitat whereas those in the Salt Wash Member, which have strongly developed annual growth bands, suggest annual precipitation cyclity. Bivalves in the upper part of the Brushy Basin Member possess irregular banding that is produced by the complex interrelationship of weakly developed annual growth bands complicated by pseudoannual bands, which may have resulted from a combination of seasonality and aperiodic environmental stresses that could have been related to isolated storm-runoff turbidity, predation attacks, or the large quantities of volcanic ash that were carried into the basin at irregular intervals.

Thus, growth band studies suggest an optimum habitat, probably with no seasonality, during deposition of the Tidwell Member. In contrast, seasonality is strongly indicated during deposition of the Salt Wash Member. Seasonality is somewhat suggested for the Brushy Basin Member, but the irregular growth bands suggest additional nonperiodic environmental stresses that could have arisen from the random input of volcanic ash into the depositional basin or other non-cyclic environmental perturbations.

TABLE 1.

BIVALVE SPECIES LIST FOR THE MORRISON FORMATION

Class Bivalvia
- Subclass Lamellibranchia
  - Order Schizodonta
    - Family Unionidae
      - *Hadrodon jurassicus* Yen, 1952
      - *Hadrodon lateralis* Yen, 1952
      - *Hadrodon trigonus* Yen, 1952
      - *Unio baileyi* Logan, 1900
      - *Unio felchi* White, 1886
      - *Unio iroides* White, 1886
      - *Unio knighti* Logan, 1900
      - *Unio lapilloides* White, 1886
      - *Unio macropisthus* White, 1886
      - *Unio mammillaris* Yen, 1952
      - *Unio nucalis* Meek and Hayden, 1858
      - *Unio stewardi* White, 1876
      - *Unio toxonotus* White, 1886
      - *Vetulonaia faberi* (Holt), 1942
      - *Vetulonaia mayoworthensis* (Branson) 1935
      - *Vetulonaia whitei* (Branson) 1935
      - *Vetulonaia willistoni* Yen, 1952

TABLE 2(A).

OPTIMAL UNIONID ECOLOGICAL HABITAT

Abiotic Ecological Requirements
- Clean water (high turbidity damages gills)
- Well oxygenated water (lentic or wave/current-mixed lotic habitat)
- pH slightly greater than 7
- Lime-rich water
- Shallow water (less than 7 meters)
- Perennial aquatic habitat
- At least seasonably warm
- Stable substrate

Biotic Ecological Requirements
- Abundant plankton (filter feeders)
- Fish (and rarely amphibian) hosts for parasitic glochidial larvae
- Modern unionid predators: Raccoons (minor), humans (in archeological times)
- Potential Jurassic unionid predators: Lungfish (have shell-crushing toothplates)

REFERENCES CITED

Branson, C. C., 1935, Fresh-water invertebrates from the Morrison Formation (Jurassic?) of Wyoming: Journal of Paleontology, v. 9, p. 514-522.

Branson, C.C., 1964, Morrison fresh-water fauna in Wyoming: Oklahoma Geology Notes, v. 24, p. 238-243.

Davis, G.M., and Fuller, S.L.H., 1981, Genetic relationships among recent Unionacea (Bivalvia) of North America: Malacolgia, v. 20, p. 217-253.

Dodd, R.J., and Stanton, R.J. Jr., 1981, Paleoecology, concepts and application: Wiley, New York, 559 p.

Dubiel, R.F., and Parrish, J.T., Parrish, J.M., and Good, S.G., 1991, The Pangaean Megamonsoon, evidence from the Upper Triassic Chinle Formation, Colorado Plateau: Palaios, v. 6, no. 4, p. 347-370.

Evanoff, E., Good, S.C., and Hanley, J.H., 1998, An overview of freshwater mollusks from the Morrison Formation (Upper Jurassic, Western Interior, USA): Modern Geology, v. 22, nos. 1-4, p. 423-450. .

Good, S.C., 1989, Growth banding in freshwater bivalves (Family Unionidae) from the Upper Triassic Chinle Formation of Arizona and Utah (abst.): Geological Society of America, Abstracts With Programs, v. 21, no. 7, p. A340.

Good, S.C., 1992, Molluscan Paleobiogeography of the Upper Triassic Chinle and Dockum Basins of the American Southwest : Geological Society of America, Abstracts With Programs, v. 24, p. A325.

Good, S.C., 1993a, Molluscan paleobiology of the Upper Triassic Chinle Formation, Arizona and Utah: Unpublished Ph.D. Dissertation, University of Colorado, Boulder, 276 p.

Good, S.C., 1993b, Stratigraphic distribution of the mollusc fauna of the Chinle Formation and molluscan biostratigraphic zonation; in, S.G. Lucas and M. Morales (eds.), The Nonmarine Triassic: New Mexico Museum of Natural History and Science, Bulletin 3, p. 155-159.

Good, S.C., 1993c, Growth banding in freshwater unionacean bivalves from the Upper Triassic Chinle Formation: evidence of monsoonal circulation over western Pangaea: Society of Economic Paleontologists and Mineralogists, 1993 Theme Meeting, College Station, Abstracts Volume, p. 20

Good, S.C., and Ridgeley, J., 1989, Paleontology and sedimentology of the upper clastic member of the Wanakah Formation, Chama Basin, New Mexico: Lacustrine depositional environments: American Association of Petroleum Geologists Bulletin, v. 73, p. 1157.

Good, S.C., and Kozlowski, A.L., 1995, Taphonomic features of unionacean bivalves of the Upper Jurassic Brushy Basin Member of the Morrison Formation in Dinosaur National Monument, Utah: Geological Society fo America, Abstracts With Programs, v. 27, no. 1, p. 48-49.

Good, S.C., Yenik, L.A., Olsen, P.E., and McDonald, N.G., 1994, Non-marine molluscs from the Scots Bay Formation, Newark Supergroup (Early Jurassic), Nova Scotia: Taxonomic assessment and paleoecolgical significance: Geological Society of America, Abstracts wtih Program, v. 26, no. 3, p. 20.

Hanley, J.H., Evanoff, E., and Good, S.C., 1986, Paleobiology of nonmarine mollusks from the Morrison Formation, Western Interior U.S.: 4th North American Paleontological Convention, Abstracts With Programs, p. A19.

Haas, F., 1969, Superfamily Unionacea Fleming, 1828; in, Moore, R.C. (ed.), Treatise on Invertebrate Paleontology, Part N, v. 1, Mollusca 6, Bivalvia: University of Kansas, Lawrence, p. n411-n467.

Holt, E.L., 1942, A new Unio from the Morrison Formation of the Grand River valley, Colorado: Journal of Paleontology, v. 16, p. 459-460.

Kat, P.W., 1984, Parasitism and the Unionacea (Bivalvia): Biological Review, v. 59, p. 189-207.
Kat, P.W. and Davis, G.M., 1983, The species problem with fossil freshwater mollusks: Nature, v. 304, p. 660-661.
Logan, W.N., 1900, The stratigraphy and invertebrate faunas of the Jurassic formation in the Freeze-Out Hills of Wyoming: Kansas University Quarterly, v. 9, p. 109-134.
Meek, F.B., 1861, Descriptions of new lower Silurian (Primordal), Jurassic, Cretaceous, and Tertiary fossils, collected in Nebraska: Academy of Natural Sciences of Philadelphia Proceedings, v. 13, p. 415-447.
Meek, F.B., 1865, Paleontology of the Upper Missouri. Invertebrates: Smithsonian Contributions to Knowledge, v. 14, art. 5.
Meek, F.B., and Hayden, F.V., 1885, Descriptions of new organic remains collected in Nebraska Territory in the year 1857: Academy of Natural Sciences of Philadelphia Proceedings, v. 10, p. 41-59.
Ortmann, A.E., 1912, Notes upon families and genera of naiades: Annals of the Carnegie Museum, v. 8, p. 222-365.
Peterson, Fred, and Turner-Peterson, C. E., 1987, The Morrison Formation of the Colorado Plateau: Recent advances in sedimentology, stratigraphy, and paleotectonics: Hunteria, v. 2, no. 1, 18 p.
Peterson, J. A., 1972, Jurassic system; in, Mallory, W.W., (ed.), Geologic Atlas of the Rocky Mountain region: Denver, Rocky Mountain Association of Geologists, p. 177-189.
Sepkoski, J.J., and Rex, M.A., 1974, Distribution of freshwater mussels: Coastal rivers as biogeographic islands: Systematic Zoology, v. 23, p. 165-188.
Stanton, T. W., 1909, Succession and distribution of late Mesozoic invertebrate faunas in North America: Journal of Geology, v. 17, p. 410-423.
Stanton, T. W., 1915, Invertebrate fauna of the Morrison Formation: Geological Society of America, Bulletin, v. 26, p. 343-348.
Taylor, D. W., 1975, Early Tertiary mollusks from the Powder River Basin, Wyoming-Montana, and adjacent regions: U.S. Geological Survey, Open-File Report 75-331, 514 p.
Van der Schalie, H., 1944, The value of mussel distribution in tracing stream confluence: Papers of the Michigan Academy of Science, Arts and Letters, v. 30, p. 355-373.
White, C. A., 1878, Paleontological papers number 6: Descriptions of new species of invertebrate fossils from the Laramie Group: U.S. Geological and Geographical Survey of the Territories, Bulletin, v. 4, p. 707-719.
White, C. A., 1886, On the fresh-water invertebrates of the North American Jurassic: U.S. Geological Survey Bulletin 29, p. 697-725.
White, C.A., 1905, The ancestral origins of the North American Unionidae, or fresh-water mussels: Smithsonian Miscellaneous Collections, v. 48, 75-88.
Yen, T. C., 1952, Molluscan fauna of the Morrison Formation: U.S. Geological Survey Professional Paper 233-B, 51 p.

APPENDIX 1

ILLUSTRATIONS

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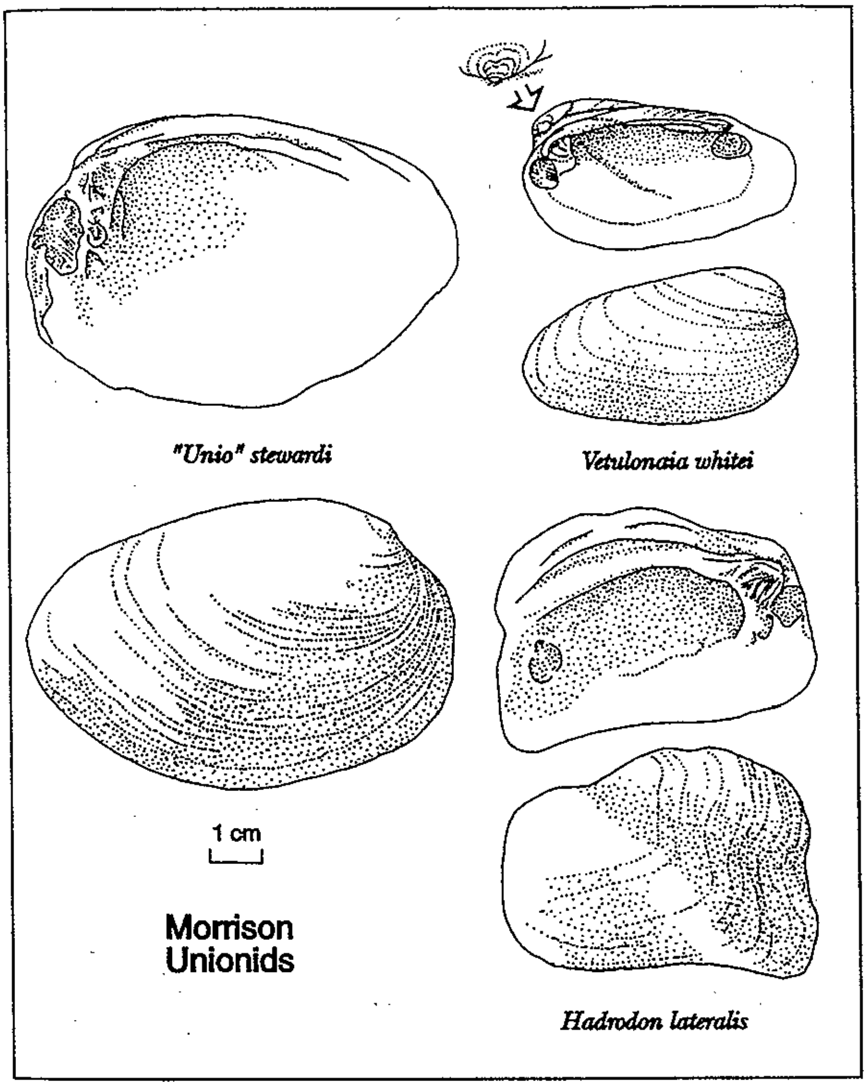

FIGURE 1 Illustrations of representative species of the unionid genera in the Morrison Formation. The illustrations of *Hadrodon lateralis* and *Unio stewardi* are after Yen (1952; Plate 5, Figs. 2(c) and 2(d); Plate 3, Figs. 3(d) and 3(e)).

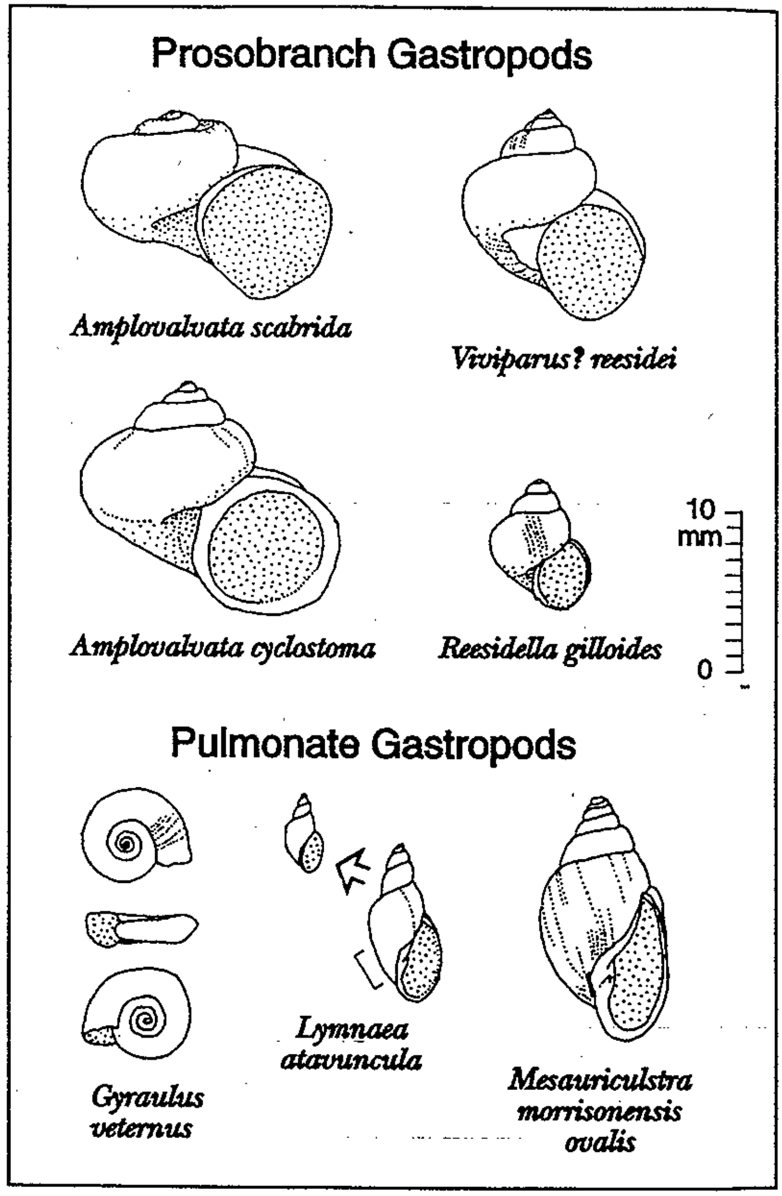

FIGURE 2 Illustrations of representative species of the most widespread and abundant gastropod genera in the Morrison Formation. All specimens are from the National Museum of Natural History (NMNH, Smithsonian Institution) and include: *Amplovalvata scabrida* – NMNH 107010; *Amplovalvata cyclostoma* – NMNH 107015 (holotype); *Viviparus? reesidei* – NMNH 107022 (paratype); *Reesidella gilloides* – NMNH 103800 (holotype); *Gyraulus veternus* – NMNH 20057; *Lymnaea atavuncula* – NMNH 107039; and *Mesauriculstra morrisonensis ovalis* – NMNH 107045 (holotype).

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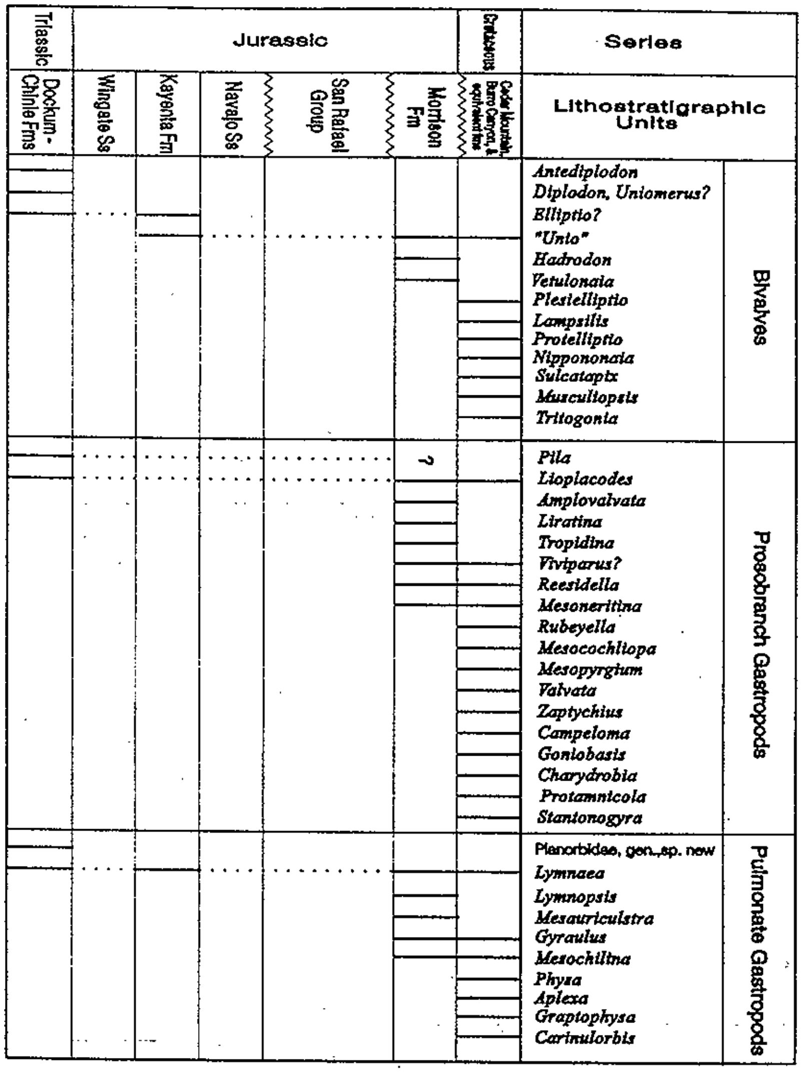


FIGURE 3 Distribution of freshwater molluscan genera in the Triassic, Jurassic, and lower Cretaceous rock units of the Western Interior. The lithostratigraphic units are in relative position, and have no thickness or absolute time significance.

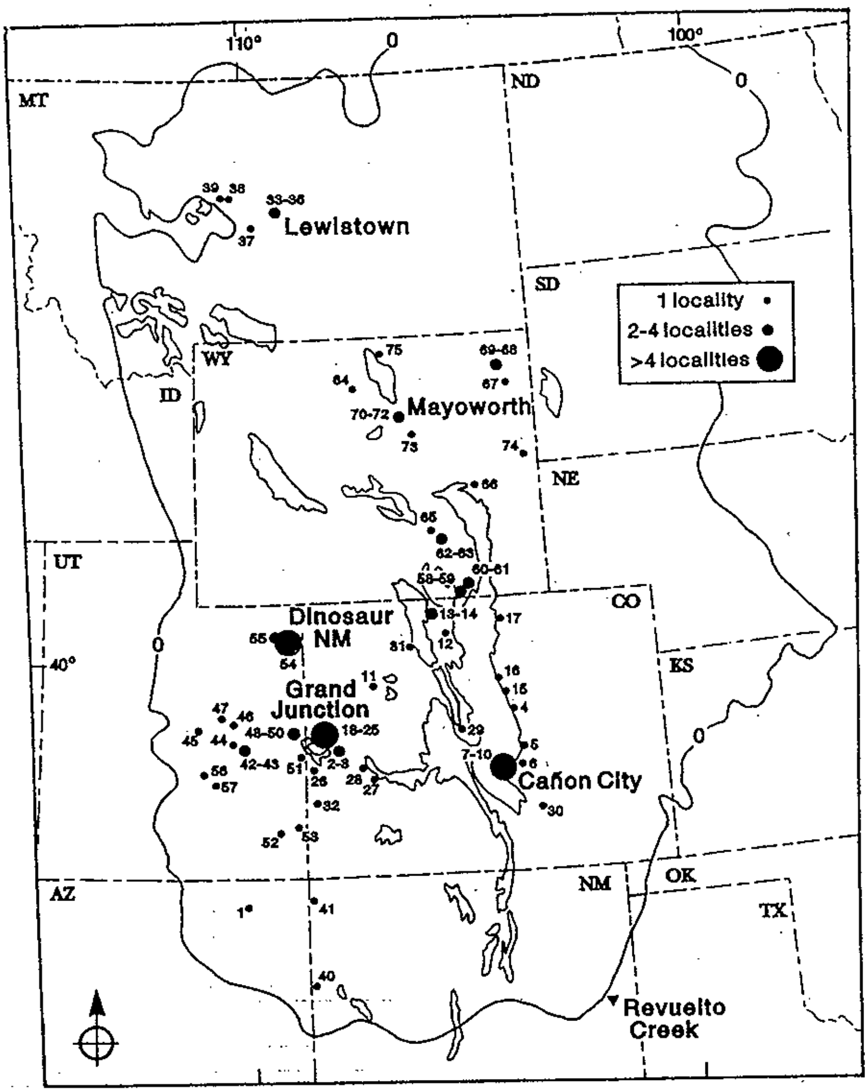


FIGURE 4 Distributions of the freshwater mollusk localities in the Morrison Formation. The numbers refer to the locality numbers listed in Table III. The triangle represents the location of the earliest pulmonate gastropods in the Dockum Formation at Revuelto Creek in eastern New Mexico. The heavy 0 line represents the edge of Morrison rocks (after Peterson, 1972), and the areas enclosed by thin lines represents the edges of modern outcrops of crystalline Precambrian rocks in Laramide uplifts.

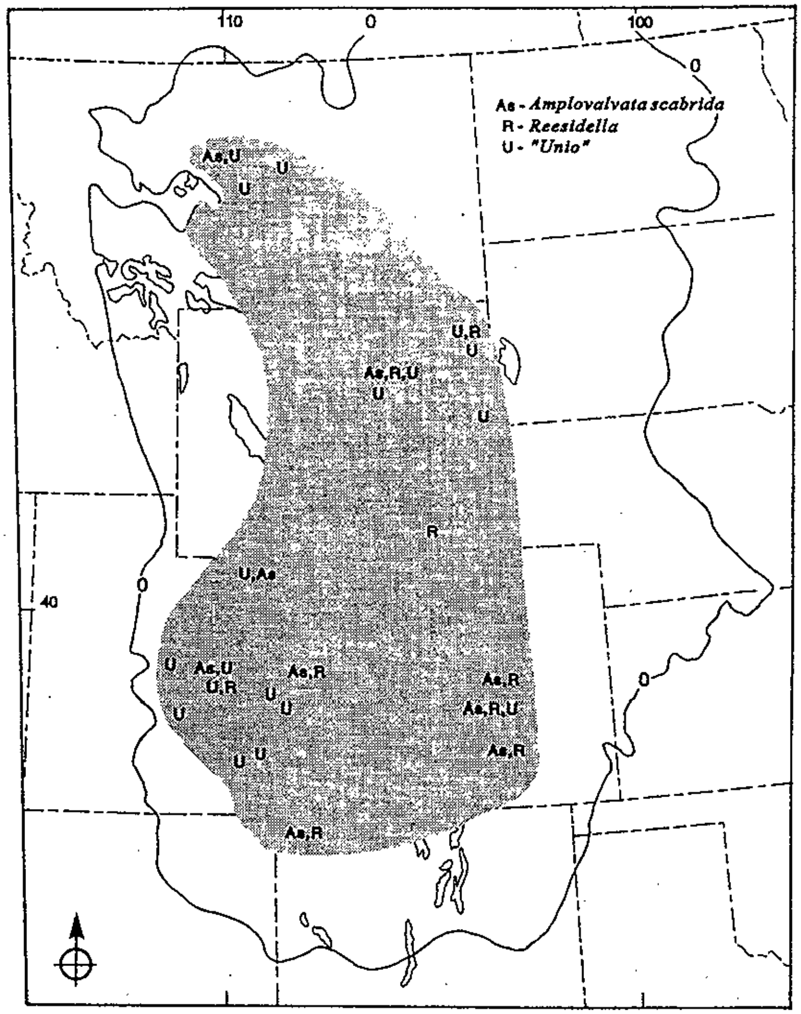
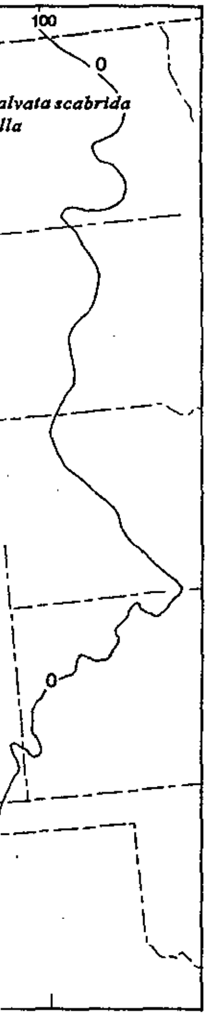


FIGURE 5 Distribution of the widespread freshwater molluscan taxa in the Morrison Formation. The heavy 0 line represents the edge of Morrison rocks (after Peterson, 1972).



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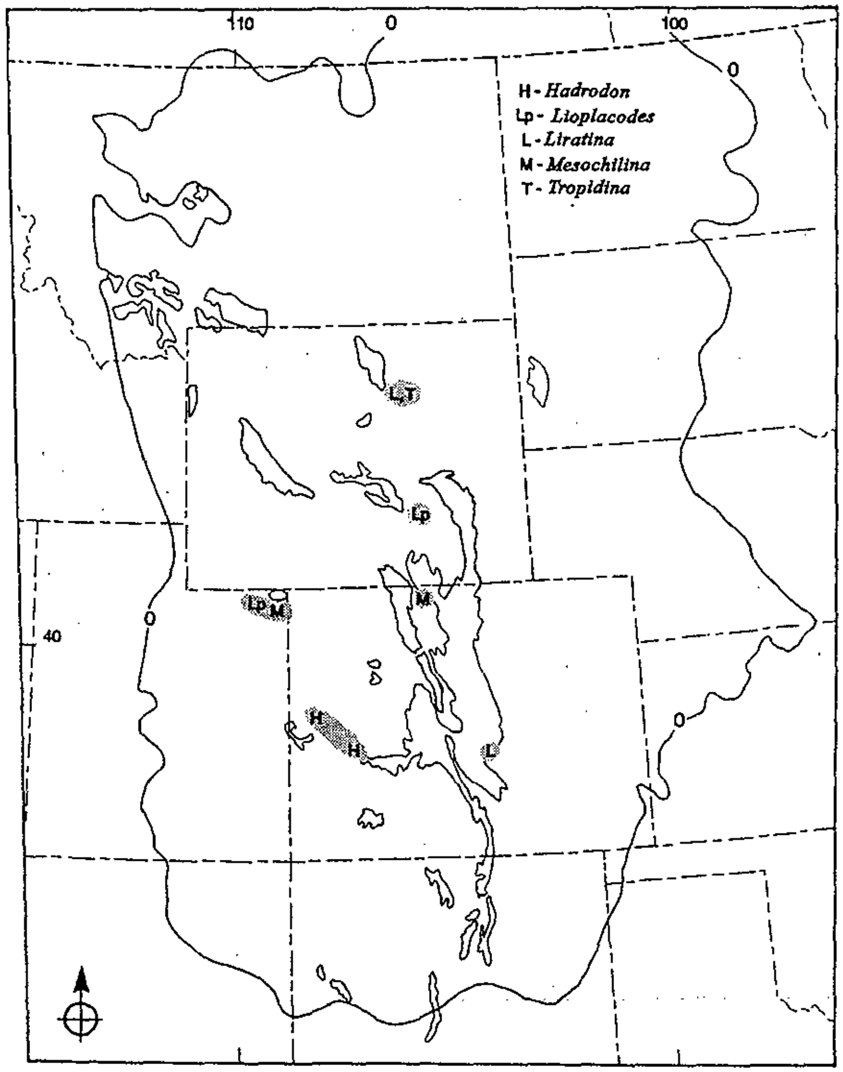


FIGURE 6 Distribution of areally restricted freshwater mollusks in the Morrison Formation. The heavy 0 line represents the edge of Morrison rocks (after Peterson, 1972).

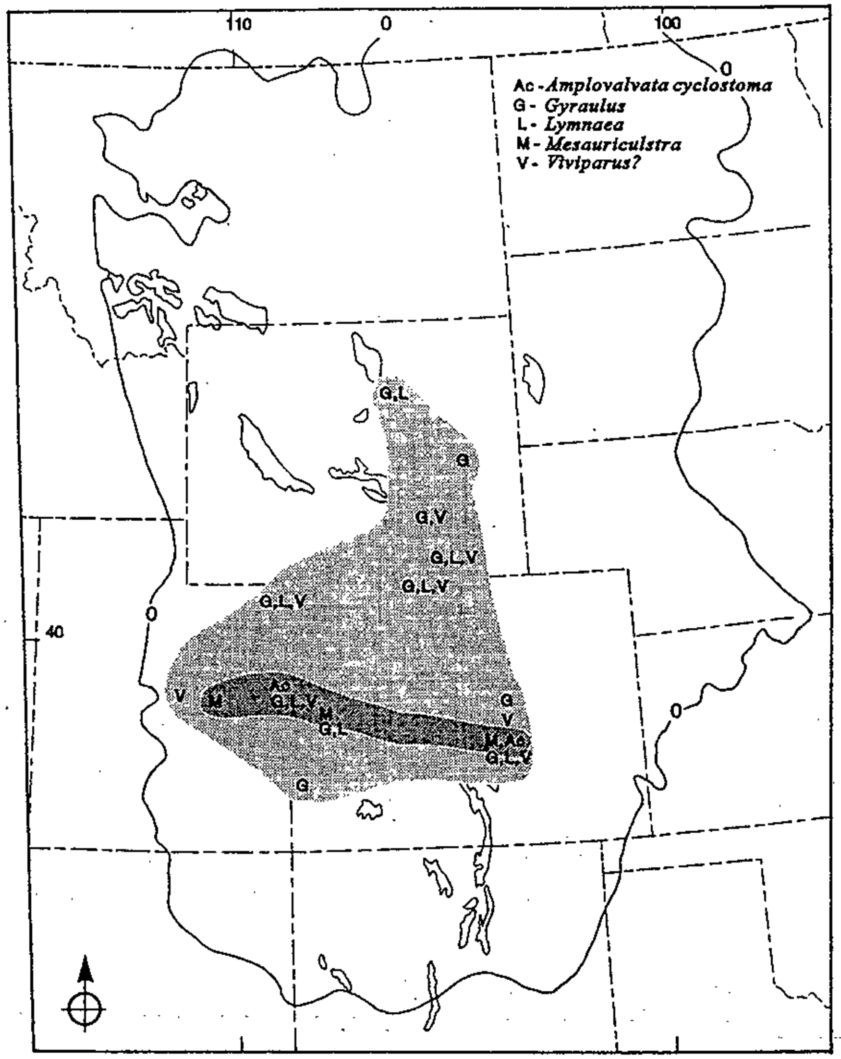


FIGURE 7 Distribution of freshwater snails that characterize the central part of the Morrison Formation, and two snails (*Amplovalvata cyclophorella* and *Mesauriculstra*) that suggest a west- to east-drainage across the Ancestral Rockies. The heavy 0 line represents the edge of Morrison rocks (after Peterson, 1972).

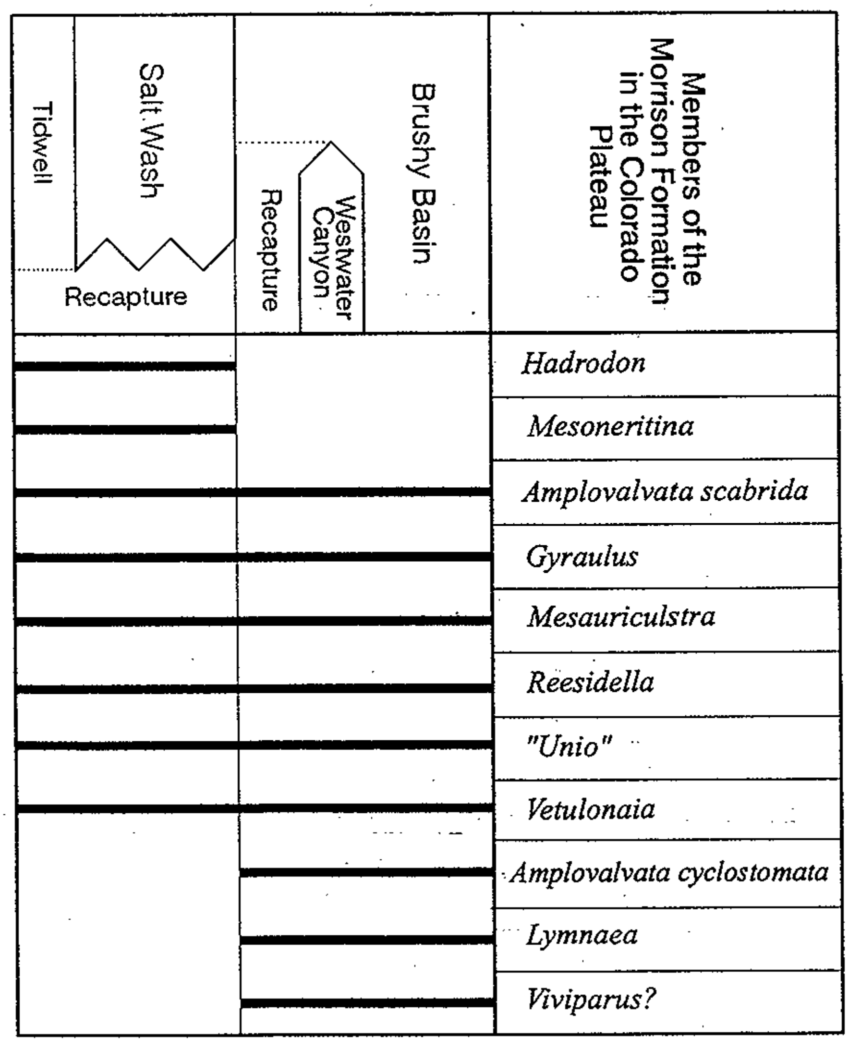


FIGURE 8 The distribution of mollusk taxa in the members of the Morrison Formation in the Colorado Plateau. The members are arranged in relative stratigraphic position, and have no thickness or absolute time significance.

APPENDIX 2

UNIONID ULTRASTRUCTURE STUDY

PHOTOMICROGRAPHS OF SHELL GROWTH BANDING AND PICTURES OF BIVALVE TRACE FOSSIL LOCALITIES.

• Green River, UT; Tidwell Mbr.

Specimen: •	Green River
Genus:	Vetulonaia
Banding Pattern:	massive
Shell Height:	29mm
Shell Thickness:	4.9mm
Shell Length:	42mm
Minimum Age:	unknown
Member:	Tidwell
Environment:	lakes

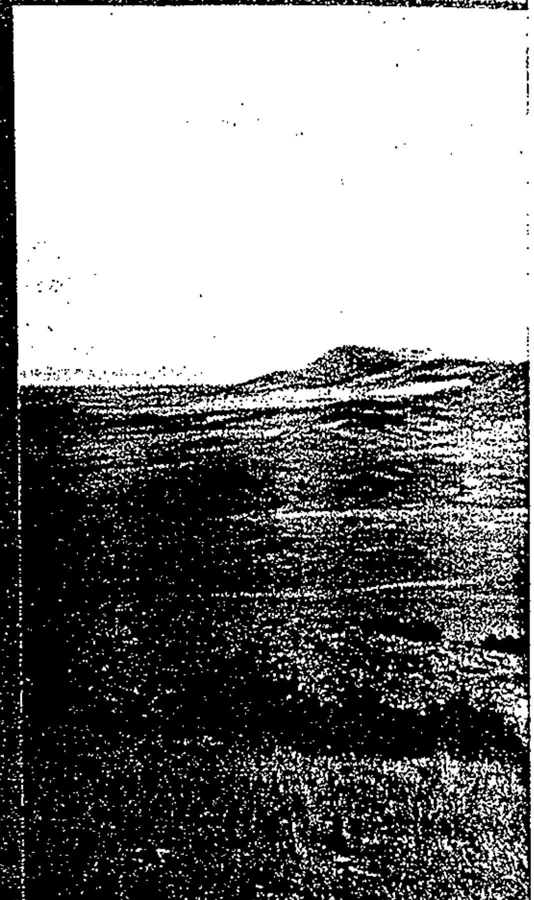
9-Absence of growth bands indicate continuous growth.

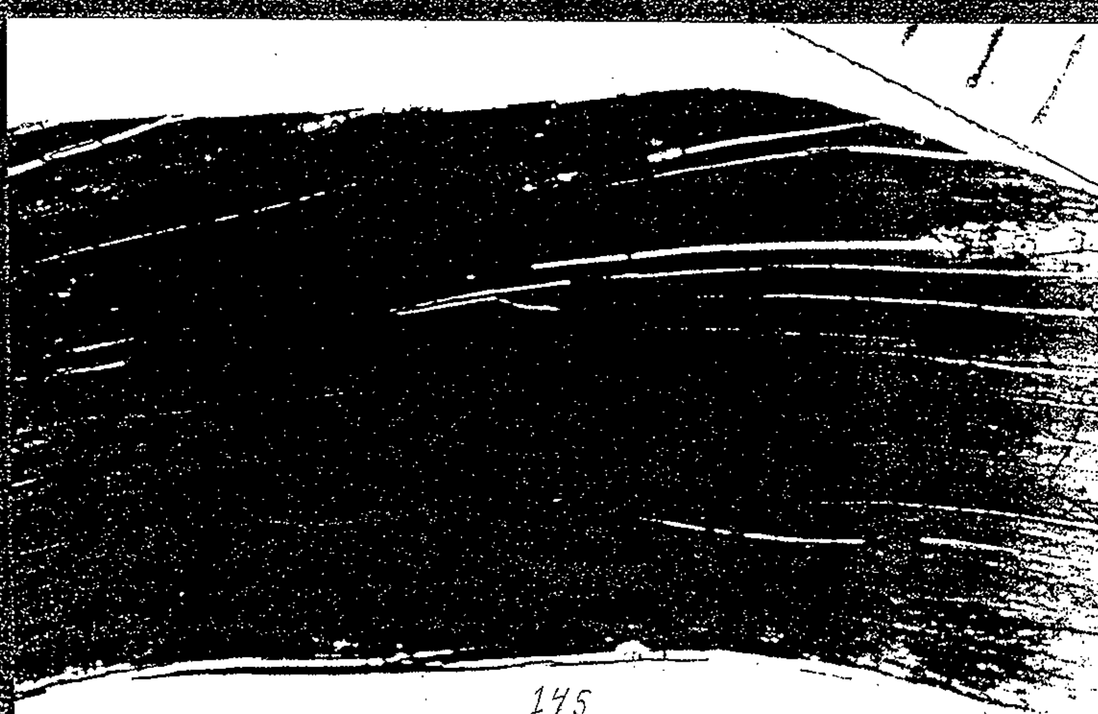
Como Bluff, WY; Tidwell Mbr

Figure 10.

Specimen:	Como-a
Genus:	*Vetulonaia*
Banding Pattern:	Massive
Shell Height:	16.6 mm
Shell Thickness:	5.9 mm
Shell Length:	45.0 mm
Minimum Age:	unknown
Member:	Tidwell
Environment:	lakes

Specimen:	Como-b
Genus:	*Vetulonaia*
Banding Pattern:	Massive
Shell Height:	21.0 mm
Shell Thickness:	7.9 mm
Shell Length:	39.0 mm
Minimum Age:	Unknown
Member:	Tidwell
Environment:	lakes

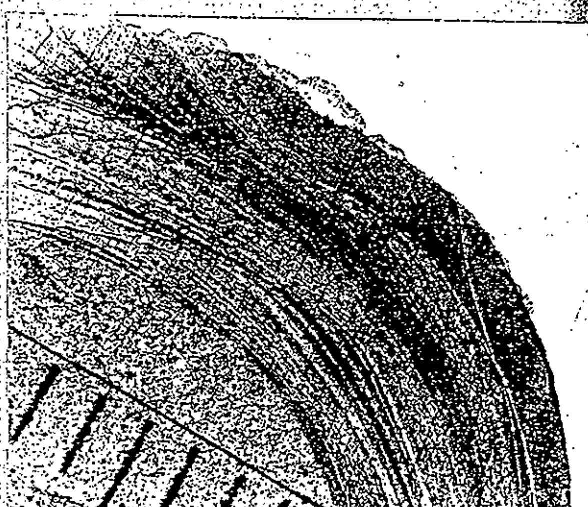




Colorado National Monument, CO; Salt Wash M

			Light Band Width (mm)	Dark Band Width (mm)	Total Band Width (mm)
Specimen:	CNM-a		0.14	0.16	0.30
Genus:	*Hadrodon*		0.13	0.16	0.34
Banding Pattern:	regular		0.16	0.10	0.26
Shell Height:	13.0 mm		0.30	0.09	0.39
Shell Thickness:	6.5 mm		0.31	0.29	0.60
Shell Length:	22.0 mm		0.12	0.29	0.41
Minimum Age:	11 years		0.20	0.13	0.33
Member:	Salt Wash		0.22	0.15	0.37
Environment:	Crevasse Splay		0.22	0.49	0.69
			0.11	0.15	0.26
			0.30	0.15	0.45
		Avg.:	0.20	0.20	0.40
		S.D.:	0.07	0.12	0.14

Specimen:	CNM-b
Genus:	Hadrodor
Banding Pattern:	regular
Shell Height:	13mm
Shell Thickness:	5.2mm
Shell Length:	31mm
Minimum Age:	unknown
Member:	Salt Wash
Environment:	Crevasse Splay



Well developed annual
climatic cyclicity. Gro
subequal light and d--k

Figure 11,

147

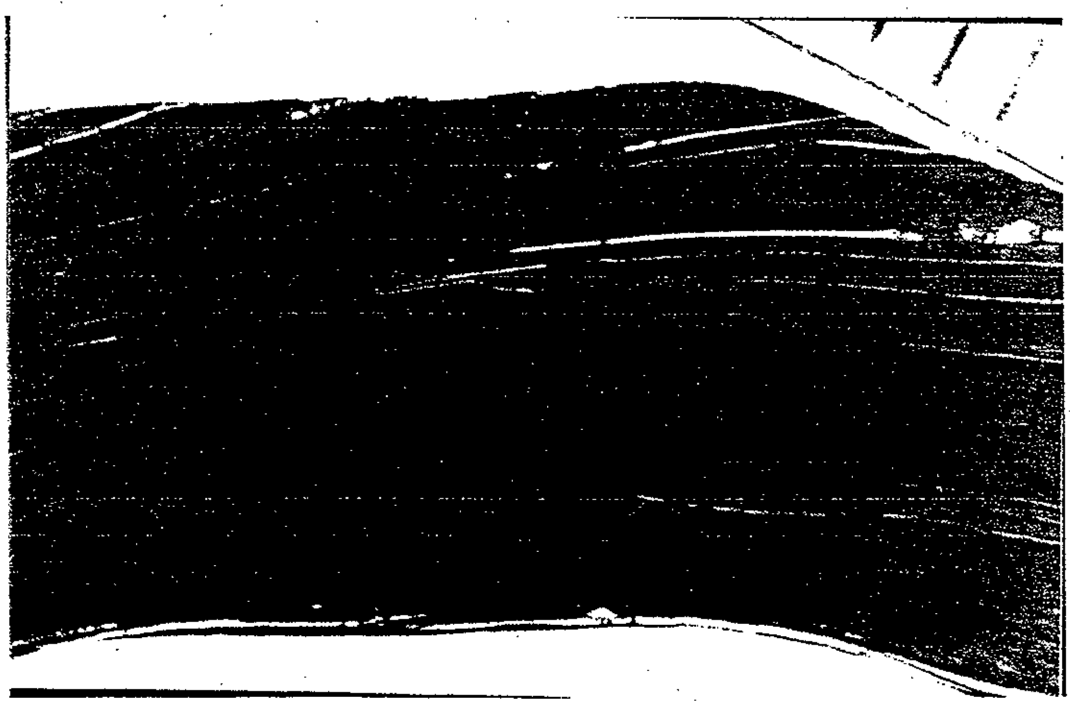
Cleveland Lloyd Quarry, UT; Brushy Basin Mbr.

			Light Band Width (mm)	Dark Band Width (mm)	Total Band Width (mm)
Specimen:	Cleveland Lloyd		0.07	0.55	0.62
Genus:	*Vetulanaia*		0.10	0.18	0.28
Banding Pattern:	irregular		0.01	0.19	0.29
Shell Height:	16.6mm		0.04	0.08	0.12
Shell Thickness:	3.8mm		0.03	0.15	0.18
Shell Length:	39.5mm		0.06	0.14	0.20
Minimum Age:	6 years				
Member:	Brushy Basin	Avg:	0.05	0.22	0.28
Environment:	lakes	S.D.:	0.03	0.17	0.18

Complex banding indicates combination of annual and pseudoannual bands.

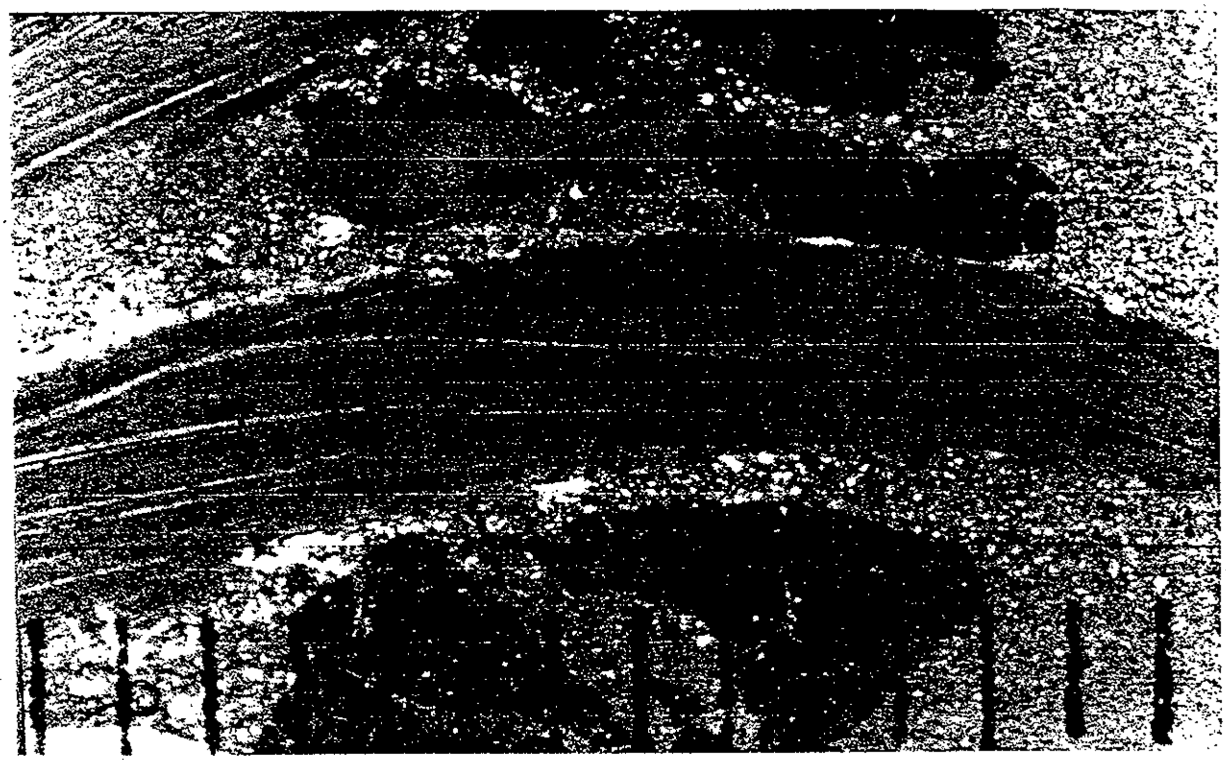
Figure 12.

Green River, UT, Tidwell Mbr.



Como Bluff, WY, Tidwell equivalent

Figure 13.



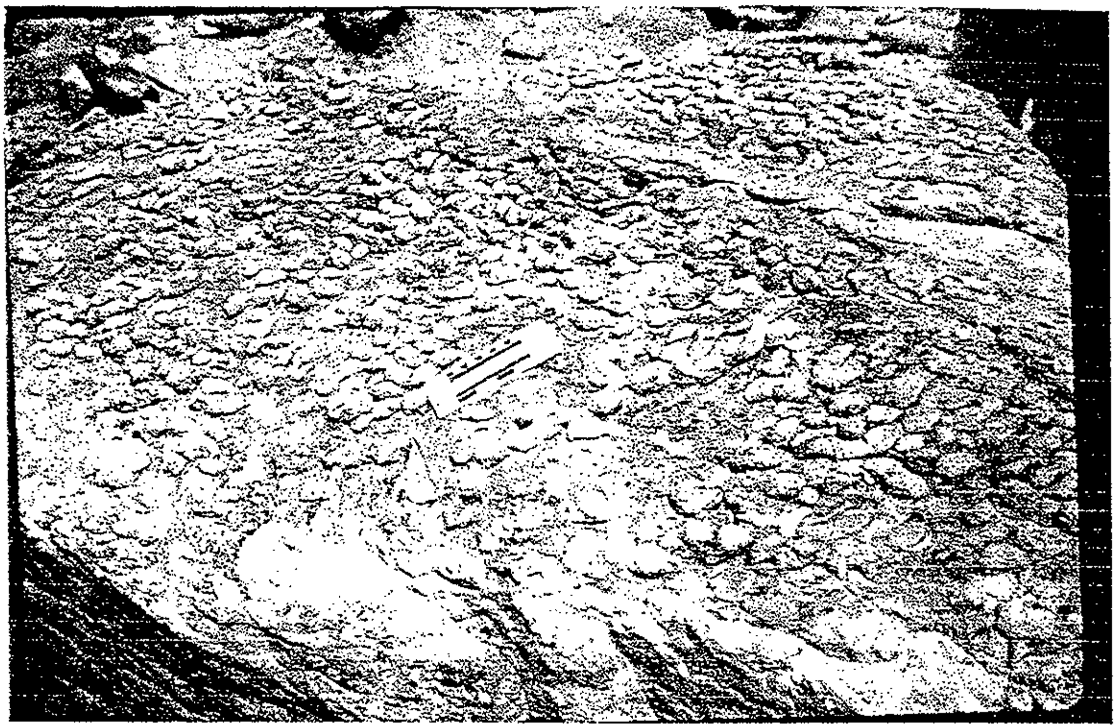
Colorado National Monument, Salt Wash Mbr.

Figure 14.

Cleveland Lloyd Quarry, UT, Brushy Basin Mbr.

Dinosaur National Monument, Brushy Basin Mbr.

Figure 15.



Cleveland Lloyd Quarry, Brushy Basin Mbr.

Alcova, WY, Bivalve Resting Trace Fossils

Figure 16.

TABLE 2.(B) CLASSIFICATIONS OF MORRISON FORMATION FRESHWATER SNAILS.

Classification after Taylor (1975), Wenz (1938-44), and Zilch (1959-60)	**Classification of Yen (1952)**
Class Gastropoda	
Subclass **Prosobranchia**	**Class Gastropoda**
Order Archaeogastropoda	
Family Neritinidae	Family Neritinidae
Genus ***Mesoneritina*** Yen, 1946	Genus ***Mesoneritina***
Mesoneritina morrisonensis Yen, 1952	*M. morrisonensis*
Order Mesogastropoda	Family Valvatidae
Family Cyclophoridae	Genus ***Amplovalvata***
Genus ***Amplovalvata*** Yen, 1952	*A. cyclostoma*
Amplovalvata cyclostoma Yen, 1952	*A. scabrida*
Amplovalvata scabrida (Meek and Hayden), 1865	*A. scabrida leei*
Amplovalvata scabrida leei (Logan), 1900	Family Viviparidae
Amplovalvata? reesidei (Yen), 1952	Genus ***Viviparus***
Superfamily Cyclophoracea, Genus Undetermined	*V. reesidei*
Gen. undet. *morrisonensis* (Yen), 1952	*V. morrisonensis*
Family Pleuroceridae	
Genus ***Lioplacodes*** Meek, 1864	Genus ***Lioplacodes***
Lioplacodes jurassicus Yen, 1952	*L. jurassicus*
Family Bithyniidae	Family Amnicolidae
Genus ***Reesidella*** Yen, 1952	Genus ***Amnicola***
Reesidella gilloides (Yen and Reeside), 1946	*A. gilloides*
Reesidella jurassica (Yen), 1952	*A. jurassica*
Family Valvatidae	Family Valvatidae
Genus ***Liratina*** Lindholm, 1906	Genus ***Liratina***
Liratina jurassica (Branson), 1935	*L. jurassica*
Genus ***Tropidina*** H. & A. Adams, 1854	Genus ***Tropidina***
Tropidina jurassica (Branson), 1935	*T. jurassica*
Genus "***Pentagoniostoma***" Branson, 1935	Systematic Position Uncertain
"*Pentagoniostoma*" *altispiratum* Branson, 1935	Genus "***Pentagoniostoma***"
	P. altispiratum
Subclass **Pulmonata**	
Order Basommatophora	
Family Ellobiidae	Family Ellobiidae
Genus ***Mesauriculstra*** Yen, 1952	Genus ***Mesauriculstra***
Mesauriculstra accelerata (White), 1886	*M. accelerata*
Mesauriculstra morrisonensis Yen, 1952	*M. morrisonensis*
Mesauriculstra morrisonensis ovalis Yen, 1952	*M. morrisonensis ovlis*
Genus ***Mesochilina***	Genus ***Mesochilina***
Mesochilina spiralis Yen, 1952	*M. spiralis*
Family Otinidae	Family Otinidae
Genus ***Limnopsis*** Yen, 1952	Genus ***Limnopsis***
Limnopsis jurassica Yen, 1952	*L. jurassica*
Family Lymnaeidae	Family Lymnaeidae
Genus ***Lymnaea*** Lamarck, 1799	Genus ***Lymnaea***
Lymnaea ativuncula White, 1886	*L. ativuncula*
Lymnaea consortis White, 1886	*L. consortis*
Lymnaea morrisonensis Yen, 1952	*L. morrisonensis*
Family Planorbidae	Family Planorbidae
Genus *Gyraulus* J. de Charpentier, 1837	Genus *Gyraulus*
Gyraulus veternus (Meek and Hayden), 1865	*G. veternus*

TABLE 3. KNOWN FRESHWATER MOLLUSK LOCALITIES IN THE MORRISON FORMATION.

Loc.	State	County	Section	Township	Range	Member	Yen Loc.	USGS Mz Loc.	References
1	AZ	Navajo		36° 39' N	110° 8' W	Salt Wash			Craig m.s., Loc. #1
2	CO	Delta	26	T. 14 S.	R. 98 W.	Salt Wash			Lohman, 1965, Loc. #1
3	CO	Delta	35	T. 14 S.	R. 98 W.	Brushy Basin	9	20322	Yen, 1952; Lohman, 1965, loc. #7
4	CO	Douglas	24	T. 9 S.	R. 69 W.	lower	18	7363	Richardson, 1915
5	CO	El Paso	107	T. 14 S.	R. 68 W.	basal	6	5420	Finlay, 1916
6	CO	Pueblo	27	T. 18 S	R. 67 W.	basal	1	1325	Finlay,1916; Yen, 1952
7	CO	Fremont	20	T.18 N.	R. 70 W.	unspecified	2	3211	Yen, 1952
8	CO	Fremont	28	T. 17 S.	R. 70 W.	lower	5	17997	Yen, 1952
9	CO	Fremont	28	T. 17 S.	R. 70 W.	lower	4	397	Yen, 1952
10	CO	Fremont	28?	T. 17 S.?	R. 70 W.	lower	3	481	Yen, 1952
11	CO	Garfield	34	T. 4 S.	R. 92 W.	lower	13	19407	Yen, 1952
12	CO	Grand	3	T. 1 N.	R. 78 W.	middle	16	6951	Yen, 1952; Izett, 1968
13	CO	Jackson	4	T. 9 N.	R. 81 W.	upper			Hail, 1965
14	CO	Jackson	33	T. 10 N.	R. 81 W.	basal	20	7116	Beekly, 1915; Yen, 1952
15	CO	Jefferson	27	T. 6 S.	R. 69 W.	basal			Scott, 1963
16	CO	Jefferson	26	T. 4 S.	R. 70 W.	lower	15	3507	Yen, 1952
17	CO	Larimer	13	T. 8 N.	R. 70 W.	unspecified	17	22408	Yen, 1952
18	CO	Mesa	30?	T. 1 N.	R. 2 W.	unspecified	12	20325	Yen, 1952
19	CO	Mesa	13	T. 1 N.	R. 3 W.	Brushy Basin			Hanley, FPA 3-81
20	CO	Mesa	13	T. 1 N.	R. 3 W.	Brushy Basin			Hanley, FPA 2-81
21	CO	Mesa	24	T. 1 N.	R. 3 W.	Salt Wash			Hanley, FPA 1-81
22	CO	Mesa	15 & 24	T. 1 N.	R. 3 W.	Brushy Basin	11	20324	Holt, 1940, 1942; Yen, 1952; Lohman, 1965
23	CO	Mesa	30?	T. 11 S.	R. 101 W.	Salt Wash			Holt, 1940, 1942; Lohman, 1965, loc. # 3
24	CO	Mesa	26	T. 11 S.	R. 101 W.	Brushy Basin			Holt, 1940; Lohman, 1965, loc. #10
25	CO	Mesa	19?	T. 12 S.	R. 100 W.	Salt Wash	10	20323	Holt, 1940, 1942; Yen, 1952; Lohman, 1965
26	CO	Mesa	11?	T. 50 N.	R. 18 W.	Salt Wash			Craig ms., Loc. 6
27	CO	Montrose	8	T. 49 N.	R. 7 W.	Wanaka? Fm.	7	3209	Yen, 1952, Hansen, 1971
28	CO	Montrose		T. 50 N.	R. 9 W.	unspecified	8	3212	Yen, 1952
29	CO	Park	23?	T. 9 S.	R. 77 W.	unspecified	14	6220	Yen, 1952
30	CO	Pueblo		T. 24 S.	R. 64 W.	lower			Stose, 1912
31	CO	Routt	15	T. 4 N.	R. 85 W.	unspecified			Snyder, 1980, Loc. 10
32	CO	San Miguel	33 or 27	T. 44 N.	R. 18 W.	Brushy Basin			Craig ms. Loc. 16
33	MT	Fergus	5?	T. 14 N.	R. 19 E.	lower	40	19418	Yen, 1952
34	MT	Fergus	5?	T. 14 N.	R. 19 E.	upper	39	4763	Calvert, 1909; Yen, 1952
35	MT	Fergus	5	T. 14 N?	R. 19 E?	upper	42	4768	Calvert, 1909; Yen, 1952
36	MT	Fergus	5	T. 14 N.	R. 19 E.	unspecified	41	19419	Yen, 1952
37	MT	Judith Basin	16	T. 11 N.	R. 15 E.	upper			Calvert, 1909
38	MT	Judith Basin	18?	T. 16 N.	R. 11 E.	unspecified	38	3963	Yen, 1952
39	MT	Judith Basin	3	T. 16 N.	R. 10 E.	upper?			Fisher, 1909
40	NM	McKinley		T. 14 N?	R. 20 W?	Westwater Canyon			Craig ms. Loc. 13
41	NM	San Juan	13	T. 29 N	R. 21 W.	Salt Wash			Craig ms., Loc. 8
42	UT	Emery	7	T. 23 S.	R. 16 E.	Salt Wash			Craig ms., Loc. 4
43	UT	Emery	18	T. 23 S.	R. 16 E.	Salt Wash			Peterson Field No. 997-K
44	UT	Emery	27	T. 22 S.	R. 14 E.	Tidwell	23	19472	Baker, 1946; Yen, 1952
45	UT	Emery	35 or 36	T. 20 S.	R. 8 E.	Brushy Basin?			Craig ms., Loc. 9
46	UT	Emery	17 & 18	T. 19 S.	R. 14 E.	Salt Wash			Gilluly, 1929
47	UT	Emery		T. 18 S.	R. 12 E?	Salt Wash	21	12572	Gilluly & Reeside, 1928; Yen, 1952
48	UT	Grand	9	T. 21 S.	R. 24 E.	Brushy Basin			Craig, LCC 5-75; Hanley 2-81
49	UT	Grand	18	T. 20 S.	R. 25 E.	Brushy Basin			Craig, LCC 4-75; Hanley 1-81
50	UT	Grand	36	T. 20 S.	R. 24 E.	Brushy Basin			Craig, LCC 6-75; Hanley 3-81
51	UT	Grand	27, 34?	T. 24 S.	R. 25 E.	Salt Wash			Craig ms., Loc. 5
52	UT	San Juan	8	T. 36 S.	R. 21 E.	Salt Wash			Craig ms., Loc. 2
53	UT	San Juan	36	T. 35 S.	R. 24 E.	Brushy Basin			Huff and Lesure, 1965
54	UT	Uintah	26-28	T. 1 N.	R. 23 E.	Brushy Basin	22	8747	Yen, 1952; Kinney, 1955; Evanoff field notes
55	UT	Uintah	10	T. 3 S.	R. 22 E.	Brushy Basin			Sloan and others, 1980
56	UT	Wayne	4	T. 27 S.	R. 9 E.	Salt Wash			Craig ms., Loc. 7
57	UT	Wayne	8	T. 29 S.	R. 11 E.	Salt Wash			Peterson 998-6
58	WY	Albany	15	T. 13 N.	R. 75 W.	lower?	27	3506	Darton and others, 1910; Yen, 1952
59	WY	Albany	10	T. 13 N.	R. 76 W.	upper	26	3505	Darton and others, 1910; Yen, 1952
60	WY	Albany	11	T. 14 N.	R. 74 W.	upper	25	3504	Darton and others, 1910; Yen, 1952
61	WY	Albany	32	T. 14 N.	R. 74 W.	lower?	24	3503	Darton and others, 1910; Yen, 1952
62	WY	Albany	9	T. 22 N.	R. 77 W.	upper	29	20326	Yen, 1952
63	WY	Albany	12	T. 22 N.	R. 77 W.	unspecified	28	3508	Darton & Siebenthal, 1909
64	WY	Bighorn	12?	T. 49 N.	R. 91 W.	unspecified	34	3184	Yen, 1952
65	WY	Carbon		T. 24 N?	R. 79 W?	unspecified	31	2389	Yen, 1952
66	WY	Converse	9	T. 31 N.	R. 71 W.	lower			Barnett, 1914; Pipiringos & O'Sullivan, 1976
67	WY	Crook	3	T. 49 N.	R. 64 W.	upper?			Robinson et al., 1964
69	WY	Crook	31 & 32	T. 52 N.	R. 65 W.	lower			Robinson et al., 1964
69	WY	Crook	16	T. 52 N.	R. 66 W.	lower			Robinson et al., 1964
70	WY	Johnson	14	T. 44 N.	R. 83 W.	lower	32	19092	Hanley 2B-81; Yen, 1952
71	WY	Johnson	14	T. 44 N.	R. 83 W.	lower			Hanley 2A-81
72	WY	Johnson	14	T. 44 N.	R. 83 W.	lower	33	20327	Hanley 2C-81; Yen, 1952
73	WY	Natrona	33	T. 41 N.	R. 81 W.	lower	30	6767	Wegemann, 1910; Yen, 1952
74	WY	Niobrara	9?	T 36 N.	R. 62 W.	lower	35	20533	Yen, 1952
75	WY	Sheridan	26	T. 55 N.	R. 86 W.	lower	36	4884	Yen, 1952

TABLE 4. THE TAXONOMIC COMPOSITION OF MORRISON FRESHWATER MOLLUSK ASSEMBLAGES FROM THE LOCALITIES LISTED IN TABLE 3.

Localities	1	2	3	4	5	6	7	8	9	10	11	12	13	14	16	17	18	19	20	21	22	23	24
Taxa																							
Hadrodon		X																					
Unio								X	X	X	X				X								
Vetulonaia																						X	
Bivalvia indet.				X																X			
Amplovalvata			X		X	X	X	X	X			X			X								X
Lioplacodes																							
Liratina									X														
Mesoneritina																							
Reesidella	X																						
Tropidina																							
Viviparus?						X								X							X		
Gyraulus		X	X		X		X	X	X					X		X	X						
Limnopsis												X											
Lymnaea			X			X	X	X				X		X		X							
Mesauriculstra						X		X	X														
Mesochilina														X									
Gastropoda indet.				X									X					X	X				

Localities	25	26	27	28	29	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49
Taxa																							
Hadrodon	X		X																				
Unio		X					X	X	X	X		X	X	X		X		X	X		X		
Vetulonaia	X						X	X	X	X		X											
Bivalvia indet.											X						X						
Amplovalvata	X			X	X								X		X			X				X	X
Lioplacodes																							
Liratina																							
Mesoneritina	X												X					X					
Reesidella																		X				X	X
Tropidina																							
Viviparus?																		X	X			X	X
Gyraulus				X	X	X												X				X	X
Limnopsis																							
Lymnaea				X																		X	X
Mesauriculstra																		X					
Mesochilina																							
Gastropoda indet.																				X	X		

Localities	50	51	52	54	55	56	57	58	59	60	61	62	63	65	66	68	70	71	72	73	74	75
Taxa																						
Hadrodon																						
Unio		X	X		X	X		X						X		X	X			X	X	
Vetulonaia				X	X									X			X		X			
Bivalvia indet.							X															X
Amplovalvata	X			X	X				X		X	X	X	X		X			X			
Lioplacodes					X									X								
Liratina																			X			
Mesoneritina																						
Reesidella	X				X						X						X		X			
Tropidina																	X		X			
Viviparus?	X			X	X					X		X										
Gyraulus	X			X	X			X	X		X	X			X		X		X			
Limnopsis														X								
Lymnaea	X			X	X			X			X		X						X			
Mesauriculstra																						
Mesochilina				X																		
Gastropoda indet.																		X				

APPENDIX 3

1. Carnegie Quarry, Dinosaur National Monument

Quarry sandstone bed, upper smectitic part of Brushy Basin Member (8-15-94).
Research presented in Good and Kozlowski, 1995.

Data

Bivalves: Vetulonaia sp.
Condition: Predominately disarticulated, little abrasion & fragmentation
Size distribution: Little variation in the size of shells
Orientation: Current stable position (convex up), one articulated specimen occurs in life position
Density: Concentrated shell lag in channel bed, in trough areas
Matrix: Course sand to gravel conglomerate
Preservation: Silicified (preserving no internal structure or vague ghosts of shell ultrasturcture

Interpretation

Bivalve shells represent a death assemblage that has been entrained, transported, and deposited in troughs between channel bed bedforms. The hydrodynamic behavior of the shells indicate they constitute the coarsest, least-transportable clast component of the bedload. The minor fragmentation and abrasion suggests the shells have not experienced significant transport. Therefore, this occurrence represents a transported assemblage.

2. Dinosaur National Monument

Approximately 0.5 mi east of Carnegie Quarry,
Quarry sandstone unit in the upper smectitic part of the Brushy Basin Member (8-15-94)
Research presented in Good and Kozlowski, 1995.

Data

Bivalves: Fossil shells
Condition: Predominately disarticulated, little abrasion & fragmentation
Size distribution: Little variation in the size of shells
Orientation: Current stable position (convex up)
Density: Concentrated shell lag in channel bed, in trough areas
Matrix: Course sand to gravel conglomerate
Preservation: Silicified (preserving no internal structure or vague ghosts of shell ultrasturcture

Interpretation

Bivalve shells represent a death assemblage that has been entrained, transported, and deposited in troughs between channel bed bedforms. The hydrodynamic behavior of the shells indicate that they constitute the coarsest, least-transportable clast component of the bedload. The minor fragmentation and abrasion suggests the shells have not experienced significant transport. Therefore, this occurrence represents a transported assemblage.

3. Cleveland Lloyd Quarry, UT

Upper smectitic part of Brushy Basin Member (8-9-95)
Research reported in Shultz, Steinhardt and Good, 1997

Data

Bivalves: Resting trace fossils from the base of the sandstone bed capping the bluff above the quarry site
Condition: Resting traces of large bivalves
Size distribution: Nearly uniform size
Orientation: In life position

Density: Highly concentrated, nearly continuous pavement of shell traces
Matrix: Medium-grained sandstone, traces preserved as infilled depressions in underlying mudstone.
Preservation: No shell material preserved

Interpretation

This location provides an excellent opportunity to observe the abundance of bivalves within their optimum habitat. The bivalves were inhabiting a muddy substrate, probably in a pond environment.

Data

Bivalves: Fossil shells from a site lateral to the bivalve trace fossil bed mentioned above, outside the Cleveland-Lloyd State Park boundary
Condition: Original shell material, subequal articulated and disarticulated, very well preserved
Size distribution: Moderate range in size, mostly larger specimens
Orientation: random
Density: Moderately concentrated
Matrix: Greenish-grey mudstone
Preservation: Very well preserved, wall ultrastructure showing complex banding that is a product of annual and pseudoannual banding

Interpretation

The locality represents a disturbed neighborhood assemblage (the specimens are preserved in sedimentary rocks inhabited during life, but out of life position). This is indicated by their excellent preservation and the relatively high proportion of articulated specimens. The fine-grained matrix and the morphology of the bivalves suggest a pond habitat. The assemblage was preserved by rapid burial from rapid deposition of the overlying fluvial sandstone bed.

4. South of Green River, UT

Tidwell Member, (8-10-95),
Research reported in Shultz, Steinhardt and Good, 1997.

Data

Bivalves: Vetulonaia sp.
Condition: Predominately articulated, little fragmentation or abrasion
Size distribution: Wide range in size (from juveniles to very large adult specimens)
Orientation: Random orientation
Density: Highly concentrated over an approximately 7 m (20 ft) lateral distance
Matrix: In greenish-grey mudstone underneath channel sandstone bed
Preservation: Very well preserved ultrastructure, continuous growth indicated by absence of banding within the shell

Interpretation

The morphology of this shell type (large obese specimens) suggests quiet water pond conditions, an interpretation substantiated by the mudstone matrix. The continuous size gradation and excellent surface ornament preservation and articulation indicate this was a living community of bivalves that was preserved due to the rapid influx of sand sediment that buried this ecological association (disturbed neighborhood assemblage). The homogenous ultrastructure indicates an absence of seasonal variability in temperature or precipitation. The abundance of specimens suggests optimum living conditions for these bivalves; that is, clean, well-oxygenated, lime-rich water with pH greater than 7, the water was shallow (less than 7 m or 20 ft depth), in a perennial aquatic habitat that was at least seasonably warm and had a stable substrate and abundant plankton food resources.

5. Como Bluff, WY

Tidwell Member equivalent, (7-9-96),)
Research reported in Shultz, Steinhardt and Good, 1997

Data

Bivalves: Vetulonaia sp.
Condition: Very well preserved, minor fragmentation & abrasion, predominately disarticulated
Size distribution: Relatively uniformly large size
Orientation: Random
Density: Moderate to low density
Matrix: Greenish gray mudstone
Preservation: Absence of growth bands, indicating continuous, uninterrupted growth

Interpretation

The morphology of this shell type (large obese specimens) suggests quiet water pond conditions, an interpretation substantiated by the mudstone matrix. The homogenous ultrastructure indicates an absence of seasonal variability in temperature or precipitation.

6. Alcova, WY

Lower Morrison

Data

Bivalves: Bivalve resting trace fossils that occur in the basal 1.1 m (4 ft) of sandstone in approximately 6 distinct sandstone beds, each with basal bivalve resting trace fossils.
Condition: Trace fossils, no shell material
Size distribution: Uniformly of moderate size
Orientation: In life position
Density: Very abundant and nearly continuous coverage of channel bed cross-section
Matrix: Conglomeratic (mostly mud-chip) sandstone, also some petrified wood and dinosaur bone fragments
Preservation: Trace fossils

Interpretation

The bivalves inhabited the channel bed and were episodically washed away, leaving traces on the channel bed that were infilled by material of distinct composition. Demonstrates optimum bivalve habitat of clean, well-oxygenated, lime-rich water with pH greater than 7, in shallow depths (less than 7 m or 20 ft), a perennial aquatic habitat that was at least seasonably warm, had a stable substrate and had abundant plankton food resources.

Data

Bivalves: Bivalve shell material in sandstone bed about 1 m (3 ft) above the top of the bivalveresting trace-bearing bed. The one foot thick bed was strongly cemented, making sample collection difficult.
Condition: Predominately articulated, many preserved as internal molds, shell material very abraded
Size distribution: Medium to large size
Orientation: Random
Density: Moderately dense
Matrix: Medium-grained sandstone, smectitic at top
Preservation: Poorly preserved, precluding growth-band study

Interpretation

This probably is a crevasse-splay deposit with bivalves representing a transported assemblage.

7. Gibson Reservoir, MT

Unknown stratigraphic position (7-16-96)

Data

Bivalves: Too incomplete for identification
Condition: Well preserved
Size distribution: Moderate size
Orientation: Random, commissures parallel to bedding plane
Density: Very low density
Matrix: Greenish fine-grained sandstone, previous collections taken from mudstone units
Preservation: Well preserved as impressions, insufficient shell material for ultrastructure study.

Interpretation

Minimal outcrop and few specimens preclude detailed interpretation. Adult size individuals indicate adequate habitat, but the few specimens suggests that this was not an optimal habitat.

8. Colorado National Monument

Middle unit of Salt Wash Member (7-19-96)
Research reported in Shultz, Steinhardt and Good, 1997

Data

Bivalves: Hadrodon sp.
Condition: Very well preserved, predominately articulated, little fragmentation and abrasion
Size distribution: Variable sizes represented
Orientation: Random orientations
Density: Highly concentrated
Matrix: Grayish-green mudstone
Preservation: Very well preserved, ultrastructure study yielded well developed annual banding

Interpretation

This assemblage is interpreted as a disturbed neighborhood assemblage inhabing a floodplain pond. The climate had well-developed annual cyclicity, forcing prolonged annual closure of the bivalves during adverse conditions.

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SYNTHESIS OF TERRESTRIAL AND FRESHWATER TRACE FOSSILS, UPPER JURASSIC MORRISON FORMATION, ROCKY MOUNTAIN REGION, USAÑWHAT ORGANISM BEHAVIOR TELLS US ABOUT JURASSIC ENVIRONMENTS AND CLIMATES; FINAL REPORT

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INTRODUCTION

The traces of Jurassic plants and animals reveal important information about ancient environmental, ecologic, and climatic settings in the Rocky Mountain region between 155-145 million years ago. Study is the first systematic search for evidence of terrestrial and freshwater organisms not preserved by body fossils in any Jurassic continental rocks world-wide. The collection of Jurassic roots, burrows, nests, tracks, and trails preserves details about organism behavior that allow us to infer physical, chemical, and biological conditions of the: (1) depositional setting, (2) ecosystem, (3) hydrologic regime, (4) soil formation, (5) seasonality of precipitation and temperature, and (5) climatic trends throughout the Late Jurassic.

RESEARCH SUMMARY

Over 34 Jurassic outcrop localities where worked on between 1994-1996 field seasons in the Rocky Mountain region stretching from northwestern New Mexico to northwestern Montana. Numerous outcrops visited in National parks and monuments and Paleontological areas included Arches National Park [ANP] (UT), Bighorn Canyon National Recreation Area [BCR] (WY), Canyonlands National Park [CNP] (UT), Cleveland-Lloyd Quarry [CLQ] (UT), Colorado National Monument [CNM] (CO), Comanche National Grasslands [CNG] (CO), Curecanti National Recreation Area [CNR] (CO), Garden Park Paleontological Area [GPP] (CO), Dinosaur National Monument

[DNM] (UT/CO), Dinosaur Ridge National Historic Site [DRN] (CO), Fruita Paleontological Area [FPA] (CO), Picket Wire Natural Area [PWN] (CO), Red Rocks State Park [RRS] (NM), and Roxborough State Park [RSP] (CO). Other Morrison localities were investigated in portions of Colorado (Boulder [BO], Dillon [DI], Glenwood Springs [GS], Park Creek Reservoir [PCR], Rabbit Valley [RV]), Montana (Bridger[BR], Belt [BE], Gibson Reservoir [GR], Great Falls [GF]), New Mexico (Aneth [AN], Gallup [GP]), Utah (I-70 Corridor [I-70U], Beclabito Dome [BD], Hanna [HA], Moore Cutoff [MC], Montezuma Creek [MZ], Ruby Ranch [RR], Salt Valley Anticline [SVA]), and Wyoming (Arminto [AR], Alcova [AV], Como Bluff [CB], Grey Bull [GB], Thermopolis [TH]).

RESULTS

The Morrison trace fossils and their implications are presented as a collective of observations that were used to interpret the environmental, ecological and climatological settings of terrestrial and freshwater deposits within one or more closely related intervals. Nine intervals were defined as "time-related sequences" and were based on relative stratigraphic equivalency and chronostratigraphic data such as age dates from volcanic ash beds and microfossils, like pollen and ostracodes. The intervals are as follows:

1). Basal contact surface of the Morrison Formation and correlative rocks (J-5 and correlative surface).
2). Windy Hill and Tidwell Members beneath the lower alluvial complex (or lower rim Salt Wash Member) in the Colorado Plateau region, lowermost beds of the Bluff Sandstone and Junction Creek Sandstone Member, and Swift Member in Wyoming and Montana.
3). Lower alluvial complex and "Lower Rim" of the Salt Wash Member in western Colorado Plateau, as well as correlative beds of the Tidwell, Bluff, and Junction Creek Members, and correlative beds in the Recapture Member.
4). Middle alluvial sandstone and mudstone complex of the Salt Wash Member in the Colorado Plateau and middle mudstone unit in the eastern part of the Plateau; also includes correlative beds in the Tidwell Member where the lower beds of the Salt Wash pinch-out, Bluff and Junction Creek Members, and correlative beds of the Recapture Member.
5). Upper alluvial sandstones and mudstones of the Salt Wash member in the western part of the Colorado Plateau and "Upper Rim" of the Salt Wash in the eastern Colorado Plateau; also includes correlative beds in the Tidwell Member, Bluff and Junction Creek Members, and correlative beds of the Recapture Member.

6). Lowerpart of the Brushy Basin Member from the top of the Salt Wash to the clay change within the Brushy Basin; near the top includes the lowerpart of the Westwater Canyon Member in eastern Colorado Plateau, the lower and middle mudstones and alluvial sandstones of the Fiftymile Member in the Kaiparowits Plateau, and the uppermost Recapture Member in the southern Colorado Plateau.
7). Upperpart of the Brushy Basin Member from the clay change to the base of the uppermost Morrison alluvial sandstone beds including the middle and upper Westwater Canyon Member and upper alluvial sandstones in the Fiftymile Member.
8). Uppermost part of the Brushy Basin Member, including the Jackpile Sandstone Member in the southern Colorado Plateau and correlative, unnamed alluvial Morrison sandstones elsewhere.
9). Upper contact of the Morrison Formation with the Lower Cretaceous rocks above the K-1 or K-2 where present.

The following sections contain groups of intervals with similar environmental, ecological, and climatic interpretations that were allied by their ichnofossil and paleosol content. Each section begins with the trace fossils occurring in those intervals, a summery of the environments present, and ending with the interpretation of the ecologic and climatic setting.

INTERVALS 1-2

In the Colorado Plateau and surrounding areas (Shitamoring Canyon [SC], Trachyte Ranch [TR], Hanna [HA], Alcova [AV], Colorado National Monument [CNM],Dinosaur National Monument [DNM], Como Bluff [CB], etc.), the trace fossils include marine and brackish-water stromatolites (with and without bivalve borings), oyster encrusting grounds, horseshoe crab trails, crustacean burrows and surface feeding traces, clam resting traces, amphipod suspension feeding burrows, polychaete deposit-feeding burrows, snail grazing trails, nematode crawling trails, pterosaur tracks and feeding traces, and theropod and sauropod dinosaur tracks. Most of these traces occur in as low diversity assemblages (2 or 3 kinds found together at most), but with great abundance. These traces suggest marine and marginal-marine to tidal environments with high depositional energy- and salinity-stressed systems in warm to hot humid settings. The brackish-water to tidal assemblages of trace fossils imply that coast lines most likely had embayments to form tidal sediments and tidal assemblages of organisms. The traces in lacustrine settings include mayfly deposit-feeding burrows, midge fly and crane fly deposit-feeding burrows (Diptera), aquatic earthworm trails, nematode trails, pterosaur tracks and feeding traces (scratched surfaces), clam resting traces, crayfish burrows and crawling trails and small horizontal burrows, and theropod and sauropod dinosaur footprints. These continental traces suggest that the marginal-lacustrine and lacustrine environments had episodic depositional rates and seasonally high water tables, which would have also created imperfectly-drained and poorly-developed paleosols. Overbank deposits and paleosols contain solitary bee nests, crayfish burrows, beetle burrows, bug burrows, root traces and mottling patterns, steinkerns of large 10 cm diameter horsetails (Neocalamites), and theropod and sauropod dinosaur footprints. Alluvial environments had weakly-developed soils, many with compound and cumulative profiles resulting in successions of weakly modified distal overbank deposits. Many of these ancient soils contain weakly-developed B horizons, or zones of clay accumulation due to water infiltration and animal activity, with mottling of gray, green, yellow, and purple. This colors suggest seasonally imperfectly-drained settings (gray, green, yellow) with drier intermediate periods (purple and red).

In the Four Corners area and scatter up through western Colorado and Wyoming, small eolian dune fields persisted. Ichnofaunas are sparse and simple, composed of mainly indistinct horizontal and vertical burrows. These dunes were associated with the marginal-marine and marginal-lacustrine environments.

In the Front Range of Colorado (Horsetooth Reservoir [HR], Park Creek Reservoir [PCR]), the trace fossils were similar to that of the Colorado Plateau, but are dominated by stromatolites (also with borings) and polychaete feeding burrows. These traces indicate that predominately marine and marginal-marine (estuarine and tidal) environments existed in the Fort Collins, Greely areas. Lacking in this area were the more common high abundance, low diversity brackish-water to stressed-marine assemblages of the Colorado Plateau region. These Front Range trace fossil occurrences suggest a more restricted environment with either higher salinity or higher energy settings. The climatic setting in the

Front Range was probably similar to that of the Plateau, however, there may have been less precipitation and higher evaporation in the Front Range due to subtle orographic effects of the ancestral Rocky Mountains.

INTERVAL 3-5

In the Colorado Plateau and surrounding areas (Shitamoring Canyon [SC], Trachyte Ranch [TR], Hanna [HA], Alcova [AV], Dinosaur National Monument [DNM], Como Bluff [CB], etc.), the abundant and diverse trace fossils included at least four types of large and small termite nests, four types of ant nests, three types of bee nests, wasp cocoons, at least five types of beetle burrows (vertical and horizontal), dung beetle nests, soil bug trails, bivalve resting traces, snail trails, crayfish burrows, various types of plant roots (small plants up to large trees), and several types of sauropod and theropod dinosaur footprints. These trace fossils suggest the environments were dominated by alluvial proximal and distal floodplains that formed on and between channel and sheet sandstones with fewer amounts of overbank fine-grained sediments (greater amounts of fines in western Colorado Plateau). In several localities termite and ant nests co-occurred with several types of beetle burrows and solitary bees nests in moderately to well-developed paleosols. Many of the paleosols that contain discernible trace fossils (e.g., Shitamoring Canyon, Bullfrog, Curecanti) indicates that bioturbation out-paced pedoturbation (soil-forming processes) and sedimentation. For other paleosols in the same and at different localities (e.g., Hanna, Salt Valley Anticline) pedoturbation out-paced bioturbation and sedimentation. In general, many localities contained paleosols that had parent material and pedogenic characters that were strongly dominated by sedimentation rates that out-paced pedoturbation.

In the Four Corners area (Bluff Member and Eolian Facies of the Recapture Members) isolated eolian erg fields persisted from Interval 1-5. During these intervals, the sedimentary facies and trace fossils suggest increasingly wetter settings that eventually stabilized the erg systems with vegetation and soil formation, which included intensive nesting by solitary and social insects. In the area of Gallup, New Mexico, the upper parts of the ergs (Recapture) contain rhizoliths and termite nests. The uppermost part contains termite nests 30+ m long that followed rhizoliths of trees and small shrubs below the surface. The bulk of the nests are within the top 15 m, however, galleries and stacked chambers can be traced to the base of the Bluff, for a total length of nearly 40 m.

INTERVAL 6-7

In the Colorado Plateau and surrounding areas (Beclabito Dome [BD], Bighorn Res. [BR], Hanksville [HK], Canon City-Marsh Felch [MF at GPP], Montezuma Creek [MZ], Moore Cutoff [MC]), the trace fossils included crayfish burrows, termite nests, ant nests, cicada burrows, beetle burrows (horizontal and vertical), rare beetle larvae burrows (Scoyenia), beetle-borings (pupal chambers) in dinosaur bones, earthworm pellets and burrows, various sizes of plant roots (small to large diameter, tree-size), and several types of sauropod and theropod dinosaur footprints.

The trace fossil assemblages in these rocks suggest that larger amounts of precipitation fell during the rainy season in these intervals and intervals 8-9. Crayfish burrows are more abundant than ant nests and termite nests in proximal overbank deposits in the Brushy Basin and Recapture Members (GPP, RV, AN, MC). In more distal facies (also better drained paleosols) ant nests are more dominant than termite nests in most areas (HA, MC, SC), however both are shallower in overal depth compare to similar structures in the lowerpart of the Morrison. There are more occurrences of solitary to primitively-social bees nests in these intervals as well (MZ, GPP).

INTERVAL 8-9

Ichnofossils in these intervals include indistinct horizontal and vertical burrows, large (but rare) termite nests, beetle burrows, soil bug burrows and trails, crayfish burrows, and various sized root traces. These traces occur predominantly in paleosols in fine-grain overbank deposits and in buried channel/levee deposits on floodplains. In interval 8, numerous paleosols occur from simple and immature to mature and cumulative. Many of these developed on paludal to marginal-lacustrine settings in Wyoming, or were developed on poorly-drained overbank floodplains with episodic deposition. Near the end of this interval and including the interval 9 (the boundary), paleosols became increasingly more mature and better developed.

Paleosols that formed at interval 9 are quite variable and were the result of different lengths of subaerial exposure under particular types of groundwater regimes and depositional settings. For example, the thick sequence of paleosols (10 m+) developed at Ruby Ranch are composed of cummulative and compound profiles dominated by crayfish burrows and rhizoliths. These paleosols formed under seasonally high, but fluctuating groundwater table in an area imperfectly drained. These palsosols were later calcretized by an early Cretaceous event. The boundary paleosols (2 m+) at Salt Valley Anticline are drab-colored olive-green, mottled red, yellow, and brown by primary and secondary tap-root rhizoliths and by finer-scale rootlets. The boundary paleosol at Dinosaur Ridge National Historic Site is a thick clay accumulation (2 m) that is well-developed and represents a long term surface of exposure. The paleosol is domianted by red, purple, mottles with minor amoutns of yellow and white mottles; the paleosol is intensely bioturbated with soil bugs, beetles, and fine rootlets.

CONCLUSIONS

Based on the ichnofossil assemblages and paleosols, the environments of the Morrison Formation through time became increasingly wetter from the Salt Wash to the end of Brushy Basin and equivalent deposits. Paleosols become better developed upsection, especially at major periods of subaerial exposure. These resulted in surfaces that could be used as sequence stratigraphic boundaries signaling changes in regional base level, tectonics, and climate.

PUBLICATIONS

Hasiotis, S.T., 1995, Terrestrial and freshwater-aquatic trace fossils in the Upper Jurassic Morrison Formation, Colorado Plateau: Invertebrates out-shine the dinosaurs: Third National Biological Service Biannual Conference of Research on the Colorado Plateau, Abstracts With Program, v. 3, p. 33.

Hasiotis, S.T., 1996, Termite (Insecta: Isoptera) nests from the Upper Jurassic Morrison Formation: Evolutionary, paleoecologic, and paleoclimatic implications: Geological Society of America, Abstracts With Programs, v. 28, no. 4, p. 10.

Hasiotis, S.T., 1996, Invertebrate ichnofossils from the Upper Jurassic Morrison Formation, Colorado Plateau: Jurassic biodiversity, ecologic, and climatic implications: Geological Society of America, Abstracts With Programs, v. 28, no. 4, p. 10.

Hasiotis, S.T., 1998, Continental trace fossils as the key to understanding Jurassic terrestrial and freshwater ecosystems: Modern Geology, v. 22, nos. 1-4, p. 451-460.

Hasiotis, S.T., and Demko, T.M., 1996, Ant (Hymenoptera: Formicidae) nest ichnofossils, Upper Jurassic Morrison Formation, Colorado Plateau: Evolutionary and ecologic implications: Geological Society of America, Abstracts With Programs, v. 28, no. 7, p. A-106.

Hasiotis, S.T., and Demko, T.M., 1996, Terrestrial and freshwater trace fossils, Upper Jurassic Morrison Formation, Colorado Plateau; in, Morales, M., (ed.)., The continental Jurassic: Museum of Northern Arizona Bulletin 60, p. 355-370.

Hasiotis, S.T., and Kirkland, J.I., 1996, Crayfish fossils and burrows, Upper Jurassic Morrison Formation, Colorado Plateau, USA: International Association of Astacology, Freshwater Crayfish XI, Abstracts With Program, Thunder Bay, Ontario, p. 37.

Hasiotis, S.T., and Demko, T.M., 1998, Ichnofossils from Garden Park Paleontological Area, Colorado: Implications for paleoecologic and paleoclimatic reconstructions of the Upper Jurassic: Modern Geology, v. 22, nos. 1-4, p. 461-480.

Hasiotis, S.T., Kirkland, J.I., and Callison, G., 1998, Crayfish fossils and burrows from the Upper Jurassic Morrison Formation of western Colorado: Modern Geology, v. 22, nos. 1-4, p. 481-492.

Hasiotis, S.T., Kirkland, J.I., Windscheffer, G.W., and Safris, C., 1998, Fossil caddisfly cases (Insecta: Trichoptera), Upper Jurassic Morrison Formation, Fruita Paleontological Area, Colorado: Modern Geology, v. 22, nos. 1-4, p. 493-502.

Hirsch, K.F., Hasiotis, S.T., Bray, E.S., Demko, T.M., Currie, B., Ekart, D., and the Morrison Research Group, 1996, Dinosaur eggshell from the uppermost part of the Upper Jurassic Morrison Formation, southeastern Utah: Geological Society of America, Abstracts With Programs, v. 28, no. 7, p. A-296.

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THE ISOTOPIC AGE OF THE MORRISON FORMATION IN THE WESTERN INTERIOR; FINAL REPORT

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ABSTRACT

The Morrison Formation in Utah and Colorado contains many volcanic ash layers and ashy beds, now altered mostly to bentonite, that have yielded isotopic ages. The Brushy Basin Member, at the top of the formation, gives single-crystal, laser-fusion and step-heating, plateau $^{40}Ar/^{39}Ar$ ages on sanidine that range systematically between 148.1±0.5 (1 standard error of mean) Ma at the top of the member to 150.3±0.3 Ma near the bottom. The Tidwell Member, at the base of the Morrison Formation, contains one ash bed about 3 m above the J-5 unconformity that occurs in at least two widely separated sections. This ash in the Tidwell Member has been dated by three of the authors by $^{40}Ar/^{39}Ar$ dating of sanidine and gives ages of 154.75±0.54 Ma (Deino NTM sample, laser-fusion), 154.82±0.58 Ma (Deino RAIN sample, laser-fusion), 154.87±0.52 (Kunk NTM sample, plateau), and 154.8±1.4 Ma (Obradovich NTM sample, laser-fusion). The Morrison Formation, therefore, represents deposition during about 7 million years and ranges in age from about 148 to 155 Ma. Based upon fossil evidence reported elsewhere in this volume by Litwin and others and Schudack and others, the formation is entirely Late Jurassic in age and was deposited during the Kimmeridgian and early Tithonian Ages.

INTRODUCTION

One of the significant unresolved problems related to the Morrison Formation is its age, both chronostratigraphically and biostratigraphically. The formation has been labeled as Jurassic, Cretaceous, and Jurassic-Cretaceous over the years (e.g., Emmons and others, 1896; Darton, 1922; Simpson, 1926; Stokes, 1944; Imlay, 1952; Imlay, 1980; Bilbey-Bowman and others, 1986; Hotton, 1986; Kowallis and others, 1986; Kowallis and Heaton, 1987). In one of the most recent papers to address this problem, Kowallis and others (1991) observed that, "Precise ages from the uppermost part of the Brushy Basin Member are still needed to determine if the Jurassic-Cretaceous boundary lies within the uppermost Brushy Basin Member." The authors might also have added that very little is known about the age of the lower members of the Morrison Formation. The age data reported in this paper, in addition to those ages reported earlier in Kowallis and others (1991), and in conjunction with the biostratigraphic information reported by Schudack and others (this volume) and Litwin and others (this volume), provide a solid framework for determining the age, both isotopic and biostratigraphic, of the Morrison Formation.

PREVIOUS AGE ASSIGNMENTS

Table 1 lists studies reporting isotopic ages from the Morrison Formation (most of the previously published ages came from the Brushy Basin Member), excluding the new ages reported here. These radiometric ages span the Cretaceous-Jurassic boundary according to published time scales (e.g., the Jurassic-Cretaceous boundary is given as 130 Ma by Kennedy and Odin, 1982; 145.6 Ma by Harland and others, 1990; 141.1 Ma by Bralower and others, 1990; and 142 Ma by Obradovich, 1993), and do not resolve longstanding debates concerning the age of the formation (i.e., is the formation Jurassic, Cretaceous, or a bit of both?).

These previously published isotopic ages have helped to better define the age of the formation, but they all have inherent problems. The Rb-Sr age by Lee and Brookins

(1978) comes from authigenic clay and thus must be viewed as a minimum age. The K-Ar biotite ages are questionable because biotite is almost universally altered to some extent in bentonites, and potassium in biotite can be redistributed during alteration of the volcanic ash beds without affecting the appearance of the grains. Turner and Fishman (1991) and Christiansen and others (1994b) have shown that potassium was quite mobile during alteration of the Brushy Basin Member ash beds. The fission-track data have large errors, include ages on some detrital material, and give several ages that appear to be too young when compared with other methods.

The best set of previously published data are the $^{40}Ar/^{39}Ar$ laser-fusion plagioclase ages (Kowallis and others, 1991), but plagioclase has fairly low levels of potassium, increasing the errors in these ages. In addition, plagioclase appears to be more susceptible to alteration in the Morrison ash beds than sanidine.

The paleontological data base has also been a source of shifting age assignments for the Morrison Formation. Table 2 lists significant previously published references related to the biostratigraphic age of the Morrison Formation. We have attempted to compile a list of references that is representative and fairly complete, but we have undoubtedly missed some references because the Morrison literature is quite extensive. These references show that early in this century the formation was thought to be Jurassic, Cretaceous, or Jurassic-Cretaceous; during the mid-1900's the formation was thought to be definitely Jurassic; whereas most recently the age has again been questioned, with some scientists proposing a Jurassic-Cretaceous age.

In addition to the isotopic and paleontological age determinations listed in Tables 1 and 2, a few papers have been published on the paleomagnetic reversal sequence in the Morrison Formation. Steiner and Helsley (1975a and 1975b), Steiner (1980), and Steiner et al. (1994) observed that the reversal sequence seen in the Morrison Formation correlates "well with the reversal sequence of about the same age [Kimmeridgian], derived from the oldest observed magnetic anomalies in the sea floor." Swierc and Johnson (1990) examined the reversal pattern in the Morrison and Cloverly Formations in the Bighorn Basin of Wyoming and inferred a maximum of 7 million years of deposition for the Morrison Formation during the Late Jurassic. They also estimated a minimum of 15 million years of nondeposition between the Morrison and Cloverly Formations. However, the nature and position of the contact between the Morrison and Cloverly formations in Wyoming is problematic and no reliable isotopic ages have been obtained there. One zircon fission-track age of 129±14 Ma has been reported from central Wyoming by DeCelles and Burden (1992) from sediments they believe to be Cloverly Formation, but which have been previously assigned to the Morrison. Until these problems are resolved, a chronologic interpretation of the Wyoming paleomagnetic data will be imprecise.

STRATIGRAPHY

The Morrison Formation in the Colorado Plateau consists largely of interbedded conglomerate, sandstone, mudstone, and altered volcanic ash with relatively small amounts of marlstone, limestone, and claystone. The ash was derived from dacites or rhyolites erupted from a continental margin volcanic arc (Christiansen and others, 1994a; Christiansen and others, 1994b) and has been altered to bentonite throughout most of the depositional basin. Progressing eastward to eastern Colorado, the formation loses much of the conglomerate and sandstone and gains more limestone and marlstone. Altogether, the Morrison contains nine formally named members on the Colorado Plateau, although only four of these need be considered in this report (Fig. 1). In addition, the formation can be divided into two informal members at Garden Park near Canon City in eastern Colorado. Peterson (1994) provided paleogeographic reconstructions for the Morrison Formation throughout the southern part of the Western Interior.

Table 1.—Isotopic Ages from the Morrison Formation.

Reference	Age±Error (σ)	Material	Method	Location & Member*
Lee and Brookins, 1978	148±9 Ma	Clay	Rb-Sr	New Mexico (BB)
Obradovich, 1984 pers. comm.	134±1.2 Ma	Biotite	K-Ar	Colorado (BB)
Bilbey, 1992	147.2±1.0 Ma	Biotite	K-Ar	Cleveland-Lloyd Q. (BB)
Bilbey, 1992	146.8±1.0 Ma	Biotite	K-Ar	Cleveland-Lloyd Q. (BB)
Bilbey, 1992	135.2±5.5 Ma	Biotite	K-Ar	Dinosaur Nat'l. Mon. (BB)
Kowallis and others, 1986	99-144±8 Ma	Zircon	Fission Track	Notom,Utah (BB)
Kowallis and Heaton, 1987	142-195±9 Ma	Zircon	FissionTrack	Notom, Utah (SW)
Kowallis and Heaton, 1987	157±7Ma	Zircon	Fission Track	Notom, Utah (T)
Kowallis and Heaton, 1987	145±13 Ma	Apatite	Fission Track	Notom, Utah (BB)
Kowallis and Heaton, 1987	132±10 Ma	Apatite	Fission Track	Notom, Utah (SW)
Kowallis and others, 1991	147.6±0.8 Ma	Plag.	Ar-Ar L-F	Montezuma Creek (BB)
Kowallis and others, 1991	147.0±0.6 Ma	Plag.	Ar-Ar L-F	Montezuma Creek (BB)
Kowallis and others, 1991	145.2±1.2 Ma	Plag.	Ar-Ar L-F	Montezuma Creek (BB)
Kowallisand others, 1991	147.8±0.6 Ma	Plag.	Ar-Ar L-F	Montezuma Creek (BB)
Kowallis and others, 1991	149.4±0.7 Ma	Plag.	Ar-Ar L-F	Montezuma Creek (BB)
Kowallis and others, 1991	152.9±1.2 Ma	Plag.	Ar-Ar L-F	Dinosaur Nat'l. Mon. (BB)
DeCelles and Burden, 1992	129.2±27.5 Ma	Zircon	Fission Track	Central Wyoming (BB?)

*Members are:
- BB=Brushy Basin
- SW=Salt Wash
- T=Tidwell

Plag. = Plagioclase
L-F = Laser-Fusion

Table 2.—Biostratigraphic Age Information for the Morrison Formation.

Reference	Age	Type of Evidence
Emmons et al,1896	Cretaceous-Jurassic	Vertebrates similar to Jurassic forms elsewhere
Marsh, 1896	Jurassic	Dinosaurs are like those of European Jurassic
Logan, 1900	Jurassic	Invertebrates similar to Jurassic Wealden of Europe
Ward, 1900	Jurassic	Cycadeoid flora is like that ofthe Jurassic
Riggs, 1902	Jurassic	Dinosaurs are like those of EuropeanJurassic
Williston, 1905	Cretaceous	Vertebrates indicate a Cretaceous age
Ward, 1906	Jurassic	Cycads like Jurassic forms
Lull, 1911	Cretaceous	Fauna like that of Cretaceous Arundel Formation, MD
Berry, 1915	Cretaceous	Flora similar to Cretaceous Potomac Group
Lee, 1915	Cretaceous	Morrison fauna needed more time to evolve than Jurassic
Lull, 1915	Cretaceous	Dinosaurs similar to African (Tendaguru Fm.) Cret. forms
Osborn, 1915	Cretaceous-Jurassic	Kimmeridgian dinosaurs are like Morrison's, but could be Cretaceous
Stanton, 1915	Cretaceous-Jurassic	Invertebrates inconclusive, but more likely Jurassic
Knowlton, 1916	Cretaceous	Plants argue for a Cretaceous age
Mook, 1916	Cretaceous	Fauna like that of Cretaceous Arundel Formation, MD
Schuchert, 1918	Jurassic	Dinosaurs similar to African (Tendaguru) Jurassic forms
Simpson, 1926	Jurassic	Dinosaurs similar to African (Tendaguru) Jurassic forms
Schuchert, 1934	Jurassic	Dinosaurs similar to African (Tendaguru) Jurassic forms
Baker and others, 1936	Jurassic	Evaluation of published fossil & other evidences
Peck and Reker, 1948	Jurassic	Microfossils and mollusks indicate a Jurassic age
Imlay, 1952	Jurassic	Fossil evidence suggests a Kimmeridgian age
Yen, 1952	Jurassic	Molluscan fauna suggests Morrison is pre-Purbeckian
Peck, 1957	Jurassic	Charophytes similar to German Kimmeridgian forms
Brown, 1975	Jurassic	Ginkgophytes from Montana suggest Jurassic age
Galton, 1976	Jurassic	EuropeanJurassic dinosaur similar to Morrison form
Madsen,1976	Jurassic	Charophytes similar to German Kimmeridgian forms
Galton, 1977	Jurassic	Dinosaurs similar to East African (Tendaguru) forms
Hotton, 1986	Jurassic	Palynology suggests a Kimmeridgian-Oxfordian age
Bakker, 1990	Cretaceous-Jurassic	Youngest Morrison dinosaurs may be Cretaceous
Miller and others, 1991	Cretaceous(?)-Jurassic	Advanced stage of dinosaur evolution
Litwin, this volume	Jurassic	Palynomorphs indicate latest Oxfordian(?), Kimmeridgian, & early Tithonian Ages
Schudack, thisvolume	Jurassic	Charophytes indicate latest Oxfordian(?), Kimmeridgian, & early Tithonian(?) Ages

The Windy Hill Member at the base of the Morrison in the northern part of the Colorado Plateau is a thin glauconitic grayish-brown sandstone unit containing minor gray mudstone interbeds (Peterson, 1994). No ash beds have been found in this member. It was deposited in shallow marine waters and contains the only known marine beds in the , other than some glauconite-bearing sandstone beds near just below the coal zone that is at the top of the formation in north-central Montana.

The overlying Tidwell Member consists largely of gray mudstone interbedded with lesser amounts of brown sandstone and gray limestone. It interfingers with the Windy Hill Member or is the basal member farther south in the central part of the Colorado Plateau. Bentonite beds are rare in the member and only one suitable for radiometric dating was found in the central and northern parts of the Colorado Plateau. The Tidwell consists largely of continental strata deposited on mudflats and locally in stream beds. Because it interfingers with the Windy Hill Member, some of the beds could be of marine origin, as suggested by the recent discovery of dinoflagellates in the Tidwell in the northern part of the Colorado Plateau (R.J. Litwin, oral commun., 1994).

The Salt Wash Member consists predominantly of gray or brown sandstone beds and lesser quantities of red and green mudstone beds. Roughly the upper half of the member consists of pebbly or conglomeratic sandstone, or even conglomerate in much of the northern and western parts of the Colorado Plateau. Bentonitic beds are absent or rare in the Salt Wash Member. The member was deposited by streams that flowed generally eastward from highland source regions west of the Colorado Plateau in western Utah and eastern Nevada (Peterson, 1994). Another local source area was in the ancestral Rocky Mountains in what is now the Wet Mountains and Pikes Peak region west and north of Canon City (Peterson, 1994).

The Brushy Basin Member consists largely of mudstone and is divided into lower and upper parts (Figs. 1 and 2) based largely upon the dominant type of clay minerals within it. The thin lower part of the member consists of mudstone composed largely of nonswelling illitic clay, tends to be red (although other colors are also present and locally predominate), and locally contains brown to white sandstone beds (Owen and others, 1989). It was deposited in fluvial and overbank floodplain environments on a broad alluvial plain (Turner and Fishman, 1991).

The thick upper part of the Brushy Basin Member consists largely of mudstone, although sandstone beds occur locally, especially at or near the top. The mudstone beds tend to be grayish green with red beds locally significant near the top or throughout the unit on the west side of the Colorado Plateau. The finer-grained fraction consists largely of swelling or smectitic clays (Owen and others, 1989) derived from the alteration of volcanic ash that was carried onto the Colorado Plateau region by winds from a continental margin volcanic arc several hundred kilometers west and southwest of the Plateau region (Turner and Fishman, 1991). This part of the formation contains numerous altered volcanic ash beds. In the east-central part of the Colorado Plateau, the upper part of the Brushy Basin Member was deposited in a large saline alkaline lake that graded laterally into mudflat, fluvial, and overbank floodplain environments (Turner and Fishman, 1991). Freshwater lake deposits occur locally in this interval to the north and east of the saline, alkaline lake deposits and are represented by mudstone and limestone beds containing charophytes, ostracodes, scarce conchostracons, and gastropods.

In eastern Colorado at Garden Park near Canon City, the Morrison can be divided into two informal members based on the dominant clay mineral in the mudstone beds. The lower member consists largely of mudstone containing nonswelling clay. Other lithologies include uncommon sandstone and scarce thin limestone beds. The member is largely overbank floodplain and lacustrine mudstones with a few fluvial sandstone beds. It was deposited on a broad plain locally traversed by streams that also included extensive overbank floodplain areas, mudflats, and fairly common lakes or ponds.

The upper member in the Garden Park area contains the abundant swelling clays typical of the upper part of the Brushy Basin Member on the Colorado Plateau. This vertical clay mineral change provides one of the best means of correlating the Colorado Plateau Morrison with the eastern Colorado Morrison where formally named members are not recognized (Fig. 1). One of the bentonite beds from low in the upper member, which is well exposed in an open-pit bentonite mine, was selected for isotopic dating. The uppermost part of this member contains several pebbly sandstone beds and interbedded mudstone beds that tend to be nonsmectitic. Most of the upper member was deposited in lacustrine and mudflat environments although the uppermost beds were deposited by streams and on adjacent overbank floodplains.

Physical correlation of the Morrison Formation and certain strata within it between the Colorado Plateau and eastern Colorado is established by stratigraphic markers. These include the J-5 and K-1 unconformities at the base and top to the formation (Peterson, 1994), a zone of authigenic chert (usually red), called the welded chert (Ogden, 1954) (which is in the Tidwell Member of the Colorado Plateau, the lower part of the lower member near Canon City, and in the Ralston Creek Formation west of Denver) and the change in dominant clay minerals in about the middle of the formation (Fig.1).

SAMPLE LOCALITIES

Since the publication of our earlier paper on the age of the Brushy Basin Member of the Morrison Formation (Kowallis and others, 1991), we have obtained several additonal ages, mostly using sanidine grains, from new and old localities. Most of these additional ages come from the Brushy Basin Member, with a few ages from the basal Tidwell Member. The localities from which samples were collected for dating are shown in Figure 3.

Montezuma Creek, Utah and Notom, Utah

The Montezuma Creek (MC) and Notom (NTM) Utah sections have been described in Kowallis and others (1991). Five separates of plagioclase, all containing a few sanidine crystals, were dated previously by single-crystal $^{40}Ar/^{39}Ar$ laser-probe methods from the

MC section (Kowallis and others, 1991) and several fission track ages are available from the NTM section (Kowallis and Heaton, 1987). We chose two additional samples from the middle (MC-39, 51 m above the base of the member) and upper (MC-52, 69.3 m above the base of the member) parts of the Brushy Basin Member in the MC section for dating because they contain abundant sanidine, as well as one sanidine-rich sample from near the top of the Brushy Basin Member (0.5 m below the Cedar Mountain Formation contact and 48.5 m above the base of the member) in the NTM section (NTM-17). Another sanidine-bearing ash was collected from 2.4 m above the base of the Tidwell Member in the Notom section (NTM-1319-1). The other sections are new and will be briefly described here with additional information on location of the sections given in Appendix I.

Little Cedar Mountain, Utah

The Little Cedar Mountain (LCM) section is in Emery County, Utah. There the Brushy Basin Member of the Morrison Formation is about 106 m thick. We collected 39 samples from the Brushy Basin Member; of these, 10 of the samples contained datable (>about 0.2 mm in size), euhedral sanidine grains. The sample nearest the top of the section (LCM-39, 104.5 m above the base of the Brushy Basin Member) and the sample nearest the base (LCM-1, 3.8 m above the base of the member) were selected for dating.

Dinosaur Quarry West, Utah

The Dinosaur Quarry West (DQW) section, Utah is in Dinosaur National Monument near the visitor center. The formation is about 185 m thick at DQW, and the Brushy Basin Member is about 98 m thick. Ages reported by Kowallis and others (1991) and Bilbey (1992) were obtained from samples collected less than 1 km from the DQW section. From the Brushy Basin Member in this section, 26 samples of altered ash were collected; 10 contained datable quantities of sanidine and several contained abundant biotite. Three samples were chosen for dating from this section: biotite from DQW-5 16.5 m above the base of the Brushy Basin Member and 4.5 m above the clay change (Fig. 1), sanidine from DQW-17 48.3 m above the base of the member and 36.3 m above the clay change, and sanidine from DQW-21 55.4 m above the base of the member and immediately below the main dinosaur quarry sandstone.

Rainbow Draw, Utah

Also within Dinosaur National Monument is the Rainbow Draw (RAIN) section. We collected four samples from this section and found datable plagioclase in one waxy green ash bed (RAIN-1) immediately below a darker organic-rich layer that has been quarried for microvertebrates from the Brushy Basin Member (see Engelmann and others, 1989). Datable sanidine was found in another bentonite (RAIN-1325-4+4) from the Tidwell Member 2.7 m above the base of the formation. This bentonite appears to be the same ash bed from which we collected sample NTM-1319-1. We base this conclusion on the following observations: 1) the four ages from the two sample localities are identical within analytical precision [154.84±0.29 from NTM (Deino), 154.90±0.32 from RAIN (Deino), 154.87±0.52 from NTM (Kunk), and 154.8±1.4 from NTM (Obradovich)]; 2) NTM-1319-1 and RAIN-1325-4+4 have similar phenocryst assemblages – sanidine > quartz > biotite > zircon > apatite; plagioclase is absent; 3) sanidine and apatite compositions are similar (Figs. 4 and 5); 4) major and trace element compositions were strongly perturbed during alteration to clay minerals, but are compatible with the samples coming from a single eruption (for example, both have high concentration of Nb, as compared to altered ash in the Brushy Basin Member); and 5) the samples come from approximately the same stratigraphic level (NTM-1319-1 is from 2.4 m above the base of the Morrison Formation and RAIN-1325-4+4 comes from 2.7 m above the base) in an interval of the Morrison Formation that has very few other know ash beds.

Fruita Paleontological Site, Colorado

At the Fruita Paleontological Site one sample (FPS-1) was collected by Dr. James Kirkland from the level of the main microvertebrate quarry of Callison et al. (1986). At this locality, the Morrison Formation is about 180 m thick; the Tidwell Member comprises about 23 m, the Salt Wash Member about 73 m, and the Brushy Basin Member about 84 m. FPS-1 comes from about 13.7 m above the base of the Brushy Basin Member or 4.0 m above the change in clay minerals (CC in Figs. 1 & 2). This sample contains abundant plagioclase, but, unfortunately, the grains did not produce enough gas during fusion to obtain an age.

Garden Park, Colorado

The Garden Park (GP) section, Colorado and the locations of the two samples collected for dating from this section (GP-1346-28+23 from the Brushy Basin Member and GP-1346-18+14 from the Tidwell Member) are described above in the section on stratigraphy. GP-1346-18+14 from the Tidwell Member was thought to perhaps be the same ash bed found at the NTM and RAIN sections, but it contained mostly rounded detrital grains and no primary phenocrysts for dating. In addition, the few feldspars that were found are high potassium orthoclase/microcline grains, probably derived from older plutonic or metamorphic rocks, and quite different from the sanidine compositions from the other two samples (Fig. 4).

ISOTOPIC DATING

Most of the samples were dated at the Berkeley Geochronology Center by single-crystal $^{40}Ar/^{39}Ar$ total fusion of individual sanidine grains using a laser probe. A few additional samples were dated by $^{40}Ar/^{39}Ar$ step-heating methods at the U.S. Geological Survey laboratory in Reston, Virginia. One sample from the Tidwell Member was dated by single-crystal $^{40}Ar/^{39}Ar$ total fusion at the U.S. Geological Survey laboratory in Reston. We report on each type of analysis separately below.

Single-Crystal $^{40}Ar/^{39}Ar$ Laser-Fusion Ages

The procedures used to obtain single-crystal $^{40}Ar/^{39}Ar$ laser-fusion ages at the Berkeley Geochonology Center have been described in detail in Deino and Potts (1990), Deino and others (1990), Chesner and others (1991), and Kowallis and others (in press). Table 3 lists the single-crystal ages and the weighted mean average ages for each of the mineral separates that were analyzed. Sample NTM-1319-1 was also dated at the USGS laboratory in Reston and the results are reported in Table 4.

The ages all fit into a consistent stratigraphic framework (Fig. 2) with the exception of MC-39 with a weighted mean age of 147.82±0.63 Ma (1 σ), which is about 1 Ma too young. This sample also has the greatest variability of single-crystal ages with a range of over 4 Ma (Table 3), which may indicate a greater degree of alteration than the other samples.

Bulk $^{40}Ar/^{39}Ar$ Step-Heating Ages

High-precision $^{40}Ar/^{39}Ar$ age-spectrum dating of two sanidine separates (MC-39 and NTM-1319-1) was preformed using a low-blank, double-vacuum resistance furnace similar in design to that described by Staudacher et al. (1978) for step-heating. Additional details of the methodology used in data collection and reduction can be found in Wintsch et al. (1991), Haugerud and Kunk (1988), and Kowallis and others (in press). The plateau age for NTM-1319-1 is 154.87±0.52 Ma (1 σ) and is indistinguishable from the single crystal ages on this same ash bed (Fig. 6 and Tables 3, 4, and 5). MC-39 is the sample that gave a mean single-crystal age that was stratigraphically too young.

Table 3.—Single-crystal $^{40}Ar/^{39}Ar$ Laser Probe Analytical Data (Deino).

Lab ID#	J ± 1σ (x 10^{-2})	Ca/K	$^{36}Ar/^{39}Ar$ ± 1 σ	$^{40}Ar^{*}/^{39}Ar$	%$^{40}Ar^{*}$	Age±Error (Ma)
Sample DQW-21						
6068/2C-07	1.067±0.003	0.0267	0.00024	8.021	99.1	148.14±0.60
6068/2B-03	1.067±0.003	0.0295	0.00066	8.025	97.6	148.22±0.55
6068/2B-11	1.067±0.003	0.0285	0.00023	8.038	99.2	148.45±0.54
6068/2C-05	1.067±0.003	0.0342	0.00024	8.043	99.1	148.53±0.56
6068/2C-01	1.067±0.003	0.0217	0.00037	8.049	98.7	148.64±0.58
6068/2B-09	1.067±0.003	0.0284	0.00019	8.057	99.3	148.79±0.52
6068/2B-01	1.067±0.003	0.0257	0.00018	8.064	99.3	148.91±0.52
6068/2B-08	1.067±0.003	0.0274	0.00034	8.065	98.8	148.92±0.52
6068/2B-04	1.067±0.003	0.0287	0.00032	8.067	98.9	148.97±0.54
6068/2C-03	1.067±0.003	0.0277	0.00012	8.071	99.6	149.03±0.56
6068/2B-10	1.067±0.003	0.0223	0.00022	8.071	99.2	149.04±0.55
6068/2B-02	1.067±0.003	0.0278	0.00047	8.071	98.3	149.04±0.53
6068/2C-06	1.067±0.003	0.0301	0.00011	8.082	99.6	149.23±0.59
6068/2C-02	1.067±0.003	0.0245	0.00013	8.095	99.5	149.46±0.57
6068/2C-04	1.067±0.003	0.0271	0.00015	8.104	99.5	149.62±0.55
6068/2B-07	1.067±0.003	0.0279	0.00017	8.105	99.4	149.64±0.56
6068/2B-06	1.067±0.003	0.0243	0.00022	8.107	99.2	149.97±0.53
			Weighted Average, 1σ error without error in J =			148.97±0.12
				1σ error with error in J =		±0.42
Sample GP-1346-28+23						
7738/1-23	1.674±0.001	0.0026	0.00010	5.165	99.4	149.61±0.34
7738/1-32	1.674±0.001	---	0.00005	5.173	99.7	149.83±0.34
7738/1-37	1.674±0.001	0.0041	0.00005	5.174	99.7	149.84±0.35
7738/1-06	1.674±0.001	---	0.00010	5.185	99.4	150.16±0.37
7738/1-17	1.674±0.001	0.0002	0.00000	5.204	100.0	150.70±0.32
7738/1-25	1.674±0.001	0.0031	0.00027	5.221	98.5	151.16±0.48
7738/1-18	1.674±0.001	---	0.00008	5.226	99.6	151.32±0.34
			Weighted Average, 1σ error without error in J =			150.33±0.26
				1σ error with error in J =		±0.27

Table 3.—Continued

Lab ID#	J ± 1σ (x 10^{-2})	Ca/K	$^{36}Ar/^{39}Ar$ ± 1 σ	$^{40}Ar^{*}/^{39}Ar$	$\%^{40}Ar^{*}$	Age±Error (Ma)
Sample GP-1346-28+23, inferred contaminants						
7738/1-16	1.674±0.001	---	0.00005	5.328	99.7	154.14±0.34
7738/1-27	1.674±0.001	0.0115	0.00005	5.717	99.7	164.88±0.38
7738/1-11	1.674±0.001	---	0.00006	6.397	99.7	183.52±0.44
7738/1-09	1.674±0.001	0.2189	0.00010	6.493	99.7	186.15±0.42
7738/1-12	1.674±0.001	0.0140	0.00008	6.499	99.6	186.31±0.40
7738/1-30	1.674±0.001	---	0.00004	6.648	99.8	190.37±0.42
7738/1-02	1.674±0.001	---	0.00006	6.650	99.7	190.42±0.41
7738/1-14	1.674±0.001	---	0.00008	17.442	99.9	462.15±0.91
7738/1-15	1.674±0.001	---	0.00012	20.808	99.8	539.17±1.03
7738/1-26	1.674±0.001	---	0.00020	21.917	99.7	563.84±1.07
7738/1-28	1.674±0.001	---	0.00005	27.131	99.9	675.51±1.25
7738/1-01	1.674±0.001	---	0.00002	31.479	100.0	763.62±1.42
7738/1-35	1.674±0.001	---	0.00005	34.937	100.0	830.75±1.50
7738/1-24	1.674±0.001	---	0.00063	50.630	99.6	1107.44±1.85
7738/1-10	1.674±0.001	---	0.00008	58.961	100.0	1238.74±2.04
7738/1-19	1.674±0.001	---	0.00009	59.568	100.0	1247.93±2.01
Sample LCM-1						
5048-02	3.816±0.013	0.0211	0.00003	2.269	99.7	149.78±0.55
5048-01	3.816±0.013	0.0179	0.00007	2.270	99.2	149.84±0.59
5048/2C-07	3.816±0.013	0.0102	0.00002	2.276	99.8	150.22±0.60
5048-10	3.816±0.013	0.0199	0.00003	2.276	99.6	150.23±0.55
5048B-01	3.816±0.013	0.0137	0.00002	2.276	99.8	150.25±0.55
5048B-04	3.816±0.013	0.0115	0.00003	2.277	99.7	150.31±0.56
5048-05	3.816±0.013	0.0170	0.00002	2.280	99.8	150.50±0.55
			Weighted Average, 1σ error without error in J =			150.18±0.11
				1σ error with error in J =		±0.50
Sample LCM-39						
5042-03	3.801±0.013	0.0139	0.00013	2.237	98.3	147.21±0.69
5042-06	3.801±0.013	0.0315	0.00007	2.239	99.2	147.37±0.59
5042/2C-05	3.801±0.013	0.0428	0.00035	2.246	95.6	147.79±0.67
5042-01	3.801±0.013	0.0120	0.00010	2.252	98.7	148.16±0.63
5042-04	3.801±0.013	0.0119	0.00007	2.253	99.1	148.22±0.56
5042/2C-04	3.801±0.013	0.0453	0.00007	2.254	99.2	148.30±0.68
5042/2C-02	3.801±0.013	0.0009	0.00009	2.254	98.9	148.33±0.65
5042/2C-01	3.801±0.013	0.0012	0.00003	2.257	99.6	148.50±0.62
5042-07	3.801±0.013	0.0501	0.00010	2.258	98.8	148.55±0.62
			Weighted Average, 1σ error without error in J =			148.07±0.17
				1σ error with error in J =		±0.51

Table 3.—Continued

Lab ID#	J ± 1σ (x 10^{-2})	Ca/K	$^{36}Ar/^{39}Ar$ ± 1 σ	$^{40}Ar^*/^{39}Ar$	%$^{40}Ar^*$	Age±Error (Ma)
Sample MC-39						
5044-03	3.823±0.013	0.0253	0.00010	2.202	98.8	145.81±0.54
5044-01	3.823±0.013	0.0383	0.00007	2.203	99.2	145.87±0.53
5044-05	3.823±0.013	0.0256	0.00008	2.205	99.0	146.04±0.56
5044-04	3.823±0.013	0.0268	0.00008	2.206	99.0	146.09±0.56
5044-02	3.823±0.013	0.0270	0.00004	2.225	99.5	147.27±0.56
5044/2C-03	3.823±0.013	0.0537	0.00007	2.231	99.2	147.66±0.62
5044/2C-01	3.823±0.013	0.0260	0.00005	2.241	99.4	148.28±0.59
5044/2C-02	3.823±0.013	0.0267	0.00003	2.249	99.7	148.81±0.61
5044-06	3.823±0.013	0.0266	0.00004	2.250	99.5	148.85±0.54
5044-10	3.823±0.013	0.0252	0.00003	2.252	99.6	148.97±0.54
5044-09	3.823±0.013	0.0313	0.00006	2.252	99.2	148.98±0.57
5044/2C-05	3.823±0.013	0.0312	0.00003	2.256	99.7	149.27±0.63
5044-08	3.823±0.013	0.0333	0.00008	2.263	99.0	149.72±0.65
5044-07	3.823±0.013	0.0342	0.00006	2.269	99.3	150.05±0.60
			Weighted Average, 1σ error without error in J =			147.82±0.42
				1σ error with error in J =		±0.63
Sample MC-52						
5046-02	3.832±0.013	0.0426	0.00004	2.240	99.5	148.55±0.55
5046-10	3.832±0.013	0.0601	0.00005	2.241	99.5	148.63±0.58
5046-05	3.832±0.013	0.0289	0.00005	2.246	99.4	148.94±0.58
5046-01	3.832±0.013	0.0246	0.00004	2.251	99.6	149.26±0.57
5046-09	3.832±0.013	0.0297	0.00004	2.251	99.5	149.27±0.58
5046-06	3.832±0.013	0.0265	0.00007	2.256	99.2	149.55±0.56
5046B-02	3.832±0.013	0.0667	0.00005	2.260	99.5	149.86±0.60
5046B-05	3.832±0.013	0.0450	0.00013	2.265	98.4	150.18±0.58
5046B-04	3.832±0.013	0.0304	0.00002	2.270	99.7	150.47±0.59
			Weighted Average, 1σ error without error in J =			149.39±0.23
				1σ error with error in J =		±0.53
Sample NTM-17						
5058B-02	3.824±0.013	0.0794	0.00016	2.250	98.1	148.91±0.80
5058B-03	3.824±0.013	0.0957	0.00009	2.251	99.0	148.95±0.57
5058/2-08	3.824±0.013	0.0540	0.00006	2.258	99.4	149.41±0.67
5058/2-03	3.824±0.013	0.0673	0.00007	2.258	99.2	149.43±0.73
5058B-05	3.824±0.013	0.1670	0.00009	2.262	99.1	149.65±0.67
5058/2-05	3.824±0.013	0.3532	0.00011	2.269	99.2	150.10±0.81
			Weighted Average, 1σ error without error in J =			149.29±0.19
				1σ error with error in J =		0.52

Table 3.—Continued

Lab ID#	J ± 1σ (x 10^{-2})	Ca/K	$^{36}Ar/^{39}Ar$ ± 1 σ	$^{40}Ar^{*}/^{39}Ar$	%$^{40}Ar^{*}$	Age±Error (Ma)
Sample NTM-1319-1						
5056/2-08	3.793±0.013	0.0165	0.00005	2.351	99.4	154.12±0.66
5056/2-05	3.793±0.013	0.0145	0.00003	2.354	99.7	154.25±0.68
5056/2-06	3.793±0.013	0.0192	0.00002	2.356	99.7	154.39±0.68
5056/2-07	3.793±0.013	0.0131	0.00006	2.356	99.3	154.40±0.70
5056/2-04	3.793±0.013	0.0133	0.00005	2.362	99.4	154.79±0.71
5056/2-03	3.793±0.013	0.0146	0.00003	2.364	99.6	154.91±0.71
5056/2-01	3.793±0.013	0.0162	0.00003	2.368	99.7	155.13±0.84
5056/2-09	3.793±0.013	0.0160	0.00001	2.369	99.8	155.19±0.69
5056/2-10	3.793±0.013	0.0103	0.00000	2.371	100.0	155.32±0.80
5056/2-02	3.793±0.013	0.0146	0.00002	2.375	99.8	155.58±0.68
			Weighted Average, 1σ error without error in J =			154.75±0.18
				1σ error with error in J =		±0.54
Sample RAIN-1325-4+4						
5064/2-04	3.811±0.013	0.0090	0.00014	2.344	98.3	154.37±0.80
5064B-08	3.811±0.013	0.0179	0.00011	2.351	98.7	154.79±0.71
5064/2-03	3.811±0.013	0.0052	0.00011	2.360	98.6	155.35±0.96
5064/2-01	3.811±0.013	0.0089	0.00004	2.361	99.6	155.43±1.29
			Weighted Average, 1σ error without error in J =			154.82±0.30
				1σ error with error in J =		±0.58

Notes: Errors in age quoted for individual runs are 1σ analytical uncertainty. Weighted averages are calculated using the inverse variance as the weighting factor (Taylor, 1982), while errors in the weighted averages are 1σ standard error of the mean (Samson and Alexander, 1987). Ca/K is calculated from $^{37}Ar/^{39}Ar$ using a multiplier of 1.96; where no entries appear for Ca/K, ^{37}Ar was below the level of detection. $^{40}Ar^{*}$ refers to radiogenic argon. $\lambda = 5.543 \times 10^{-10} y^{-1}$. Isotopic interference corrections for sample DQW-21: $(^{36}Ar/^{37}Ar)_{Ca} = (2.64 \pm 0.02) \times 10^{-4}$, $(^{39}Ar/^{37}Ar)_{Ca} = (6.7 \pm 0.4) \times 10^{-4}$, $(^{40}Ar/^{39}Ar)_{K} = (8.4 \pm 0.2) \times 10^{-3}$; for sample GP-1346-28+23: $(^{36}Ar/^{37}Ar)_{Ca} = (2.64 \pm 0.02) \times 10^{-4}$, $(^{39}Ar/^{37}Ar)_{Ca} = (6.7 \pm 0.4) \times 10^{-4}$, $(^{40}Ar/^{39}Ar)_{K} = (7 \pm 3) \times 10^{-4}$; for all other samples: $(^{36}Ar/^{37}Ar)_{Ca} = (2.58 \pm 0.06) \times 10^{-4}$, $(^{39}Ar/^{37}Ar)_{Ca} = (6.7 \pm 0.3) \times 10^{-4}$, $(^{40}Ar/^{39}Ar)_{K} = (2.35 \pm 0.04) \times 10^{-2}$.

Table 4.—Single-crystal $^{40}Ar/^{39}Ar$ Analytical Data for NTM-1319-1 (Obradovich).

Lab ID#	J ± 1σ (x 10^{-2})	$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	$^{40}Ar^*/^{39}Ar$	%$^{40}Ar^*$	Age±Error (Ma)
90Z0943	0.886±0.004	0.016258	0.000563	10.1796	98.13	155.8±1.1
90Z0944	0.886±0.004	0.011097	0.000029	10.0973	99.64	154.6±0.9
90Z0945	0.886±0.004	0.011331	0.000104	10.0671	99.42	154.1±0.9
				Average Age with 1σ error in J =		154.8±1.4

Notes: Isotopic interference corrections: $(^{36}Ar/^{37}Ar)_{Ca}$ = 0.000251, $(^{39}Ar/^{37}Ar)_{Ca}$ = 0.000671, $(^{40}Ar/^{39}Ar)_K$ = 0.0285. MMhb-1 monitor age = 520.4 Ma.

It gives plateau ages of 148.21 or 148.63±0.50 Ma (1 σ) depending on the temperature steps used in calculating the age. Both of these ages are statistically indistinguishable from the laser-fusion mean age at the 95% confidence level, but are somewhat closer to fitting in with the rest of the stratigraphic framework (Fig. 2).

DISCUSSION

Some idea of the maximum possible age range of the Morrison Formation and its bounding unconformities can be obtained from the ages of rocks just below and just above the formation. The available biostratigraphic age information on rocks that enclose the Morrison indicates that the maximum time span represented by the Morrison Formation and the bounding J-5 and K-1 unconformities ranges from latest Oxfordian to possibly Barremian.

The youngest unit below the Morrison is the Oxfordian age Redwater Shale Member, which is included in either the Sundance or Stump Formations of eastern or western Wyoming, respectively. Most of this unit is well dated by ammonites and ranges through the entire early and middle Oxfordian according to Imlay (1980) and Callomon (1984). The undated uppermost beds of the Redwater Shale, above the highest fossil collections, could extend into the earliest part of the late Oxfordian. Allowing some time for formation of the J-5 unconformity at the top of the Redwater Shale, the base of the Morrison should be latest Oxfordian at the oldest. Preliminary examination of trace-fossil assemblages across the Redwater-Windy Hill contact at Dinosaur National Monument, Utah, suggests continuous deposition. Either there is no unconformity between these units there or the J-5 unconformity is stratigraphically lower than has been thought (S.T. Hasiotis and T.M. Demko, oral Commun., 1994). This problem is currently being investigated.

The oldest rocks above the Morrison Formation are included in the Burro Canyon and Cedar Mountain Formations, which appear to be correlative units, at least in part (Aubrey, this volume), in the eastern and western parts of the Colorado Plateau, respectively.

Palynomorphs recovered from the uppermost part of the Burro Canyon Formation indicate "an Aptian-early Albian age, with the remote possibility of a late Barremian age" according to Tschudy and others (1984, p. 19). Palynomorphs recovered from the uppermost part of the Cedar Mountain Formation indicate that it is "clearly of late or latest Albian age" (Tschudy and others, 1984, p. 11). The lower parts of both formations have not been well dated, but a small dinosaur fauna recovered from the lower beds of the Cedar Mountain Formation suggest a Barremian age (Kirkland, 1992). Thus, the dinosaurs and palynomorphs indicate that the Cedar Mountain and Burro Canyon Formations above the K-1 unconformity are about Barremian to Albian in age. Accordingly, the Morrison Formation is older than Barremian.

The results of our current dating efforts allow us to more confidently place the Morrison Formation in its proper time-stratigraphic position (Fig. 2). The ages from the Tidwell Member suggest that deposition of the Morrison Formation began around 155 Ma, which is close to the Oxfordian-Kimmeridgian boundary that Harland et al. (1990) place at 154.7 Ma. According to Schudack and others (this volume), Kimmeridgian fossils were found just above the level of the dated bentonite bed in the Tidwell Member near Grand Junction, Colorado and Kimmeridgian charophytes and palynomorphs were recovered from higher strata in the Tidwell (Litwin and others, this volume; Schudack and others, this volume). The new ages reported here are the most precise isotopic age data yet published from latest early Kimmeridgian-age sedimentary rocks. Consequently, these new data suggest that the hiatus at the J-5 unconformity is probably on the order of 1 million years in duration.

Table 5.—$^{40}Ar/^{39}Ar$ Age Spectrum Data (Kunk).

T (C)	%^{39}Ar of Total	$^{40}Ar_R/^{39}Ar_K$†	Apparent K/Ca‡	K/Cl	Radiogenic Yield (%)	$^{39}Ar_K$§ ($\times 10^{-12}$ moles)	Apparent Age ±Precision (Ma)
Sample MC-39			J = 0.007422±0.25%		Sample wt. = 0.2512 g		
1075	9.3	11.549	15.99	****	99.9	1.649	148.37±0.21
1120	8.1	11.511	11.42	****	99.7	1.425	147.89±0.26
1150	8.2	11.517	20.50	****	99.7	1.443	147.97±0.19
1180	8.8	11.503	7.60	****	99.6	1.549	147.79±0.44
1220	10.7	11.549	16.06	****	100.0	1.899	148.36±0.13
1260	12.3	11.519	13.55	****	99.7	2.172	147.99±0.31
1300	13.4	11.559	0.00	****	99.8	2.369	148.49±0.23
1350	17.5	11.590	164.85	****	100.0	3.093	148.87±0.09
1450	11.8	11.623	370.61	****	99.9	2.085	149.27±0.29
			Total Gas	K/Ca = 80.7		Age	148.41±????
			Plateau Age (70.7% of gas on plateau, steps 1075-1300°C)				148.21±0.50
			Plateau Age (53.9% of gas on plateau, steps 1220-1350°C)				148.63±0.50
Sample NTM-1319-1			J=0.007424±0.25%		Sample wt. = 0.1914 g		
1075	9.4	12.208	39.96	****	100.0	2.128	156.51±0.22
1120	8.0	12.095	81.47	****	99.8	1.816	155.12±0.39
1150	8.2	12.095	636.27	****	99.9	1.851	155.12±0.12
1180	8.6	12.066	17.34	****	99.8	1.944	154.77±0.05
1220	10.6	12.071	0.00	****	99.8	2.396	154.83±0.24
1260	11.7	12.091	23.78	****	99.9	2.653	155.07±0.17
1300	12.1	12.093	0.00	****	99.7	2.744	155.09± 0.35
1350	19.1	12.197	87.31	****	100.0	4.326	156.38±0.24
1450	12.2	12.411	105.74	****	99.8	2.747	159.00±0.35
			Total Gas	K/Ca = 96.2		Age	155.89±????
			Plateau Age (59.3% of gas on plateau, steps 1120-1300°C)				154.87±0.52

† This ratio has been corrected for mass discrimination, atmospheric argon, and the production of interfering isotopes during irradiation using the values reported by Dalrymple et al. (1981) for $(^{36}Ar/^{37}Ar)_{Ca}$, $(^{39}Ar/^{37}Ar)_{Ca}$, and $(^{40}Ar/^{39}Ar)_K$.

‡ Apparent K/Ca ratios were calculated using the equation given in Fleck, Sutter, and Elliot (1977).

§ ^{39}Ar concentrations were calculated using the measured sensitivity of the mass spectrometer and have a precision of about 5%.

¶ Comparisons between steps for the determination of the existence of an age plateau were done using the larger of: the calculated uncertainty from the analyses or, the reproducibility limit of the mass spectrometer as determined by replicate measurements of FCT-3. During the period of time in which these samples were analyzed the reproducibility limit was 0.15%.

Sanidine ages from the Brushy Basin Member range from 150.33±0.27 Ma (1 standard error of mean) to 147.82±0.63 Ma; they suggest a Kimmeridgian-early Tithonian age for this member based on the time scales of Obradovich (1993), Bralower and others (1990), or Harland and others (1990). The paleontological data reported in this volume by Litwin and others and Schudack and others indicate that the Brushy Basin Member is Kimmeridgian to early Tithonian in age. We conclude that deposition of the Morrison Formation ended well before the end of the Jurassic, and that the formation is entirely Late Jurassic in age. The hiatus at the K-1 unconformity is approximately 20 million years in duration and includes the later part of the Tithonian, the entire Berriasian, Valanginian, and Hauterivian, and part or all of the Barremian Ages.

PUBLICATIONS

Kowallis, B.J., Christiansen, E.H., Deino, A.L., Peterson, F., Turner, C.E., and Blakey, R.C., 1996, Implications of new high precision $^{40}Ar/^{39}Ar$ laser-microprobe ages for the Jurassic time scale; in, Morales, M., (ed.), The Continental Jurassic: Museum of Northern Arizona Bulletin 60, p. 7-8.

Kowallis, B.J., Christiansen, E.H., Deino, A.L., Peterson, F., Turner, C.E., Kunk, M.J., and Obradovich, J.D., 1998, The age of the Morrison Formation: Modern Geology, v. 22, nos. 1-4, p. 235-260. .

REFERENCES CITED

Baker, A.A., Dane, C.H., and Reeside, J.B., Jr., 1936, Correlation of the Jurassic formations of parts of Utah, Arizona, New Mexico, and Colorado: U.S. Geological Survey Professional Paper 183, p. 1-63.

Bakker, R.T., 1990, A new latest Jurassic vertebrate fauna, from the highest levels of the Morrison Formation at Como Bluff, Wyoming: Hunteria, v. 2, n. 6, p. 1-19.

Berry, E.W., 1915, Paleobotanic evidence of the age of the Morrison Formation: Geological Society of America Bulletin, v. 26, p. 335-342.

Bilbey, S.A., 1992, Stratigraphy and sedimentary petrology of the Upper Jurassic-Lower Cretaceous rocks at Cleveland-Lloyd Dinosaur Quarry with a comparison to the Dinosaur National Monument Quarry, Utah: Unpublished Ph.D. Dissertation, University of Utah, Salt Lake City, 295 p.

Bilbey-Bowman, S.A., Bowman, J.T., and Drake, R.E., 1986, Interpretation of the Morrison Formation as a time-transgressive unit: 4th North American Paleontological Convention, Boulder, Colorado, Abstracts with Programs, p. A5.

Bralower, T.J., Ludwig, K.R., Obradovich, J.D., and Jones, D.L., 1990, Berriasian (Early Cretaceous) radiometric ages from the Grindstone Creek section, Sacramento Valley, California: Earth and Planetary Science Letters, v. 98, p. 62-73.

Callison, G., Rasmussen, T.E., and Kirkland, J.I., 1986, The Fruita microvertebrate site: Enivronment of deposition and paleoecology: 4th North American Paleontological Convention, Boulder, Colorado, Abstracts with Programs, p. A8.
Callomon, J.H., 1984, A review of the biostratigraphy of the post-lower Bajocian Jurassic ammonites of western and northern North America; in, Westermann, G.E.G., (ed.), Jurassic-Cretaceous biochronology and paleogeography of North America: Geological Association of Canada, Special Paper 27, p. 143-174.
Christiansen, E.H., Kowallis, B.J., and Barton, M.D., 1994a, Temporal and spatial distribution of volcanic ash in Mesozoic sedimentary rocks of the Western Interior: An alternative record of Mesozoic magmatism; in, Caputo, M.V., Peterson, J.A., and Franczyk, K.J., (eds.), Mesozoic systems of the Rocky Mountain region, USA: Rocky Mountain Section SEPM, Denver, Colorado, p. 73-94.
Christiansen, E.H., Kowallis, B.J., Turner, C., and Peterson, F., 1994b, Geochemistry of altered volcanic ash in the Morrison Formation: The Upper Jurassic Morrison Formation: An Interdisiplinary Symposium sponsored by the Denver Museum of Natural History, Denver, Colorado, Abstracts Volume.
Chesner, C.A., Rose, W.I., Deino, A.L., Drake, R., and Westgate, J.A., 1991, Eruptive history of Earth's largest Quaternary caldera (Toba) clarified: Geology, v. 19, p. 200-203.
Dalrymple, G.B., Alexander, E.C., Jr., Lanphere, M.A., and Kraker, G.P., 1981, Irradiation of samples for $^{40}Ar/^{39}Ar$ ddating using the Geological Survey TRIGA reactor: U.S. Geological Survey Professional Paper 1176, 55 p.
Darton, N.H., 1922, Geologic structure of parts of New Mexico: U.S. Geological Survey Bulletin, v. 726, p. 173-275.
DeCelles, P.G., and Burden, E.T., 1992, Non-marine sedimentation in the overfilled part of the Jurassic-Cretaceous Cordilleran foreland basin: Morrison and Cloverly Formations, central Wyoming, USA: Basin Researach, v. 4, p. 291-313.
Deino, A.L. and Potts, R., 1990, Single-crystal 40Ar/39Ar dating of the Olorgesailie Formation, Southern Kenya Rift: Journal of Geophysical Research, v. 95, p. 8453-8470.
Deino, A.L., Tauxe, L., Monaghan, M., and Drake, R., 1990, Single-crystal $^{40}Ar/^{39}Ar$ ages and the litho- and paleomagnetic stratigraphies of the Ngorora Formation, Kenya: Journal of Geology, v. 98, p. 567-587.
Emmons, S.F., Cross, W., and Eldridge, G.H., 1896, Geology of the Denver basin in Colorado: U.S. Geological Survey Monograph 27, 527 p.
Engelmann, G.F., Chure, D.J., and Madsen, S.K., 1989, A mammalian fauna from the Jurassic Morrison Formation of Dinosaur National Monument: Journal of Vertebrate Paleontology, v. 9, n. 3, p. 19A.
Fleck, R.J., Sutter, J.F., and Elliot, D.H., 1977, Interpretation of discordant $^{40}Ar/^{39}Ar$ age spectra of Mesozoic tholeiites from Antarctica: Geochimica et Cosmochimica Acta, v. 41, p. 15-32.
Galton, P.M., 1976, Iliosuchus, a Jurassic dinosaur from Oxfordshire and Utah: Palaeontonlgy, v. 19, p. 587-589.
Galton, P.M., 1977, The Upper Jurassic Ornithopod dinosaur Drysaurus—Evidence for a Laurasia-Gondwanaland connection: Journal of Paleontology, v. 51, (2 suppl., part III), p. 11-12.
Harland, W.B., Armstrong, R.L., Cox, A.V., Craig, L.E., Smith, A.G., and Smith, D.G., 1990, A Geologic Time Scale 1989: Cambridge University Press, Cambridge, 263 p.
Haugerud, R.A. and Kunk, M.J., 1988, ArAr*, A computer program for reduction of ^{40}Ar-^{39}Ar data: U.S. Geological Survey Open File Report 88-261, 68 pp.
Hotton, C.L., 1986, Palynology of the Morrison Formation: North American Paleontological Convention, 4th, Boulder, Colorado, Abstracts with Programs, p. A20.

Imlay, R.W., 1952, Correlation of the Jurassic formations of North America exclusive of Canada: American Association of Petroleum Geologists Bulletin, v. 63, p. 952-992.

Imlay, R.W., 1980, Jurassic paleobiogeography of the conterminous United States in its continental setting: U.S. Geological Survey Professional Paper 1062, 134 p.

Kennedy, W.J. and Odin, G.S., 1982, The Jurassic and Cretaceous time scale in 1981, in, Odin, G.S., ed., Numerical Dating in Stratigraphy, Part II: John Wiley & Sons Ltd., Chichester, p. 557-592.

Kirkland, J.I., 1992, Dinosaurs define a two-fold Lower Cretaceous zonation of the Cedar Mountain Formation, central Utah: Geological Society of America, Abstracts with Programs, v. 24, n. 6, p. 22.

Knowlton, F.H., 1916, Note on a recent discovery of fossil plants in the Morrison formation: Journal of the Washington Academy of Science, v. 6, p. 180-181.

Kowallis, B.J., and Heaton, J.S., 1987, Fission-track dating of bentonites and bentonitic mudstones from the Morrison Formation in central Utah: Geology, v.15, p. 1138-1142.

Kowallis, B.J., Heaton, J.S., and Bringhurst, K., 1986, Fission-track dating of volcanically derived sedimentary rocks: Geology, v. 14, p. 19-22.

Kowallis, B.J., Christiansen, E.H., and Deino, A.L., 1991, Age of the Brushy Basin Member of the Morrison Formation, Colorado Plateau, western USA: Cretaceous Research, v. 12, p. 483-493.

Kowallis, B.J., Christiansen, E.H., Deino, A.L., Kunk, M.J., and Heaman, L.M., in press, Age of the Cenomanian-Turonian Boundary in the Western Interior of the United States: Cretaceous Research.

Lee, M.J., and Brookins, D.G., 1978, Rubidium-Strontium minimum ages of sedimentation, uranium mineralization, and provenance, Morrison Formation (Upper Jurassic), Grants Mineral Belt, New Mexico: American Association of Petroleum Geologists Bulletin, v. 62, p. 1673-1683.

Lee, W.T., 1915, Reasons for regarding the Morrison an introductory Cretaceous formation: Geological Society of America Bulletin, v. 26, p. 303-314.

Litwin, R.J., Turner, C.E., and Peterson, F., 1998, Palynological evidence on the age of the Morrison Formation, Western Interior U.S.: Modern Geology, v. 22, nos. 1-4, p. 297-320.

Logan, W.N., 1900, The stratigraphy and invertebrate faunas of the Jurassic formation in the Freeze-out Hills of Wyoming: Kansas University Quarterly, v. 9, p. 132-134.

Lull, R.S., 1911, The Reptilia of the Arundel formation: Maryland Geological Survey, Lower Cretaceous, p. 178.

Lull, R.S., 1915, Sauropoda and Stegosauria of the Morrison of North America compared with those of Europe and eastern Africa: Geological Society of America Bulletin, v. 26, p. 323-334

Madsen, J.H., Jr., 1976, Allosaurus fragilis: A revised osteology: Utah Geological and Mineral Survey Bulletin 109, 163 p.

Marsh, O.C., 1896, Vertebrate paleontology, in, Emmons, S.F., Cross, W., and Eldridge, G.H., Geology of the Denver basin in Colorado: U.S. Geological Survey Monograph 27, p. 473-550.

Miller, W.E., Baer, J.L., and Stadtman, K.L., 1991, The Dry Mesa Dinosaur Quarry, Mesa County, Colorado: Guidebook for Dinosaur Quarries and Tracksites Tour, western Colorado and eastern Utah, Grand Junction Geological Society, p. 31-46.

Mook, C.C., 1916, A Study of the Morrison formation: New York Academy of Science Annals, v. 27, p. 39-191. Obradovich, J.D., 1993, A Cretaceous time scale, in, Caldwell, W.G.E. and Kauffman, E.G., eds., Evolution of the Western Interior Basin: Geological Association of Canada, Special Paper 39, p. 379-396.

Ogden, L., 1954, Rocky Mountain Jurassic time surface: American Association of Petroleum Geologists Bulletin, v. 38, p. 914-916.

Osborn, H.F., 1915, Close of Jurassic and opening of Cretaceous time in North America: Geological Society of America Bulletin, v. 26, p. 295-302.
Owen, D.E., Turner-Peterson, C.E., and Fishman, N.S., 1989, X-ray diffraction studies of the <0.5 m fraction from the Brushy Basin Member of the Upper Jurassic Morrison Formation, Colorado Plateau: U.S. Geological Survey Bulletin 1808-G, p. G1-G25.
Peck, R.E., 1957, North American Mesozoic Charophyta: U.S. Geological Survey Professional Paper 294-A, 42 p.
Peck, R.E. and Reker, C.C., 1948, The Morrison and Cloverly Formations: Wyoming Geological Association Guidebook 3rd Annual Field Conference, p. 125-139.
Petersen, L.M. and Roylance, M.M., 1982, Stratigraphy and depositional environments of the Upper Jurassic Morrison Formation near Capitol Reef National Park, Utah: Brigham Young University Geology Studies, v. 29, pt. 2, p. 1-12.
Peterson, F., 1994, Sand dunes, sabkhas, streams, and shallow streams: Jurassic paleogeography in the southern part of the Western Interior basins, in, Caputo, M.V., Peterson, J.A., and Franczyk, K.J., eds. Mesozoic Systems of the Rocky Mountain Region, USA: Denver, Rocky Mountain SEPM, p. 233-272.
Riggs, E.S., 1902, The dinosaur beds of the Grand River Valley of Colorado: Scientific American, v. 53, p. 22061-22062.
Samson, S.D. and Alexander, E.C., Jr., 1987, Calibration of the interlaboratory 40Ar/39Ar dating standard, MMhb-1: Chemical Geology, v. 66, p. 27-34.
Schuchert, Charles, 1918, Age of the American Morrison and East African Tendaguru Formations: Geological Society of America Bulletin, v. 29, p. 245-280.
Schuchert, Charles, 1934, The Upper Jurassic age of the Tendaguru dinosaur beds: American Journal of Science, v. 27, p. 463-466.
Schudack, M.E., Turner, C.E., and Peterson, F., 1998, Biostratigraphy, paleoecology and biogeography of charophytes and ostracodes from the Upper Jurassic Morrison Formation, Western Interior, USA: Modern Geology, v. 22, nos. 1-4, p. 379-414.
Simpson, G.G., 1926, The age of the Morrison Formation: American Journal of Science, v. 12, p. 198-216.
Stanton, T.W., 1915, Invertebrate fauna of the Morrison Formation: Geological Society of America Bulletin, v. 26, p. 343-348.
Staudacher, Th., Jessberger, E.K., Dorflinger, D., and Kiko, J., 1978, A refined ultrahigh-vacuum furnace for rare gas analysis: Journal of Physical Earth Science Instrumentation, v. 11, p. 781-784.
Steiner, M.B., 1980, Investigation of the geomagnetic field polarity during the Jurassic: Journal of Geophysical Research, v. 85, p. 3572-3586.
Steiner, M.B., and Helsley, C.E., 1975a, Reversal pattern and apparent polar wander for the Late Jurassic: Geological Society of America Bulletin, v. 86, p. 1537-1543.
Steiner, M.B, and Helsley, C.E., 1975b, Late Jurassic magnetic polarity sequence: Earth and Planetary Science Letters, v. 27, p. 108-112.
Steiner, M.B., Lucas, S.G., and Shoemaker, E.M., 1994, Correlation and age of the Upper Jurassic Morrison Formation from magnetostratigraphic analysis: in, Caputo, M.V., Peterson, J.A., and Franczyk, K.J., eds. Mesozoic Systems of the Rocky Mountain Region, USA: Denver, Rocky Mountain Section SEPM, p. 315-330.
Stokes, W.L., 1944, Morrison and related deposits in and adjacent to the Colorado Plateau: Geological Society of America Bulletin, v. 55, p. 951-992.
Swierc, J.E., and Johnson, G.D., 1990, The timing of Late Jurassic and Early Cretaceous nonmarine sedimentation, northeastern Bighorn Basin, Wyoming: magnetostratigraphic implications: Geological Society of America Abstracts with Programs, v. 22, n. 7, p. A322.
Taylor, J.R., 1982, An introduction to error analysis: Mill Valley, California,University Science Books, 270 p.

Tschudy, R.H., Tschudy, B.D., and Craig, L.C., 1984, Palynological evaluation of Cedar Mountain and Burro Canyon Formations, Colorado Plateau: U.S. Geological Survey Professional Paper 1281, 24 p.

Turner, C.E., and Fishman, N.S., 1991, Jurassic Lake T'oo'dichi': A large alkaline, saline lake, Morrison Formation, eastern Colorado Plateau: Geological Society of America Bulletin, v. 103, p. 538-558.

Ward, L.F., 1900, Description of a new genus and twenty new species of fossil cycadean trunks from the Jurassic of Wyoming: Proceedings of the Washington Academy of Science, v. 1, p. 253-300.

Ward, L.F., 1906, Jurassic cycads from Wyoming: U.S. Geological Survey Monograph 48, p. 179-203.

Williston, S.W., 1905, The Hallopus, Baptanodon, and Atlantosaurus beds of Marsh: Journal of Geology, v. 13, p. 342-348.

Wintsch, R.P., Kunk, M.J., Cortesini, H., Jr., and Sutter, J.F., 1991, $^{40}Ar/^{39}Ar$ age spectrum data for the Avalon and Putnam-Nashoba lithotectonic zones, eastern Connecticut and western Rhode Island: U.S. Geological Survey Open File Report 91-399, 133 pp.

Yen, Teng-Chien, 1952, Molluscan fauna of the Morrison Formation: U.S. Geological Survey Professional Paper 233-B, p. 21-51.

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APPENDIX I

LOCATION OF MEASURED SECTIONS AND ISOTOPICALLY DATED SAMPLES

Dinosaur Quarry West Section

About 0.6 km west of the Carnegie Quarry Building at Dinosaur National Monument along the west side of a small canyon locally known as Douglas Draw. SE¼ NE¼ SE¼ Sec. 27, T 4 S, R 23 E, Uintah Co., Utah. Top of measured section at 40° 26' 20" North Latitude, 109° 17' 40" West Longitude.

Fruita Paleontological Site Section

Sample collected on the northeast side of a small hill locally known as Al Look hill. SE¼ SE¼ SW¼ Sec. 13, T 1 N, R 3 W, Mesa Co., Colorado. 39° 09' 00" North Latitude, 108° 46' 06" West Longitude. Section measured by J.I. Kirkland (oral commun., 1993), modified after a partial section measured by F. Peterson (unpublished data).

Garden Park Section

Sample came from artificial cuts at a bentonite mine on the north side of a small west-draining tributary to Fourmile Creek. N½ NE¼ NW¼, E½ SE¼ NW¼, SW¼ SW¼ NE¼, NW¼ NW¼ SE¼ Sec. 26, T 17 S, R 70 W, Fremont Co., Colorado. The bentonite mine is at 38 32' 39" North Latitude, 105 11' 52" West Longitude.

Little Cedar Mountain Section

In a slight reentrant on the south side of Little Cedar Mountain. NW¼ NW¼ SE¼, SW¼ SW¼ NE¼, SE¼ SE¼ NW¼ Sec. 5, T 19 S, R 10 E, Emery Co., Utah. Top of measured section at 39° 12' 02" North Latitude, 110° 49' 25" West Longitude.

Montezuma Creek Section

At the head of a small tributary draw to Montezuma Creek. W½ SE¼, SW¼ NE¼ Sec. 7, T 40 S, R 24 E, San Juan Co., Utah. Top of measured section at 37° 19' 15" North Latitude, 109° 26' 26" West Longitude.

Notom Section

On the east side of a small north-draining draw that is a tributary to the Fremont River. SW¼ SE¼ Sec. 24, T 29 S, R 7 E, Wayne Co., Utah. Top of measured section at 38° 16' 44" North Latitude, 111° 07' 35" West Longitude. Partly from a section measured by Petersen and Roylance (1982, section A).

Rainbow Draw Section

In the head of a small tributary canyon to Rainbow Draw. SE¼ SE¼ NW¼, NE¼ NE¼ SW¼ Sec. 14 and NW¼ SE¼ SE¼, E½ SW¼ SE¼ Sec. 23, T 3 S, R 24 E, Uintah Co., Utah. Top of measured section at 40° 33' 30" North Latitude, 109° 11' 36" West Longitude.

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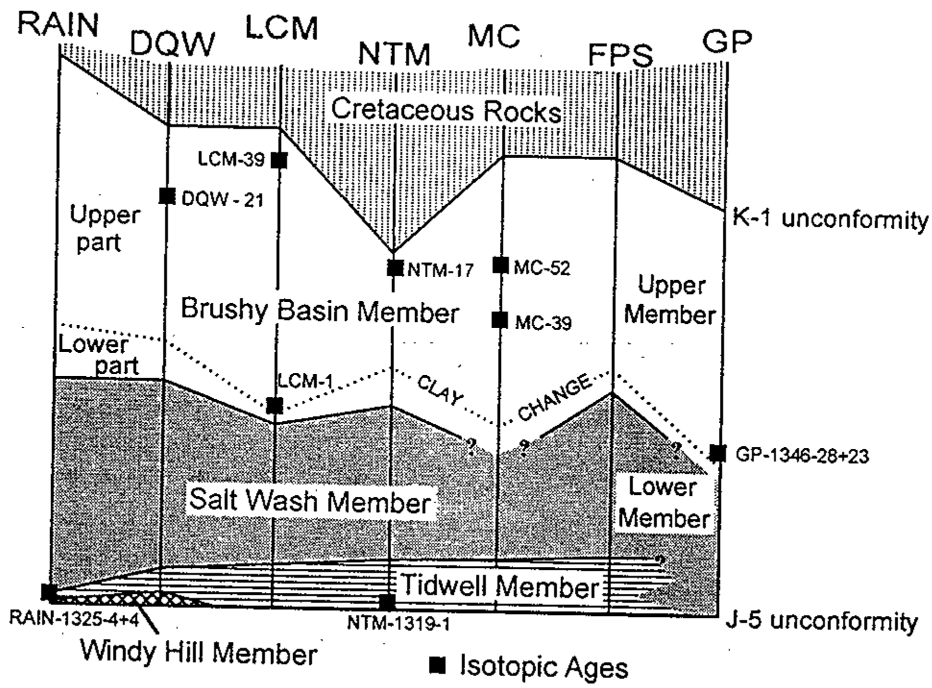

FIGURE 1 Schematic stratigraphic sections of the Morrison Formation at each locality shown on Fig. 3. The base of the figure is the J-5 unconformity. The clay change shown in the lower Brushy Basin Member is a marker horizon that can be traced throughout the study area. The clays below are illitic and non-swelling, while those above are smectitic, swelling clays.

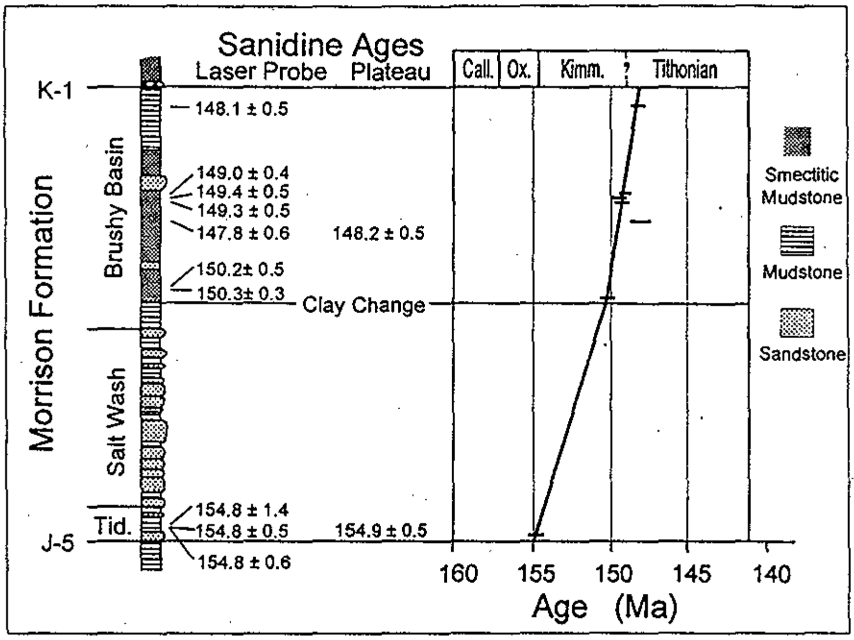

FIGURE 2 Composite stratigraphic section showing the locations of the new sanidine ages reported in this study by both single-crystal (laser probe) and step-heating (plateau) methods. Only one of the samples does not fit on the suggested "best fit" line. The change in slope of the line in the upper Morrison may indicate an increase in sediment accumulation rate. The stage boundaries are from Harland and others (1990) except for the Kimmeridgian–Tithonian boundary that is placed at about 149 Ma based on the ages we have obtained from the upper part of the Morrison Formation, and the Tithonian–Berriasian boundary that is from Bralower and others (1990).

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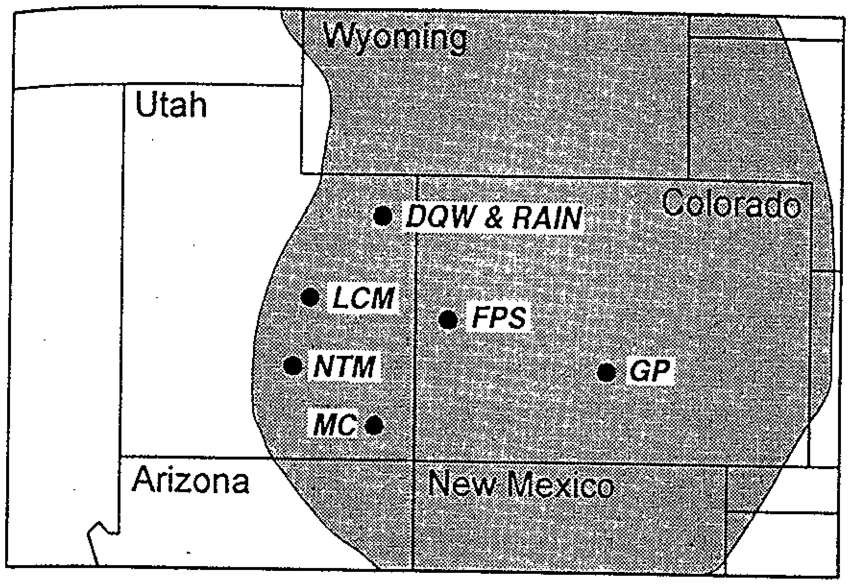

FIGURE 3 Index map showing the locations of sample sections (dots) and the Morrison Formation depositional basin (stippled). Sections are: DQW = Dinosaur Quarry West, FPS = Fruita Paleontological Site, GP = Garden Park, LCM = Little Cedar Mountain, MC = Montezuma Creek, and NTM = Notom.

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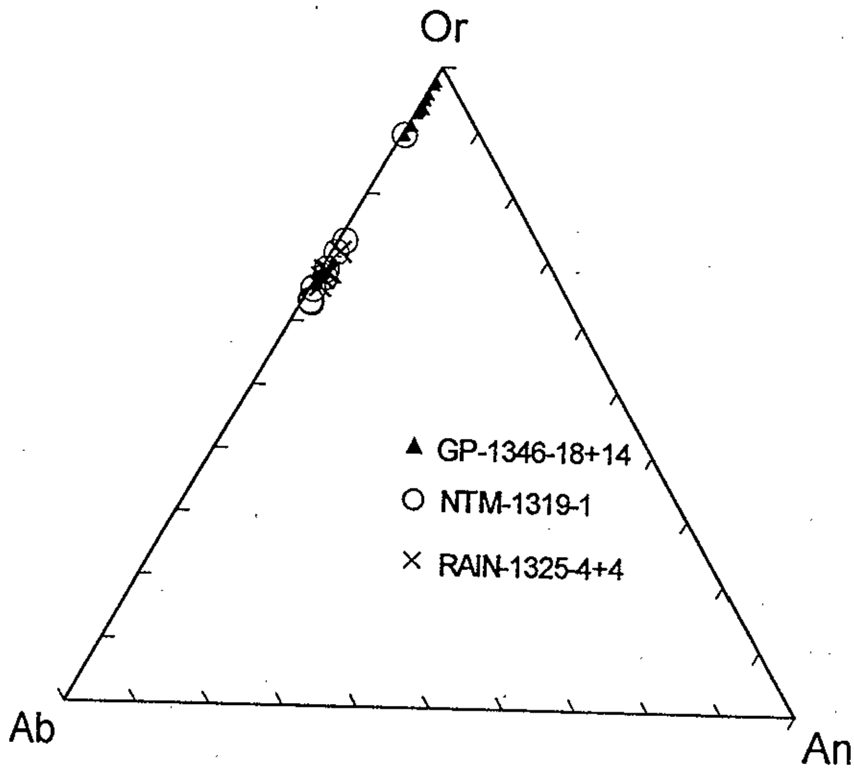

FIGURE 4 Feldspar compositions from Tidwell Member ash bed at two locations, Notom and Rainbow Valley. Also, included is a sample from Garden Park that we thought might be the same ash as at the other two localities, but it only had detrital microcline.

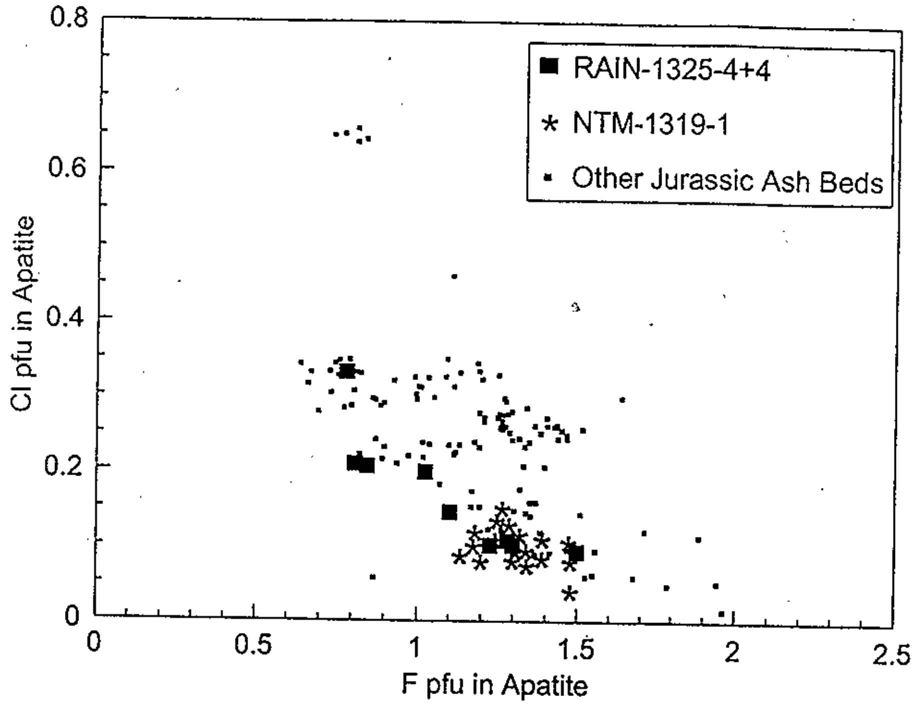

FIGURE 5 Apatite F and Cl compositions from Tidwell Member ash bed at Notom and Rainbow Valley. The data are shown as atoms per formula unit (pfu).

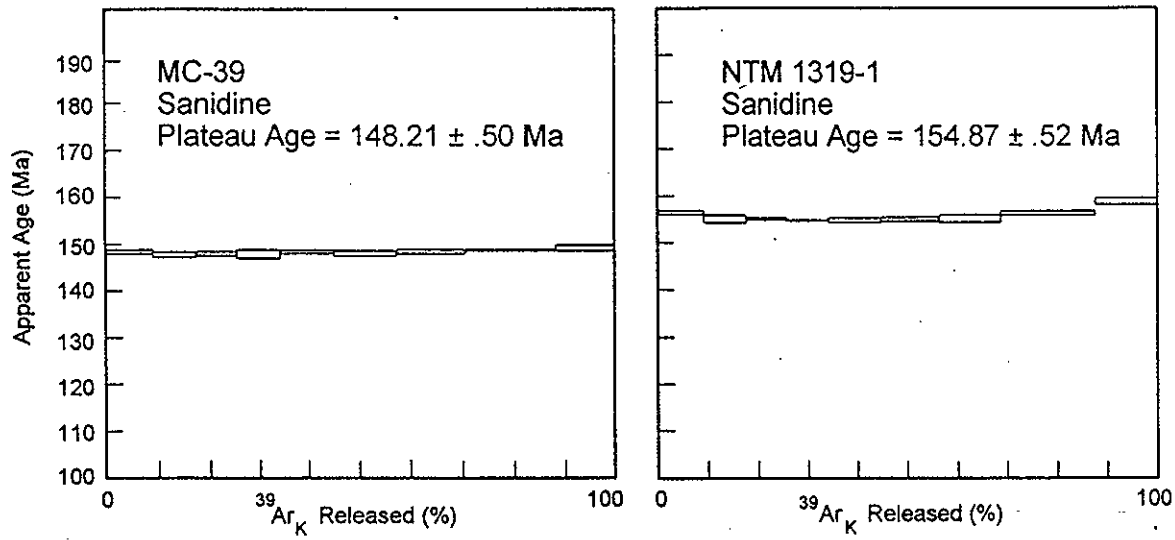

FIGURE 6 $^{40}Ar/^{39}Ar$ age spectra for MC-39 and NTM-1319-1.

PALYNOLOGICAL EVIDENCE ON THE AGE OF THE MORRISON FORMATION IN THE WESTERN INTERIOR U.S.; FINAL REPORT

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ABSTRACT

More than 200 rock samples from the Morrison Formation in the Western Interior U.S. were analyzed recently for fossil palynomorphs (spores and pollen). Twenty-six of the best-preserved and most diverse of the assemblages recovered were selected to establish maximum and minimum relative (paleontological) ages for the members of the Morrison Formation. Additionally, one sample of the Redwater Member of the Stump Formation (Oxfordian; from Dinosaur National Monument, UT) and one sample from the Purgatoire Formation (Albian; from near Boise City, OK) were examined to determine the biostratigraphic constraints for the strata that underlie and overlie the Morrison Formation in parts of its outcrop area.

Palynomorph evidence from this study indicates: (1) deposition of the Morrison began no earlier than the latest part of the Oxfordian Age of the Late Jurassic (but more probably during the Kimmeridgian), and continued until, but not beyond, the Tithonian (~early Volgian) Age of the Late Jurassic, (2) none of the microfossil evidence recovered during this study, or evidence from new $^{40}Ar/^{39}Ar$ tephra analyses and fossil charophyte and ostracode analyses corroborated recently published accounts proposing an early Cretaceous age for the upper part of the Morrison Formation, and (3) parts of the Morrison depositional basin contained highly diverse mesic floras during much or most (the first ~5-6 my) of Morrison time. This paleoclimatic interpretation accords with other paleobotanical

(plant megafossil) evidence, but appears to contrast markedly with previously-reported evidence of arid playa conditions in the upper part of the Morrison Formation (the upper part of the Brushy Basin Member) and the occurrence of eolian sandstones in the Morrison Formation in the Four Corners region.

INTRODUCTION

This research comprises one part of a cooperative interdisciplinary study (this volume) on the Morrison Formation: this component involved a cooperative effort between the National Park Service (Dinosaur National Monument) and the U.S. Geological Survey. The goals of this study were: 1) to determine definitive paleontological ages for the members of the Morrison Formation, including a review of previous paleontological age assessments, 2) to correlate these members to time-equivalent strata regionally and globally, and 3) to make a preliminary assessment of the original fossil plant diversity in the Morrison depositional basin.

Until now, recent studies have not resolved fully the long-term disputes on the age of the Morrison Formation. Over the past fifteen years, its age has been interpreted variously as ranging from entirely pre-Kimmeridgian (early Late Jurassic) to Aptian (Early Cretaceous), a span of approximately 30 million years (per Harland et al., 1990). We consider it important to constrain the age of the Morrison Formation accurately because it has proven to be one of the most prolific strata in the world for fossilized dinosaur remains. The flora (microfossils and megafossils) of the Morrison ecosystem is relatively much less well known and has been studied in detail only more recently (e.g., Tidwell and others, 1986; Kirkland, 1987; Chure and others, 1989; Engelmann and others, 1989a, 1989b; Kirkland and others, 1990; Tidwell, 1990a,b; Tidwell and Ash, 1990; Medlyn and Tidwell, 1992; Chure, 1992; Engelmann, 1992; Henrici, 1992; Kirkland and Armstrong, 1992; Tidwell and Medlyn , 1992; Evans and Milner, 1993; Ash, 1994; Ash and Tidwell, this volume). We believe such studies are important because assessments of fossil diversity and distribution within the formation will provide independent lines of evidence on the climate and biostratigraphic succession in the U.S. Western Interior through Morrison time. The Morrison flora has special relevance because it was the primary food source for both: (1) some of the largest land animals ever to inhabit our planet, and (2) some of the world's early mammal faunas.

MATERIALS AND METHODS

For this study, more than 200 samples of Morrison mudstones, siltstones, and fine-grained sandstones were processed for light microscope analysis; more than half produced at least some fossil palynomorphs. Of these, 26 of the best fossil assemblages form the core of this report; their geographic locations are given in Fig. 1 and Table 1. Collectively, 19 of these form a regional, composite stratigraphic transect (Fig. 2). Palynomorph assemblages were recovered from all of the members of the Morrison as well as from the Redwater Member of the underlying Stump Formation and the base of the Glencairn Member of the Purgatoire Formation, that overlies the Morrison Formation in the extreme southeastern portion of its outcrop belt.

Procedures for extraction of fossil pollen from these samples are detailed only briefly here. Each sample was prepared by decalcification in HCl, disaggregation and demineralization in HF, clay fractionation in aqueous low-sudsing detergent solution, vacuum filtration of the clay suspension through 10 μm nylon filters, specific gravity separation of the organic silt fraction by centrifugation in aqueous $ZnCl_2$, recombination of the filtered silt (after separation from the clay filtrate) and organic silt fractions, oxidation of the lignitic fraction in HNO_3, dissolution of humin in NH_4OH, and mounting the final residue (in a glycerin jelly matrix) onto microscope slides for light microscope analysis.

The first appearance datums (FADs) and last appearance datums (LADs) of age-diagnostic species in these fossil assemblages enabled us to assign a geologic age or age range to each sample and to correlate to other time-equivalent strata outside of the study area. However, biostratigraphically useful taxa most commonly occurred in relative frequencies of less than 1:500. These marker taxa were identified from examination of more than 200,000 total fossil palynomorph specimens. Although we suggest geologic ages for the samples in this study, it is done so with the caution that the I.U.G.S. Stratigraphy Commission is still considering definitive age/stage and period/system boundaries through this interval. Accordingly, it should be noted that these results are preliminary. Our findings are summarized below.

AGE OF THE STUMP FORMATION

In order to assess the age of the Morrison Formation accurately, we also examined samples from the upper part of the Redwater Member of the Stump Formation (a lateral equivalent of the Redwater Shale Member of the Sundance Formation), that underlies the Morrison in the vicinity of Dinosaur National Monument (Figs. 1 and 2; Sample R4792A). The representative assemblage selected for this report contained >65 palynomorph taxa. Preservation and diversity of these microfossils were excellent. However, the majority of the taxa present in this sample ranged through the Morrison Formation and thus were not suitable as biostratigraphic markers. Among the taxa we have identified to date in the Redwater Member that do not appear to range entirely through the Morrison Formation are *Staplinisporites caminus*, *Callialasporites trilobatus*, *Callialasporites rugulatus*, *Densoisporites velatus*, *Ginkgocycadophytus* sp., *Januasporites* sp., *Schizosporis* sp., *Circulisporites* sp., and *Sphagnumsporites* sp. (Figure 3). In addition, the Redwater sample contained common *Araucariacites fissus* but lacked *Cicatricosisporites* and *Concavissimisporites irroratus*, thereby precluding an age assignment younger than Oxfordian. Sample R4792A also contained a diverse dinoflagellate assemblage that includes common *Wanea clathrata*, as well as *Wanea spectabilis* and *Scriniodinium crystallinum* also is present in this sample (Fig. 4(v)- 4(x)).

The acme of *Wanea clathrata* in Australian Mesozoic rocks was proposed by Helby et al. (1987) to have occurred in the Oxfordian. An Oxfordian age also is consistent with the ages proposed by Fensome (1987) and by Helby and others (1987) for pollen assemblages in Canada and Australia that are similar to that from sample R4792A. Imlay (1980) previously proposed an early to middle Oxfordian age for the Redwater, on the basis of cardioceratid ammonites (*Cardioceras* and *Goliathiceras*) recovered from it. Between the top of the Redwater Member and the Windy Hill Member above it lies the Stump Formation- Morrison Formation boundary, and possibly the J-5 regional unconformity of Pipiringos and O'Sullivan (1978). The J-5 regional unconformity, if present, does not seem to be well expressed in the area of Dinosaur National Monument (T.M. Demko, 1994, pers. comm.).

AGE OF THE MORRISON FORMATION: PALYNOLOGICAL EVIDENCE

On the basis of the palynomorph taxa recovered during this study, we believe that Morrison deposition may have begun as early as the latest part of the Oxfordian and lasted perhaps into the Tithonian (~early Volgian). Present palynomorph evidence suggests that the stratigraphic bulk of the formation was deposited during the Kimmeridgian and perhaps into the Tithonian. Palynomorph evidence (Fig. 3) also suggests that only the Windy Hill Member could be Oxfordian in age, although it appears more probably to be Kimmeridgian. The first appearances (FADs) of Kimmeridgian palynomorphs (e.g., *Concavissimisporites montuosus* and *Concavissimisporites irroratus*; Figures 4(a) and 4(d); per geologic ranges in Canadian strata (Fensome, 1987)) occur in the Tidwell Member (sample R4785K). These FADs correspond well to the most recent $^{40}Ar/^{39}Ar$ radiometric date from tephras in the lower part of the Tidwell Member. Kowallis and others (1993; this volume) reported laser-fusion $^{40}Ar/^{39}Ar$ ages of 154.75 ± 0.54 Ma, 154.82 ± 0.58 Ma, and 154.8 ± 1.4 Ma derived from sanidine phenocrysts in tuff beds at the base of the Tidwell Member at Notom, Utah, and at Rainbow Draw (in Dinosaur National Monument).

Within the Tidwell Member, Salt Wash Member, Recapture Member (sample D4930-B, reexamined here from Tschudy and others, 1988a), Westwater Canyon Member (sample D4927, reexamined here from Tschudy and others, 1981), and the lower part of the Brushy Basin Member (up to the stratigraphic level of the clay change -- from largely non-smectitic clays below to smectitic clays above -- per Bell (1983, 1984, 1986) and Turner and Fishman (1991)) all contain a similar combination of index taxa. These include *Concavisporites montuosus* (Figure 4(a)), *Cadargasporites reticulatus* (Figure 4(b)), *Microcachrydites antarcticus* (Figure 4(c)), *Concavissimisporites irroratus* (Figure 4(d)), *Cerebropollenites mesozoicus, Crassitudisporites problematicus* (Figure 4(e)), *Cerebropollenites macroverrucosus* (Figure 4(f)), *Ischyosporites disjunctus* (Figure 4(g)), *Aequitriradites acusus* (Figure 4(h)), *Staplinisporites caminus* (Figure 4(i)), *Concavississimisporites jurienensis* (Figure 4(j)), *Callialasporites segmentatus* (Figure 4(k)), *Callialasporites turbatus* (Figure 4(l)), *Exesipollenites tumulus* (Figure 4(m)), *Leptolepidites psarosus* (Figure 4(n)), *Rubinella major* (Figure 4(o)), *Murospora florida* (Figure 4(p)), *Lycopodiacidites austroclavatidites* (Figure 4(q)), and *Obtusisporites canadensis* (Figure 4(r)), among other taxa. We therefore interpret this entire stratigraphic interval to be Kimmeridgian in age.

Kowallis and others (1991) noted a minimum $^{40}Ar/^{39}Ar$ age of 145.2± 1.2 Ma for the Morrison Formation, derived from tephra phenocrysts in the upper part of the Brushy Basin Member (i.e., above the clay change) at Montezuma Creek. Kowallis and others (this volume) have refined the age of the upper part of the Brushy Basin Member to range from 147.8± 0.6 Ma to 150.2± 0.5 Ma.

These younger radiometric ages fall within the Tithonian Stage as defined from isotopic dates by Harland and others (1990) and Bralower and others (1990). The relationship between the two names for the latest stage of the Jurassic-- Tithonian and Volgian-- is discussed in Jeletsky (1973), Dörhofer and Norris (1977a, b), Imlay (1980), Fensome (1987), Harland et al. (1990), and Ross et al. (1992). Essentially, Tithonian is a Tethyan term and Volgian is a Boreal term. Because the Morrison basin was situated at relatively low paleolatitudes, we have used Tithonian in this report, but note that it is approximately equivalent to the lower part of the Volgian. Palynomorphs attributable to the Tithonian (~lower Volgian) have been recovered thus far only from localities stratigraphically high in the formation (roughly age-equivalent to the uppermost beds of the Brushy Basin Member) in the northern part of the depositional area (Montana, West Boulder Creek locality; Figs. 1 and 2). These assemblages include *Cicatricosisporites* sp. A of Fensome (1987) (Figure 4(s)), *Nevesisporites vallatus*, and *Araucariacites fissus*, a combination of taxa that suggests a post-Kimmeridgian, pre-Berriasian age of deposition.

We have identified more than 225 morphotypes of fossil pollen and spores from the formation; some of these are still pending identification; some may represent new taxa. A more complete list of palynomorph taxa will be presented elsewhere; Fig. 3 lists a subset of forty-five taxa that have first and/or last appearances (FADs and LADs) within the Stump, Morrison, or Purgatoire Formations. Figure 3 lists this subset by relative FADs, and illustrates the palynological evidence for our current proposed placement of the Oxfordian/Kimmeridgian, Kimmeridgian/Tithonian (~lower Volgian), and Jurassic/Cretaceous boundaries in the Western Interior U.S.

Fossil charophyte and ostracode evidence (partly from the same pollen sample sites noted in this report) appear to corroborate these boundary placements. Schudack and others (this volume) noted five charophyte/ostracode biostratigraphic zones in the formation. They assigned an early Kimmeridgian age (or possibly late Oxfordian) to their lowest assemblage zone (zone 1), and a Kimmeridgian age to the next three higher assemblage zones (zones 2-4). Only their youngest assemblage zone (zone 5) appeared to them to be younger than Kimmeridgian, on the basis of the LADs of the Kimmeridgian charophytes in zones 3 and 4 (above), and the lack of any ostracode specimens assignable to the genus *Cypridea*, a genus commonly found in Berriasian strata in Europe. Accordingly, they suggested that their youngest (highest) zone was definitely pre-Berriasian and probably Tithonian in age. They likewise found no evidence to support an early Cretaceous age for any Morrison strata they examined.

PREVIOUS PALEONTOLOGICAL STUDIES

Part of the objectives of this study included a review of previous paleontological age assessments for the Morrison Formation. Prior to this study, however, there were relatively few published reports on the fossil pollen and spores of the Morrison Formation; they are reviewed here for comparison to our current regional evidence. Gupta and others (1979) suggested a Cretaceous (Aptian) age for the Brushy Basin Member, from a site in southeastern Utah, on the basis of *Cicatricosisporites*, *Appendicisporites*, *Trilobosporites*, *Pilosisporites*, *Impardecispora*, and *Microcachrydites*. We strongly believe that the Cretaceous samples reported by them from the Blanding area almost certainly came from above the upper contact of the Morrison Formation. None of the dozens of pollen samples we have examined (from sites in New Mexico, Utah, Colorado, Wyoming, and Montana) bore specimens of *Appendicisporites* (Fig. 4(t),a taxon that postdates Jurassic rocks), with the single exception of the Lower Cretaceous Purgatoire Formation sample taken ~1-1.5 m above the upper contact of the Morrison near Boise City, Oklahoma (Sample R4788A). The other genera they proposed as evidence of Cretaceous age now are known to have species that range in the Late Jurassic in Canada (Fensome, 1987).

Gottesfeld (in Dodson and others, 1980) suggested a "lower Purbeckian" age for the Morrison, on the basis of multiple pollen taxa he studied from a site (the *Stegosaurus* 99 Quarry near Como Bluff, Wyoming) in the upper part of the Brushy Basin Member. Norris (1969) previously had examined palynomorphs of the type Purbeck Formation (England) and, on the basis of ammonite control, proposed a Tithonian to Berriasian age for the marine Upper Jurassic and nonmarine Purbeck Beds in southern England, noting that all strata above the basal Lower Purbeck Beds were Berriasian (Early Cretaceous) or younger. New microfossil evidence from the *Stegosaurus* 99 quarry (sample R4892 of this study) suggests an older, probable Kimmeridgian age for the following reasons. First, the sample lacks *Cicatricosisporites* species. Second, sample R4892 also includes relatively common *Cadargasporites reticulatus, Callialasporites segmentatus, Inaperturopollenites dubious,* abundant *Exesipollenites tumulus, Cerebropollenites mesozoicus, Leptolepidites psarosus, Araucariacites fissus,* and abundant *A. australis,* which suggest to us a probable Kimmeridgian age or, at the youngest, a possible early Tithonian age.

Tschudy and others recovered, illustrated, and identified fossil palynomorphs from many of the members of the Morrison Formation in a series of Open-File reports published over an eight year period, including assemblages from the Brushy Basin Member (Tschudy et al., 1980), the Westwater Canyon Member (Tschudy et al., 1981), the Salt Wash Member (Tschudy et al., 1988b), and the Recapture Member (Tschudy et al., 1988a). These reports did not include palynological assemblages from the Tidwell or Windy Hill Members. The reports were useful indicators of the diversity and quality of preservation for fossil palynomorphs from the Morrison. As the authors did not offer age determinations for any of these assemblages they will not be addressed further in this report.

Hotton (1986) proposed that the Morrison Formation pre-Kimmeridgian in its entirety, on the basis of *Corollina*, *Callialasporites*, and *Exesipollenites* and the absence of schizeaceous fern spores. She also reported that the assemblages were dominated by *Exesipollenites* and *Corollina*, with the latter suggesting to her a dry climate during deposition of the formation. One of her samples came from the Brushy Basin Member, from approximately 25 m above the vertebrate site at the Fruita Paleontological Resource Area, CO. Another productive Brushy Basin Member sample came from Museum of Northern Arizona locality 199a, from Carrizo Mt., AZ. A third sample referred to her for study was listed only as "Morrison Fm., Goat Mt., Arizona" (C. Hotton, 1994, pers.

comm.). She further noted that her palynomorph assemblages were generally diverse, and indicated a lack of diagnostic biostratigraphic forms.

DeCelles and Burden (1992) discussed two palynological assemblages obtained during their study of eleven sections through the Morrison and Cloverly Formations in south-central Wyoming. The lower of these was collected 15 m above the top of the Sundance Formation (in the lower part of the Morrison) near Alcova Reservoir (sample AE15). They assigned it a middle Oxfordian age on the basis of *Callialasporites crenulatus*, *Podocarpidites rousei*, *P. unicus*, and *P. multesimus*. They correlated it to zone $J3^3$ of Pocock (1970). During this study, we have documented palynomorph species no older than Kimmeridgian in the Tidwell Member in Utah; accordingly, we believe that their sample AE15 may be no older than latest Oxfordian, and perhaps Kimmeridgian in age. Their upper (younger) sample (AR2e) is discussed below.

Recently, several authors have suggested that the upper parts of the Morrison Formation are Cretaceous in age. Lucas (1989) noted that "the Jurassic-Cretaceous boundary in west-central New Mexico is almost certainly within the Morrison". This conclusion apparently was based on early fission-track, K-Ar, and Rb-Sr radiometric ages and magnetostratigraphic evidence of other workers, and not on Lucas's field research. More recently, Lucas (1991, fig. 3; 1993, fig. 5) espoused a minimum age of Valanginian for the top of the Morrison Formation, but provided no evidence or citation to support these correlations. B. Kowallis (1994, pers. comm.) has noted that single crystal laser-fusion $^{40}Ar/^{39}Ar$ ages have proven to be more reliable than the older radiometric dating techniques (e.g., fission-track results from the upper part of the Brushy Basin Member in Kowallis and Heaton, 1987) and that such young dates for the Morrison, although precise, may be unreliable. This seems likely to us, as we have found no pollen evidence and Schudack and others (this volume) have found no charophyte or ostracode evidence during our respective regional studies that might support such a young age interpretation (nearly 10 my younger than the most recent correlations). In contrast, and as noted above, both of these regional studies have found rather more evidence to support a Late Jurassic age assignment for upper Morrison strata.

The most recent report to propose a Cretaceous age for the Morrison Formation (DeCelles and Burden, 1992, section AR) documented palynomorphs recovered from exposures near the Alcova Reservoir in Wyoming. They noted that their assemblage AR2e came from ~20 m above the base of what they considered the Cloverly Formation, and concluded that this assemblage was early Cretaceous in age on the basis of *Cicatricosisporites abacus*, *C. australiensis*, *C. crassistriatus*, *C. purbeckensis*, *Trilobosporites aornatus*, and *Pilosisporites delicatulus*. They correlated it to the Berriasian Kootenay-Blairmore palynoloflora of western Canada (Ricketts and Sweet, 1986) and to the *Pilosisporites delicatulus* subzone of the Husky, Martin Creek, and Maguire Formations of the Canadian Northwest Territories (Fensome, 1987). We concur that DeCelles and Burden's (1992) pollen assemblage AR2e seems to be correlative to the *Pilosisporites delicatulus* subzone of the *Cicatricosisporites purbeckensis* zone of Fensome (1987). However, we consider the stratigraphic placement of sample AR2e to be problematic and worth independent verification for several reasons.

First, none of the other pollen evidence we examined from the upper part of the Morrison Formation (regionally) was consistent with an early Cretaceous age. For example, none of the Morrison samples contained the diversity of *Cicatricosisporites* species present in sample AR2e, nor did any of our Morrison samples contain *Coptospora* (Figure 4(u)), a taxon common in sample AR2e and in early Cretaceous rocks elsewhere in the Western Interior. The youngest samples we examined, the upper Morrison samples at West Boulder Creek, Montana (noted above), appear to be no younger than Tithonian (~lower Volgian). Fossil charophyte, ostracode, and radiometric evidence (this volume) appear to corroborate this (above). In addition, the only *Coptospora* specimens we observed during this study were derived from our lower Cretaceous Purgatoire Formation sample (R4788A), that unconformably overlies the Morrison Formation in western Oklahoma.

Second, the assemblage we recovered from the upper Morrison near Como Bluff (R4892) during this study appears to be approximately equivalent in stratigraphic placement to the black mudstone DeCelles and Burden (1992, p. 296) figured in their stratigraphic section "CB", at approximately 82-83 m. We note that this correlation is approximate, because their section CB was measured on the southern limb of the westward-plunging anticline now exposed ~50 km east of Seminoe Reservoir. Sample R4892 was recovered by two of us (F.P. and C.E.T.) from the same relative stratigraphic position, but from the northern limb of that anticline. Additionally, we would interpret the base of the Cloverly Formation at their section "CB" to be at the base of the thick, cross-bedded sandstone that occurs at and above the "100 m" mark in their diagram (DeCelles and Burden, 1992, fig. 4); accordingly, we believe that the Cloverly-Morrison contact as placed by DeCelles and Burden (1992) may more likely represent the contact between the lower and upper parts of the Morrison (i.e., the clay change). Such a correlation appears to be supported by the Kimmeridgian age indicated by the pollen assemblage in sample R4892 (the *Stegosaurus* 99 quarry near Como Bluff). The alternative, that the palynologically diverse sample R4892 was derived from Lower Cretaceous strata of the Cloverly Formation yet contains no palynomorphs indicative of a Cretaceous age, but does contain multiple Jurassic pollen taxa, seems to us less likely. We believe that projection of their pollen sample AR2e onto section "CB" would place it at approximately the same stratigraphic position as our sample R4892, yet these two assemblages are markedly dissimilar in composition and apparent age. Because sample AR2e has important consequences bearing on the geologic age of Como Bluff dinosaur faunas, we currently are reexamining the Alcova Reservoir section for age-diagnostic palynomorph assemblages. However, as yet we have found no evidence indicative of a Cretaceous age for the upper part of the Morrison, at Alcova Reservoir or elsewhere.

Tschudy and others (1984) provided the only other published analyses of which we are aware on palynomorph assemblages from rocks that directly overlie the Morrison Formation. They reported on multiple assemblages from the Cedar Mountain and Burro Canyon Formations. The stratigraphically lowest assemblages they studied, from ~38 m above the Morrison Formation-Burro Canyon contact near Slick Rock, Colorado, contained palynomorph assemblages they interpreted as probably Aptian to early Albian but perhaps as old as Barremian. They assigned the palynomorph assemblages they recovered from upper parts of the Cedar Mountain Formation to the late Albian. As such, both of these ages are substantially younger than that reported for the Cloverly Formation sample AR2e by DeCelles and Burden (1992), although the Cedar Mountain and Burro Canyon Formation assemblages are nearly identical in age to palynological assemblages we recovered from the Glencairn Member of the Purgatoire Formation, that directly overlies the Morrison Formation in western Oklahoma (sample R4788A).

The Purgatoire Formation sample we examined was recovered from a shale-filled channel that had been incised into the upper part of the Morrison Formation, at a site near Boise City, Oklahoma (Figure 1). Recently, Cobban (1987), Kietzke (1987), and Kues and Lucas (1987) independently proposed an Albian age for the Glencairn Member in this geographic area, on the basis of ammonoids, foraminifera, and mollusks and ammonoids, respectively. We concur with these assessments as a probable maximum age for the unit; the sample we examined contained *Clavifera triplex* (Figure 4(t)), *Coptospora* sp. (Figure 4(u)), *Amosopollis cruciformis*, and *Phimopollenites* cf. *P. pannosus*. These taxa have their FADs in the *Hoegisporis* Superzone of Helby et al (1987), and most probably indicate correlation to their *Phimopollenites pannosus* or *Appendicisporites distocarinatus* zones, of middle to late Albian age. This sample also has abundant dinoflagellates in it, many taxa of which appear to be reworked from older strata (e.g., *Cassiculosphaeridia magna*). Analysis of the palynological component of this sample (R4788A) is still in progress.

In summary, we believe that many of the previously published palynological ages for the Morrison Formation were relatively accurate. The assessments of Gottesfeld (in Dodson et al., 1980), Hotton (1986), and DeCelles and Burden (1992, sample AE15) seem to be the closest of these, but for the most part previous age estimates appear to be slightly too young (e.g., Dodson and others, 1980), or slightly too old (Hotton, 1986; DeCelles and Burden, 1992). The temporal interval for Morrison Formation deposition suggested by Imlay (1980), that he had interpolated on the basis of ammonite occurrences from strata above and below the formation, seems to us to be the most accurate previous age assessment, given our present state of knowledge (including the new pollen, charophyte, ostracode, and radiometric evidence of this volume). However, it is important that each of these previous palynological studies be viewed in context, with an understanding of the difficulties inherent in Morrison biostratigraphy. Their studies likely were complicated by low pollen recovery, low relative frequency of many biostratigraphic marker taxa, and in some areas, highly tenuous stratigraphic control. Accordingly, we commend these previous researchers' accomplishments.

CORRELATION TO TIME-EQUIVALENT ASSEMBLAGES

Morrison Formation palynomorph assemblages contain many useful cosmopolitan taxa that make it possible to correlate to the palynological zones of geographically distant (but time-equivalent) strata. Several preliminary correlations are suggested here. The Morrison palynomorph assemblages appear to correlate well with the Kimmeridgian to Tithonian *Retitriletes watherooensis* and *Aequitriradites acusus* Zones of Western Australia (Backhouse, 1988) on the presence of *Microcachrydites antarcticus, Concavissimisporites variverrucatus*, and *Aequitriradites acusus*. Elements of the Oxfordian to Kimmeridgian *Murospora florida* Microflora of Western Australia (Filatoff, 1975) are represented in both the Redwater Member and Morrison Formation palynological assemblages by *Murospora florida, Callialasporites turbatus, Callialasporites dampieri*, and *Cadargasporites reticulatus*.

In England, the biostratigraphic zones most similar in composition to the Morrison assemblages were those recovered from the Oxford Clay and the Kimmeridge Clay (Couper, 1958), the *Parvisaccites radiatus* zone of the Portland Stone Formation, and perhaps(?) the lower portion of the *Apiculatisporis verbitskayae* zone of the base of the Purbeck Formation (Hunt, 1985), and "Suite A" from the "Upper Kimmeridgian and Portlandian of the Dorset Coast and the Portland Sand of Sussex, ...(and the basal Purbeck at) Durlston Bay" (Norris, 1969).

In western Canada, the biostratigraphic zones most similar to the Morrison assemblages include the *Concavissimisporites montuosus* and *Concavissimisporites abacus* Zones of the Husky Formation (Fensome, 1987) on the basis of *Ischyosporites disjunctus*, *Concavissimisporites montuosus*, *Crassitudisporites problematicus*, *Concavissimisporites irroratus*, and *Cicatricosisporites* sp. A. The Stump Formation and lowest Morrison Formation palynological assemblages also may correlate to Zone J3^3 of Pocock (1970). Assemblages derived from our study also are broadly correlative to the Tendaguru Formation assemblage from Tanzania, as reported by Jarzen (1981), on the basis of *Corollina torosa*, *Cerebropollenites mesozoicus*, *Concavisporites jurienensis*, and *Inaperturopollenites dubious*. The Tendaguru palynomorph assemblage was assigned a provisional "Late Jurassic-Early Cretaceous" age. However, ammonites recovered from the Tendaguru Formation indicate an early Tithonian age (Arkell, 1956, p. 335). Finally, correlation to time-equivalent formations in Asia is still under study, and will be addressed at a later date.

PLANT DIVERSITY AND ABUNDANCE

The third objective of this study was to assess the original plant diversity that may have existed in the area during deposition of the Morrison Formation. Previous pollen studies often have left the impression that the flora of the Morrison formation was relatively depauperate, and that the formation contained only a few good pollen-bearing intervals.

These perceptions are challenged by the results of this study. More than one hundred samples processed and examined during this study produced at least some fossil pollen. In total, more than 225 fossil pollen and spore types were differentiated (some of them probably new species), representing numerous and geographically-widespread, highly diverse plant assemblages. Figure 3 demonstrates a steady increase in plant diversity through the lower and middle parts of the formation, up to the contact between the lower and upper parts of the Brushy Basin Member (i.e., the illite-to-smectite, clay change within the formation, per Bell (1983, 1984, 1986) and Turner and Fishman, 1991). The total observed species diversity of palynomorphs is listed for each sample at the bottom of each column; note that plant (palynomorph) diversity was highest in the lower part of the Brushy Basin Member (82 morphotypes), and lowest in the upper part of the Brushy Basin Member (46 and 49 morphotypes). Fossil plant diversity diminished noticeably in the upper part of the Brushy Basin Member (smectitic interval) that is present in the southerly part of the depositional area, although diversity appeared to stay high through this stratigraphic interval (upper Brushy Basin Member) farther north. In addition, last appearance datums (LADs) increased and first appearance datums (FADs) decreased above the stratigraphic level of the clay change. Steiner and others (1994) noted an apparent shift in the polar wander path within the Morrison Formation that may be coincident with the paleovegetational shift indicated by the fossil pollen record.

Below the clay change we identified more than one hundred morphotypes of fossil lower vascular plant spores (mostly ferns). Lower vascular plant spores (LVPs) comprised 5.1 percent of the terrestrial microfossil assemblage in the Redwater Shale Member of the Stump Formation (based on a representative count of 300 specimens). By comparison, LVPs comprised 21.1 percent of the terrestrial microfossil assemblage (on average) for those Morrison Formation samples below the clay change, and 33.9 percent of the terrestrial microfossil assemblage (on average) above the clay change. After eliminating those samples above the clay change in which the LVPs may be over-represented (i.e., coaly intervals), the LVP component still averaged 21.9 percent. This significant lower vascular plant component suggests that relatively mesic climatic conditions prevailed during much of early and middle Morrison time, across most of the depositional area. This apparently is in contrast to lithologic evidence for dry conditions during deposition of those Morrison strata below the clay change. Such evidence includes small to fairly extensive eolian sandstone deposits that range from southern Arizona and northern New Mexico as far north as central Wyoming and western South Dakota (Peterson, 1988), and evaporite beds (gypsum or anhydrite) in Utah and Colorado (O'Sullivan, 1992) that occur low in the formation.

Total plant diversity (as represented by palynomorph diversity) decreases somewhat above the clay change, although diversity remained moderately high. Plant diversity in the Redwater Shale Member of the Stump Formation comprised 66 taxa, in the lower Morrison (below the clay change) comprised 66.6 taxa (on average), and in the upper Morrison comprised 60.8 taxa (on average), with a net average decrease of approximately 9 percent. The moderate plant diversity (including relatively high diversity in the LVPs), the relative lack of change in the LVP percent contribution to the total microfossil assemblage above the clay change, and the occurrence of delicate vegetative taxa such as *Coniopteris* in deposits of fossil Lake T'oo'dichi' (Ash and Tidwell, this volume) still appear to favor an interpretation of relatively mesic climatic conditions, perhaps intermittently, during deposition of the upper part of the formation. This, too, appears to be in contrast with evidence for an extensive saline-alkaline lake in the eastern part of the Colorado Plateau (Turner and Fishman, 1991).

Reconciling these contrasting lines of evidence pertaining to the Morrison paleoclimate is an intriguing problem that is beyond the scope of this report, although it is under study. Perhaps this contrast in the paleontological and stratigraphic/geochemical evidence may be more apparent than real, as it may reflect a marked increase in seasonality and a redistribution of annual precipitation patterns during the latter part of Morrison deposition.

Nonetheless, the nature of the fossil plant evidence (palynomorph FAD and LAD patterns, diversity patterns, and megafossil occurrences) is consistent with the lithological and geochemical evidence that suggests the early Tithonian saline-alkaline playa lake that developed in the southern portion of the Morrison depositional basin was of limited duration; it developed during approximately the last two million years of the ~7 million year span of Morrison deposition (i.e., relatively late). In light of the palynological evidence of this study, its seems less likely to one of us (RJL) that the conditions that promoted establishment of this saline-alkaline lake were generally representative of depositional conditions during the bulk of Morrison time; hopefully our additional studies will lead to a more complete understanding of these apparently contrasting lines of evidence.

CONCLUSIONS

We draw the following conclusions on the basis of evidence produced during this study: (1) two (three?) geologic stages may be represented in the formation- Oxfordian(?), Kimmeridgian, and Tithonian (~lower Volgian), (2) the Morrison Formation was deposited over a very diverse set of depositional environments over a relatively long interval of geologic time (~ 7 my), (3) the fossil vegetation during Morrison time was both diverse and abundant throughout the Morrison depositional basin, with more than 225 fossil plant types growing during the habitation of large-bodied herbivorous dinosaurs, (4) previous hypotheses suggesting an Early Cretaceous age for the youngest Morrison rocks were not supported (but rather seem are challenged or refuted) by the fossil pollen evidence examined in this study, (5) pollen evidence from the formation does show an apparent shift in response to climate change, whereby the lower part of the formation had a higher floral diversity and relatively more FADs and the upper part of the formation had a lower floral diversity and relatively more LADs, and (6) fossil palynomorphs are well-preserved and geographically and stratigraphically widespread throughout the depositional area of the formation. Fossil evidence preliminarily indicates that the paleovegetational shift seen in the

Brushy Basin Member may coincide with the change in polar wander path that has been proposed to have occurred during deposition of the formation.

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REFERENCES

Arkell, W.J., 1956, Jurassic geology of the world: Hafner Publishing Company, Inc., New York, 806 p.

Ash, S., 1994, First occurrence of Czekanowskia (Gymnospermae, Czekanowskiales) in the United States: Review of Palaeobotany and Palynology, v. 81, p. 129-140.

Backhouse, J., 1988, Late Jurassic and Early Cretaceous palynology of the Perth Basin, Western Australia. Geological Survey of Western Australia, Bulletin, v. 135, p. 1-233.

Bell, T.E., 1983, Deposition and diagenesis of the Brushy Basin and upper Westwater Canyon members of the Morrison Formation in Northwest New Mexico and its relationship to uranium mineralization: Unpublished Ph.D.dissertation, University of California at Berkeley, 107 pp.

Bell, T.E., 1984, Deposition and diagenesis of the Brushy Basin Member of the Upper Jurassic Morrison Formation, San Juan basin, New Mexico: Geological Society of America, Abstracts With Programs, v. 16, no. 4, p. 214.

Bell, T.E., 1986, Deposition and diagenesis of the Brushy Basin Member and upper part of the Westwater Canyon Member of the Morrison Formation, San Juan basin, New Mexico; in, Turner-Peterson, C.E., Santos, E.S., and Fishman, N.S. (eds.), A basin analysis case study; the Morrison Formation, Grants uranium region, New Mexico: American Association of Petroleum Geologists, Studies in Geology No. 22, p. 77-91.

Bralower, T.J, Ludwig, K.R., Obradovich, J.D., and Jones, D.L., 1990, Berriasian (Early Cretaceous) radiometric ages from the Grindstone Creek section, Sacramento Valley, California: Earth and Planetary Sciences Letters, v. 98, no. 1, p. 62-73.

Chure, D.J., 1992, The flora and non-dinosaurian fauna of the Morrison Formation; How rare is it?: Geological Society of America, Abstracts With Programs, v. 24, no. 6, p. 5.

Chure, D.J., Engelmann, G.F., and Madsen, S.K., 1989, Non-mammalian microvertebrates from the Morrison Formation (Upper Jurassic, Kimmeridgian) of Dinosaur National Monument, Utah-Colorado, USA: Journal of Vertebrate Paleontology, v. 9, Supplement to no. 3, p. 16.

Cobban, W.A., 1987, An ammonoid fauna from the Glencairn Shale Member of the Lower Cretaceous Purgatoire Formation, Baca County, Colorado; in, Lucas, S.G., and Hunt, A.P. (eds.), Northeastern New Mexico: New Mexico Geological Society, 38th Field Conference, p. 217-222.

Couper, R.A., 1958, British Mesozoic microspores and pollen grains: Palaeontographica, Abt. B., v. 103, p. 75-179.

DeCelles, P.G., and Burden, E.T., 1992, Non-marine sedimentation in the overfilled part of the Jurassic-Cretaceous Cordilleran foreland basin: Morrison and Cloverly Formations, central Wyoming, U.S.A.: Basin Research, v. 4, p. 291-313.

Dodson, P., Behrensmeyer, A.K., and Bakker, R.T., 1980, Taphonomy of the Morrison Formation (Kimmeridgian-Portlandian) and Cloverly Formation (Aptian-Albian) of the western United States: Mémoires de la Société Géologique de France, N.S., v. 139: p. 87-93.

Dörhofer, G., and Norris, G.,(1977a, Palynostratigraphische Beiträge zur Korrelierung Jurassich-kretazischer Grenzschichten in Deutschland and England: Neues Jahrbuch, Geologische Paläontologie Abhandlungen, v. 153, p. 50-69.

Dörhofer, G., and Norris, G., 1977b, Discrimination and correlation of highest Jurassic and lowest Cretaceous terrestrial palynofloras in north-west Europe: Palynology, v. 1, p. 79-93.

Engelmann, G.F., 1992, Paleontological Survey of the Jurassic Morrison Formation in Dinosaur National Park: Park Science, v. 12, no. 3, p. 8-9.

Engelmann, G.F., Chure, D.J., and Madsen, S.K., 1989a, A microvertebrate fauna from the Morrison Formation (Upper Jurassic, Kimmeridgian) of Dinosaur National Monument, Utah, USA: Geological Society of America, Abstractgs With Programs, v. 21, no. 6, p. 342.

Engelmann, G.F., Chure, D.J., and Madsen, S.K., 1989b, A mammalian fauna from the Jurassic Morrison Formation of Dinosaur National Monument: Journal of Vertebrate Paleontology, v. 9, Supplement to no. 3, p. 19.

Evans, S.E., and Milner, A.R., 1993, Frogs and salamanders from the Upper Jurassic Morrison Formation (Quarry Nine, Como Bluff) of North America: Journal of Vertebrate Paleontology, v. 13, no. 1, p. 24-30.

Fensome, R.A., 1987, Taxonomy and biostratigraphy of schizaealean spores from the Jurassic-Cretaceous boundary beds of the Aklavik Range, District of Mackenzie: Palaeontologie Canadiana, v. 4, p. 1-49.

Filatoff, J., (1975) Jurassic palynology of the Perth Basin, Western Australia: Palaeontographica, Abt. B, v. 154, p. 1-113.

Gupta, S., Rajeshwar, R., and La Prade, K.E., 1979, Palynological age of the upper part of the Brushy Basin Member of the Morrison Formation near Blanding, southeastern Utah, U.S.A.; in, Sharma, A.K., Mitra, G.C., and Banerjee, M. (eds.), Proceedings of the Symposium on evolutionary botany and biostratigraphy, New Delhi: Today and Tomorrow's Printers & Publishers, v. 10, p. 499-514.

Harland, W.B., Armstrong, R.L., Cox, A.V., Craig, L.E., Smith, A.G., and Smith, D.G., 1990, A Geologic Time Scale 1989: Cambridge University Press, 263 p.

Henrici, A., 1992, Fossil frogs, Dinosaur National Monument. Park Science: v. 12, no. 3, p. 11.

Helby, R., Morgan, R., and Partridge, A.D., 1987, A palynological zonation of the Australian Mesozoic: Memoirs of the Association of Australasian Paleontology, v. 4, 94 p.

Hotton, C.L., 1986, Palynology of the Morrison Formation: Fourth North American Paleontological Convention, Abstracts and Programs, Boulder, Colorado, p. A20.

Hunt, C.O., 1985, Miospores from the Portland Stone Formation and the lower part of the Purbeck Formation (Upper Jurassic/ Lower Cretaceous) from Dorset, England: Pollen and Spores, v. 27, p. 419-451.

Imlay, R.W., 1980, Jurassic paleobiogeography of the conterminous United States in its continental setting: U.S. Geological Survey Professional Paper 1062, 134 p.

Jarzen, D.M., 1981, A preliminary report on the palynomorphs recovered from Tendaguru Hill (Tanzania): Pollen and Spores, v. 23, no. 1, p. 149-163.

Jeletsky, J.A., 1973, Biochronology of the marine boreal latest Jurassic, Berriasian and Valanginian in Canada; in, Casey, R., and Rawson, P.F. (eds.), The Boreal Lower Cretaceous: Geological Journal Special Issue 5, Seel House Press, Liverpool, p. 41-80.

Kietzke, K.K., 1987, The Lower Cretaceous Gulf Coast (Tethyan)–Western Interior transition: Microfossil evidence from northeastern New Mexico and adjacent states; in, Lucas, S.G., and Hunt, A.P. (eds.), Northeastern New Mexico: New Mexico Geological Society, 38th Field Conference, p. 199-205.

Kirkland, J.I., 1987, Upper Jurassic and Cretaceous lungfish toothplates from the Western Interior, the last dipnoan faunas of North America: Hunteria, v. 2, no. 2, p. 1-16.

Kirkland, J.I., Mantzios, C., Rasmussen, T.E., and Callison, G., 1990, Taphonomy and environments; Fruita Paleontological Resource Area, Upper Jurassic, Morrison Formation, western Colorado: Journal of Vertebrate Paleontology, v. 10, Supplement to no. 3, p. 31.

Kirkland, J.I., and Armstrong, H.J., 1992, Taphonomy of the Mygatt-Moore Quarry, middle Brushy Basin Member, Morrison Formation (Upper Jurassic), western Colorado. Journal of Vertebrate Paleontology, v. 12, Supplement to no. 3, p. A37.

Kowallis, B.J., and Heaton, J.S., 1987, Fission-track dating of bentonites and bentonitic mudstones from the Morrison Formation in central Utah: Geology, v. 15, no. 12, p. 1138-1142.

Kowallis, B.J., Christiansen, E.H., and Deino, A.L., 1991, Age of the Brushy Basin Member of the Morrison Formation, Colorado Plateau, western USA: Cretaceous Research, v. 12, no. 5, p. 483-493.

Kowallis, B.J., Christiansen, E.H., Tingey, D.G., Deino, A.L., Peterson, F., and Turner, C.E., 1993, Volcanic ash layers in the Tidwell Member of the Upper Jurassic Morrison Formation; minimum age of the J-5 unconformity on the Colorado Plateau. Geological Society of America, Abstracts With Programs, v. 25, no. 6, p. 472-473.

Kues, B.S., and Lucas, S.G., 1987, Cretaceous stratigraphy and paleontology in the Dry Cimarron Valley, New Mexico, Colorado and Oklahoma; in, Lucas, S.G., and Hunt, A.P. (eds.), Northeastern New Mexico: New Mexico Geological Society, 38th Field Conference, p. 167-198.

Lucas, S.G., 1993, Vertebrate biochronology of the Jurassic-Cretaceous boundary, North American Western Interior: Modern Geology, v. 18, p. 371-390.

Lucas, S.G., 1991, Dinosaurs and Mesozoic biochronology: Modern Geology, v. 16, p. 127-138.

Lucas, S.G., 1989, Jurassic-Cretaceous boundary in west-central New Mexico: in, Anderson, O.J., Lucas, S.G., Love, D.W., and Cather (eds.), Southeastern Colorado Plateau: New Mexico Geological Society, Socorro, p. 6-7.

Medlyn, D.A., and Tidwell, W.D., 1992, An Araucarioxylon species from the Upper Jurassic Morrison Formation: Geological Society of America, Abstracts With Programs, v. 24, no. 6, p. 52.

Norris, G., 1969, Miospores from the Purbeck beds and marine Upper Jurassic of Southern England: Palaeont., v. 12, no. 4, p. 574-620.

O'Sullivan, R. B., 1992, The Jurassic Wanakah and Morrison Formations in the Telluride-Ouray-Western Black Canyon area of southwestern Colorado: U.S.Geological Survey Bulletin 1927, 24 p.

Peterson, F., 1988, Pennsylvanian to Jurassic eolian transportation systems in the western United States: Sedimentary Geology, v. 56, nos. 1-4, p. 207-260.

Pipiringos, G.N., and O'Sullivan, R.B., 1978, Principal unconformities in Triassic and Jurassic rocks, Western Interior United States—A preliminary survey: U.S. Geological Survey Professional Paper 1035-A, 29 p.

Pocock, S.J., 1970, Palynology of the Jurassic sediments of Western Canada: Palaeontographica, Abt. B, v. 130, p. 12-136.

Ricketts, B.D., and Sweet, A.R., 1986, Stratigraphy, sedimentology and palynology of the Kootenay-Blairmore transition in southwestern Alberta and southeastern British Columbia: Geological Survey of Canada Paper 84-15, 41 p.

Ross, C.A., Moore, G.T., and Hayashida, D.N., 1992, Late Jurassic paleoclimate simulation–paleoecological implications for ammonoid provinciality: Palaios, v. 7, no. 5, p. 487-507.

Steiner, M.B., Lucas, S.G., and Shoemaker, E.M., 1994, Correlation and age of the Upper Jurassic Morrison Formation from magnetostratigraphic analyses; in, Caputo, M.V., Peterson, J.A., and Franczyk, K.J. (eds.), Mesozoic systems of the Rocky Mountain Region, USA: Rocky Mountain Section SEPM (Society for Sedimentary Geology), p. 315-330.

Tidwell, W.D., 1990a, a new osmundaceous species (Osmundacaulis lemonii n. sp.) from the Upper Jurassic Morrison Formation, Utah: Hunteria, v. 2, no. 7, p. 3-11.

Tidwell, W.D., 1990b, Preliminary report on the megafossil flora of the Upper Jurassic Morrison Formation: Hunteria, v. 2, no. 8, p. 1-11.

Tidwell, W.D., and Ash, S.R., 1990, On the Upper Jurassic stem Hermanophyton and its species from Colorado and Utah, USA: Palaeontographica, Abt. B, v. 218, p. 77-92.

Tidwell, W.D., Britt, B.B., and Call, V.B., 1986, The plant macrofossil record of the Morrison Formation: Fourth North American Paleontological Convention, Boulder, Colorado, p. 46.
Tidwell, W.D., and Medlyn, D.A., 1992, Short shoots from the Upper Jurassic Morrison Formation, Utah, Wyoming, and Colorado, USA: Review of Palaeobotany and Palynology, v. 71, p. 219-238.
Tschudy, R.H., Tschudy, B.D., and Craig, L.C., 1984, Palynological evaluation of Cedar Mountain and Burro Canyon Formations, Colorado Plateau: U.S. Geological Survey Professional Paper 1281, 24 p.
Tschudy, R.H., Tschudy, B.D., Van Loenen, S., and Doher, G., 1980, Illustrations of plant microfossils from the Morrison Formation. I. Plant microfossils from the Brushy Basin Member: U.S. Geological Survey Open-File Report 81-35, p. 1-29.
Tschudy, R.H., Tschudy, B.D., and Van Loenen, S., 1981, Illustrations of plant microfossils from the Morrison Formation. II. Plant microfossils from the Westwater Canyon Member: U.S. Geological Survey Open-File Report 81-1154, p. 1-20.
Tschudy, R.H., Tschudy, B.D., and Van Loenen, S.D., 1988a, Illustrations of plant microfossils from the Morrison Formation. III. Plant microfossils from the Recapture Member. U.S. Geological Survey Open-File Report 88-234, p. 1-12.
Tschudy, R.H., Tschudy, B.D., and Van Loenen, S.D., 1988b, Illustrations of plant microfossils from the Morrison Formation. IV. Plant microfossils from the Salt Wash Member. U.S. Geological Survey Open-File Report 88-235, p. 1-40.
Turner, C.E., and Fishman, N.S., 1991, Jurassic Lake T'oo'dichi: A large alkaline, saline lake, Morrison Formation, eastern Colorado Plateau: Geological Society of America Bulletin, v. 103, no. 4, p. 538-558.

TABLE 1. Geographic locations of Stump, Morrison, and Purgatoire Formation measured sections and sample assemblages examined for this report. Localities with asterisks (*) are measured sections currently under study.

1. Dinosaur National Monument, UT and CO. Samples R4693B, R4803D, R4765A-L, R4785K, R4785B, R4761B, R4793F, R4792B, and R4792A. Dinosaur National Monument (Dinosaur Quarry west): NW 1/4 SW 1/4 sec. 26, NE 1/4 SE 1/4 sec. 27, T. 4 S., R 23 E., Uintah Co., Utah, Dinosaur Quarry 7.5' quadrangle.
2. McKinley Co., NM. Samples D4927 and D4930-B. Recapture Member of the Morrison Formation: SE 1/4 SE 1/4 sec. 1, T. 15 N., R. 16 W., McKinley Co., New Mexico, Pinedale 7.5' quadrangle. Westwater Canyon Member of the Morrison Formation: SE 1/4 sec. 5, T. 15 N., R. 16 W., McKinley Co., New Mexico, Church Rock 7.5' quadrangle.
3. Boise City, OK. Sample R4788A. NW 1/4 SW 1/4 sec. 34, T. 5 N., R. 5 E., Cimarron Co., Oklahoma, Flagg Springs 7.5' quadrangle.
4. Montezuma Creek (Montezuma Trading Post), UT. Sample R4319. SW 1/4 sec. 7, T. 40 S., R. 24 E., San Juan Co., Utah, Montezuma Creek 7.5' quadrangle.
5. Lisbon Valley*, UT. SE 1/4 sec.27, T. 29 S., R. 24 E., San Juan Co., Utah, La Sal West 7.5'quadrangle.
6. Broughton Fruit Farm, Grand Junction, CO. Sample R4700C. NW 1/4 SE 1/4 sec. 26, T. 14 S., R. 98 W., NW 1/4 NE 1/4 sec. 19, T. 4 S., R. 3 E., Delta Co., Colorado, Dominguez 7.5'quadrangle.
7. Cañon City* (Cope's Nipple), CO. SE 1/4 SW 1/4 sec. 21, NE 1/4 NW 1/4 sec. 28, T. 17 S., R. 70 W., Fremont Co., Colorado, Cooper Mountain 7.5' quadrangle.
8. Morrison*, CO. SW 1/4 SE 1/4 sec. 35, T. 4 S., R. 70 W., Jefferson Co., Colorado, Morrison 7.5' quadrangle. Golden*, CO. NW 1/4 SW 1/4 sec. 14, T. 4 S., R. 70 W., Jefferson Co., Colorado, Morrison 7.5' quadrangle.
9. Como Bluff (Ninemile Hill), WY. Sample R4892. SE 1/4 NW 1/4 sec. 23, T. 23 N., R. 78 W., Carbon Co., Wyoming, Medicine Bow 7.5' quadrangle.
10. Alcova Reservoir*, WY. NW 1/4 NW 1/4 sec. 1, T. 29 N., R. 83 W., Natrona Co., Wyoming, Alcova 7.5' quadrangle.
11. Piedmont South* (SD). NE 1/4 NE 1/4 sec. 25, T. 3 N., R. 6 E., SW 1/4 NW 1/4 sec 30, T. 3 N., R. 7 E., Meade Co., South Dakota, Blackhawk 7.5' quadrangle.
12. Poison Creek*, WY. NW 1/4 SW 1/4 sec. 36, T. 47 N., R. 83 W., Johnson Co., Wyoming, Robinson Canyon 7.5' quadrangle. Poison Creek North, WY. Sample R4888. NW 1/4 NW 1/4 sec. 36, T. 47 N., R. 83 W., Johnson Co., Wyoming, Robinson Canyon 7.5' quadrangle.
13. Strickland Creek, MT. Samples R4684A and R4684B. NW 1/4 NW 1/4 sec. 29, T. 3 S., R. 9 E., Park Co., Montana, Chimney Rock 7.5' quadrangle.
14. West Boulder Creek, MT. Samples R4690A, R4690C, and R4690E. NE 1/4 SW 1/4 sec. 26, T. 3 S., R. 11 E., Park Co., Montana, Mount Rae 7.5' quadrangle.

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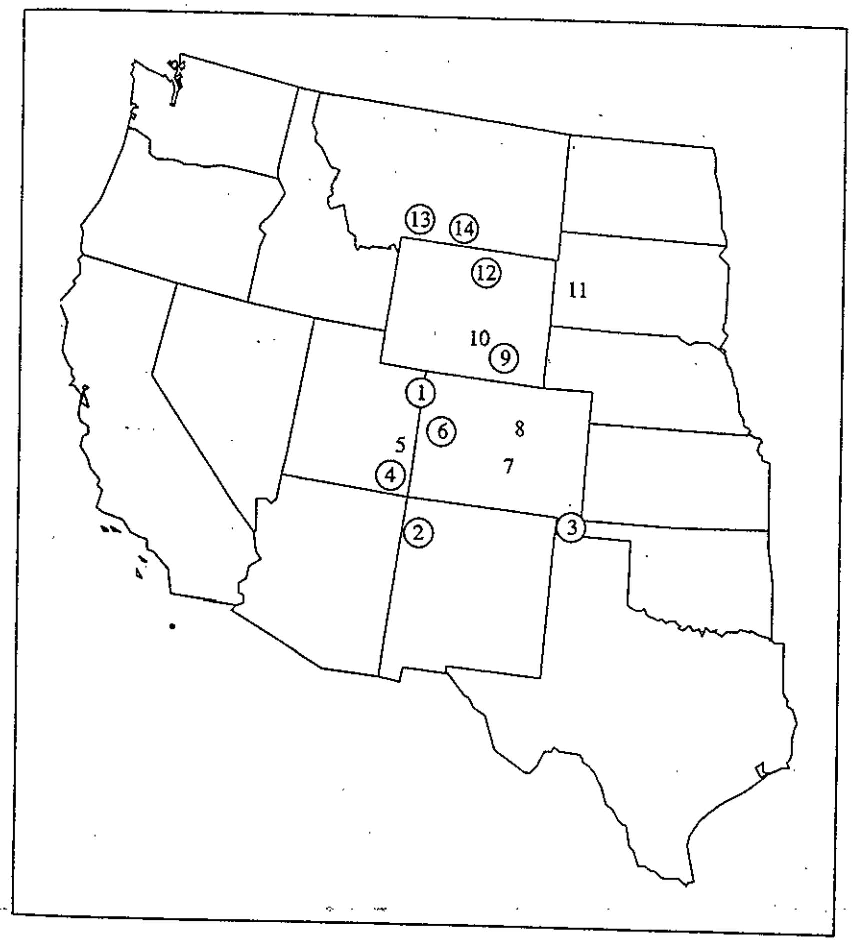

FIGURE 1 Geographic localities of Stump, Morrison, and Purgatoire Formation samples examined for this report. Circled localities are productive sites noted in the text. Uncircled sites are stratigraphic sections currently under study. (1) Dinosaur National Monument (UT, CO). Samples R4693B, R4803D, R4765A-L, R4785K, R4785B, R4761B, R4793F, R4792B, and R4792A. (2) McKinley Co. (NM). Samples D4927 and D4930-B. (3) Boise City (OK). Sample R4788A. (4) Montezuma Creek (UT). Sample R4319. (5) Lisbon Valley (UT). (6) Broughton Fruit Farm, Grand Junction (CO). Sample R4700C. (7) Cañon City (CO). (8) Morrison, Golden (CO). (9) Como Bluff (WY). Sample R4892. (10) Alcova Reservoir (WY). (11) Piedmont South (SD). (12) Poison Creek, Poison Creek North (WY). Sample R4888. (13) Strickland Creek (MT). Samples R4684A and R4684B. (14) West Boulder Creek (MT). Samples R4690A, R4690C, and R4690E.

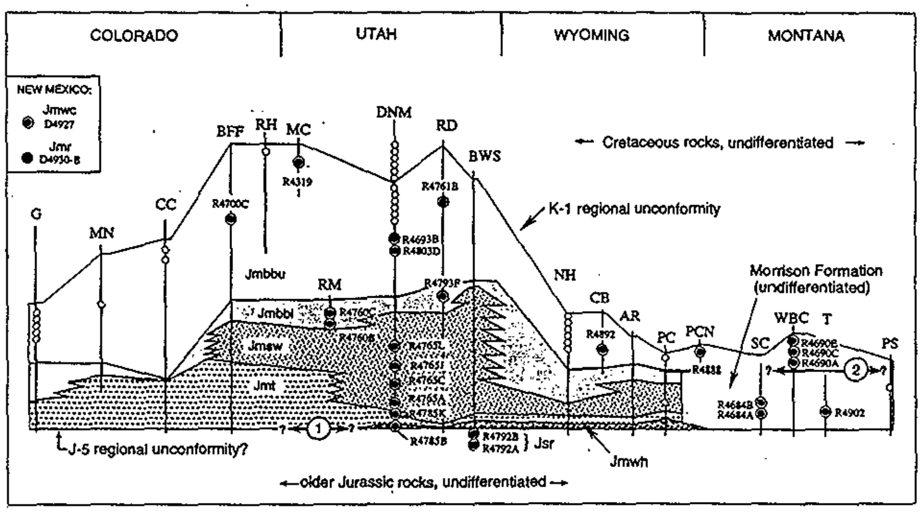

FIGURE 2 Regional composite stratigraphic section of Morrison Formation samples (this study). Numbered circles denote samples discussed in text. White circles denote sections/samples still under study. "1" and "2" denote our preliminary placements of the Oxfordian–Kimmeridgian and Kimmeridgian–Tithonian boundaries, respectively. Measured stratigraphic sections are coded as follows: G = Golden (CO), MN = Morrison, north (CO), CC = Cañon City (CO), BFF = Broughton Fruit Farm, RH = Riggs Hill, Grand Junction (CO), MC = Montezuma Creek (UT), RM = Rattlesnake Mine (UT), DNM = Dinosaur National Monument, Quarry West section (UT), RD = Rainbow Draw (UT), BWS = Bill White Spring (UT), NH = Ninemile Hill (WY), CB = Como Bluff (WY), AR = Alcova Reservoir (WY), PC = Poison Creek (WY), PCN = Poison Creek North (WY), SC = Strickland Creek (MT), WBC = West Boulder Creek (MT), T = Tolson (MT), PS = Piedmont South (SD). Stratigraphic code is denoted as follows: Jsr = Redwater Member of the Stump Formation, Jmwh = Windy Hill Member of the Morrison Formation, Jmt = Tidwell Member of the Morrison Formation, Jmsw = Salt Wash Member of the Morrison Formation, Jmbbl = Brushy Basin Member of the Morrison Formation (lower part), Jmbbu = Brushy Basin Member of the Morrison Formation (upper part). J-5 and K-1 refer to regional unconformities of Pipiringos and O'Sullivan (1978). Base fence diagram from F. Peterson (1994, personal communication).

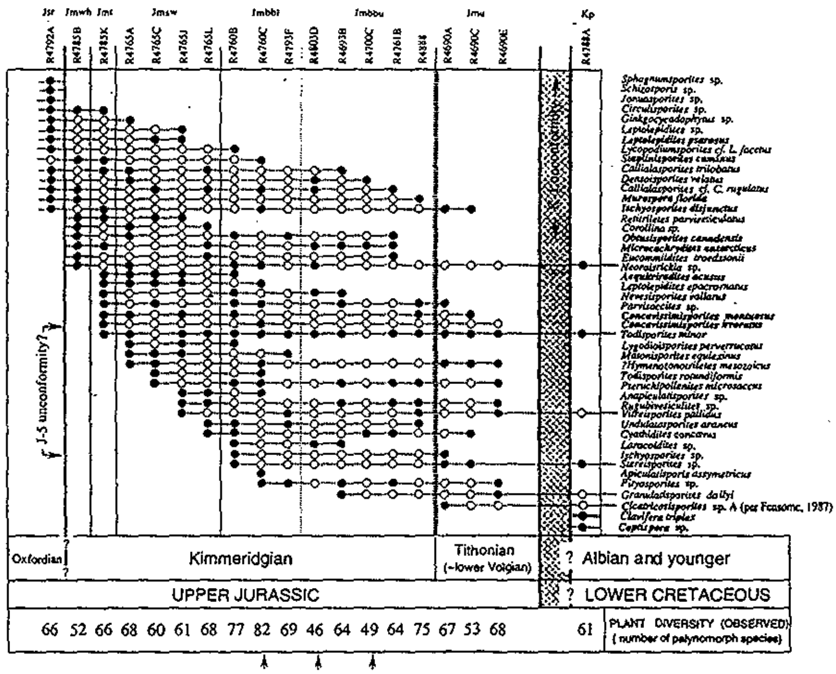

FIGURE 3 Preliminary stratigraphic distribution of selected palynomorph taxa in samples of the Stump, Morrison, and Purgatoire Formations (this study). Stratigraphic code and sample numbers as in Fig. 2. Bottom of figure lists the observed taxon diversity for each sample (column). Taxa illustrated in Fig. 4 are listed in bold (right hand column). White circles denote geologic range-through of taxon, stratigraphically between confirmed occurrences.

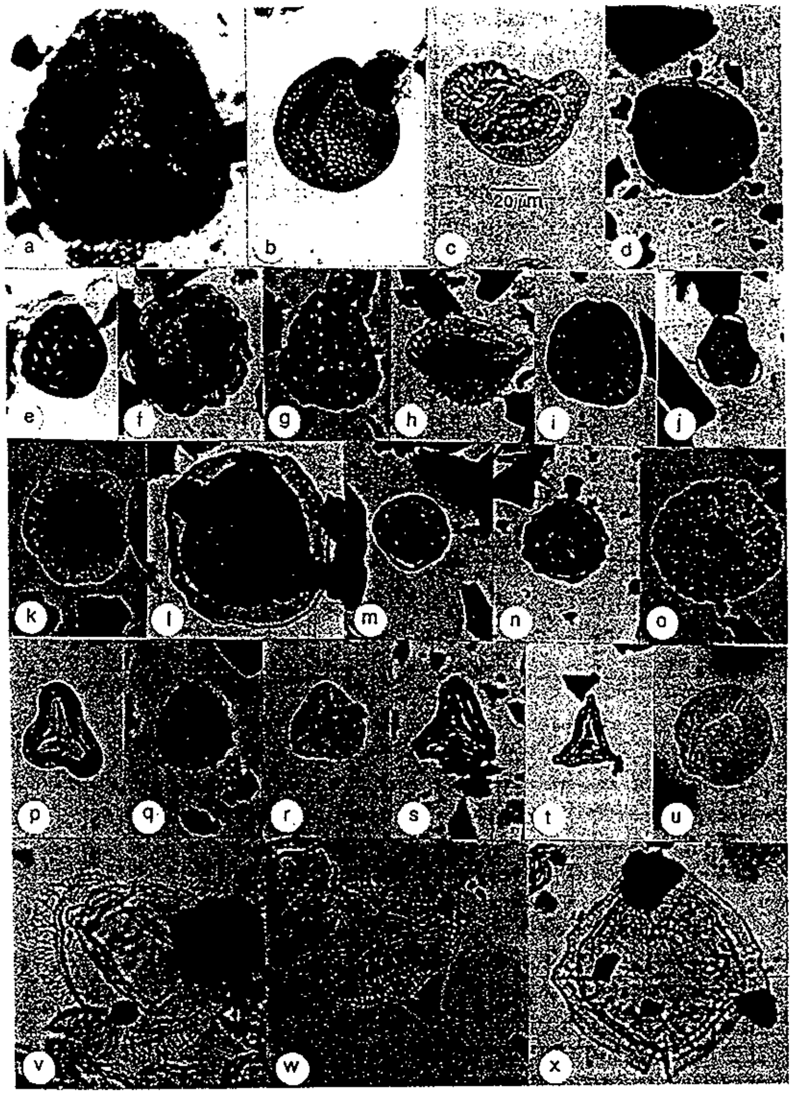

FIGURE 4 Selected palynomorph taxa recovered from the Redwater Member of the Stump Formation, Morrison Formation, and Purgatoire Formation (this study). Specimens illustrated at 500 × (scale bar equals 20 µm). (a) *Concavissimisporites montuosus.* (b) *Cadargasporites reticulatus.* (c) *Microcachrydites antarcticus.* (d) *Concavissimisporites irroratus.* (e) *Crassitudisporites problematicus.* (f) *Cerebropollenites macroverrucosus.* (g) *Ischyosporites disjunctus.* (h) *Aequitriradites acusus.* (i) *Staplinisporites caminus.* (j) *Concavissimisporites jurienensis.* (k) *Callialasporites segmentatus.* (l) *Callialasporites turbatus.* (m) *Exesipollenites tumulus.* (n) *Leptolepidites psarosus.* (o) *Rubinella major.* (p) *Murospora florida.* (q) *Lycopodiacidites austroclavatidites.* (r) *Obtusisporites canadensis.* (s) *Cicatricosisporites* sp. A per Fensome (1987). (t) *Appendicisporites* sp. (u) *Coptospora* sp. (v) *Wanea clathrata.* (w) *Wanea spectabilis.* (x) *Scriniodinium crystallinum.*

THE PALEOECOLOGICAL FRAMEWORK OF THE UPPER PART OF THE BRUSHY BASIN MEMBER OF THE MORRISON FORMATION (UPPER JURASSIC), FRUITA PALEONTOLOGICAL RESOURCE AREA, COLORADO; FINAL REPORT

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INTRODUCTION

The following work was done in support of a Master's thesis describing the geology of the upper part of the Brushy Basin Member of the Morrison Formation at the Fruita Paleontological Resource Area (FPA), Colorado. Data presented in this report are restricted to those used to reconstruct the ecosystem that was active during late Morrison time in the region that is now the FPA.

The Fruita Paleontological Resource Area is approximately 5 kilometers south-southwest of Fruita, Colorado (Fig. 1). It is bounded on the south by Colorado National Monument, and by the Colorado River to the north. Fruita, Colorado, is approximately 15 km (10 mi) west of Grand Junction, Colorado on Interstate Highway 70. The FPA encompasses approximately 7 square km (2.7 sq mi), and is managed by the Bureau of Land Management. The study area includes all of the outcropping area of the upper part of the Brushy Basin Member of the Morrison Formation within the FPA.

STRATIGRAPHY

The Morrison Formation in the vicinity of the Fruita Paleontological Area (FPA) is approximately 182 m (600 ft) thick (Fig. 2). The lower beds of the Morrison consists of the Tidwell and Salt Wash Members. The Tidwell is a slope-forming unit approximately 8.0 m (26 ft) thick. This member is characterized by fine-grained, finely bedded, ripple cross-laminated sandstone beds interbedded with finely bedded mudstone and siltstones

Overlying the Tidwell is the Salt Wash Member, which is approximately 103 m (338 ft) thick. The Salt Wash is characterized by laterally continuous, medium to thick bedded, medium to coarse-grained, cross-bedded sandstone beds interbedded with finely bedded mudstone and siltstone containing scarce, superimposed paleosols. Very thin limestone units occur sporadically within the mudstone and siltstone beds. Locally, the Salt Wash Member is a cliff -forming unit. The base of the Salt Wash is generally picked at the first relatively continuous fluvial sandstone bed. The top of the member is picked at the highest laterally continuous fluvial sandstone (Demko, 1996b), and locally this unit can be fairly conglomeratic (Demko, 1996b; Peterson, 1996). Overlying the Salt Wash Member, the Brushy Basin Member at the FPA is a slope-forming unit approximately 70.5 m (231 ft) thick. The unit is dominated by green-gray, red, orange, and purple siltstone and mudstone beds containing superimposed paleosols. Interbedded with these sedimentary rocks are continuous, thin, fine-grained, massive, tabular sandstone beds and discrete, fine to coarse-grained, medium bedded, cross-bedded sandstone beds. The Brushy Basin Member is overlain unconformably by conglomeratic sandstones at the base of the Lower Cretaceous Burro Canyon Formation (Kirkland, 1996).

Figure 3 is a representative measured section detailing the lithologies in the Brushy Basin Member of the Morrison Formation that is exposed at the FPA. The Brushy Basin Member is generally separated into informally named lower and upper parts, here informally referred to as the lower or upper Brushy Basin Member. At the FPA, the lower Brushy Basin Member is approximately 5.0 m (16.4 ft) in thickness. Sedimentary rocks in the lower part include finely bedded siltstones and mudstones; calcareous paleosols; thin, laterally continuous, fine-grained, massive, tabular sandstones; and thick, medium to very coarse grained, thickly bedded, cross-bedded sandstones displaying lateral accretion bedding.

The upper Brushy Basin Member is approximately 65.5 m (215 ft) thick in the study area. Interbedded finely bedded siltstones and mudstones containing superimposed paleosols, and thin, tabular, continuous, massive, fine-grained sandstones dominate the section. Additionally, lacustrine mudstone intervals and individual channel-fill sandstones occupy various positions in the section (Fig. 3). Figure 4 is a geologic map of the upper Brushy Basin Member; the spatial relationships of the channel fill and lacustrine mudstone units are depicted here. Figure 5 is a fence diagram constructed from measured sections shown in Figure 4. The lateral relationships between the channel fill and lacustrine units are evident.

SEDIMENTOLOGY

The sedimentary rocks of the upper Brushy Basin Member within the Colorado Plateau are recognized as derived from a fluvial-lacustrine system (Bell, 1986; Callison, 1987; Demko, 1996a; Kantor, 1995; Kirkland, 1991; Peterson and Turner-Peterson, 1987; Turner and Fishman, 1991; Turner and Peterson, 1996; Turner-Peterson, 1987). Five distinct floodplain elements representing depositional environments are recognized within the unit:

1. Fluvial Channel-Fill deposits
2. Channel Levee deposits
3. Crevasse Splay deposits
4. Floodplain Paleosols
5. Lacustrine Deposits

Fluvial Channel-Fill Deposits

Twelve distinct fluvial channels were identified. The channel fills are composed of fine to coarse-grained, poorly to moderately well-sorted, quartz rich, silica and/or calcite cemented sandstone beds. Sedimentary structures within the sandstones include trough cross-bedding, tabular cross-bedding, planar bedding, and ripple cross-laminations. The cross-bedding structures are on average perpendicular to the channels, indicating that they were formed by the downstream migration of dunes and ripples. The channel sandstones are, on average, 30 to 40 m (100-130 ft) wide by 1 to 2 m 3-6 ft) deep; the width to depth ratio for the sandstone bodies ranges from 15 to 20. The channel fills have abrupt basal contacts and commonly have coarse basal lags containing gravels, floodplain rip-ups, and dinosaur bones. The upper contacts are, in general, abrupt but in some places they grade into interbedded siltstones and fine-grained sandstones. Lateral accretion sets are absent and amalgamation of channels is not observed. Laterally, the channel fills pinch out rapidly into floodplain strata. In planform, the channel fills are best described as low sinuosity ribbon sandstones.

Channel Levee Deposits

The channel levee deposits are composed of very fine- to medium-grained, moderately well-sorted sandstone beds interbedded with siltstone and mudstone. They are packages of massive to cross-bedded, rippled, and planar-bedded sandstone interbedded with laminated siltstone and mudstone. These beds dip gently away from their associated channel fill deposits and get progressively finer grained away from the channels. In some areas, individual sandstone beds in the levee deposits can be traced laterally into associated floodplain crevasse-splay deposits. Channel-levee deposits are adjacent to fluvial channel-fill deposits and typically are aggraded above the channel-fill sandstones. Levees are most prominent at bends in the channel fill deposits. At these bends, levee complexes have aggraded up to 3 m (10 ft) above the channel sandstone. Paleosols were not observed within the levees; perhaps because of poor preservation potential. Vertebrate fossils are common and trace fossils are very common within the levee complexes.

Crevasse Splay Deposits

Crevasse splay complexes are composed of very fine- to fine-grained, massive to ripple cross-laminated, calcareous sandstone beds overlain by siltstone and mudstone. Sedimentary structures are common near fluvial channel fills but are rare distally, indicating a reduction in depositional energy with increasing distance from the associated fluvial channel. The sandstone beds range in thickness from several centimeters to a meter (from about an inch to 3 ft), but thicknesses on the order of 20 cm (8 in) are the most common. The measured lateral extent of some splay deposits is as much as 800 m (2625 ft) from the associated channel. The splay sandstone beds commonly show burrow structures and other trace fossils. The sandstones have very abrupt basal and upper contacts, and are overlain by thick siltstone and mudstone accumulations. The siltstones and mudstones are finely laminated and highly smectitic. Paleosols are commonly superimposed on these rocks. Vertebrate fossils are especially common in these units and the majority of the major vertebrate quarries at the FPA are within crevasse splay complexes.

Floodplain Paleosols

The paleosols range from very poorly developed to moderately developed. They are recognized by the destruction of the finely laminated bedding that is characteristic of the siltstone/mudstone parent lithology and by mottling, horizonation, root traces, rhizoconcretions, and pedogenic carbonate nodules. Rhizoconcretions are precipitated in the soil due to respiration of the plant root and form in the rhizosphere of a root, preserving the root structure in the paleosol (Mora et al., 1993). There is, on average, an increase in development of the paleosols with increasing distance from contemporaneous fluvial channel fills and lacustrine intervals. Paleosols show some of the best development lateral to large floodplain lakes, some of which show the development of argillic horizons. Argillic horizons are recognized by deeply reddened, clay rich horizons. When thick, the paleosols often show a stacked or cumulate texture. This texture is represented by repeating intervals of thin rooted horizons (paleosol), siltstone and mudstone beds, and rare thin, calcareous sandstones. Vertebrate fossils in the paleosols are rare and poorly preserved when found.

Classification of the paleosols can be accomplished in two ways: The U.S. Department of Agriculture Soil Taxonomy classification system or the proposed classification of paleosols by Mack and James (1992). Using USDA Soil Taxonomy, most of the paleosols would best fit into the entisol soil order. The close proximity of the paleosols to fluvial systems would suggest classification to the Fluvent suborder. Paleosols exhibiting more development, such as those with potential argillic horizons, may fit into the inceptisol or aridisol soil orders. Alternatively, these paleosols would classify as protosols and calcic protosols using the paleosol classification proposed by Mack and James (1992).

Lacustrine Deposits

Five lacustrine intervals were identified at the FPA. These intervals have been associated with stratigraphically equivalent channel fill sandstone beds. The lacustrine deposits are characterized by very thinly laminated smectitic mudstone beds containing sparse, very fine-grained calcareous sandstone beds. These intervals range in thickness from 1.5 to 10 m (5-33 ft). Where channel levee deposits are present, the lacustrine strata often appear to be interfingered with them, but some of the thicker intervals occur well above and over the channel levees. Some of the thinner deposits appear to have accumulated in low areas of the floodplain and abutted against the channel levee deposits.

Lacustrine intervals can be separated into well-developed and poorly-developed deposits. Well-developed lake deposits exist exclusively above channel fill deposits, contained in part by channel levees, and include abundant plant debris, carbonaceous material, conchostracans, and fish fossils. These intervals range in thickness from 2 to 10 m (7-33 ft). Adjacent to some of these intervals are fairly thick, laterally continuous, moderately-developed paleosol horizons. Vertebrate material is common and occurs as broken and disarticulated bone fragments.

The poorly-developed lacustrine intervals are very thin lack conchostracans and fish fossils. These beds range from 1 to 2 m (3-7 ft) thick and commonly occur within floodplain deposits adjacent to levee deposits that appear to be acting as dams. The poorly-developed lacustrine strata grade laterally into floodplain deposits. These areas of the floodplain also lack paleosols. Carbonaceous debris is locally abundant, in addition to well preserved, articulated micro-vertebrate fossil remains.

DEPOSITIONAL STYLE

The interpretation of the depositional style of the Upper Brushy Basin Member is as that of an anastomosing fluvial system. This conclusion is based on the sedimentology and fluvial architecture of the system as compared to modern and ancient examples.

Anastomosis has been described in modern and ancient settings by various authors (Eberth and Miall, 1991; Kantor, 1995; Kirschbaum and McCabe, 1992; Miall, 1996; Rust, 1981; Rust and Legun, 1983; Schumm, 1968; Schumm et al., 1996; Smith, 1983; Smith, 1986; Smith and Putnam, 1980; Smith and Smith, 1980; Smith et al., 1989). Smith (1986) defines an anastomosing river system as:

> "Anastomosing rivers consist of low-energy, multiple, interconnected, laterally stable, deep sand bed channels, confined by prominent silty levees"

Table 1 summarizes the important diagnostic characteristics of modern and ancient anastomosing systems as reported in the literature.

Table 2 summarizes the characteristics of the upper Brushy Basin Member fluvial system. Note the great similarities in characteristics between modern and ancient anastomosing systems and fluvial deposits of the upper Brushy Basin fluvial system.

Table 2. Upper Brushy Basin Member Fluvial System Characteristics

Channel W/D	**Sinuosity**	**Lateral Stability**	**% Floodplain**	**Floodplain Elements**
15 - 20	Low	High	85 - 90	FC, CL, CS, FP, FL, P, FM

FC = Fluvial Channels
CL = Channel Levees
FL = Floodplain Lakes
P= Paleosols
CS = Crevasse Splays
FM = Floodplain Muds and Silts
FP = Floodplain Ponds

All of the modern anastomosing systems that have been described, (Rust, 1981; Smith, 1983; Smith, 1986; Smith and Putnam, 1980; Smith and Smith, 1980) mention fine-grained cohesive bank deposits. The cohesive nature of the banks is related to the fine-grained bedload and high suspended load of the rivers. The cohesive banks provide lateral stability and allow aggradation of high, silty levees. Additionally, crevasse splay deposits in the modern examples are deposited during flood events that top the channel levees (Rust, 1981; Smith, 1983; Smith, 1986; Smith and Putnam, 1980; Smith and Smith, 1980). Individual channel positions may have multiple crevasse-splay sequences attributed to them before migration to a new position. Due to the lateral stability, migration is primarily due to avulsion (Smith et al., 1989). Fluvial systems aggrade vertically with periodic flooding until major flood events cause the rivers to avulse and occupy new positions elsewhere on the floodplain (Eberth and Miall, 1991; Miall, 1996; Smith, 1983; Smith, 1986; Smith and Putnam, 1980; Smith and Smith, 1980). Frequent flooding in combination with avulsion creates periodically wet floodplains ringed by levees and containing ponds and lakes.

The model for deposition provided from modern and inferred ancient examples works very well for the upper Brushy Basin Member fluvial system. The system was aggradational with limited lateral migration of channels. Lateral stability was most likely due to cohesive banks and relatively low stream energy. Floodplains and channel banks were fine grained and cohesive due to a high suspended sediment load. High levees aggraded due to frequent flooding events. Migration of channel systems occurred primarily due to avulsion, relocating channels to new positions in low areas of the floodplain.

PEDOGENESIS

As stated previously, soil development in the preserved paleosol horizons ranges from very poor to moderate. Pedogenic processes responsible for the soil development included bioturbation, illuviation of clay and carbonate, and ped formation. The resultant soils exhibit very subtle to moderate horizonation, disruption of primary sedimentary structures, burrow structures, and pedogenic carbonate precipitation. In the most developed paleosol horizons, deeply reddened Bt horizons can be identified. Some of these are thick enough to be classified as Argillic horizons (USDA, 1994). Some horizons contain pedogenic carbonate in addition to clay accumulation, classifying them as Btk horizons.

Insights for Paleoclimate and Paleoecology

The presence of pedogenic carbonate within horizons of accumulation of illuviated clay suggests fluctuating environmental conditions. These soil horizons are referred to as Btk horizons based on the USDA Soil Taxonomy. Wetter conditions would encourage the downward illuviation of clays into subsurface horizons, whereas carbonate precipitation indicates dry conditions with high evaporation. The genesis of a Btk horizon would entail wet conditions followed by a period of drying.

The paleosols at the FPA argue against a wholesale climate change from wetter to drier. Paleosols throughout the entire Brushy Basin Member show similar properties. Several paleosols with Btk horizons were observed, and they exist at different stratigraphic levels from low to high stratigraphic positions within the member. This suggests that the climate, or at least the floodplain, fluctuated from wet to dry conditions periodically throughout deposition of the Brushy Basin Member.

Carbonate horizons also exist within the floodplain deposits. The genesis of these horizons is not clear. They could be shallow ground-water carbonates, calcretes, or palustrine carbonates. The argument can be made that the ledges are precipitated from the evaporation of a wet floodplain. Many of these carbonate horizons show evidence of pedogenesis, indicating periods of subaerial exposure These carbonates exist through the entire member, suggesting periodic wet conditions followed by extended drying.

Additional evidence supporting the hypothesis of floodplains shifting periodically from wet to dry conditions is the texture of the soil profiles. The paleosols show a cumulic or stacked texture characteristic of alluvial paleosols (Retallack, 1990). Pulses of sedimentation on the floodplain either add to existing soils, or are thick enough to shut off pedogenesis in the buried soil and a new soil profile forms on the new sediments. At the FPA, periodic sediment pulses were probably provided by fluvial processes that overtopped channel levees. Carbonate horizons and crevasse-splay sandstone beds are often found within the floodplain deposits. The association of splay sandstone deposits, alluvial paleosols, and carbonate ledges suggest that sedimentation and subsequent wet floodplain conditions were caused by periodic flood events. The carbonate ledges and splay sandstones occur on a somewhat regular vertical spacing of 1 to 1.5 meters through the Brushy Basin Member at the FPA. The repetition and regular spacing of these rocks argues for a regular fluctuation between wet and dry conditions; however, the time scale associated with the fluctuation is not known.

The generally poor paleosol development at the FPA seems to argue for limited riparian vegetation. However, the magnitude of soil development may not be a proxy for degree of vegetation. Soils adjacent to the modern-day Colorado River, near the study area, are poorly developed. However, the riparian vegetation is significant. The lack of stability adjacent to fluvial systems limits the degree of soil development. Frequent flooding and large sediment supply to the floodplain prevents soil development. Also, flooding events may erode any developed soil horizons, limiting their preservation potential. Some moderately developed paleosols are preserved in several locations of the floodplain beds at the FPA, and they are associated with the larger lacustrine deposits. The moderate development in these paleosols argues for fairly long-lived soil systems. These lacustrine riparian zones may have been important habitats and food sources for the large vertebrate assemblage found at the FPA.

STABLE ISOTOPES

Stable isotopic data include values for delta 13-Carbon ($\delta^{13}C$) and delta 18-Oxygen ($\delta^{18}O$). Both are in units of per mil relative to the PDB carbonate standard. The delta value for an isotope is calculated using the following relationship:

$$\delta\ ‰ = [(R_{sample}/R_{PDB}) - 1] \times 1000$$

Where R is the ratio of the heavy to the light isotope (e.g. $^{13}C/^{12}C$) (Cerling, 1991; Hoefs, 1987; Kelly et al., 1991; Mora et al., 1993).

Five morphologies of carbonate deposits were identified:

- Micritic calcite nodules
- Sparry calcite nodules
- Rhizoconcretions
- Micritic calcite horizons
- Sparry calcite horizons

Figure 6 is a $\delta^{13}C$ vs. $\delta^{18}O$ plot showing the carbonate morphologies. The mean isotopic values for the individual carbonate morphologies are summarized in Table 3.

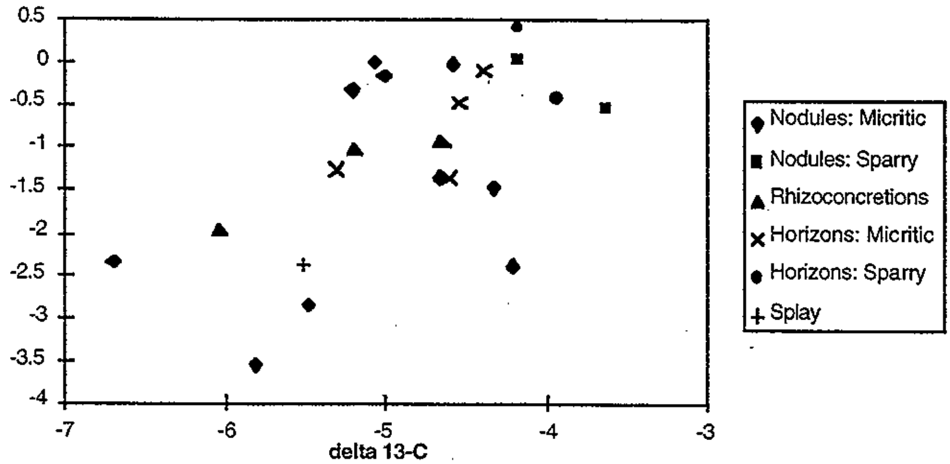

Figure 6. $\delta^{13}C$ vs. $\delta^{18}O$ (‰ PDB): All carbonate morphologies.
(The left side is delta 18-O)

Table 3 Mean isotopic values for carbonate morphologies with standard deviations.

Morphology	$\delta^{13}C$ PDB	$\delta^{18}O$ PDB[a]	$\delta^{18}O$ SMOW[b]
Nodules: Micritic	-5.106 +/- 0.753	-1.445 +/- 1.296	29.37 +/- 1.336
Nodules: Sparry	-3.904 +/- 0.393	-0.257 +/- 0.397	30.595 +/- 0.41
Ledges: Micritic	-4.715 +/- 0.397	-0.793 +/- 0.607	30.043 +/- 0.625
Ledges: Sparry	-4.065 +/- 0.168	-0.006 +/- 0.573	30.853 +/- 0.591
Rhizoconcretions	-5.293 +/- 0.702	-1.3 +/- 0.575	29.520 +/-0.592

[a] At 25°C

[b] $\delta^{18}O$ SMOW=1.03086 X $\delta^{18}O$ PDB + 30.86 (Hoefs, 1987)

Stratigraphic position is used as a proxy for relative age in order to look for trends in the isotopic values of the carbonates through time. Stratigraphic position, in this case, is relative to the top of the Salt Wash Member (base of the lower part of the Brushy Basin Member). Figures 7 and 8 are $\delta^{13}C$ and $\delta^{18}O$ vs. stratigraphic position for just the micritic nodules and rhizoconcretions. The micritic nodules are only associated with paleosols and may be pedogenic based on their morphology. The rhizoconcretions may also be pedogenic based on their root morphology and association with paleosols. Pedogenic nodules and rhizoconcretions are documented as having isotopic signatures that may be sensitive to climate, environment, and plant cover (Cerling, 1983; Cerling, 1991; Cerling, 1992; Kelly et al., 1991; Mora et al., 1993; Quade et al., 1995). A linear regression was applied to each data set, and correlation coefficients are provided on the plots.

Discussion

The genesis of the individual carbonate morphologies identified at the FPA will influence their isotopic signatures. Carbon and oxygen isotopic signatures in terrestrial carbonates are sensitive to climatic and environmental factors, and if these isotopic signatures are preserved through burial diagenesis, they can be used as a tool in paleoclimatic and paleoenvironmental interpretations (Cerling, 1983; Cerling, 1991; Cerling, 1992; Mora et al., 1993; Quade et al., 1995). Carbon isotope signatures in carbonates have been shown to withstand significant diagenesis whereas oxygen isotope signatures are more sensitive and can be reset during diagenetic alteration (Mora et al., 1993).

Carbon Isotopes

Carbonates precipitated during pedogenic processes are the most useful for paleoenvironmental and paleoecological interpretations. The carbon isotope signature of soil carbonate can reflect the vegetation type, the pCO_2 of the atmosphere, and limited environmental conditions such as water stress (Bocherens et al., 1993; Cerling, 1983; Cerling, 1991; Cerling, 1992; Mack et al., 1991; Mora et al., 1993). The carbonate morphologies from the FPA that were most likely precipitated by pedogenic processes are the micritic nodules and the rhizoconcretions. Micritic nodules are interpreted as pedogenic due to their exclusive association with paleosols and their morphology and texture (Mora et al., 1993). Rhizoconcretions are also associated only with paleosols, and they have a characteristic root morphology. In high respiration soils, the $\delta^{13}C$ value for pedogenic carbonate should reflect the $\delta^{13}C$ value of the associated soil organic carbon (Kelly et al., 1991). The organic carbon is derived from the vegetation. The photosynthetic pathway used by the vegetation controls the carbon isotope signature of the organic carbon and, subsequently, the isotopic signature of the soil carbonate. Plants using the C_4 photosynthetic pathway did not evolved until the Miocene, and the majority of plants during the Jurassic are assumed to have used the C_3 photosynthetic pathway (Cerling, 1992). The isotopic fractionation between soil organic carbon and soil carbonate ranges from 14 to 16 per mil (Cerling, 1992; Kelly et al., 1991; Mora et al., 1993). The degree of fractionation is a function of soil respiration rates and temperature, with isotopically heavier fractionation being attributed to higher temperatures and/or low soil respiration rates (Cerling, 1992). Modern C_3 plants have $\delta^{13}C$ values ranging from –20 to –35 per mil, but are skewed toward the –24 to –28 per mil range (Mora et al., 1993). Table 4 provides the calculated soil organic carbon $\delta^{13}C$ from the micritic nodules and rhizoconcretions using a fractionation of 15 per mil.

The values for soil organic carbon in Table 4 are on the isotopically heavy end of the range for C_3 plants, and fall out of the normal range of –24 to –28 per mil. Cerling (1989) reports that low respiration soils, such as those in arid regions, see mixing of atmospheric CO_2 to depths as much as 50 cm, and isotopically heavy atmosphere in the zone of soil carbonate precipitation can produce up to 2 per mil enrichments in the $\delta^{13}C$ of soil carbonate. Also, shallow depth of soil carbonate precipitation allows for isotopic influence from the atmosphere, producing enrichments in the $\delta^{13}C$ of soil carbonates (Mack et al., 1991; Mora et al., 1993). Therefore, the isotopically heavy $\delta^{13}C$ values for soil carbonates at the FPA suggest low respiration soils and/or the shallow precipitation of carbonate. Mack (1991) suggests that low soil respiration rates and/or shallow carbonate precipitation are related to low plant productivity and aridity.

Figure 7. $\delta^{13}C$ (‰ PDB) vs. stratigraphic position for micritic carbonate nodules and rhizoconcretions. Linear regression and correlation coefficient provided.

(The left side is meters above top of Salt Wash Member or base of Brushy Basin Member)

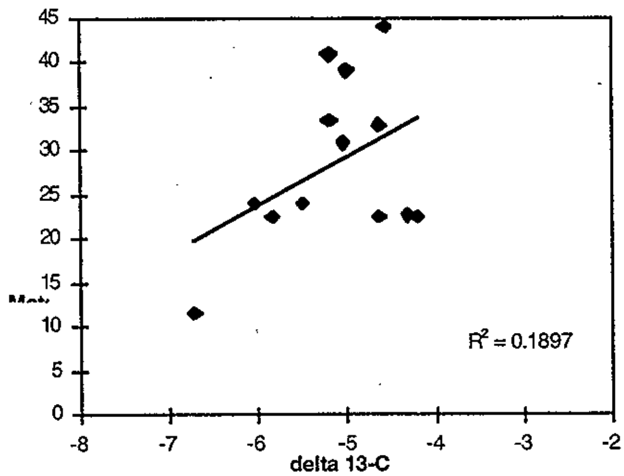

Figure 8. $\delta^{18}O$ (‰ PDB) vs. stratigraphic position for micritic carbonate nodules and rhizoconcretions. Linear regression and correlation coefficient provided.

(The left side is meters above top of Salt Wash Member or base of Brushy Basin Member)

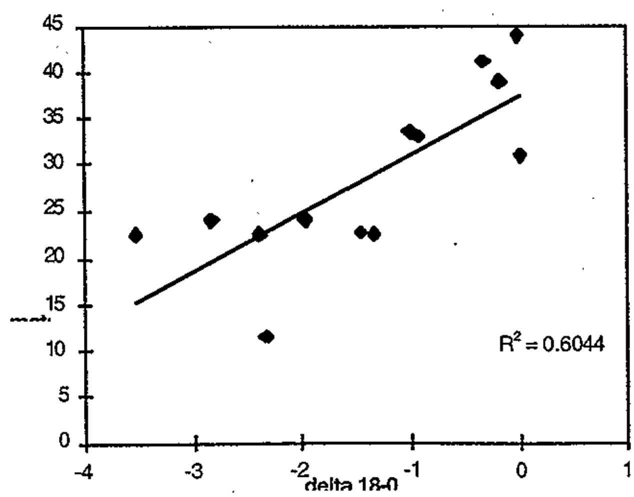

Table 4. Calculated Mean Soil Organic Carbon $\delta^{13}C$ for Micritic Nodules and Rhizoconcretions.

	$\delta^{13}C$ Carbonate	$\delta^{13}C$ Soil Organic Carbon
Micritic Nodules	-5.106	-20.106
Rhizoconcretions	-5.293	-20.293

Bocherens (1993) reports that C_3 $\delta^{13}C$ values greater than –23 per mil are rare and indicative of plants under environmental stresses. These stresses include water stress and salt stress, indicating aridity with high evaporation. Water and salt stresses induce closing of plant stomata which in turn enriches the carbon isotopic signature (Bocherens et al., 1993). The carbon isotopic signatures of soil carbonates suggests that conditions during deposition of the upper Brushy Basin Member at the FPA were arid with high evaporation, at least periodically.

Oxygen Isotopes

In the absence of significant diagenetic alteration, the oxygen isotope signature of carbonates should reflect the meteoric waters from which they precipitated. The isotopic signature of meteoric water is derived from precipitation. The oxygen isotope signature of precipitation is highly variable and is a function of temperature, latitude, elevation, and geographic setting (Cerling, 1983; Cerling and Ekart, 1996; Mora et al., 1993). Also, the amount of precipitation (amount effect) can alter the isotopic signature. Low precipitation tends to produce heavier oxygen isotopic signatures (Hoefs, 1987). The isotopic signature of the carbonates is strongly controlled by the temperature of precipitation. Pedogenic carbonates are generally assumed to precipitate near the atmospheric temperature, whereas lacustrine and groundwater carbonates can be precipitated at temperatures much different than that of the atmosphere. In addition to temperature, evaporation can strongly influence oxygen isotopes. Carbonate precipitation in soils and sediments that experience strong evaporation will result in isotopic signatures that are enriched compared to the meteoric water (Mack et al., 1991; Mora et al., 1993). When interpreting paleoclimatic conditions using oxygen isotopes, it is important to realize that the isotopic signature is a time-averaged value as the carbonates precipitate relatively slowly. Also, in strongly seasonal climates, carbonate may only precipitate during warm periods, which will bias the isotopic signatures toward these climatic conditions (Mora et al., 1993).

The micritic nodules and rhizoconcretions are considered pedogenic, and their oxygen isotope signatures could have paleoclimatic and paleoenvironmental significance. Soil carbonate $\delta^{18}O$ values from the Morrison formation have been reported as ranging from –12 to –6 per mil PDB (Cerling and Ekart, 1996). Cerling et al. (1996) calculates the associated precipitation as ranging from –17 to –9 per mil SMOW for a temperature of 25°C. Precipitation with these isotopic values are found in high latitudes and in continental rain shadows such as the Great Basin of the U.S. Since the Colorado Plateau region was at lower latitudes during Morrison time than today, Cerling et al. (1996) attribute calculated precipitation with these isotopic values to a rain-shadow effect. Soil carbonates from the FPA have $\delta^{18}O$ values that are substantially heavier than the reported data. The precipitation associated to the FPA soil carbonates would be in the range of –2 per mil SMOW, well out of the range of waters associated with continental rain shadows (Cerling and Ekart, 1996). Given the reported isotopic data for the Morrison formation and paleogeographic interpretations for the Colorado Plateau region during Morrison time, it is unlikely that the FPA isotopic data reflect the paleo-precipitation.

The oxygen isotopes from the FPA soil carbonates could be significantly enriched compared to other Morrison paleosol carbonates due to several processes. Diagenesis could have affected these carbonates, resetting or adjusting the oxygen isotopic signature. In the absence of diagenetic alteration, the isotopic signatures suggest soils with low respiration rates, aridity, high evaporation, and shallow depths of carbonate precipitation. Aridity implies limited precipitation. The "amount" effect (Hoefs, 1987) will cause isotopic enrichment under these conditions. Evaporation is also know to cause enrichments in oxygen isotopes of soil carbonates (Mack et al., 1991; Mora et al., 1993). If the paleoecological and paleoclimatic interpretation based on carbon isotopes is valid, then the apparent enrichment of heavy oxygen in the FPA soil carbonates could be due to aridity.

Isotopic Trends Through Time

Isotopic trends were investigated through time with stratigraphic height used as a proxy for time. Figures 7 and 8 compare the carbon and oxygen isotope signatures for soil carbonates with stratigraphic position. Linear regression for the carbon isotopes (r^2 = 0.19) indicates no significant trend with time. The linear regression for the oxygen isotopes ($r^2 = 0.60$) indicates a significant relationship over time. The oxygen isotopes for soil carbonates appear to have become more enriched with time.

The significance of the oxygen isotopic trends is not known. Mack et al. (1991) report a similar increase in terrestrial carbonate $\delta^{18}O$ over time in the Permian Abo Formation. They attribute the enrichment over time to increasing atmospheric temperatures and aridity. The trends in the oxygen isotope data from FPA could also indicate increasing aridity and evaporation over time, providing carbonates that are more and more isotopically enriched. However, petrographic data from the FPA indicates that burial diagenesis was moderate. If the oxygen isotopes have been altered by burial diagenesis, then some diagenetic gradient must have existed over the Brushy Basin Member strata to produce the apparent trend. A diagenetic trend is not seen through petrographic observations. It seems that a linear diagenetic gradient over the relatively thin Brushy Basin sediment was unlikely, but it cannot be ruled out.

CONCLUSIONS

Based on sedimentologic data and observations, the depositional environment of the upper Brushy Basin Member at the FPA was by an anastomosing fluvial system.

Preserved in this system are low sinuosity fluvial channel-fill deposits, channel-levee deposits, crevasse-splay deposits, floodplain lake and pond deposits, and poor to moderately-developed floodplain paleosols.

The paleosols are very poorly to moderately-developed. Pedogenesis is indicated by disruption of bedding, mottling, horizonation, root traces, rhizoconcretions, and pedogenic carbonate nodules. These paleosols could be classified as entisols, inceptisols, and aridisols using the USDA soil taxonomy, or as protosols and calcic protosols using the classification scheme proposed by Mack and James (1992). In some cases, paleosol development appears to increase with distance from lacustrine units and channel-fill sandstone beds. However, in general the preserved paleosols are very poorly developed and gradations across the floodplain are not evident.

The paleoecological framework inferred from the sedimentological evidence was of a complex floodplain composed of microenvironments. The fluvial style, tectonic setting, and climate were key factors. Individual channels of the anastomosing river system would have remained laterally stationary for fairly long periods of time, followed by rapid relocation through avulsion. During stable periods, the surrounding floodplains would develop. High levees developed due to periodic flooding and a high suspended load. High suspended loads in the fluvial systems was likely, due to a high volcanic ash input from volcanism in the arc to the west. Levees may have been heavily vegetated, defining riparian belts along the channels. How far the riparian zones expanded into the floodplain is unknown. Soils developed on these floodplains and the paleosols containing Btk horizons argue for fluctuating wet and dry periods. Additionally, cumulate and stacked paleosols suggest periodic fluvial sediment input from flooding. The vegetation type and density occupying the floodplains is unknown. Rhizoconcretions and drab halo root traces are abundant locally, suggesting fairly dense vegetation, at least periodically. Small ponds occupied low areas of the floodplains and may have frequently evaporated to dryness.

Some abandoned channels developed into longer-lived lacustrine systems that survived several aggradation and avulsion events in the associated fluvial channels.

The alternating wet and dry floodplain conditions inferred from paleosol evidence are highly important in the ecological and climatic interpretations. Wet floodplains could be due to flooding and (or) a high water table. Paleosol carbonate nodules and horizons argue for periods of aridity and high evaporation. The hypothesized playa system of Lake T'oo'dichi' to the west, south, and southeast also argues for periods of aridity. Flooding, therefore, could have occurred seasonally. Flooding and aridity could have also occurred on a longer drought scale. In addition to climatic factors, tectonics may have driven or contributed to the flood frequency. Sedimentological evidence argues for a high ash input into flood deposits on the floodplain. Vertebrate death assemblages in tuffaceous crevasse splay deposits also support this conclusion. Perhaps periods of increased volcanism choked the fluvial systems with ash, thereby inducing flooding. This could easily have been coupled with seasonal or longer-scale climatic fluctuations to create flood events. Carbonates in the soils and sediments could have been due to a fluctuating water table. The high water table could have been due to the same possibilities discussed above. Regional scale fluctuations from the Lake T'oo'dichi' basin could have also been a factor.

Stable isotope data from paleosol carbonates also suggest aridity. Carbon isotopes from pedogenic carbonates are enriched, suggesting water and (or) salt stressed C_3 vegetation. Oxygen isotopes are also enriched, suggesting high evaporation and a shallow depth of carbonate precipitation, characteristic of arid conditions. However, the oxygen isotopes could have been altered during diagenesis. Oxygen isotopes also indicate a trend over time toward more enriched values, suggesting aridity intensified during deposition of the upper Brushy Basin Member.

In summary, the upper Brushy Basin Member at the Fruita Paleontological Resource Area preserves sedimentary rocks from a Late Jurassic anastomosing fluvial system on the flanks of the Lake T'oo'dichi' basin. Floodplains were a complex mosaic of microenvironments existing in a dynamic system. Flooding and stream avulsion, as well as periods of dryness, were commonplace. Volcanism in the arc to the west and southwest provided large volumes of ash to the system. Climatically, the evidence argues for semi-arid to arid conditions.

The large assemblages of vertebrates, large and small, found at the FPA, and the evidence for arid conditions seem to contradict each other. Perhaps large vertebrates migrated to the regions during wet floodplain conditions when vegetation was most abundant. Or perhaps, riparian zones were lush enough to support them year round. Small vertebrates could have survived in the riparian zones, even through periods of aridity.

REFERENCES CITED

Bell, T.E., 1981, A Jurassic closed basin in the Morrison Formation: Geological Society of America, Abstracts with Programs, v. 13, p. 406.

Bell, T.E., 1986, Deposition and diagenesis in the Brushy Basin Member and upper part of the Westwater Canyon Member of the Morrison Formation, San Juan Basin, New Mexico., in, Turner-Peterson, C.E., Santos, E. S. and Fishman, N. S., (eds.), A Basin Analysis Case Study: The Morrison Formation, Grants Uranium District, New Mexico: American Association of Petroleum Geologists Studies in Geology No. 22, p. 77-91.

Bocherens, H., Friis, E.M., Mariotti, A., and Pedersen, K.R., 1993, Carbon isotopic abundances in Mesozoic and Cenozoic fossil plants: Paleoecological implications: Lethaia, v. 26, p. 347-358.

Callison, G., 1987, Fruita: A place for wee fossils; in, Averett, W.R., (ed.), Paleontology and geology of the Dinosaur Triangle: Grand Junction Geological Society and Museum of Western Colorado, p. 91-96.

Cerling, T.E., 1983, The isotopic composition of soil and paleosol carbonate as a paleoclimatic indicator: Geological Society of America, Abstracts with Programs, v. 15, p. 541.

Cerling, T.E., 1991, Carbon dioxide in the atmosphere: Evidence from Cenozoic and Mesozoic paleosols: American Journal of Science, v. 291, p. 377-400.

Cerling, T.E., 1992, Use of carbon isotopes in paleosols as an indicator of the pCO2 of the paleo-atmosphere: Global Biogeochemical Cycles, v. 6, p. 307-314.

Cerling, T.E., and Ekart, D.D., 1996, Annual Report, The Morrison Formation Extinct Ecosystems Project; USGS Administrative Report, p. 15-25.

Demko, T., personal communication, 1995, The extent of Morrison deposition.

Demko, T., 1996a, Annual Report, The Morrison Formation Extinct Ecosystems Project; USGS Administrative Report, p. 26-28.

Demko, T., personal communication, 1996b, The base of the Salt Wash Member of the Morrison Formation.

Eberth, D.A., and Miall, A.D., 1991, Stratigraphy, sedimentology and evolution of a vertebrate-bearing, braided to anastomosed fluvial system, Cutler Formation (Permian-Pennsylvanian), north-central New Mexico: Sedimentary Geology, v. 72, p. 225-252.

Hoefs, J., 1987, Stable Isotope Geochemistry: New York, Springer Verlag, 241 p.

Kantor, D.C., 1995, Stratigraphy and sedimentology of the upper Brushy Basin Member, Morrison Formation (Jurassic), eastern central Utah: Unpublished M.S. thesis, University of Wisconsin, Madison.

Keith, M.L., and Weber, J.N., 1964, Carbon and oxygen isotopic composition of selected limestones and fossils: Geochemica et Cosmochemica Acta, v. 28, p. 1787-1816.

Kelly, E.F., Amundson, R.G., Marino, B.D., and DeNiro, M.J., 1991, Stable carbon isotopic composition of carbonate in Holocene grassland soils: Journal of the Soil Science Society of America, v. 55, p. 1651-1658.

Kirkland, J.I., 1991, The Fruita Paleontological Resource Area, Upper Jurassic Morrison Formation: Environment of Deposition and Paleoecology: Grand Junction Geological Society, May Meeting, Grand Junction, Colorado.

Kirkland, J.I., personal communication, 1996, The upper contact of the Brushy Basin Member at Fruita, Colorado.

Kirschbaum, M.A., and McCabe, P.J., 1992, Controls on the accumulation of coal and on the development of anastomosed fluvial systems in the Cretaceous Dakota Formation of southern Utah: Sedimentology, v. 39, p. 581-598.

Mack, G.H., Cole, D.R., Giordano, T.H., Schaal, W.C., and Barcelos, J.H., 1991, Paleoclimatic controls on stable oxygen and carbon isotopes in caliche of the Abo Formation (Permian), south-central, New Mexico, U.S.A.: Journal of Sedimentary Petrology, v. 61, p. 458-472.

Mack, G.H., and James, W.C., 1992, Paleosols for Sedimentologists, Short Course Manual for the Geological Society of America: Cincinnati, Ohio, 127 p.

Mack, G.H., James, W.C., and Monger, H.C., 1993, Classification of Paleosols: Geological Society of America Bulletin, v. 105, p. 129-136.

Miall, A.D., 1996, The Geology of Fluvial Deposits: Sedimentary Facies, Basin Analysis, and Petroleum Geology; Springer-Verlag, New York, 582 p.

Mora, C.I., Driese, S.G., and Fastovsky, D.E., 1993, Geochemistry and Stable Isotopes of Paleosols: Geological Society of America Continuing Education Short Course, Studies in Geology 23, 66 p..

Peterson, F., 1984, Fluvial sedimentation on a quivering craton; influence of slight crustal movements on fluvial processes, Upper Jurassic Morrison Formation, western Colorado Plateau: Sedimentary Geology, v. 38, p. 21-49.

Peterson, F., personal communication, 1996, Conglomeratic sandstone at the top of the Salt Wash Member of the Morrison Formation.

Peterson, F., and Turner-Peterson, C.E., 1987, The Morrison Formation of the Colorado Plateau: Recent Advances in sedimentology, stratigraphy, and paleotectonics: Hunteria, v. 2, p. 2-18.

Quade, J., Cater, J.M.L., Ojha, T.P., Adam, J., and Harrison, T.M., 1995, Late Miocene environmental change in Nepal and the northern Indian subcontinent; stable isotopic evidence from Paleosols: Geological Society of America Bulletin, v. 107, p. 1381-1397.

Retallack, G.J., 1990, Soils of the Past: An introduction to paleopedology: Unwin Hyman, Boston, 520 p.

Rust, B.R., 1981, Sedimentation in an arid-zone anastomosing fluvial system: Cooper's Creek, central Australia: Journal of Sedimentary Petrology, v. 51, p. 745-755.

Rust, B.R., and Legun, A.S., 1983, Modern anastomosing-fluvial deposits in arid central Australia, and a Carboniferous analogue in New Brunswick, Canada; in, Collinson J.D., Lewin, J., (eds), Modern and ancient fluvial systems: International Association of Sedimentologists Special Publication 6., p. 385-392.

Schumm, S.A., 1968, Speculations concerning paleohydrologic controls of terrestrial sedimentation: Geological Society of America Bulletin, v. 79, p. 1573-1588.
Schumm, S.A., Erskine, W.D., and Tilleard, J.W., 1996, Morphology, hydrology, and evolution of the anastomosing Ovens and King Rivers, Victoria, Australia: Geological Society of America Bulletin, v. 108, p. 1212-1224.
Smith, D.G., 1983, Anastomosed fluvial deposits: modern examples from western Canada; in, Collinson J.D., Lewin, J., (eds), Modern and ancient fluvial systems: International Association of Sedimentary Petrology Special Publication 6., p. 155-168.
Smith, D.G., 1986, Anastomosing river deposits, sedimentation rates and basin subsidence, Magdalena River, northwestern Columbia, South America: Sedimentology Geology, v. 46, p. 177-196.
Smith, D.G., and Putnam, P.E., 1980, Anastomosed river deposits: modern and ancient examples in Alberta, Canada.: Canadian Journal of Earth Science, v. 17, p. 1396-1406.
Smith, D.G., and Smith, N.D., 1980, Sedimentation in anastomosed river systems: Examples from alluvial valleys near Banff, Alberta.: Journal of Sedimentary Petrology, v. 50, p. 157-164.
Smith, N.D., Cross, T.A., Dufficy, J.P., and Clough, S.R., 1989, Anatomy of an avulsion.: Sedimentology, v. 36, p. 1-23.
Stokes, W.L., 1944, Morrison Formation and related deposits in and adjacent to the Colorado Plateau: Geologic Society of America Bulletin, v. 55, p. 951-992.
Tidwell, W.D., 1990, Preliminary report on the megafossil flora of the Upper Jurassic Morrison Formation: Hunteria, v. 2, p. 1-11.
Turner, C.E., personal communication, 1995, The nature of the "clay-change".
Turner, C.E., and Fishman, N.S., 1991, Jurassic Lake T'oo'dichi': A large alkaline, saline lake, Morrison Formation, eastern Colorado Plateau: Geological Society of America Bulletin, v. 103, p. 538-558.
Turner, C.E., and Peterson, F., 1996, Annual Report, The Morrison Formation Extinct Ecosystems Project; USGS Administrative Report, p. 40-54.
Turner, C.E., Santos, E.S., and Fishman, N.S., 1986, A basin analysis case study: The Morrison Formation, Grants Uranium Region, New Mexico, AAPG Studies in Geology No. 22, 391 p.
Turner-Peterson, C.E., Gundersen, L.C., Francis, D.S., and Aubrey, W.M., 1980, Fluvio-lacustrine sequences in the Upper Jurassic Morrison Formation and the relationship of facies to tabular uranium ore deposits in the Poison Canyon area, Grants mineral belt, New Mexico, in, Turner-Peterson, C.E., (ed.), Uranium in sedimentary rocks—Application of the facies concept to exploration: Rocky Mountain Section SEPM, Short Course Notes, p. 177-211.
Turner-Peterson, C.E., 1987, Sedimentology of the Westwater Canyon and Brushy Basin Members, Upper Jurassic Morrison Formation, Colorado Plateau, and relationship to uranium mineralization: Ph.D. dissertation, Univ. of Colorado, Boulder, 168 p.
Tyler, N., 1981, Jurassic depositional history and vanadium-uranium deposits, Slick Rock District, Colorado Plateau [Dissertation]: Fort Collins, CO, United States, Colorado State University.
U. S. Department of Agriculture, 1994, Keys to Soil Taxonomy, 6th ed.: USDA Soil Conservation Service.
Walker, T.R., 1967, Formation of red beds in modern and ancient deserts: Geological Society of America Bulletin, v. 73, p. 237-242.
Walker, T.R., Waugh, B., and Grone, A.J., 1978, Diagenesis in first-cycle desert alluvium of Cenozoic age, southwestern United States and northwestern Mexico: Geological Society of America Bulletin, v. 89, p. 19-32.

APPENDIX

Locality: F (Fruita Paleontological Resource Area, CO)

(Interval: 7, Upper Part of Brushy Basin Member)

1. Data

Low sinuosity channel fill sandstones: 1 to 2 meters thick, width/depth=15 to 20; high channel levees, extensive crevasse-splay deposits (1 to 1.5 meter intervals: thin sandstone/siltstone overlain by mudstones); floodplain lacustrine deposits; poor to moderately developed alluvial paleosols; off channel area ≥90%.

Interpretation

Anastomosing fluvial system. Vertical aggradation followed by channel relocation by avulsion. Lateral accretion absent. Crevasse splay deposits indicate that flooding was frequent and important. Channels contained by high fine-grained levees, and stream system lacks the stream power to erode its banks. Dynamic floodplain with multiple microenvironments: channel riparian zones, lacustrine riparian zones, periodically wet and dry floodplains.

2. Data

Very poor to moderately developed paleosols: Bt and Btk horizons, root traces, rhizoconcretions, pedogenic carbonate nodules, mottling. Some soil horizons thicken and increase in development with increased distance from a floodplain element (stream, lake).

Interpretation

Entisols, inceptisols, and aridisols (USDA Soil Taxonomy), or protosols and calcic protosols (Mack and James, 1992). Bt horizons indicate illuviated clay and wet floodplain conditions. Btk horizons indicate a superimposed dry period marked by the precipitation of pedogenic carbonate. Floodplain appears to experience wet conditions followed by extended dry periods. Thickening soil horizons with distance from some floodplain elements suggests stable conditions in some parts of the floodplain for extended periods.

3. Data

Highly smectitic floodplain sediments. XRD indicates smectite actually R0 illite(0.5)/montmorillonite. Several splay siltstones show well preserved volcanic shard texture.

Interpretation

High felsic volcanic ash source to fluvial system. Slight transformation to I/S suggests minimal temperatures during burial diagenesis.

4. Data

Cumulate and stacked paleosol textures.

Interpretation

Floodplain aggradation due to fluvial processes indicating alluvial paleosols.
Stacked texture: sedimentation rate > soil development rate.
Cumulate: Soil development rate > sedimentation rate.

5. Data

Sandstones classify as lithic arenites, sublithic arenites, and subarkosic arenites. Rock fragments dominated by felsic to intermediate volcanic rocks.

Interpretation

Provenance: Felsic to intermediate volcanic source. Likely from the volcanic arc to the west and southwest.

6. Data

Paleoflow direction to east and northeast.

Interpretation

Sedimentary source to west and southwest. Consistent with provenance from sandstone petrology.

7. Data

Delta ^{13}C for pedogenic carbonate nodules and rhizoconcretions average –5.1 and –5.3 per mil PDB respectively.

Interpretation

These values are enriched compared to pedogenic carbonates precipitated in soils dominated by C_3 vegetation. This suggests high evaporation, shallow carbonate precipitation, and low respiration soils. Carbon isotopes argue for arid to semi-arid conditions (at least during periods of carbonate precipitation).

8. Data

Delta ^{18}O values for pedogenic carbonate averages –1.4 per mil PDB. Also, there is a statistically significant trend toward more enriched values progressively higher in the member.

Interpretation

Oxygen isotopes suggest high evaporation, shallow carbonate precipitation, and low respiration soils that point to arid and semi-arid conditions during carbonate precipitation. The trend toward more enriched values over stratigraphic position suggests and increase in aridity during carbonate precipitation over time.

9. Data

Calcite and barite are major pre-compactional diagenetic cements in the fluvial and crevasse-splay sandstones.

Interpretation

These cements indicate alkaline diagenetic pore waters. The alkaline conditions could be due to evaporative concentration of surface waters or possible alkaline ground-water influences from the Lake T'oo'dichi' basin.

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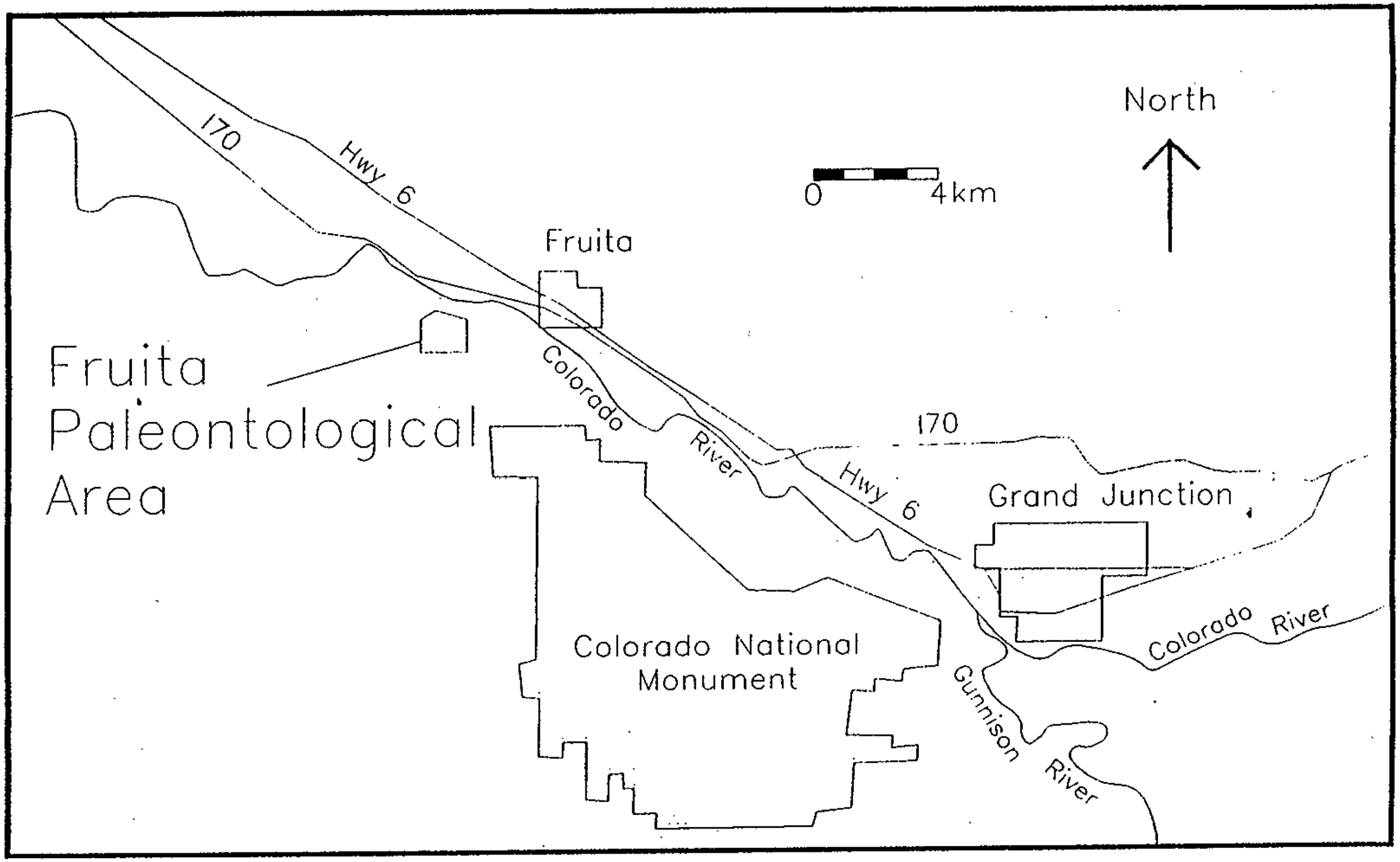

Figure 1. Location Map. Fruita Paleontological Resource Area, Colorado.

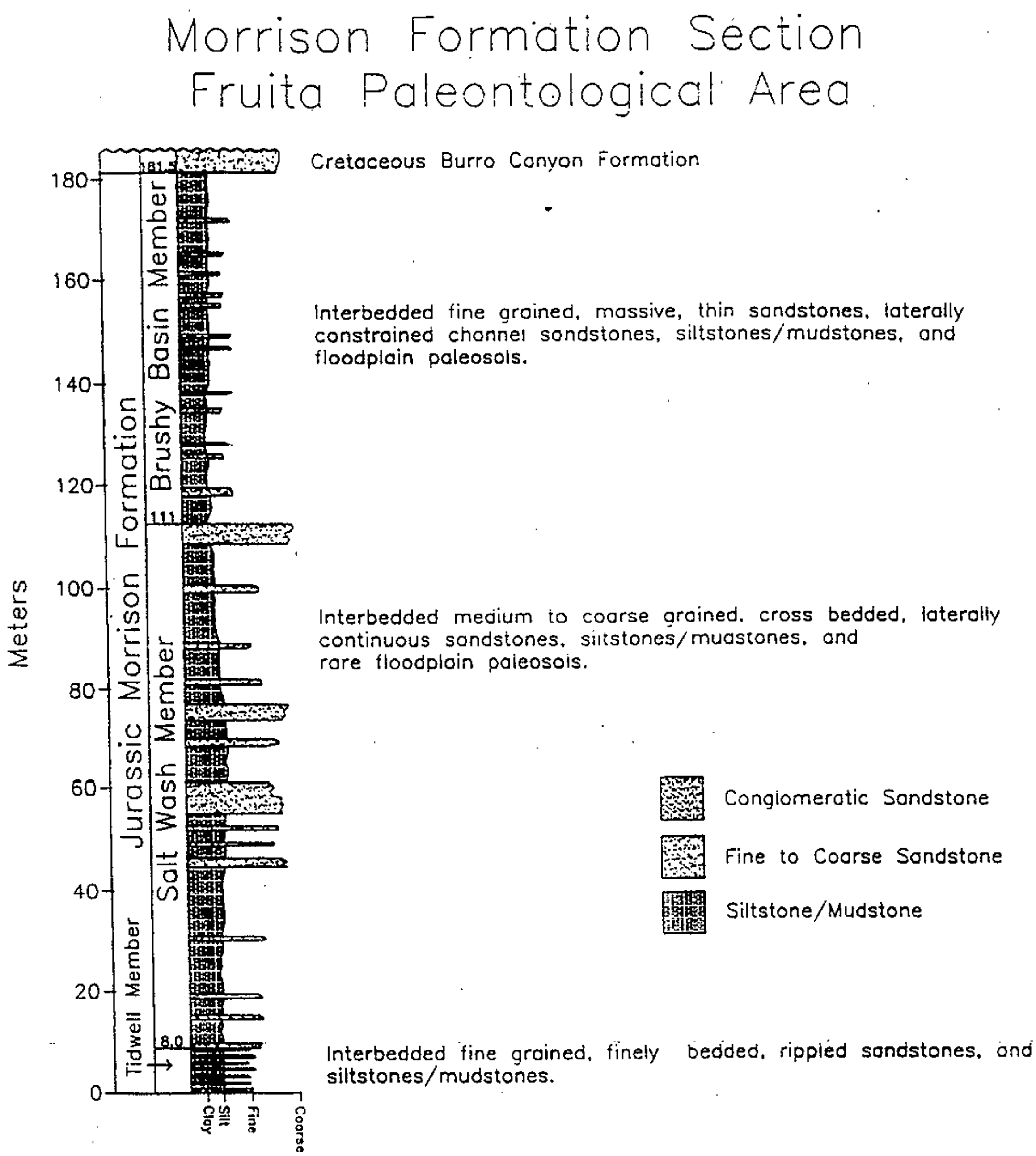

Figure 2. Morrison Formation stratigraphic section at the Fruita Paleontological Resource Area

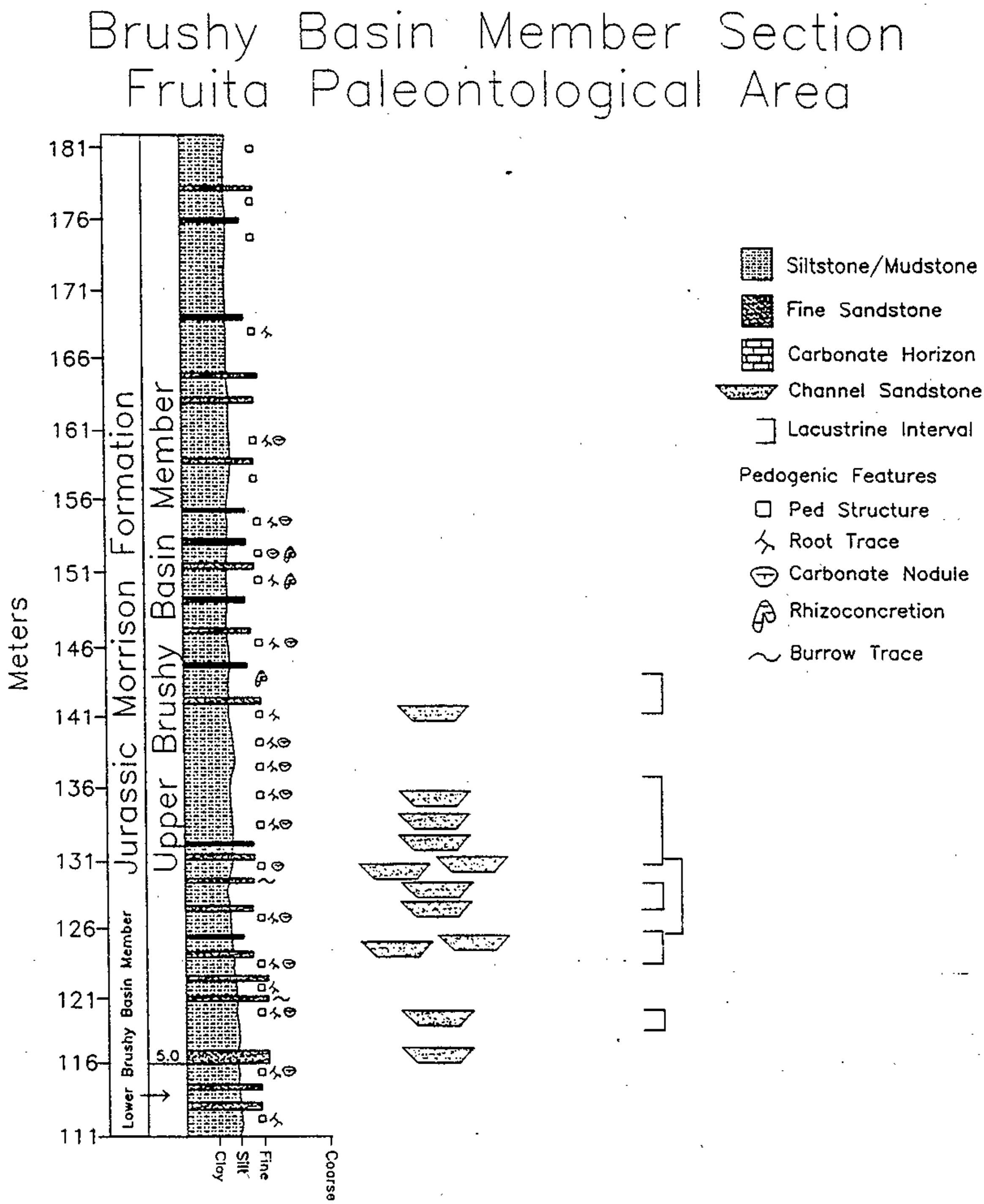

Figure 3. Brushy Basin Member of the Morrison Formation stratigraphic section at the Fruita Paleontological Resource Area.

Upper Brushy Basin Member of the Morrison Formation
Fruita Paleontological Resource Area

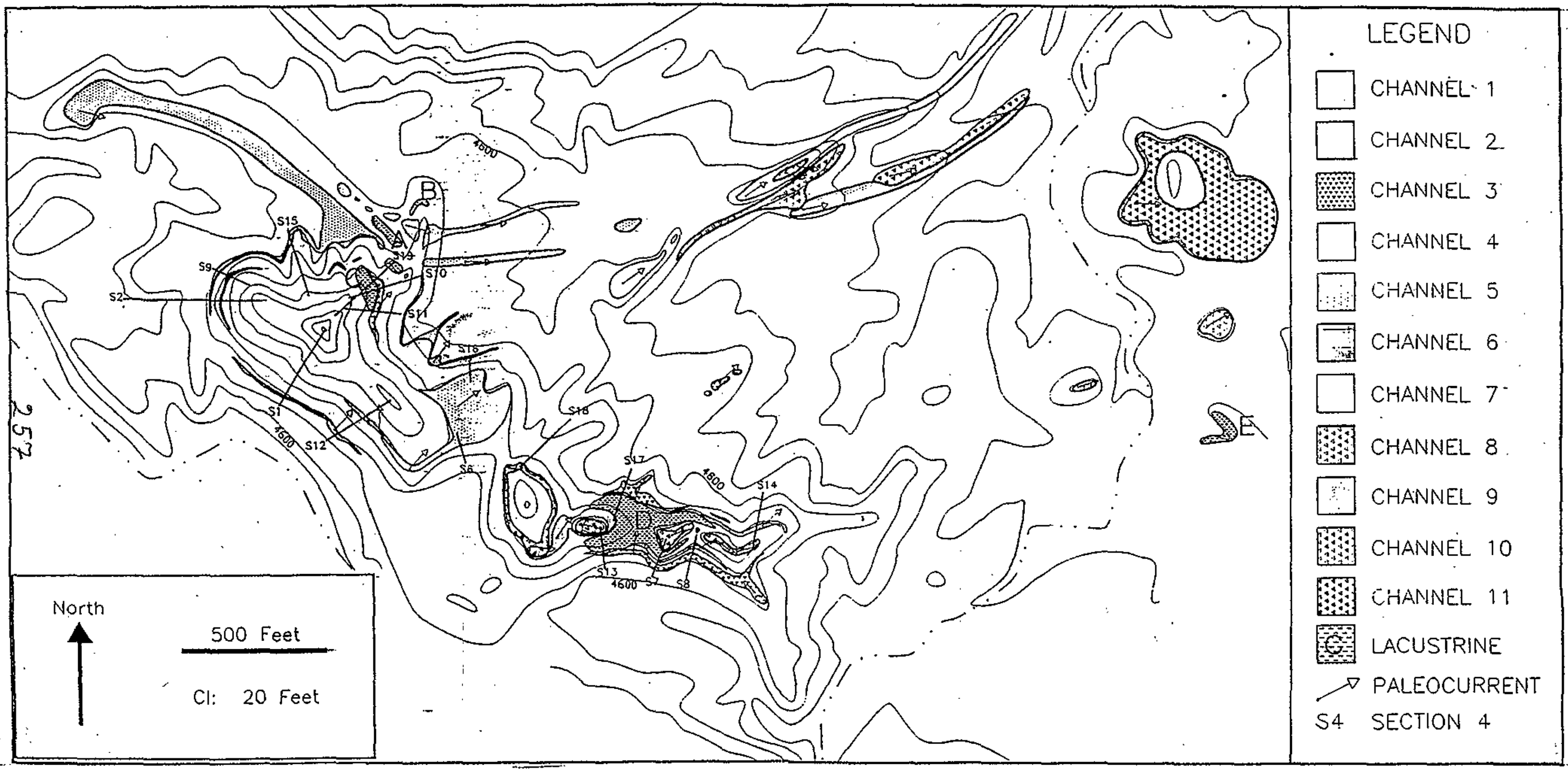

Figure 4. Geological map of the Upper Brushy Basin Member of the Morrison Formation at the Fruita Paleontological Resource Area, Colorado. Channel fill sandstones and lacustrine deposits delineated. Channels numbered in ascending order from one to eleven which represents their relative stratigraphic position, one being lowest and eleven being highest. Also note locations of measured stratigraphic sections for reference to Plate 2.

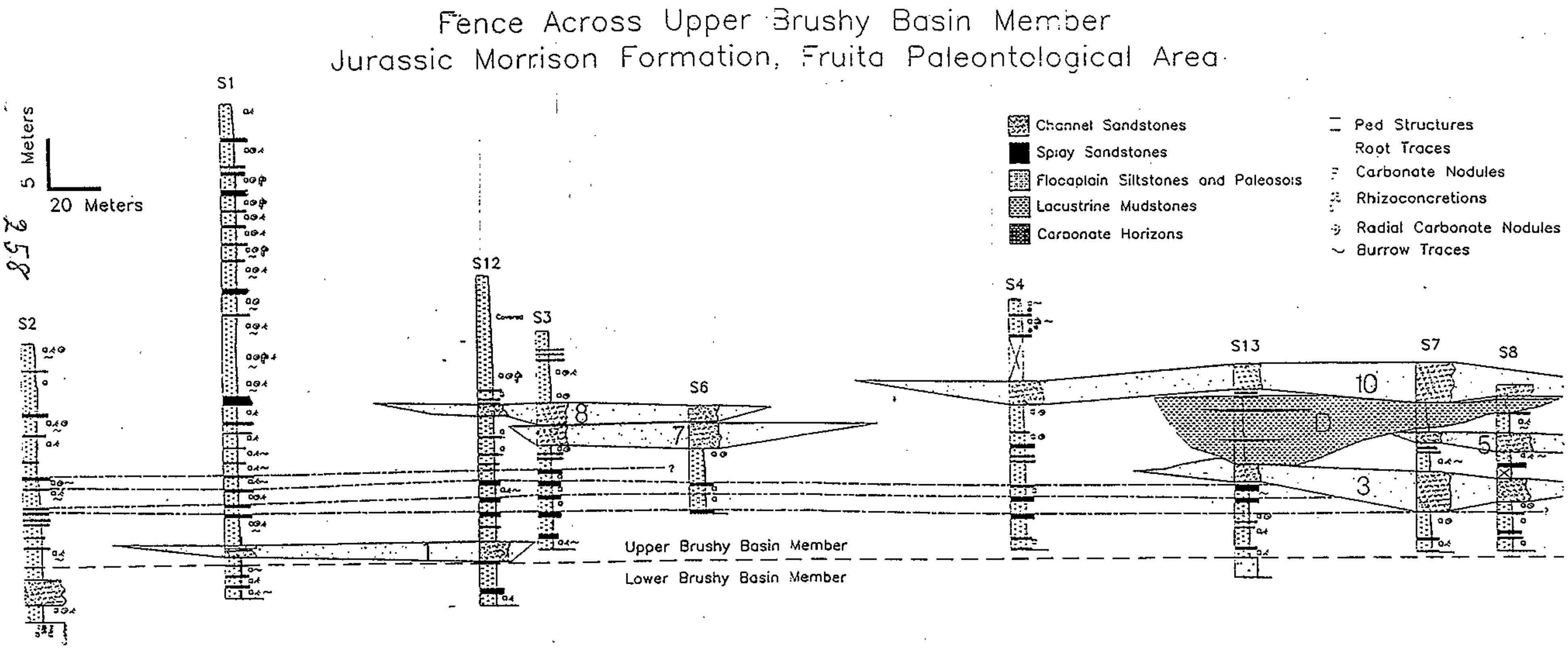

Figure 5. Fence diagram across the Brushy Basin Member of the Morrison Formation at the Fruita Paleontological Resource Area (FPA), Colorado. Fence is constructed from measured stratigraphic sections along the major ridge-line comprising most of the FPA. See Plate 1 for location of the ridge-line and the sections used in the fence construction. Channel numbers correspond to those on Plate 1.

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Table 1. Modern and Ancient Anastomosing Systems: Characteristics

Author	Modern/ Ancient	Channel W/D	Sinuosity	Lateral Stability	% Floodplain	Floodplain Elements	Climate
Kirschbaum and McCabe (1992)	Ancient	15 -20	Variable	Moderate	NR	FC, CS, P, WF, FL	Humid, warm
Eberth and Miall (1991)	Ancient	15	NR	High	NR	FC, CC, CS, FM, FP, P	Semi- arid, warm
Smith (1986)	Modern	20	Low	High	70 - 90	FC, CS, CL, FL, WF, S	Savanna-tropical
Smith (1983)	Modern	NR	Low	High	NR	FC, CS, CL, FL, WF, S	Subarctic, wet
Rust (1981)	Modern	NR	High	High	80 - 97	FC, FM	Arid, warm
Smith and Putnam (1980)	Both	NR	Low	High	60 - 90	FC, CS, CL, WF, FM, FP, S, P	Modern: Subarctic, wet; Ancient: Humid
Smith and Smith (1980)	Modern	13 - 16	Variable	High	NR	FC, CS, CL, FP, WF, S	Subarctic, wet

NR = Not Reported
FP = Floodplain Ponds
CS = Crevasse Splays
CL = Channel Levees
FL = Floodplain Lakes

FC = Fluvial Channels
CC = Crevasse Channels
FM = Floodplain Muds and Silts
WF = Wet Floodplains
S (P)= Soils (Paleosols)

BIOSTRATIGRAPHY, PALEOECOLOGY, AND BIOGEOGRAPHY OF CHAROPHYTES AND OSTRACODES FROM THE UPPER JURASSIC MORRISON FORMATION OF THE WESTERN INTERIOR; FINAL REPORT

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ABSTRACT

Nonmarine charophytes and ostracodes from the Morrison Formation were examined in an effort to determine the age of the Morrison Formation and stratigraphically related beds and to provide preliminary information on paleoecology and paleobiogeography. Our findings are based on examination of 132 productive microfossil samples collected from 20 measured sections in Colorado, Montana, New Mexico, Oklahoma, South Dakota, Utah, and Wyoming. The Morrison Formation and related beds are here defined to include all strata between the J-5 and K-1 unconformities and include the Ralston Creek Formation that crops out west of Denver, Colorado.

The samples yielded 38 charophyte and ostracode species. Based on their stratigraphic distribution, the Morrison Formation and related beds can be divided into 5 biozones, with zone 1 as the lowest and zone 5 being highest. In the central and southern parts of the Western Interior, a major change in clay mineralogy is present at the boundary between biozones 3 and 4. Predominantly non-smectitic clays are in biozones 1-3 and predominantly smectitic clays or other authigenic minerals are above in biozones 4-5.

Diagnostic information on the age of the Morrison was obtained from those species that also occur in western Europe where the strata have been dated by other fossils including

ammonites. Our findings indicate that biozones 1–4 are Kimmeridgian in age, with the qualification that the unfossiliferous basal few meters of the Morrison could, conceivably, be latest Oxfordian in age. Zone 5 at the top of the Morrison lacks age-diagnostic microfossils and could be Kimmeridgian or Tithonian in age. We tentatively consider Zone 5 Tithonian(?) in age because (1) it has a somewhat different calcareous microfossil assemblage than the older zones, (2) that age is in agreement with isotopic and palynological age determinations determined from other studies, and (3) the calcareous microfossil assemblage indicates that these beds are not Cretaceous in age.

Paleoecological interpretations made by comparison of the ostracode and charophyte genera with their modern counterparts suggest mostly nonmarine environments, although the salinity could have been slightly higher in several beds, perhaps to about 16 parts per thousand in some cases. An analysis of the spatial distribution of both ostracodes and charophytes suggests close but complex biogeographic relationships between North America and Europe during Late Jurassic time.

In the appendix, one new ostracode genus (Helmdachia) and seven new species (Cypridea acuticyatha, Candona coloradensis, C. morrisonensis, Timiriasevia guimarotensis, Helmdachia petersoni, H. turneri, H. prima) are described by M.E. Schudack.

INTRODUCTION

The Morrison Formation is a widespread, predominantly continental formation (Fig. 1) that contains a wealth of fossils. Although it is well known for its spectacular dinosaur fauna, the remains of these extinct beasts have not proven useful for age determinations, because (1) they do not provide as short a stratigraphic range as microfossils, (2) their biostratigraphic relationships have not been determined, and (3) they have not been dated by independent means. In contrast, the biostratigraphic zonation of microfossils found in the formation, especially the charophytes and ostracodes that this report deals with and the palynomorphs studied by Litwin and others (this volume), is fairly well understood. The biostratigraphic zonation of the Late Jurassic and Early Cretaceous charophytes and ostracodes has been determined primarily from studies in Western Europe, and can now be applied to resolving the question of the age of the Morrison Formation in North America. Ostracodes were first reported from beds that were later named the Morrison Formation by Jones (1886), and the first charophytes from the Morrison were described by Peck (1937).

Charophytes are green algae that have been found in Upper Silurian and younger strata deposited, for the most part, in fresh-water to moderately brackish-water environments. Their gyrogonites are minute (mostly about 0.25–0.75 mm in diameter) oval or round calcareous bodies that represent the calcified parts of the oögonium, i.e. the female reproductive organ. Where circumstances are amenable, the plant can grow to about 2 m (6 ft) in height, although they are most commonly found much shorter (about 0.3–0.6 m or 1–2 ft; Peck, 1957). Most of the plant consists of organic matter that decays shortly after death. Under some circumstances, the stems and branches of the plant become calcified and are also preserved in the geologic record, locally in considerable abundance. In the Morrison Formation, they are 1–2 mm in diameter and resemble twisted strands of rope when viewed with a hand lens. From this, the name "ropey limestone" has sometimes been applied to limestone beds containing large quantities of these vegetative remains.

Ostracodes are minute (mostly about 0.5–2 mm long) crustaceans with a calcareous bivalved carapace. They live in a wide variety of nonmarine, marginal-marine, marine, and hypersaline aquatic environments and have been used extensively for age and environmental interpretations.

METHODS

We examined 157 samples from 20 measured sections of the Morrison Formation. Samples were processed by K.L. Conrad in the Calcareous Microfossil Laboratory at the

U.S. Geological Survey in Denver and shipped to Schudack for analysis. Of these samples, 132 were productive, and many of these were highly fossiliferous.

In the Morrison Formation, charophytes and ostracodes are most readily observed in limestone but they are extremely difficult to extract from these beds and can only be studied in thin sections. For isolated specimens, the most productive sampling procedure is to first identify the presence of microfossils in a limestone bed with a hand lens and then to sample the 5–10 cm (2–4 in) of calcareous mudstone or marl that generally occurs immediately above and (or) below a limestone bed for laboratory separations. Experience has shown that noncalcareous mudstone or red mudstone will seldom yield calcareous microfossils (R.M. Forester and K.L. Conrad, oral commun., 1994), although there are exceptions, and in one case, a red mudstone bed at Dinosaur National Monument yielded abundant ostracodes. Thin mudstone beds interbedded with thicker sandstone beds also tend to be nonproductive.

The measured sections were selected not only for fossil productivity but also to contribute to the problem of correlating the various parts of the Morrison from the Colorado Plateau northward into Wyoming and Montana and eastward to the type localities of the Ralston Creek and Morrison Formations. Two lines of measured sections covering a broad areal distribution and significant facies changes were examined (Fig. 1). One line of sections covers the Front Range foothills and other eastern localities (Fig. 2), and the second line of sections extends from the Colorado Plateau northward across Wyoming and into Montana (Fig. 3). Important dinosaur localities are at or near several of these localities, including the sections at Kenton, Oklahoma; Dilley Ranch and Cope´s Nipple near Cañon City, Colorado; Morrison, Colorado; Cleveland–Lloyd Dinosaur Quarry and Dinosaur National Monument, Utah; Ninemile Hill, Poison Creek, and Tri-Moon Wash, Wyoming; and Strickland Creek, Montana.

STRATIGRAPHY

The Morrison Formation is characterized by lithologic heterogeneity (Fig. 1) that includes sandstone, clay, shale, limestone, and dolomite in the description of the measured type section west of Denver (Waldschmidt and LeRoy, 1944). Small quantities of anhydrite and pyrite are visible in thin sections of some of these beds (Waldschmidt and LeRoy, 1944).

On the Colorado Plateau, the Morrison Formation has been divided into nine members based on lithologic characteristics (for more discussion, see Peterson, 1994). The members will not be discussed here because they interfinger and their distinction is not especially important for biostratigraphic purposes. Of considerably greater biostratigraphic value are the stratigraphic markers that serve to identify formation boundaries or that represent isochronous or roughly isochronous markers within the formation and correlative beds. These stratigraphic markers are discussed by Peterson and Turner (this volume).

The most important temporal horizon within the Morrison is the prominent change in clay mineralogy and certain other minerals that is present between the lower and upper parts of the Brushy Basin Member (Turner and Fishman, 1991) on the Colorado Plateau and within the undivided Morrison Formation along the eastern foothills of the Colorado Front Range (Figs. 1, 2, 3). In most places, the clay change marks the boundary between predominantly non-smectitic clays below and smectitic clays above. A large alkaline, saline lake existed in the eastern part of the Colorado Plateau during the Late Jurassic. The geochemistry of the lake influenced the type of authigenic minerals that were produced. The change in mineralogy is from predominantly non-smectitic clays in the lower part of the section to authigenic smectite, clinoptilolite, analcime plus potassium feldspar, or albite, in the upper part, depending on geographic location within the ancient lake system.

The smectite clays or other authigenic minerals that occur above the clay change reflect geochemical and hydrological processes that altered volcanic ash carried onto the Colorado Plateau region by southwesterly winds from a magmatic arc that lay several hundred kilometers farther west along the western edge of the Late Jurassic North American continent. The clay change becomes less distinct northward along the Front Range and is not identifiable in the easternmost exposures of the Morrison north of Denver. However, an approximately equivalent horizon can be projected north of Denver based on the charophyte and ostracode assemblages. Similarly, the clay change disappears in the northernmost extent of the western line of sections (Fig. 3). Figures 2 and 3 show that the clay change also diminishes eastward across Wyoming and is not recognizable in the Black Hills of western South Dakota and adjacent northeastern Wyoming. The eastward and northward diminishment of smectite above the clay change marks the maximum extent of the volcanic ash clouds. Because the Late Jurassic winds tended to blow from west or southwest to east or northeast (Peterson, 1988), the northern limit of smectitic clays in the upper part of the Morrison is a function of the northward extent of volcanoes in the magmatic arc farther west.

As shown elsewhere in this volume (Peterson and Turner, this volume), the Ralston Creek Formation, which underlies the type Morrison west of Denver, must also be included in any discussion concerning the regional stratigraphy of the Morrison and related beds. This is because the lowermost beds of the Morrison Formation in many other areas correlate with the Ralston Creek near Denver whereas the middle and upper parts of the Morrison elsewhere correlate with the type Morrison (Figs. 2, 3). The type Morrison and Ralston Creek have an interfingering contact relationship, possess similar lithologies, and are closely related depositionally. The J-5 unconformity is at the base of the Morrison Formation at many places farther west on the Colorado Plateau and farther north in Wyoming. The same unconformity is at the base of the Ralston Creek Formation at and near its type locality west of Denver. Peterson and Turner (this volume) restrict the Ralston Creek geographically to the area near Denver. Farther north, the Ralston Creek grades laterally into lower Morrison strata. Farther south near Cañon City, Colorado, Middle Jurassic as well as lower Morrison beds were included in the Ralston Creek. When Middle

Jurassic strata there were recognized as a separate formation (Bell Ranch Formation), use of the term Ralston Creek was abandoned that far south (Peterson and Turner, this volume) and the Morrison was extended down to the J-5 unconformity (Fig. 2, sections 3–5).

The Ralston Creek Formation consists largely of mudstone at the type locality by Ralston Reservoir west of Denver, but it also includes some sandstone, limestone, and dolomite. The mudstone beds tend to exhibit a larger range of colors than the Morrison Formation, including red, purple, gray, grayish-green, and yellow. This contrasts with mudstone beds in the Morrison that are predominantly red or locally purple near the base and top and predominantly gray to grayish-green in the middle of that formation. In a limited stretch of outcrops about 4 km (2.5 mi) in known extent south of the town of Morrison, the Ralston Creek Formation also contains gypsum interbedded with mudstone and rare limestone.

BIOSTRATIGRAPHY

In order to evaluate the biostratigraphy of the ostracodes and charophytes in a manner free from any influence of facies and member variations, and to directly compare the stratigraphic ranges and occurrences of species, we standardized the measured sections graphically to equal lengths by two different methods.

1. Using the clay change as an isochronous reference surface and defining two time-stratigraphic units, each with equal thicknesses between the clay change and the respective higher or lower unconformable bounding surface (Figs. 4–6).
2. Recalibrating the measured sections so that they are all of equal thickness between the J-5 and K-1 unconformities.

In most cases, biostratigraphic correlation was considerably better (and the vertical range of the species was shorter) when the clay change was used as an isochronous reference surface. For this reason, we only used this methodology in the following discussions.

The charophytes (Fig. 4) and ostracodes (Fig. 5) exhibit similar patterns and allow subdivision into five successive biozones. Figure 6 summarizes the biostratigraphic ranges and relative abundances of species from both groups of organisms. The five biozones (local in the sense of the Western Interior) can, in principle, be identified both on the Colorado Plateau and farther north as well as farther east in the Front Range foothills. However, some of the biozones are more diagnostic locally and not throughout the study area.

Zone 1: Species restricted to this zone are thus far only from the Colorado Plateau and Montana. Only long-ranging species occur in the lower beds in the Front Range foothills. The Ralston Creek Formation did not yield microfossils where we sampled, but the unit has yielded the charophyte Echinochara pecki about 32 km (20 mi) south of Morrison (Scott, 1963). An additional note is that the only brackish-water to marine ostracode faunas as well as oysters came from the lowermost Morrison of the Devil's Slide section in Montana.

Zone 2: Several species have their first appearance in zone 2. The associations are typical in several areas such as the Colorado Plateau, farther north, and along the Front Range foothills. There are important guide fossils among both groups like Aclistochara obovata and Cetacella striata.

Zone 3: Most species of zone 2 range into this zone but others have their first appearances here, such as Aclistochara latisulcata, Bisulcocypris pustulosa, Cypridea acuticyatha, Trapezoidella aff. rothi, and Cetacella armata. Species restricted to this zone are Porochara minima, Helmdachia turneri, and Ostracode gen. et sp. indet. Some of these more important guide fossils occur only on the Colorado Plateau like Helmdachia turneri, and Ostracode gen. et sp. indet, others occur there and farther east. The top of this zone is the clay change.

Zone 4: This is a well-defined zone that occurs just above the clay change and contains easily identified guide fossils like Porochara arguta, Trapezoidella aff. rothi, and

Helmdachia petersoni. Some species begin or end in the zone but none are restricted to it. Important species in the zone occur on the Colorado Plateau, farther north, and farther east in the Front Range foothills.

Zone 5: This zone marks the uppermost part of the Morrison Formation. There are no species restricted to this zone but many taxa from below do not make it up into this zone. Although we do not have many samples from zone 5, there are enough to recognize the loss of many species. Among the five biozones we have established in the Morrison Formation and related beds, this is certainly the poorest in terms of being defined by the species of ostracodes and charophytes.

AGE OF THE MORRISON FORMATION

Among the various species in the five local biozones shown in Figure 6, there are several taxa that also occur in well-dated sections in western Europe. Other taxa are endemic to the Morrison depositional basin and thus cannot be used for such long-distance correlations. The endemics include several species that are excellent stratigraphic markers within the Morrison. These include the charophytes Latochara bellatula, Aclistochara obovata, A. latisulcata, and Porochara arguta, as well as some of the ostracodes, especially the species of the endemic new genus Helmdachia.

The species that are present on both continents suggest the ages for the five biozones listed below. Kimmeridgian in this report follows French usage (sensu gallico) in which the Kimmeridgian Stage is succeeded by the Tithonian Stage. This Kimmeridgian (sensu gallico) does not include the Upper Kimmeridgian of British terminology (sensu anglico), which has the Kimmeridgian Stage succeeded by the Portlandian Stage.

Zone 1: All of the species found in both continents occur in the European Kimmeridgian. Among the charophytes, these are Mesochara voluta, Echinochara pecki, Aclistochara bransoni, and Latochara latitruncata; among the ostracodes, these are Theriosynoecum wyomingense, Timiriasevia guimarotensis, and Bisulcocypris pahasapensis. Some of these species, such as Echinochara pecki and Aclistochara bransoni, would also allow a late Oxfordian age but others, such as Mesochara voluta, Latochara latitruncata, Theriosynoecum wyomingense, Timiriasevia guimarotensis, and Bisulcocypris pahasapensis, do not, at least with present knowledge. Therefore, we think that this zone is (early ?) Kimmeridgian in age.

Zone 2: Same age as zone 1. Among the species occurring on both continents, the charophyte Porochara fusca and the ostracodes Cetacella striata and Rhinocypris jurassica make their first appearance in this zone. These species support the Kimmeridgian age as they do not occur in the European Oxfordian.

Zone 3: Same age as zones 1 and 2. This zone contains more European species but they are longer ranging. The new species include the charophytes Porochara minima and P. kimmeridgensis as well as the ostracode Cetacella armata. Porochara minima is restricted to this zone. Zone 3 also marks the highest occurrence of Porochara fusca, Theriosynoecum wyomingense, Cetacella striata, and Rhinocypris jurassica. Typical Kimmeridgian species persist.

Zone 4: No new European species are present but this zone marks the highest occurrence of the following Kimmeridgian species: among the charophytes, Mesochara voluta, Echinochara pecki, Aclistochara bransoni, and Porochara kimmeridgensis; among the ostracodes, Timiriasevia guimarotensis and Cetacella armata. Unfortunately, the guide fossils that are especially useful for intraformational correlation (see Fig. 6) are endemic and cannot be used for international correlation and dating. However, judging from the available international charophyte and ostracode species, this zone should also be Kimmeridgian in age.

Zone 5: Typical European Kimmeridgian species are not present in this zone. Therefore, this part of the formation could be Tithonian in age. However, because all of the remaining European species are long-ranging and also exist in the Kimmeridgian, there is no definite indication of a Tithonian age. We suggest, however, that a Tithonian age is possible. This is consistent with the Tithonian age determined by palynomorphs (Litwin and others, this volume) and by isotopic methods (Kowallis and others, this volume). European species that range upward into this zone include the charophyte Latochara latitruncata and the ostracode Bisulcocypris pahasapensis. No species, including the endemics, are restricted to this zone.

As far as a possible Cretaceous age for the upper part of the Morrison is concerned, there is no suggestion of this from the calcareous microfossils. All of the typical guide fossils for the European Berriasian Stage (that is, the lowest stage in the Cretaceous), which are widespread over Europe from the Iberian Peninsula to Scandinavia, are missing, even though some of these occur as far away as China. Judging from ostracode biogeography and dispersal strategies, primarily those that are distributed throughout the world, rich and diverse cypridacean faunas should also occur in the Morrison if some part of it were Berriasian in age. Because such an ostracode fauna is not present in the Morrison, we do not believe that any part of the formation (or at least the parts and sections that we have studied) extends into the basal Cretaceous.

PALEOECOLOGY

With only a single exception, all of the charophyte and ostracode genera in the Morrison Formation allow the interpretation of a fresh-water habitat (see Fig. 7). Many of these taxa can also tolerate brackish-water habitats, but not normally more than about 16 parts per thousand. Several of the genera (mainly ostracodes) are typical freshwater organisms. As a consequence, we interpret that many of the lakes or ponds in which the ostracodes and charophytes lived contained fresh water.

The single paleosalinity exception is found in the basal strata of the Morrison Formation at the Devil's Slide section in southwestern Montana (Figs. 1, 3). Fresh-water or brackish-water species occur in association with brackish-water to marine organisms such as oysters and poorly preserved marine cytheracean ostracodes (? Aparchitocythere). The Morrison

Formation is conformable on shallow marine sandstone beds of the Swift Formation in this area, suggesting a marine invasion into the Morrison depositional basin. Recent work by us farther north in the Little Rockies of north-central Montana confirm an earlier report (Knechtel, 1959) that glauconitic sandstone beds, highly suggestive of shallow marine deposition, are present in the middle of the Morrison Formation there. Farther south in Wyoming and northernmost Utah and Colorado, shallow marine beds of the Windy Hill Member are present at the base of the Morrison. Thus, marine deposits are not unheard of in the Morrison and may be expected, especially because Kimmeridgian and possibly younger Jurassic marine strata have been reported in southern Canada (southeastern British Columbia; Smith, 1994).

BIOGEOGRAPHY

The distribution of Morrison ostracode and charophyte species in North America and Europe provides interesting geographic patterns when comparing (1) the Western Interior with (2) Portugal, (3) northern and eastern Spain, and (4) northern Germany (Figs. 8, 9). These patterns are significantly different for ostracodes and charophytes. Among the ostracodes, the distribution patterns for the nonmarine representatives of the two main superfamilies (Cypridacea and Cytheracea) suggest rather different dispersal strategies and (or) paleoclimatic zonations.

In the Upper Jurassic of the Western Interior, 13 nonmarine ostracode species have been identified specifically (Fig. 8). Seven Western Interior species are also present in western Europe (Helmdach, 1971; M.E. Schudack, 1987, and unpublished work; U. Schudack 1989, 1994) and suggest closer biogeographic relationships than have been presumed thus far, even for the nonmarine ostracode faunas (compare Bate, 1977, and Tambareau, 1982). Moreover, the distribution patterns of the two superfamilies Cypridacea and Cytheracea correspond well with the possibilities allowed by their respective dispersal strategies. The distribution patterns of the two superfamilies also correspond with the paleoclimatic, paleogeographic, and tectonic regime on North America, the Proto-North Atlantic, and Western Europe in the Late Jurassic (see Ziegler, 1988, for a summary of Late Jurassic paleogeography and tectonics in the North Atlantic and Western Tethyan areas).

Many species of the superfamily Cypridacea (Fig. 8) lack sexual dimorphism and thus might have had the option of parthenogenetic reproduction (reproduction by development from unfertilized eggs). In addition, many species did not provide brood care and their eggs would have been resistant to desiccation and cold temperatures (Helmdach, 1979; Whatley, 1990, 1992). As a consequence, their dispersal strategies were extremely effective, leading to the possibility that their eggs were transported from one continent to another by strong winds, possibly by cold jet streams in a west to east direction (see Moore and others, 1992a,b). In theory, a single egg might have been the pioneer of a new population in Europe by this dispersal strategy. Four out of the cypridacean species listed here (Cetacella armata, C. striata, Rhinocypris jurassica, and Candona coloradensis) are widespread, not only in the Western Interior (Fig. 8, region 1) but also in Central Europe (Fig. 8, region 4) and therefore they crossed the faunal barrier of the Bay of Biscay Rift and the Proto-North Atlantic (Fig. 8). The preferred west to east migration of these species would correspond to the prevailing direction of the jet streams (Moore and others, 1992a,b) as well as to the main direction of surface winds on and near the Colorado Plateau (Parrish and Peterson, 1988).

In contrast, the nonmarine species of the superfamily Cytheracea (that is, the limnocytherids) had less favorable dispersal strategies. Sexual dimorphism and brood care, typical for most species of this group, must be considered disadvantageous in this context. Wind-driven dispersion of these taxa was almost impossible because of delicate single-walled eggs, and the limnocytherid Morrison species only occur in North America and the Iberian Peninsula (Fig. 8). This distribution is understood if the Late Jurassic paleogeography of the Iberian peninsula is considered. Tectonic studies suggest that Iberia was close to North America in the Late Jurassic and that they were only separated by shallow seas containing many islands, whereas Iberia was separated from the land masses in western and central Europe by a wider and more open extent of the deep sea that lacked islands (see Ziegler, 1988). Therefore, migration of limnocytherids by means of non-flying animals may have been possible from North America to Portugal and Spain, but more distant migration to Central Europe across the Bay of Biscay Rift and the Proto-North Atlantic was much less likely.

The distribution of charophyte species follows an entirely different pattern (Fig. 9). Of the 18 Morrison species, seven are present in central Europe (northern Germany, region 4 in Fig. 9) but only four species have been found on the Iberian Peninsula (regions 2 and 3 in Fig. 9; M.E. Schudack, 1993a). This indicates that the Morrison charophyte flora is much more similar to that of central Europe than to Iberia. This is consistent with paleolatitudinal relationships (Smith and others, 1994) and with a subdivision into two biogeographic provinces suggested for European charophyte floras through the Late Jurassic and at least into the Berriasian (M.E. Schudack, work in progress). Northern European charophyte communities in England, Denmark, and northern Germany are partly dominated by Aclistochara and Latochara. Southern European communities in Switzerland, southern France, Sardinia, Portugal, and Spain are partly dominated by clavatoraceans including Dictyoclavator. A possible paleoclimatic boundary, approximately at a paleolatitude of 37–38 degrees north according to the reconstruction of Smith and others (1994), would separate the two provinces.

Paleolatitudinal correlation between Europe and the Western Interior, however, cannot fully explain the similarities between Morrison and northern European charophyte floras. Some of the Morrison localities (for example, those in Oklahoma, New Mexico, and the southern part of Colorado) have yielded rich floras and were located slightly farther south in the Late Jurassic (Peterson, 1988; Smith and others, 1994). Regional climatic conditions must also be considered. The Western Interior Basin was well within the North

American continent during the Late Jurassic, where winter temperatures probably were lower than in western European areas of the same paleolatitude (Valdes and Sellwood, 1992), but the North Atlantic probably buffered winter temperatures in western Europe. Differences in summer temperatures between the two continents probably were less (Valdes and Sellwood, 1992), but the distribution of plants in many cases is restricted more by minimum than maximum temperatures. Morrison charophytes can be considered to be part of a relatively cold and northern flora when compared with floras of the European continent.

In a recent study, M.E. Schudack (1995) examined the geographic distribution of charophyte genera preferring relatively cold or warm waters within the Morrison depositional basin. A north-south gradient, in the sense of a latitudinal climatic zonation within the basin, is evident.

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APPENDIX

THE OSTRACODES AND CHAROPHYTES OF THE MORRISON FORMATION

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INTRODUCTION

The ostracodes of the Morrison Formation have never been described in a monograph covering the complete fauna, although considerable work has been done by Jones (1886), Roth (1933), Harper and Sutton (1935), and Branson (1935, 1936) for specific areas. More recent contributions to Morrison ostracode faunas have come from Peck and Reker (1948), Branson (1961, 1964, 1966), Pinto and Sanguinetti (1962), and Sohn and Peck (1963). "Metacypris" todiltensis, described by Swain (1946) from New Mexico is, according to the stratigraphic revision of the San Juan Basin by Condon and Peterson (1986), from the Middle Jurassic rather than the Morrison Formation. Finally, Sohn (1979), in his extensive revision, suggested an Early Cretaceous rather than a Late Jurassic age for the Black Hills faunas, and he suggested that the Black Hills ostracodes most likely came from the Lower Cretaceous Lakota Formation rather than the Upper Jurassic Morrison Formation (see also Sohn, 1958).

The only ostracode species in common both to the Black Hills fauna of Roth (1933), Harper and Sutton (1935), and Sohn (1979), and to the Morrison fauna described herein is Bisulcocypris pahasapensis. All the other so-called "Morrison" species of Roth (1933) and Harper and Sutton (1935) are apparently restricted to the Lower Cretaceous Lakota Formation.

Morrison ostracodes are (in taxonomic order, see Plates 1 and 2): Cetacella armata Martin, 1958, Cetacella striata (Helmdach, 1971), Cetacella sp. (with smooth surfaces), Cypridea acuticyatha n. sp., ? Cypridea sp., Rhinocypris jurassica (Martin, 1940), Candona coloradensis n.sp., Candona morrisonensis n.sp., Trapezoidella aff. rothi Sohn, 1979, Bisulcocypris pahasapensis (Roth, 1933), Bisulcocypris pustulosa (Sohn, 1982), Theriosynoecum wyomingense (Branson, 1935), Timiriasevia guimarotensis n. sp., Helmdachia petersoni n. sp., Helmdachia turneri n. sp., Helmdachia prima n. sp., ?Aparchitocythere sp., Darwinula spp., Ostracode gen. et sp. indet.

In contrast to the ostracodes, charophytes have been studied in several rather extensive papers, including monographs by Peck (1937, 1957), Ott (1958), and Ross (1960). As a consequence, we have not found any new taxa. However, a few species are here reported from the Morrison Formation for the first time (Porochara fusca and Porochara kimmeridgensis), and others are synonymized with known taxa (now Porochara kimmeridgensis, Porochara minima, and Peckisphaera glypta).

Morrison charophytes are (in taxonomic order, see Plate 3): Porochara arguta (Peck, 1957) n. comb., Porochara fusca (Mädler, 1952) Mädler, 1955, Porochara kimmeridgensis (Mädler, 1952) Mädler, 1955, Porochara minima (Mädler, 1952) Shaikin, 1976, Latochara bellatula Peck, 1957, Latochara collina Peck, 1957, Latochara concinna Peck, 1957, Latochara latitruncata (Peck, 1937) Mädler, 1955, Latochara aff. mensinki Schudack, 1990, Latochara spherica Peck, 1957, Aclistochara bransoni Peck, 1937, Aclistochara jonesi Peck, 1937, Aclistochara latisulcata Peck, 1957, Aclistochara mädleri (Peck, 1957) n. comb., Aclistochara obovata Peck, 1937, Mesochara voluta (Peck, 1937) Grambast, 1965, Peckisphaera verticillata (Peck, 1937) Grambast, 1962, Peckisphaera glypta (Peck, 1934) Feist & Grambast-Fessard, 1982, Echinochara pecki (Mädler, 1952) Grambast, 1965.

Two species are recombined:

Porochara arguta (Peck, 1957) n. comb. = Stellatochara arguta Peck, n.sp. (in Peck, 1957: p. 31, pl. 6, Figs. 14–23)

Aclistochara mädleri (Peck, 1957) n. comb. = Obtusochara madleri Peck, n.sp. (in Peck, 1957: p. 38, pl. 6, Figs. 5–8)

The specimens illustrated in Plates 1–3 (including the types) are housed in the micropaleontological collection of Michael E. Schudack, Martin-Luther-University Halle-Wittenberg, Halle (Saale), Germany (slide numbers MES 351-392).

SYSTEMATIC DESCRIPTIONS OF NEW TAXA

Subclass Ostracoda Latreille 1802
Order Podocopida Müller 1894
Suborder Podocopina Sars 1866
Superfamily Cypridacea Baird 1845
Family Ilyocyprididae Kaufmann 1900
Subfamily Cyprideinae Martin 1940
Genus Cypridea Bosquet 1852

Cypridea acuticyatha n. sp.
(Pl. 1, Figs. 4–6)

Derivation of name: Latin, acutus acute, relating to the pointed cyathus of most specimens.

Diagnosis: A species of Cypridea with a variable, but mostly acute cyathus; rostrum and alveolus hardly developed. Left valve larger than right valve. Anterocardinal angle well-defined, dorsal margin straight, with strong posterior slope. Posterocardinal angle indistinct, posterior margin truncate. Anterior margin almost equally rounded. Surface of valves unornamented.

Holoype: Carapace from sample 1340-2-32, MES 356 (Pl. 1, Fig. 6).

Paratypes: Carapace from sample 1340-2-32, MES 355 (Pl. 1, Fig. 5).

Type locality: Kenton section: C-SW¼ Sec. 18, T. 5 N., R. 1 E., Cimarron Co., Oklahoma; Kenton 7.5' Quadrangle.

Type level: Upper part of Morrison Formation, Kimmeridgian, biozone 4 (this paper), 40 meters above Bell Ranch Formation (Kenton section).

Description: Carapace large, oblique-trapezoidal in lateral outline, highest anterior to the center. The left valve is larger than the right one and overlaps it along the whole outline except for the hinge area. Anterior margin broad, almost equally rounded, infracurvate. Anterocardinal angle well-defined, but rounded. From this point, the dorsal margin slopes straight to the indistinct posterocardinal angle. Posterior margin truncate, almost vertical. Rostrum and alveolus hardly developed. The cyathus is variable, although there are specimens with an indistinct cyathus

(Pl. 1, Fig. 4), it is very distinct and acute in typical specimens (Pl. 1, Fig. 5, 6). Ventral margin of right valve slightly concave. Surface of valves unornamented.

Dimensions (mm): Length 0.95–1.02, height 0.53–0.61.

Material: 60 carapaces and valves from 2 samples.

Remarks: Cypridea acuthicyatha n. sp. differs from other species of the same genus by its combination of the typical cyathus, the form of the dorsal margin and the oblique-trapezoidal outline.

Distribution: Morrison zones 3 and 4 (Kimmeridgian) of the Front Range foothills in Oklahoma and Colorado.

Family Cyprididae Baird 1845
Subfamily Candoninae Daday 1900
Genus Candona Baird 1845

Candona coloradensis n.sp.
(Pl. 1, Figs. 7–9)

Derivation of name: After Colorado, the US State in which the species is most frequent.

Diagnosis: A candonid species with very large carapace, highest slightly anterior to the center. Anterior margin almost equally rounded. Posterior margin straight, steep. Posterocardinal angle distinct, but rounded. Surface of valves unornamented.

Holoype: Carapace from sample 1346-28+7, MES 357 (Pl. 1, Fig. 7).

Paratypes: 7 carapaces from sample 1346-28+7, MES 358 (Pl. 1, Figs. 8–9).

Type locality: Felch Creek section: NW¼, NW¼ SE¼ Sec. 26, T. 17, R. 70 W., Fremont Co., Colorado; Cooper Mountain 7.5' Quadrangle.

Type level: Upper part of Morrison Formation, Kimmeridgian, biozone 4 (this paper), 60 meters above Ralston Creek Formation (Felch Creek section).

Description: Carapace very large, rounded-trapezoidal in lateral outline; greatest height at indistinct anterocardinal angle, slightly anterior to the center; greatest length below midheight. The left valve is larger than the right one. Anterior margin almost equally rounded, infracurvate. Ventral margin slightly concave. Dorsal margin strongly convex, posterocardinal angle distinct, but rounded; posterior margin straight and steep, strongly infracurvate. Carapace lenticular in dorsal view (Pl. 1, Fig. 9). Surface of valves unornamented.

Dimensions (mm): Length 1.48–1.65, height 0.88–0.97.

Material: Several thousand carapaces from 18 samples.

Distribution: The species is very frequent in Morrison zones 3 and 4 (Kimmeridgian), but less frequent in Morrison zones 1–2 (Kimmeridgian) and 5 (? Early Tithonian). It can be found throughout the study area. In the Garden Park Area, Colorado (sections 3 and 4), it occurs in rock-forming abundance.

<u>Candona</u> <u>morrisonensis</u> n. sp.
(Pl. 1, Figs. 10–11)

Derivation of name: After its occurrence in the Morrison Formation.

Diagnosis: A candonid species with very large carapace, highest slightly anterior to the center. Anterior and posterior margins almost equally rounded. Surface of valves unornamented.

Holoype: Carapace from sample 1346-28+7, MES 360 (Pl. 1, Fig. 11).

Paratypes: 4 carapaces from sample 1346-28+7, MES 359 (Pl. 1, Fig. 10).

Type locality: Felch Creek section: NW¼, NW¼ SE¼ Sec. 26, T. 17, R. 70 W., Fremont Co., Colorado; Cooper Mountain 7.5' Quadrangle.

Type level: Upper part of Morrison Formation, Kimmeridgian, biozone 4 (this paper), 60 meters above Ralston Creek Formation (Felch Creek section).

Description: Carapace very large, elongated-trapezoidal in lateral outline; greatest height at indistinct anterocardinal angle, slightly anterior to the center; greatest length at midheight. The left valve is larger than the right one and overlaps it around the whole margin. Anterior margin almost equally rounded, infracurvate. Ventral margin slightly concave. Dorsal margin convex, posterocardinal angle indistinct. Posterior margin rounded, strongly infracurvate. Surface of valves unornamented.

Dimensions (mm): Length 1.57–1.62, height 0.91–0.95.

Material: Several hundred carapaces from 8 samples.

Remarks: Candona coloradensis and C. morrisonensis are associated in several samples, for example at their type locality and stratigraphic level. Therefore, it was questioned if they are just males and females of the same species. However, their stratigraphic and geographic distribution is too different to justify such a combination.

Distribution: Morrison zones 3 and 4 (Kimmeridgian) in the Front Range foothills of Colorado and in the Black Hills of South Dakota.

Superfamily Cytheracea Baird 1850
Family Limnocytheridae Klie 1938
Genus Timiriasevia Mandelstam 1947

Timiriasevia guimarotensis n. sp.
(Pl. 2, Figs. 1–3)

1971 Timiriasevia mackerowi Bate 1965–Helmdach, p. 79, pl. 4, Figs. 1–2.

Derivation of name: After the coal mine Guimarota in Portugal, the locality from which the species was first described (as T. mackerowi) and where it is most abundant.

Diagnosis: A species of the genus Timiriasevia with an ornamentation of fine longitudinal ridges which mostly follow the outline of the carapace except for the central area. The longitudinal ridges are connected by short cross-ridges to, mostly in the posterior part of the valves. A sexual dimorphism is very distinct.

Holoype: Male carapace from sample 1392-6, MES 365 (Pl. 2, Fig. 1).

Paratypes: 16 carapaces and one valve from sample 1392-6, MES 366 (Pl. 2, Figs. 2–3).

Type locality: Ladder Canyon section: NE¼ NW¼ Sec. 30, T. 12 S., R. 100 W., Mesa Co., Colorado; Island Mesa 7.5' Quadrangle.

Type level: Lowermost part of Morrison Formation, Kimmeridgian, biozone 1 (this paper), 8 meters above Wanakah Formation (Ladder Canyon section).

Description: Carapace of medium size, oval in lateral outline, greatest height slightly behind center, greatest length clearly below midheight. Dorsal margin convex, equally rounded, without cardinal angles. Ventral margin straight or slightly convex at the center and slightly concave anterior to the center. Anterior margin strongly infracurvate, posterior margin almost equally rounded, slightly infracurvate. The species shows a distinct sexual dimorphism: Female carapaces (Pl. 2, Fig. 2) are inflated posteriorly, whereas male carapaces (Pl. 2, Fig. 3) are oval and more elongated in dorsal outline, and have their greatest width in the center. The ornamentation of the valves consists of fine longitudinal ridges which mostly follow the outline of the carapace. In the central area of the valves, the ridges show an anastomosing, partly ramifying pattern. These longitudinal ridges are connected by short cross-ridges to a different degree, mostly in the posterior part of the valves.

Dimensions (mm): Females: length 0.55–0.62, height 0.33–0.35, width 0.50–0.52, males: length 0.53–0.55, height 0.30–0.31, width 0.34–0.35.

Material: About 100 carapaces and valves from 18 samples.

Remarks: <u>Timiriasevia guimarotensis</u> n. sp. differs from the middle Jurassic <u>T. mackerowi</u> by the abundance of short cross-ridges and from the early Cretaceous <u>T. punctata</u> by the lack of punctae between the longitudinal ridges. With this respect, <u>T.</u>

guimarotensis takes an intermediate position between T. mackerowi and T. punctata morphologically as well as stratigraphically.

Distribution: Morrison zones 1, 2, 3 and base of 4 (Kimmeridgian) of the Front Range foothills, on the Colorado Plateau and in Wyoming. The species is very frequent in the Kimmeridgian of Portugal (Helmdach, 1971).

Genus Helmdachia n. gen.

Type species: Helmdachia petersoni n. sp.

Derivation of name: In honor of Dr. Friedrich-Franz Helmdach for his contributions to the knowledge of fossil ostracodes, especially of the Upper Jurassic in Portugal.

Diagnosis: Carapace trapezoidal, with straight dorsal margin. Sulci hardly expressed. Median ridge always developed, a ventrolateral ridge can be present. A peripheral ridge of different relief can run along of the outline of the valves. Surface of valves smooth, covered with punctae, reticulated, or covered with fine longitudinal ridges.

Remarks: The three species of this new genus occur in a stratigraphic succession: H. prima in Morrison zone 1, H. turneri in Morrison zone 3, H. petersoni in Morrison zones 4 and 5. Although there are still a few gaps in this succession, they may represent an evolutionary lineage.

Distribution: Morrison Formation, biozones 1–5 (this paper): nonmarine Kimmeridgian (and Tithonian ?) of the Western Interior, U.S.A.

Helmdachia petersoni n. sp.
(Pl. 2, Figs. 5–9)

Derivation of name: In honor of Dr. Fred Peterson (U.S. Geological Survey, Denver) who has carried out extensive work on the Morrison Formation.

Diagnosis: A species of the genus Helmdachia with the following features: Median ridge straight, running from slightly anterior to the center to the posterior part of valves. Ventrolateral ridge strongly developed. Both ridges can be extremely extended (winged). Surface of valves smooth or covered with punctae.

Holoype: Complete carapace from sample 1388-1+5, MES 368 (Pl. 2, Fig. 5).

Paratypes: 12 carapaces from sample 1388-1+5, MES 369 (Pl. 2, Figs. 6–7,9).

Type locality: Ninemile Hill section: SW¼ NE¼ NW¼, C-N½ SE¼ NW¼ Sec. 23, T. 23 N., R. 78 W., Carbon Co., Wyoming; Medicine Bow 7.5' Quadrangle.

Type level: Upper part of Morrison Formation, Kimmeridgian, biozone 4 (this paper), 48 meters above Sundance Formation (Ninemile Hill section).

Description: Carapace small, oblique trapezoidal in lateral outline. Greatest height at distinct, but rounded posterocardinal angle; greatest length at about ⅓ height. Anterior margin equally rounded or slightly infracurvate. Anterocardinal angle distinct, but rounded. Dorsal margin straight, with very slight slope from posterocardinal to anterocardinal angle, in a few specimens shallow-concave. Posterior margin infracurvate, straight in upper part, rounded in lower part. Ventral margin concave, covered by wing-like ventrolateral ridge in central part. Shallow sulcus slightly anterior to center, extending from dorsal margin down to midheight. From the base of the sulcus, a straight median ridge ascends with very low angle to about ⅘ of valve length. Median ridge extremely extended to wing-like structure in some specimens (Pl. 2, Fig. 6). Peripheral ridge near the margin of the valves. Surface of valves mostly smooth, in some specimens covered with punctae.

Dimensions (mm): Length 0.44–0.64, height 0.23–0.38.

Material: 120 carapaces from 9 samples.

Distribution: Frequent in Morrison zone 4 (Kimmeridgian) on the Colorado Plateau and in Wyoming, rare findings in Morrison zone 5 (? Tithonian) on the Colorado Plateau and in Oklahoma.

Helmdachia turneri n. sp.
(Pl. 2, Figs. 10–11)

Derivation of name: In honor of Dr. Christine E. Turner (U.S. Geological Survey, Denver) who has carried out extensive work on the Morrison Formation.

Diagnosis: A species of the genus Helmdachia with the following features: Median ridge curved, running from slightly anterior to the center down to the posterior ventral angle. Dorsal margin straight and horizontal. Ventral margin concave. Surface of valves covered with coarse reticulation.

Holoype: Carapace from sample 1381-A+1, MES 371 (Pl. 2, Fig. 10).

Paratypes: 2 valves and one carapace from sample 1381-A+1, MES 372 (Pl. 2, Fig. 11).

Type locality: Tri-Moon Wash section: E½ NE¼ Sec. 19, E½ SE¼, SE¼ NE¼ Sec. 18,

T. 54 N., R. 91 W., Bighorn Co., Wyoming; Leavitt Reservoir 7.5' Quadrangle.

Type level: Lower part of Morrison Formation, Kimmeridgian, biozone 3 (this paper), 52 meters above Sundance Formation (Tri-Moon Wash section).

Description: Carapace small, trapezoidal in lateral outline. Greatest height along the dorsal margin which is straight and horizontal; greatest length at about ⅓ height. Anterior margin equally rounded. Posterocardinal angle distinct and sharp; anterocardinal angle distinct, but rounded, with a weakly developed eye spot directly below (Pl. 2, Fig. 11). Shallow sulcus slightly anterior to center, extending from dorsal margin down to midheight. Posterior margin strongly infracurvate, straight in upper part. Ventral margin concave. From the base of the sulcus, a curved median ridge extends down to the posterior ventral angle. Surface of valves covered with coarse reticulation.

Dimensions (mm): Length 0.39–0.48, height 0.23–0.26.

Material: 5 valves and carapaces from 2 samples.

Distribution: A rare species in Morrison zone 3 (Kimmeridgian) of Wyoming.

Helmdachia prima n. sp.
(Pl. 2, Figs. 13–14)

Derivation of name: Latin, primus the first, relating to the first appearance of the genus.

Diagnosis: A species of the genus Helmdachia with the following features: Median ridge curved, running from slightly anterior to the center down to the posterior ventral angle. Dorsal margin almost straight and horizontal, shallow concave in the anterior part. Ventral margin almost straight and horizontal, shallow concave in the posterior part. Surface of valves covered with ridges which mostly follow the outline.

Holoype: Carapace from sample 1392-6, MES 373 (Pl. 2, Fig. 13).

Paratypes: 2 carapaces from sample 1392-6, MES 374 (Pl. 2, Fig. 14).

Type locality: Ladder Canyon section: NE¼ NW¼ Sec. 30, T. 12 S., R. 100 W., Mesa Co., Colorado; Island Mesa 7.5' Quadrangle.

Type level: Lowermost part of Morrison Formation, Kimmeridgian, biozone 1 (this paper), 8 meters above Wanakah Formation (Ladder Canyon section).

Description: Carapace small, trapezoidal to elongated-oval in lateral outline. Anterior margin equally rounded. Posterior margin infracurvate. Dorsal margin almost straight and horizontal, shallow concave in the anterior part; ventral margin almost straight and horizontal, but shallow concave in the posterior part. Posterocardinal angle indistinct; anterocardinal angle distinct, but rounded, with a weakly developed eye spot directly below (Pl. 2, Fig. 14). Shallow sulcus slightly anterior to center, extending from dorsal margin down to midheight. From the base of the sulcus, a weakly developed, curved median ridge extends down to the posterior ventral angle. Surface of valves covered with ridges which mostly follow the outline. These ridges are almost as coarse as the median ridge.

Dimensions (mm): Length 0.42–0.44, height 0.21–0.22.

Material: 3 carapaces from one sample.

Distribution: A rare species in Morrison zone 1 (Kimmeridgian) of the Colorado Plateau.

REFERENCES CITED

Bate, R., 1977, Jurassic Ostracoda of the Atlantic Basin; in, Swain, F. M., (ed.), Stratigraphic micropalaeontology of Atlantic Basin and Borderlands: Developments in Stratigraphy and Palaeontology, v. 6, p. 231–242.

Branson, C.C., 1935, Freshwater invertebrates from the Morrison (Jurassic?) of Wyoming: Journal of Paleontology, v. 9, p. 514–522..

Branson, C.C., 1936, New name for a Morrison ostracode genus: Journal of Paleontology, v. 10, p. 323.

Branson, C.C., 1961, Note on the freshwater ostracode genus Theriosynoecum: Oklahoma Geology Notes, v. 21, p. 246–247.

Branson, C. C., 1964, Morrison fresh-water fauna in Wyoming: Oklahoma Geology Notes, v. 24, p. 238–243.

Branson, C. C., 1966, Freshwater ostracode genus Theriosynoecum: Oklahoma Geology Notes, v. 26, p. 87–96.

Brenner, P., 1976, Ostracoden und Charophyten des nordspanischen Wealden: Palaeontographica, (A), v. 152, p. 113–201.

Condon, S.M. and Peterson, Fred, 1986, Stratigraphy of Middle and Upper Jurassic rocks of the San Juan Basin: Historical perspective, current ideas, and remaining problems, in, Turner-Peterson, C.E., Santos, E.S. and Fishman, N.S., (eds.), A basin analysis case study—The Morrison Formation, Grants Uranium region, New Mexico: American Association of Petroleum Geologists Studies in Geology 22, p. 7–26.

Harper, F. and Sutton, A.H., 1935, Ostracodes of the Morrison Formation from the Black Hills, South Dakota: Journal of Paleontology, v. 9, p. 623–628.

Helmdach, F.-F., 1971, Stratigraphy and ostracod-fauna from the coal mine Guimarota (Upper Jurassic): Memoria dos Servicos Geologicos de Portugal, v. 17, p. 43–88.

Helmdach, F.-F., 1979, Möglichkeiten der Verbreitung nichtmariner Ostrakodenpopulationen und deren Auswirkungen auf die Phylogenie und Stratigraphie: Neues Jahrbuch für Geologie und Paläontologie, Monatshefte, v. 6, p. 378–384.

Jones, T.R., 1886, On some fossil Ostracoda from Colorado: Geological Magazine, New Series, v. 3, p. 145–148.

Kilenyi, T.I. and Allen, N.W., 1968, Marine-brackish bands and their microfauna from the lower part of the Weald Clay of Sussex and Surrey: Palaeontology, v. 11, p. 141–162.

Knechtel, M.M., 1959, Stratigraphy of the Littel Rocky Mountains and encircling foothills, Montana: U.S. Geological Survey Bulletin 1072-N, p. 723–752.

Kowallis, B.J., Christiansen, E.H., Deino, A.L., Peterson, Fred, Turner, C.E., Kunk, M.J., and Obradovich, J.D., 1998, The age of the Morrison Formation: Modern Geology, v. 22, nos. 1-4, p. 235-260. .

Litwin, R.J., Turner, C.E., and Peterson, F., 1998, Palynological evidence on the age of the Morrison Formation, Western Interior, U.S.: Modern Geology, v. 22, nos. 1-4, p. 297-320. .

Moore, G.T., Hayashida, D.N., Ross, C.A., and Jacobson, S.R., 1992a, Paleoclimate of the Kimmeridgian/Tithonian (Late Jurassic) world: I, Results using a general circulation model: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 93, p. 113–150.

Moore, G.T., Sloan, L.C., Hayashida, D.N., and Umrigar, N.P., 1992b, Paleoclimate of the Kimmeridgian/Tithonian (Late Jurassic) world: II, Sensitivity tests comparing three different paleotopographic settings: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 95, p. 229–252.

Neale, J.W., 1988, Ostracods and palaeosalinity reconstruction, in, De Deckker, P., Colin, J.-P., and Peypouquet, J.-P., (eds.), Ostracoda in the Earth Sciences: Elsevier Scientific Publishing Co., Amsterdam, p. 125–155.

Ott, H.L., 1958, Stratigraphic distribution of Charophyta in the Morrison Formation of Colorado and Utah: Unpublished M.A. thesis, University of Missouri, Columbia, 132 p.
Parrish, J.T. and Peterson, F., 1988, Wind directions predicted from global circulation models and wind directions determined from eolian sandstones of the western United States—A comparison: Sedimentary Geology, v. 56, p. 261–282.
Peck, R.E., 1937, Morrison Charophyta from Wyoming: Journal of Paleontology, v. 11, p. 83–90.
Peck, R.E., 1957, North American Mesozoic Charophyta: U.S. Geological Survey Professional Paper 294-A, 44 p.
Peck, R.E. and Reker, C.C., 1948, The Morrison and Cloverly Formations, in, Maebius, J.B., (ed.), Wind River Basin, Wyoming: Wyoming Geological Association, 3rd Annual Field Conference Guidebook, p. 125–139.
Peterson, Fred, 1988, Pennsylvanian to Jurassic eolian transportation systems in the western United States: Sedimentary Geology, v. 56, p. 207–260.
Peterson, Fred, 1994, Sand dunes, sabkhas, streams, and shallow seas: Jurassic paleogeography in the southern part of the Western Interior Basin, in, Caputo, M.V., Peterson, J.A., and Franczyk, K.J., (eds.), Mesozoic Systems of the Rocky Mountain Region, USA: Rocky Mountain Section SEPM (Society for Sedimentary Geology), p. 233–272.
Peterson, Fred and Turner, C.E., 1998, Stratigraphy of the Ralston Creek and Morrison Formations (Upper Jurassic) near Denver, Colorado: Modern geology, v. 22, nos. 1-4, p. 3-38. .
Pinto, I.D. and Sanguinetti, Y.T., 1962, A complete revision of the genera Bisulcocypris and Theriosynoecum (Ostracoda) with the world geographical and stratigraphical distribution: Escola de Geología de Puerto Alegre, Publicación Especial 4, 165 p.
Ross, C.A., 1960, Population study of charophyte species, Morrison Formation, Colorado: Journal of Paleontology, v. 34, p. 717–726.
Roth, Robert, 1933, Some Morrison Ostracoda: Journal of Paleontology, v. 7, p. 398–405.
Schudack, M.E., 1987, Charophytenflora und fazielle Entwicklung der Grenzschichten mariner Jura/Wealden in den Nordwestlichen Iberischen Ketten (mit Vergleichen zu Asturien und Kantabrien): Palaeontographica, (B), v. 204, p. 1–180.
Schudack, M.E., 1993a, Die Charophyten in Oberjura und Unterkreide Westeuropas. Mit einer phylogenetischen Analyse der Gesamtgruppe: Berliner geowissenschaftliche Abhandlungen, (E), v. 8, 209 p.
Schudack, M.E., 1993b, Möglichkeiten palökologischer Aussagen mit Hilfe von fossilen Charophyten: Festschrift Prof. W. Krutzsch, Berlin, Museum für Naturkunde, p.39–60.
Schudack, M.E., 1995, Neue mikropaläontologische Beiträge (Ostracoda, Charophyta) zum Morrison-Ökosystem (Oberjura des Western Interior, USA): Berliner geowissenschaftliche Abhandlungen, (E), v. 16, p. 389–407.
Schudack, U., 1989, Zur Systematik der oberjurassischen Ostracodengattung Cetacella Martin 1958 (syn. Leiria Helmdach 1971): Berliner geowissenschaftliche Abhandlungen, (A), v. 106, p. 459–471.
Schudack, U., 1994, Revision, Dokumentation und Stratigraphie der Ostracoden des nordwestdeutschen Oberjura und Unter-Berriasium: Berliner geowissenschaftliche Abhandlungen, (E), v. 11, 193 p.
Scott, G.R., 1963, Bedrock geology of the Kassler Quadrangle, Colorado: U.S. Geological Survey Professional Paper 421-B, p. 71–125.
Smith, A.G., Smith, D.G., and Funnel, B.M., 1994, Atlas of Mesozoic and Cenozoic coastlines: Cambridge University Press, New York, 99 p.

Smith, D.G., 1994, Paleogeographic evolution of the western Canada foreland basin, in, Mossop, G. and Shetsen, I. (compilers), Geological Atlas of the Western Canada Sedimentary Basin: Canadian Society of Petroleum Geologists and Alberta Research Council, p. 277–296.

Sohn, I.G., 1951, Check list of salinity tolerance of post-Paleozoic fossil Ostracoda: Journal of the Washington Acadamey of Science, v. 41, p. 64–66.

Sohn, I.G., 1958, Middle Mesozoic non-marine ostracodes of the Black Hills, in, Strickland, J., (ed.), Powder River Basin: Wyoming Geological Association, 13th Annual Field Conference Guidebook, p. 120–126.

Sohn, I. G., 1979, Nonmarine ostracodes in the Lakota Formation (Lower Cretaceous) from South Dakota and Wyoming: U.S. Geological Survey Professional Paper 1069, 24 p.

Sohn, I.G. and Peck, R.E., 1963, Theriosynoecum wyomingense (Branson 1935), a possible guide ostracode to the Salt Wash Member of the Morrison Formation: U.S. Geological Survey Bulletin 1161-A, 10 p.

Swain, F.M., 1946, Middle Mesozoic nonmarine Ostracoda from Brazil and New Mexico: Journal of Paleontology, v. 20, p. 543–555.

Tambareau, Y., 1982, Les ostracodes et l'évolution de l'Atlantique Nord au Crétacé: Bulletin de la Société Géologique de France, v. 24, p. 1077–1085.

Turner, C.E. and Fishman, N.S., 1991, Jurassic Lake T'oo'dichi': A large alkaline, saline lake, Morrison Formation, eastern Colorado Plateau: Geological Society of America Bulletin, v. 103, no. 4, p. 538–558.

Valdes, P.J. and Sellwood, B.W., 1992, A paleoclimate model for the Kimmeridgian: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 95, p. 47–72.

Waldschmidt, W.A. and LeRoy, L.W., 1944, Reconsideration of the Morrison Formation in the type area, Jefferson County, Colorado: Geological Society of America Bulletin, v. 55, p. 1097-1114.

Whatley, R., 1990, The relationship between extrinsic and intrinsic events in the evolution of Mesozoic non-marine Ostracoda, in, Kaufmann, E.G., and Walliser, O.H., (eds.), Extinction Events in Earth History: Lecture Notes in Earth Sciences, v. 30, p. 253-263.

Whatley, R., 1992, The reproductive and dispersal strategies of Cretaceous nonmarine Ostracoda: The key to pandemism; in, Mateer, N. J., and Chen, P.-J., (eds.), Aspects of nonmarine Cretaceous geology: Proceedings of the First International Symposium "Nonmarine Cretaceous Correlations", Urumqui, China, 1987, p. 177–192.

Ziegler, P. A., 1988, Evolution of the Arctic-North Atlantic and the Western Tethys: American Association of Petroleum Geologists Memoir 43, 198 p.

APPENDIX

TABLE 1

LOCATION OF MEASURED SECTIONS

Measured Section No.	Name and location
1.	Kenton: C-SW¼ Sec. 18, T. 5 N., R. 1 E., Cimarron Co., Oklahoma; Kenton 7.5' Quadrangle. Modified from measured section 1 of West (1975) with samples projected in from various localities near Kenton and Boise City, Oklahoma.
2.	Trujillo: NE¼ NE¼ Sec. 22, T. 15 N., R. 21 E., San Miguel Co., New Mexico; Trujillo 7.5' Quadrangle.
3.	Felch Creek: NW¼, NW¼ SE¼ Sec. 26, T. 17 S., R. 70 W., Fremont Co., Colorado; Cooper Mountain 7.5' Quadrangle.
4.	Dilley Ranch: NE¼ SE¼ Sec. 28, T. 17 S., R. 70 W., Fremont Co., Colorado; Cooper Mountain 7.5' Quadrangle.
5.	Cope's Nipple: SE¼ SW¼ Sec. 21, NE¼ NW¼ Sec. 28, T. 17 S., R. 70 W., Fremont Co., Colorado; Cooper Mountain 7.5' Quadrangle.
6.	Alameda Parkway: S½ NE¼ NW¼, NE¼ SE¼ NW¼ Sec. 26, T. 4 S., R. 70 W., Jefferson Co., Colorado; Morrison 7.5' Quadrangle.
7.	Highway I-70: W½ NW¼ SW¼ Sec. 14, T. 4 S., R. 70 W., Jefferson Co., Colorado; Morrison 7.5' Quadrangle.
8.	Owl Canyon: SE¼ NE¼ NW¼ SW¼, NW¼ NE¼ SW¼, SE¼ SW¼ SE¼ NW¼ Sec. 32, T. 10 N., R. 69 W., Larimer Co., Colorado; Livermore 7.5' Quadrangle.
9.	Piedmont: NE¼ NE¼ NE¼, SE¼ NE¼ NE¼ Sec. 25, T. 3. N., R. 6 E., N½ NW¼ SW¼ NW¼ Sec. 30, T. 3 N., R. 7 E., Meade Co., South Dakota; Blackhawk 7.5' Quadrangle.
10.	Dinosaur National Monument (Dinosaur Quarry West): NW¼ NW¼ SW¼ Sec. 26, E½ NE¼ SE¼ Sec. 27, T. 4 S., R. 23 E.,Uintah Co., Utah; Dinosaur Quarry 7.5' Quadrangle.
11.	Cleveland-Lloyd Quarry: SW¼ SE¼ SE¼, NE¼ SE¼ SW¼ SE¼, SW¼ NE¼ SW¼ SE¼ Sec. 21, T. 17 S., R. 11 E., Emery Co., Utah; Cow Flats 7.5' Quadrangle.
12.	No Thoroughfare Canyon: S½ S½ SE¼ Sec. 32, T. 1 S., R. 1 W., Mesa Co., Colorado; Grand Junction 7.5' Quadrangle.
13.	Ladder Canyon: NE¼ NW¼ Sec. 30, T. 12 S., R. 100 W., Mesa Co., Colorado; Island Mesa 7.5' Quadrangle.
14.	Broughton Fruit Farm: SE¼ NE¼ SW¼ Sec. 26, T. 14 S., R. 98 W., Delta Co., Colorado; Dominguez 7.5' Quadrangle.
15.	Main Elk Creek: NE¼ SW¼ SE¼ Sec. 15, T. 5 S., R. 91 W., Garfield Co., Colorado; New Castle 7.5' Quadrangle.
16.	Ninemile Hill: SW¼ NE¼ NW¼, C-N½ SE¼ NW¼ Sec. 23, T. 23 N., R. 78 W., Carbon Co., Wyoming; Medicine Bow 7.5' Quadrangle.

17. Poison Creek: SW¼ NW¼, NW¼ SW¼ Sec. 36, T. 47 N., R. 83 W., Johnson Co., Wyoming; Hazelton 7.5' Quadangle.
18. Tri-Moon Wash: E½ NE¼ Sec. 19, E½ SE¼, SE¼ NE¼ Sec. 18, T. 54 N., R. 91 W., Bighorn Co., Wyoming; Leavitt Reservoir 7.5' Quadrangle.
19. Devil's Slide: SW¼ NW¼ SE¼ Sec. 31, T. 8 S., R. 8 E., Park Co., Montana; Electric Peak 7.5' Quadrangle.
20. Strickland Creek: W½ NW¼ NW¼ Sec. 29, T. 3 S., R. 9 E., Park Co., Montana; Chimney Rock 7.5' Quadrangle.

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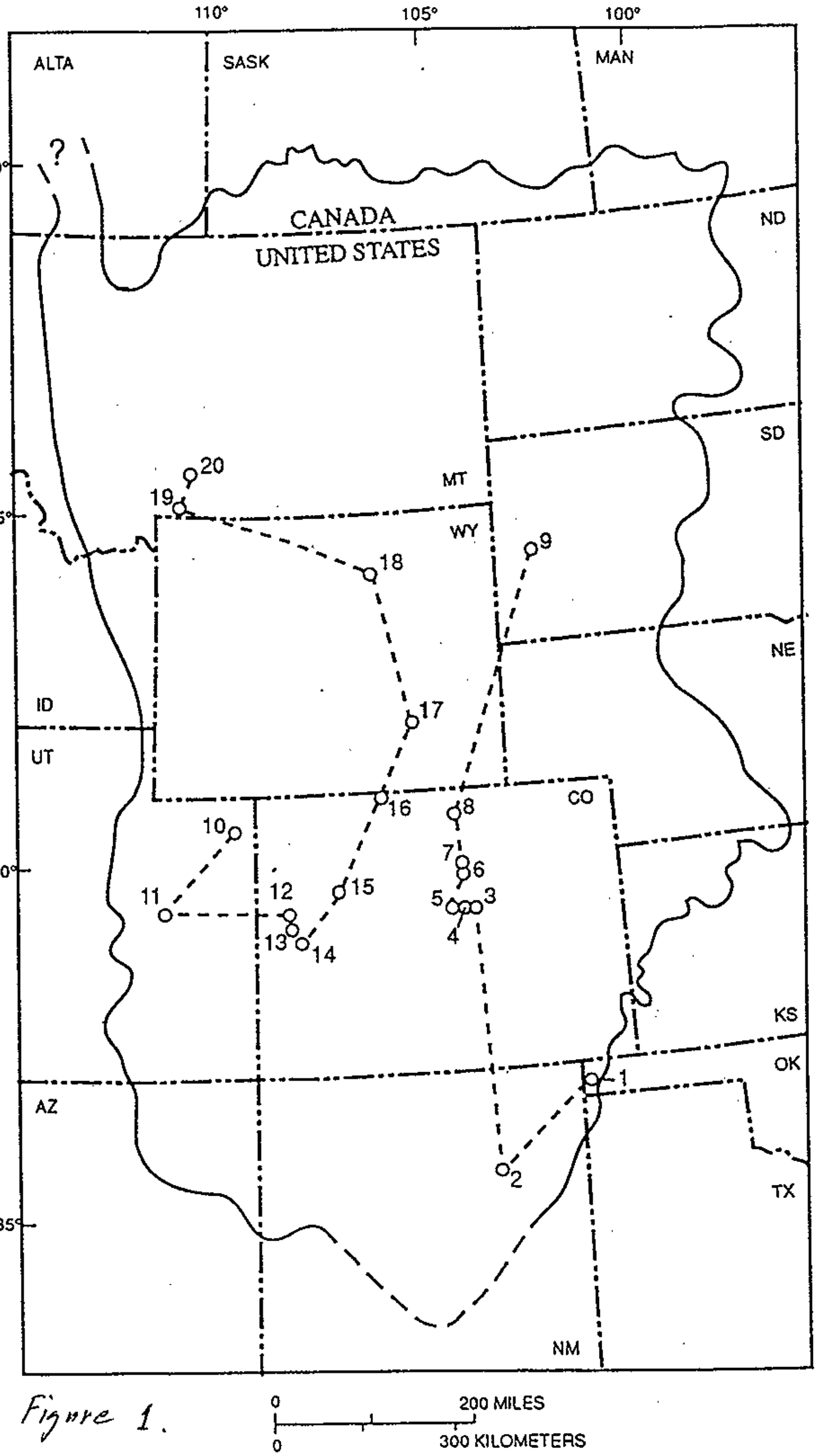
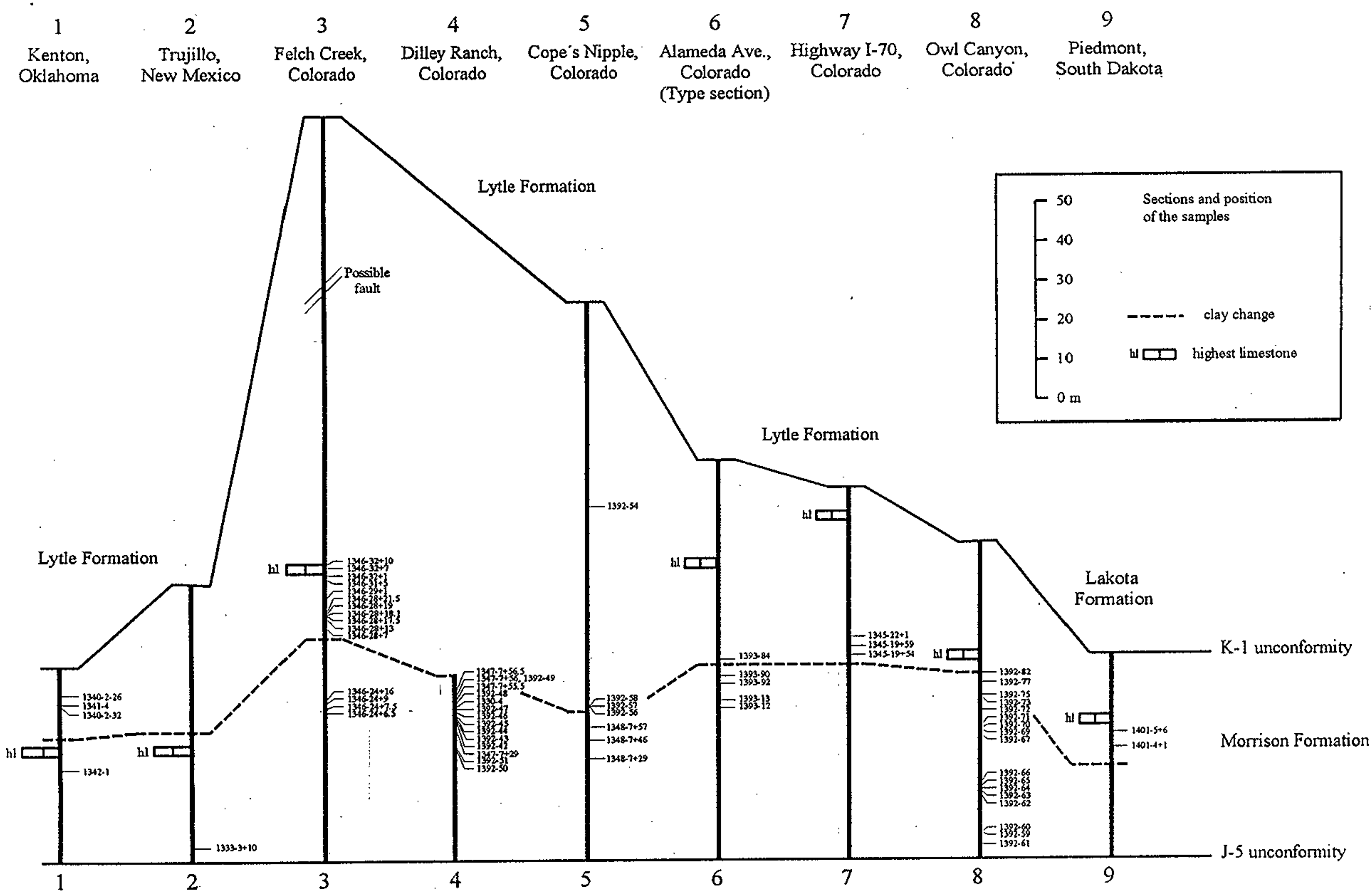
Figure 1.—Map showing outline of Morrison depositional basin and location of measured sections. Dashed lines indicate the lines of the sections in Figures 2 and 3. Detailed locations are in Table 1 of the Appendix.



110°
105°
100°
50°
45°
40°
35°
ALTA
SASK
MAN
?
CANADA
UNITED STATES
ND
SD
MT
WY
NE
ID
UT
CO
KS
OK
AZ
TX
NM
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
0
200 MILES
0
300 KILOMETERS

Figure 1.

Figure 2.—Panel of measured sections in the eastern area of Figure 1 and the stratigraphic position of the charophyte and ostracode samples. The Ralston Creek Formation is 20.7 m (68 ft) thick at section 7 but is not shown separately. The lower part of the Ralston Creek is concealed at section 6 where the position of the J-5 surface is projected from nearby sections to the north and south (see Peterson and Turner, in press).



1
Kenton, Oklahoma
2
Trujillo, New Mexico
3
Felch Creek, Colorado
4
Dilley Ranch, Colorado
5
Cope's Nipple, Colorado
6
Alameda Ave., Colorado (Type section)
7
Highway I-70, Colorado
8
Owl Canyon, Colorado
9
Piedmont, South Dakota
Lytle Formation
Possible fault
Lytle Formation
Lytle Formation
Lakota Formation
K-1 unconformity
Morrison Formation
J-5 unconformity
50
40
30
20
10
0 m
Sections and position of the samples
clay change
hl
highest limestone
1392-54
1340-2-26
1341-4
1340-2-32
1342-1
1333-3+10
1348-7+57
1348-7+46
1348-7+29
1393-84
1345-22+1
1345-19+59
1345-19+54
1401-5+6
1401-4+1
1
2
3
4
5
6
7
8
9

Figure 2.

297

Figure 3.—Panel of measured sections in the western area of Figure 1 and the stratigraphic position of the charophyte and ostracode samples.

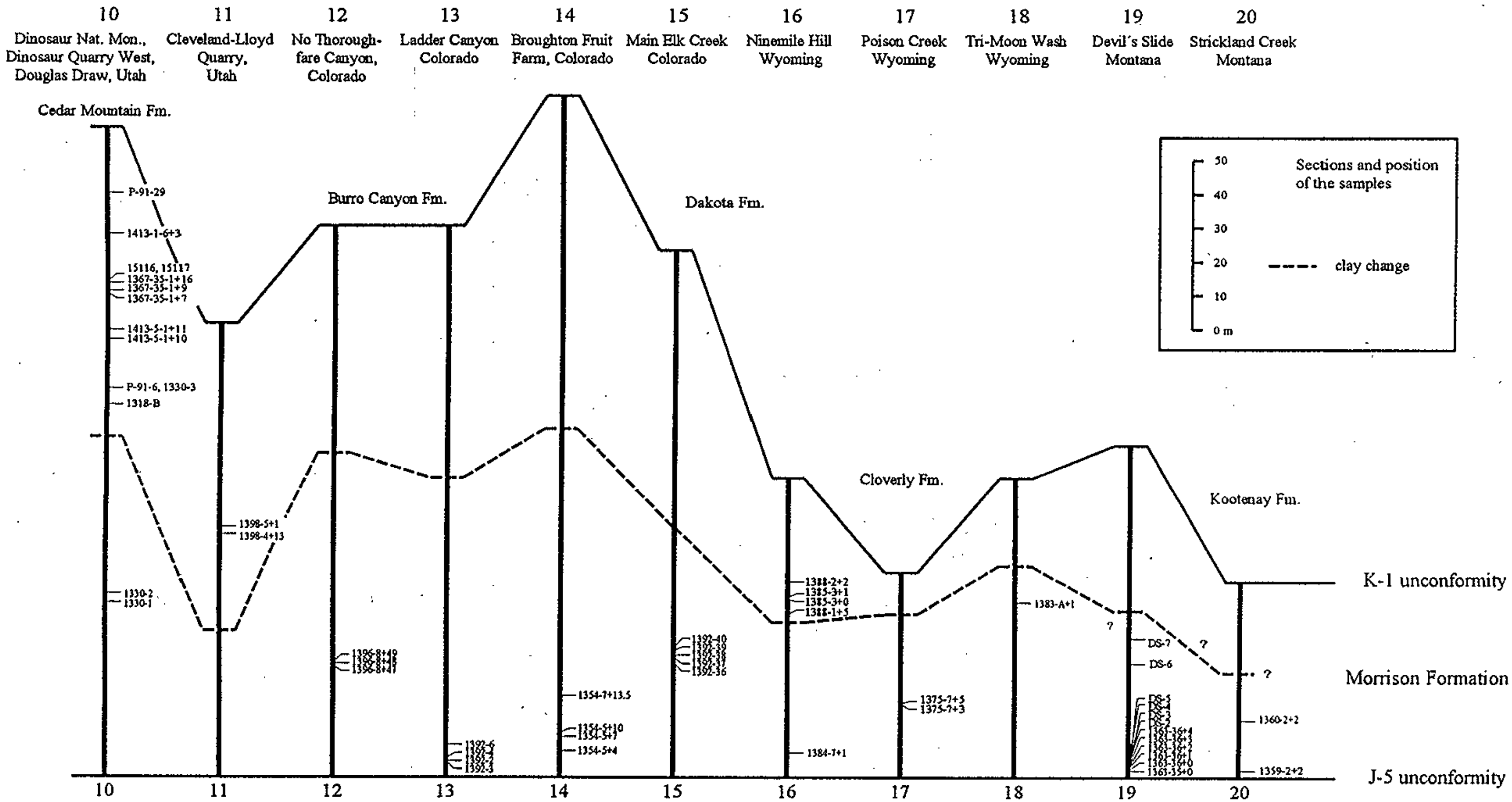

10
Dinosaur Nat. Mon., Dinosaur Quarry West, Douglas Draw, Utah
11
Cleveland-Lloyd Quarry, Utah
12
No Thoroughfare Canyon, Colorado
13
Ladder Canyon Colorado
14
Broughton Fruit Farm, Colorado
15
Main Elk Creek Colorado
16
Ninemile Hill Wyoming
17
Poison Creek Wyoming
18
Tri-Moon Wash Wyoming
19
Devil's Slide Montana
20
Strickland Creek Montana
Cedar Mountain Fm.
Burro Canyon Fm.
Dakota Fm.
Cloverly Fm.
Kootenay Fm.
Sections and position of the samples
50
40
30
20
10
0 m
clay change
P-91-29
1413-1-6+3
15116, 15117
1367-35-1+16
1367-35-1+9
1367-35-1+7
1413-5-1+11
1413-5-1+10
P-91-6, 1330-3
1318-B
1330-2
1330-1
1398-5+1
1398-4+13
1354-7+13.5
1354-5+4
1384-7+1
1375-7+5
1375-7+3
1383-A+1
DS-7
DS-6
1360-2+2
1359-2+2
K-1 unconformity
Morrison Formation
J-5 unconformity
10
11
12
13
14
15
16
17
18
19
20

Figure 3.

Figure 4.—Stratigraphic range and relative abundance of charophyte taxa in the Morrison Formation. The five local biozones are indicated by numbers on the right. 50 percent refers to the thickness from the clay change to the appropriate unconformity.

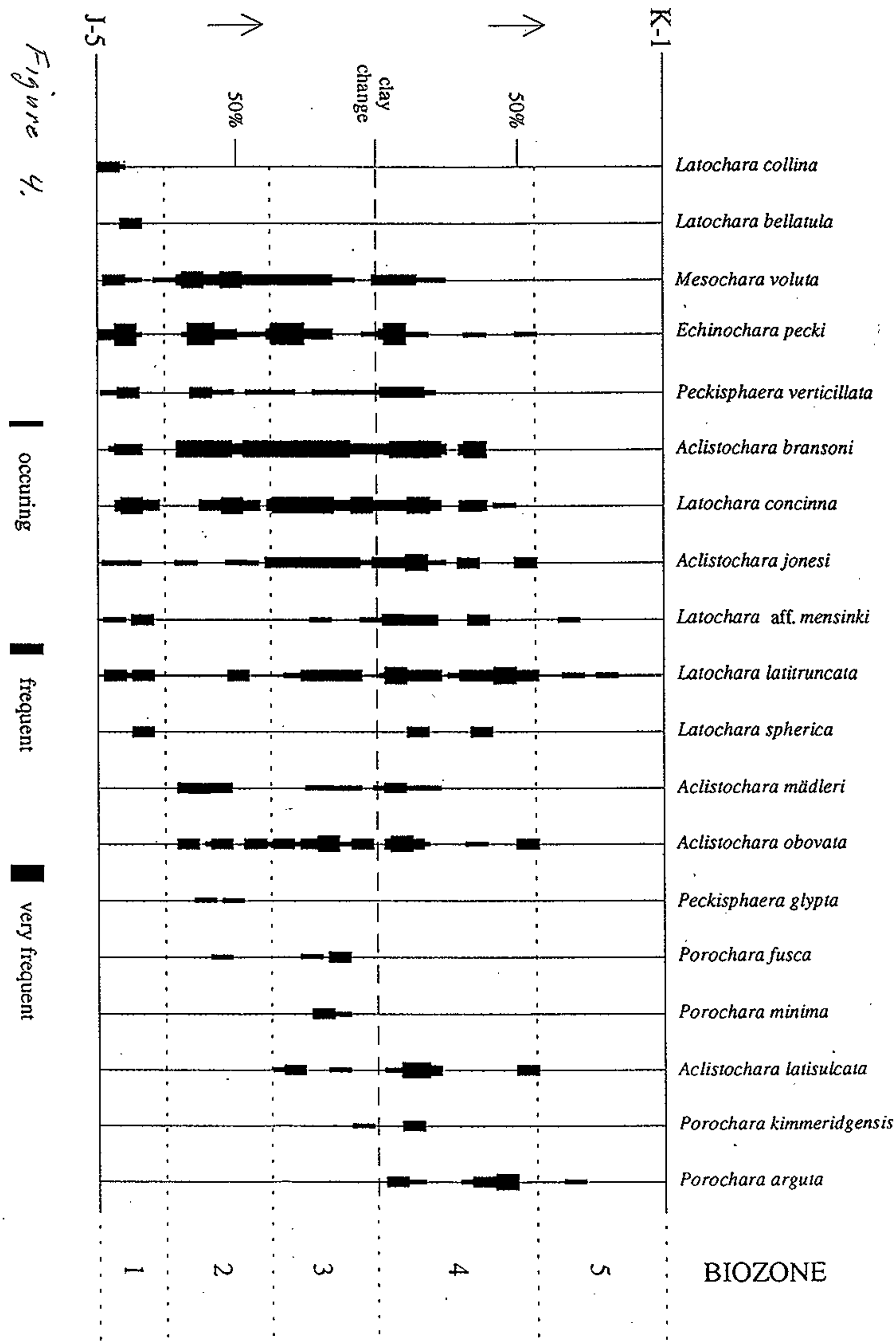

J-5
K-1
50%
clay change
50%
Latochara collina
Latochara bellatula
Mesochara voluta
Echinochara pecki
Peckisphaera verticillata
Aclistochara bransoni
Latochara concinna
Aclistochara jonesi
Latochara aff. mensinki
Latochara latitruncata
Latochara spherica
Aclistochara mädleri
Aclistochara obovata
Peckisphaera glypta
Porochara fusca
Porochara minima
Aclistochara latisulcata
Porochara kimmeridgensis
Porochara arguta
occuring
frequent
very frequent
1
2
3
4
5
BIOZONE

Figure 4.

Figure 5.—Stratigraphic range and relative abundance of ostracode taxa in the Morrison Formation. The five local biozones are indicated by numbers on the right. 50 percent refers to the thickness from the clay change to the appropriate unconformity.

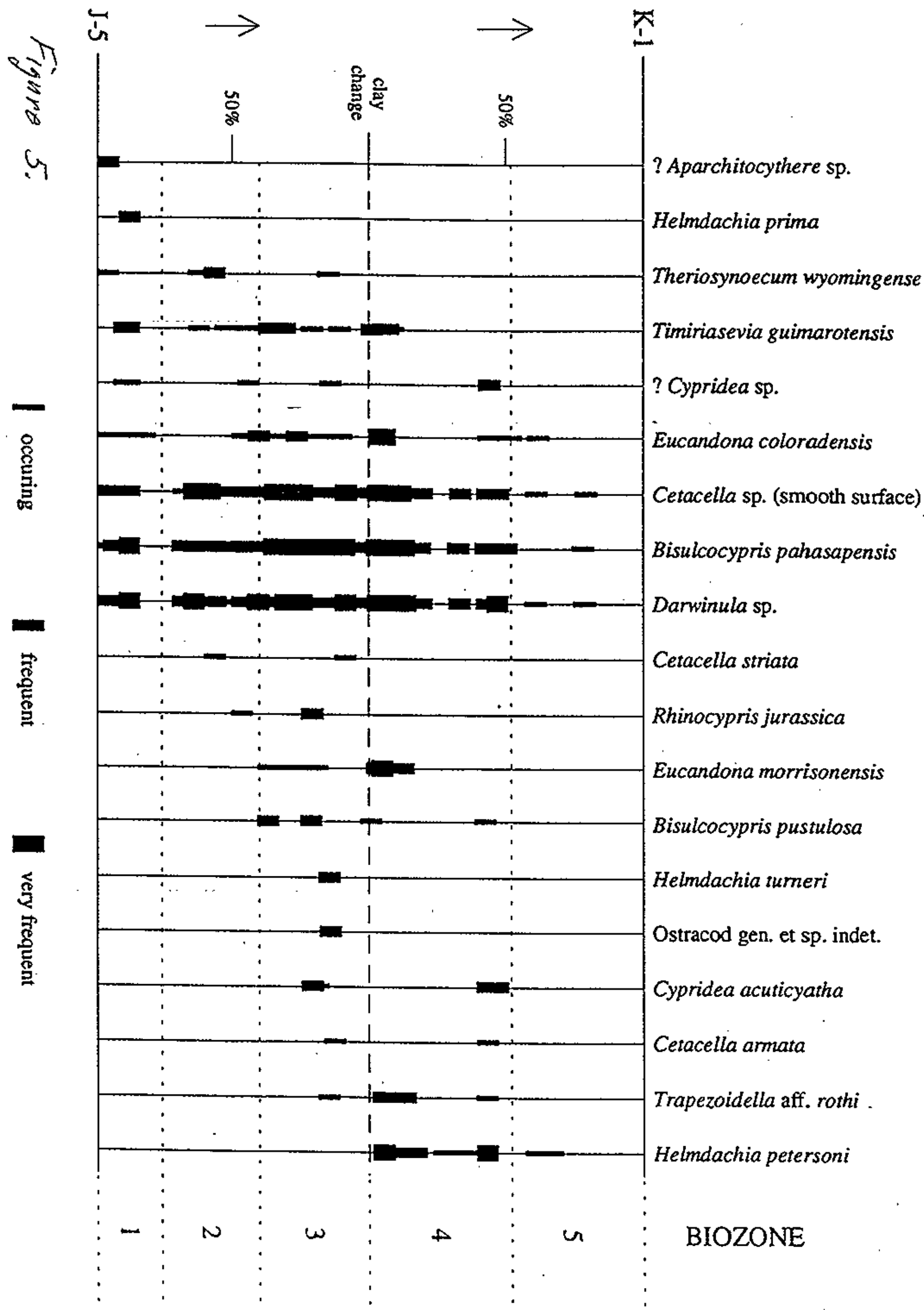
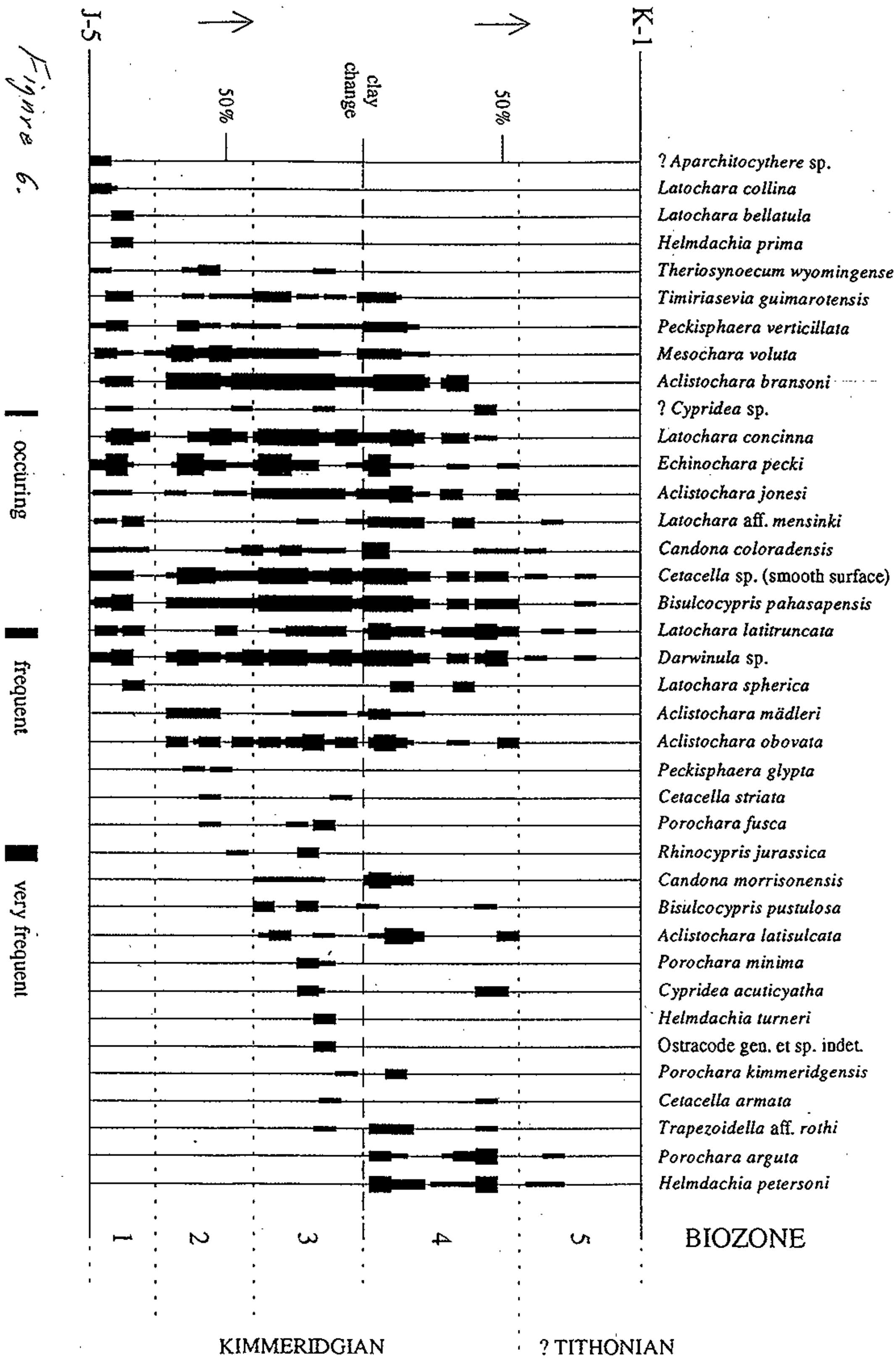

J-5
K-1
50%
clay change
50%
? Aparchitocythere sp.
Helmdachia prima
Theriosynoecum wyomingense
Timiriasevia guimarotensis
? Cypridea sp.
Eucandona coloradensis
Cetacella sp. (smooth surface)
Bisulcocypris pahasapensis
Darwinula sp.
Cetacella striata
Rhinocypris jurassica
Eucandona morrisonensis
Bisulcocypris pustulosa
Helmdachia turneri
Ostracod gen. et sp. indet.
Cypridea acuticyatha
Cetacella armata
Trapezoidella aff. rothi
Helmdachia petersoni
occuring
frequent
very frequent
1
2
3
4
5
BIOZONE

Figure 5.

Figure 6.—Summary of the stratigraphic range and relative abundance of charophyte and ostracode taxa in the Morrison Formation. The five local biozones and their ages are indicated to the right. 50 percent refers to the thickness from the clay change to the appropriate unconformity.



J-5
K-1
50%
clay change
50%
? Aparchitocythere sp.
Latochara collina
Latochara bellatula
Helmdachia prima
Theriosynoecum wyomingense
Timiriasevia guimarotensis
Peckisphaera verticillata
Mesochara voluta
Aclistochara bransoni
? Cypridea sp.
Latochara concinna
Echinochara pecki
Aclistochara jonesi
Latochara aff. mensinki
Candona coloradensis
Cetacella sp. (smooth surface)
Bisulcocypris pahasapensis
Latochara latitruncata
Darwinula sp.
Latochara spherica
Aclistochara mädleri
Aclistochara obovata
Peckisphaera glypta
Cetacella striata
Porochara fusca
Rhinocypris jurassica
Candona morrisonensis
Bisulcocypris pustulosa
Aclistochara latisulcata
Porochara minima
Cypridea acuticyatha
Helmdachia turneri
Ostracode gen. et sp. indet.
Porochara kimmeridgensis
Cetacella armata
Trapezoidella aff. rothi
Porochara arguta
Helmdachia petersoni
occuring
frequent
very frequent
1
2
3
4
5
BIOZONE
KIMMERIDGIAN
? TITHONIAN

Figure 6.

Figure 7.—Salinity tolerances of Morrison ostracode and charophyte genera based upon Sohn (1951, 1979), Kilenyi and Allen (1968), Brenner (1976), Neale (1988), and M.E. Schudack (1993ab).

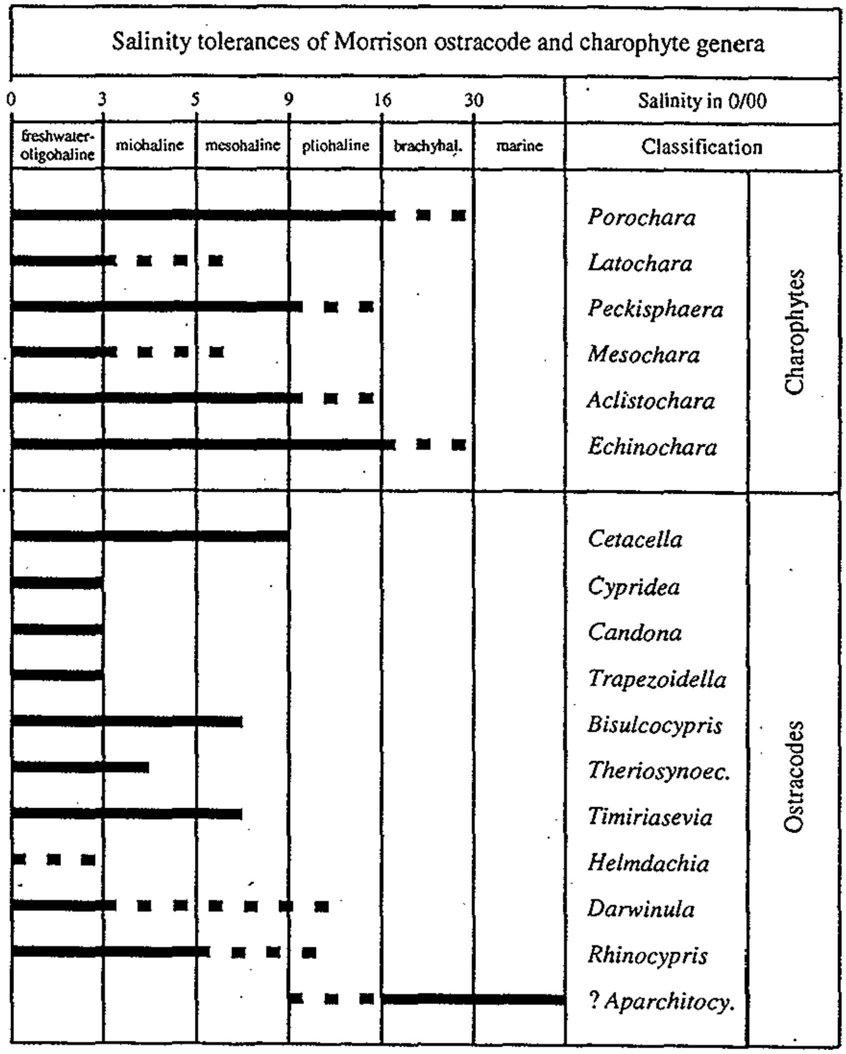

Salinity tolerances of Morrison ostracode and charophyte genera
0
3
5
9
16
30
Salinity in 0/00
freshwater-oligohaline
miohaline
mesohaline
pliohaline
brachyhal.
marine
Classification
Porochara
Latochara
Peckisphaera
Mesochara
Aclistochara
Echinochara
Charophytes
Cetacella
Cypridea
Candona
Trapezoidella
Bisulcocypris
Theriosynoec.
Timiriasevia
Helmdachia
Darwinula
Rhinocypris
? Aparchitocy.
Ostracodes

Figure 7.

Figure 8.—Occurrences of Morrison ostracodes in the Western Interior and western Europe. The figure illustrates the Importance of dispersal strategies, sexual dimorphism, and paleogeography for the two superfamilies.

Occurrences of nonmarine ostracodes Paleobiogeography		Sexual dimorphism	1 Western Interior	2 Portugal	3 N and E Spain	4 Northern Germany
Cypridacea	*Cetacella armata*	—	●	●	●	●
	Cetacella striata	—	●	●	●	●
	Cypridea acuticyatha	—	●			
	Candona coloradensis	—	●			●
	Candona morrisonensis	—	●			
	Rhinocypris jurassica	—	●	●	●	●
Cytheracea	*Bisulcocypris pahasapensis*	+	●	●	●	
	Bisulcocypris pustulosa	+	●			
	Theriosynoecum wyomingense	+	●	●	●	
	Timiriasevia guimarotensis	+	●	●		
	Helmdachia petersoni	+	●			
	Helmdachia turneri	?	●			
	Helmdachia prima	?	●			

Bay of Biscay Rift and Proto-North Atlantic

Figure 8.

Figure 9.—Occurrences of Morrison charophytes in the Western Interior and western Europe. A paleoclimatic boundary separates a northern flora (Western Interior and northern Germany) from a southern flora (Iberian Peninsula).

Occurrences of charophytes Paleobiogeography	1 Western Interior	4 Northern Germany	2 Portugal	3 N and E Spain
Porochara arguta	●			
Porochara fusca	●	●	●	●
Porochara kimmeridgensis	●	●	●	●
Porochara minima	●	●		
Latochara bellatula	●			
Latochara collina	●			
Latochara concinna	●			
Latochara latitruncata	●	●		
Latochara spherica	●			
Aclistochara obovata	●			
Aclistochara bransoni	●	●		
Aclistochara jonesi	●			
Aclistochara latisulcata	●			
Aclistochara mädleri	●			
Peckisphaera verticillata	●			
Peckisphaera glypta	●			
Mesochara voluta	●	●		●
Echinochara pecki	●	●	●	●

Figure 9.

paleoclimatic boundary

Plate 1.—Fig. 1, Cetacella armata Martin, left valve, MES 351, sample 1340-2-32 (x 93).
Fig. 2, Cetacella striata (Helmdach), left valve, MES 352, sample Conr.Morr. (x 63).
Fig. 3, Cetacella sp. (with smooth surface), left valve, MES 353, sample 1392-64 (x 78).
Figs. 4–6, Cypridea acuticyatha n. sp.: 4, left valve, MES 354, sample 1342-1 (x 58); 5, paratype, right valve, MES 355, sample 1340-2-32 (x 55); 6, holotype, left valve, MES 356, sample 1340-2-32 (x 55).
Figs. 7–9, Candona coloradensis n. sp., sample 1346-28+7; 7, holotype, left valve, MES 357 (x 34); 8, paratype, left valve, MES 358 (x 37); 9, paratype, dorsal view, MES 358 (x 35).
Figs. 10–11, Candona morrisonensis n. sp., sample 1346-28+7; 10, paratype, right valve, MES 359 (x 34); 11, holotype, right valve, MES 360 (x 35).
Fig. 12, Rhinocypris jurassica (Martin), right valve, MES 361, sample 1342-1 (x 120).
Fig. 13, Trapezoidella aff. rothi Sohn, left valve, MES 362, sample 1388-1+5 (x 88).
Fig. 14, Bisulcocypris pustulosa (Sohn), right valve, MES 363, sample 1392-67 (x 53).
Fig. 15, Bisulcocypris pahasapensis (Roth), male, left valve, MES 364, sample 1346-28+7 (x 53).

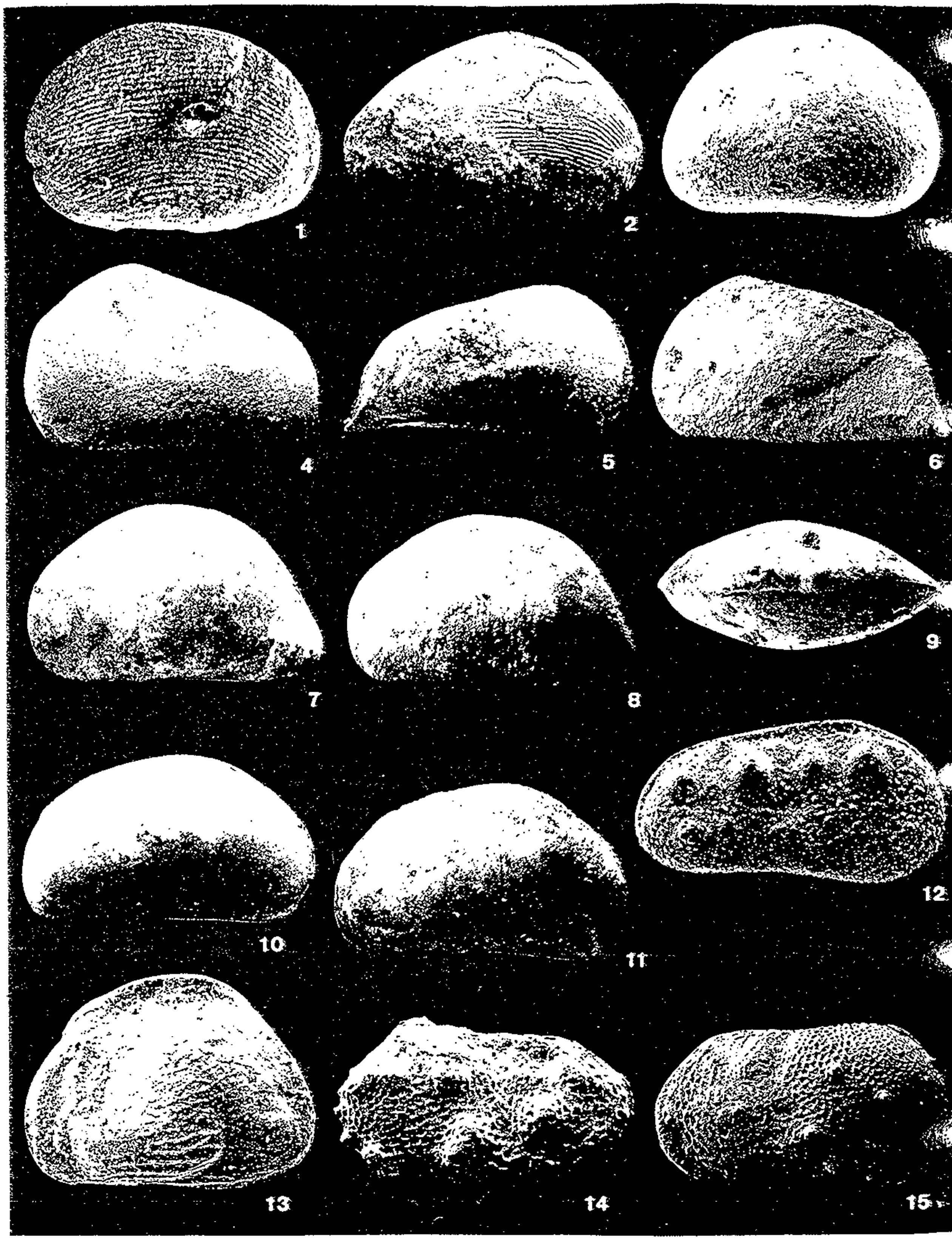


Plate 1

Plate 2.—Figs. 1–3, Timiriasevia guimarotensis n.sp., sample 1392-6; 1, holotype, male, left valve, MES 365 (x 105); 2, paratype, female, dorsal view, MES 366 (x 70); 3, paratype, male, dorsal view, MES 366 (x 102).

Fig. 4, Theriosynoecum wyomingense (Branson), right valve, sample 1392-66, MES 367 (x 45).

Figs. 5–9, Helmdachia petersoni n.sp.; 5, holotype, right valve, MES 368, sample 1388-1+5, (x 98); 6, paratype, ventral view, MES 369, sample 1388-1+5, (x 120); 7, paratype, left valve, MES 369, sample 1388-1+5, (x 90); 8, left valve, MES 370, sample 1367-35-1+7, (x 120); 9, paratype, anterior view, MES 369, sample 1388-1+5, (x 107).

Figs. 10–11, Helmdachia turneri n.sp., sample 1381-A+1; 10, holotype, left valve, MES 371 (x 128); 11, paratype, right valve, MES 372 (x 115).

Fig. 12, Darwinula sp., right valve, MES 375, sample 1346-28+7, (x 65).

Figs. 13–14, Helmdachia prima n.sp., sample 1392-6; 13, holotype, right valve, MES 373 (x 128); 14, paratype, right valve, MES 374 (x 130).

Fig. 15, Ostracode gen. et sp. indet, ? left valve, MES 376, sample 1381-A+1, (x 98).

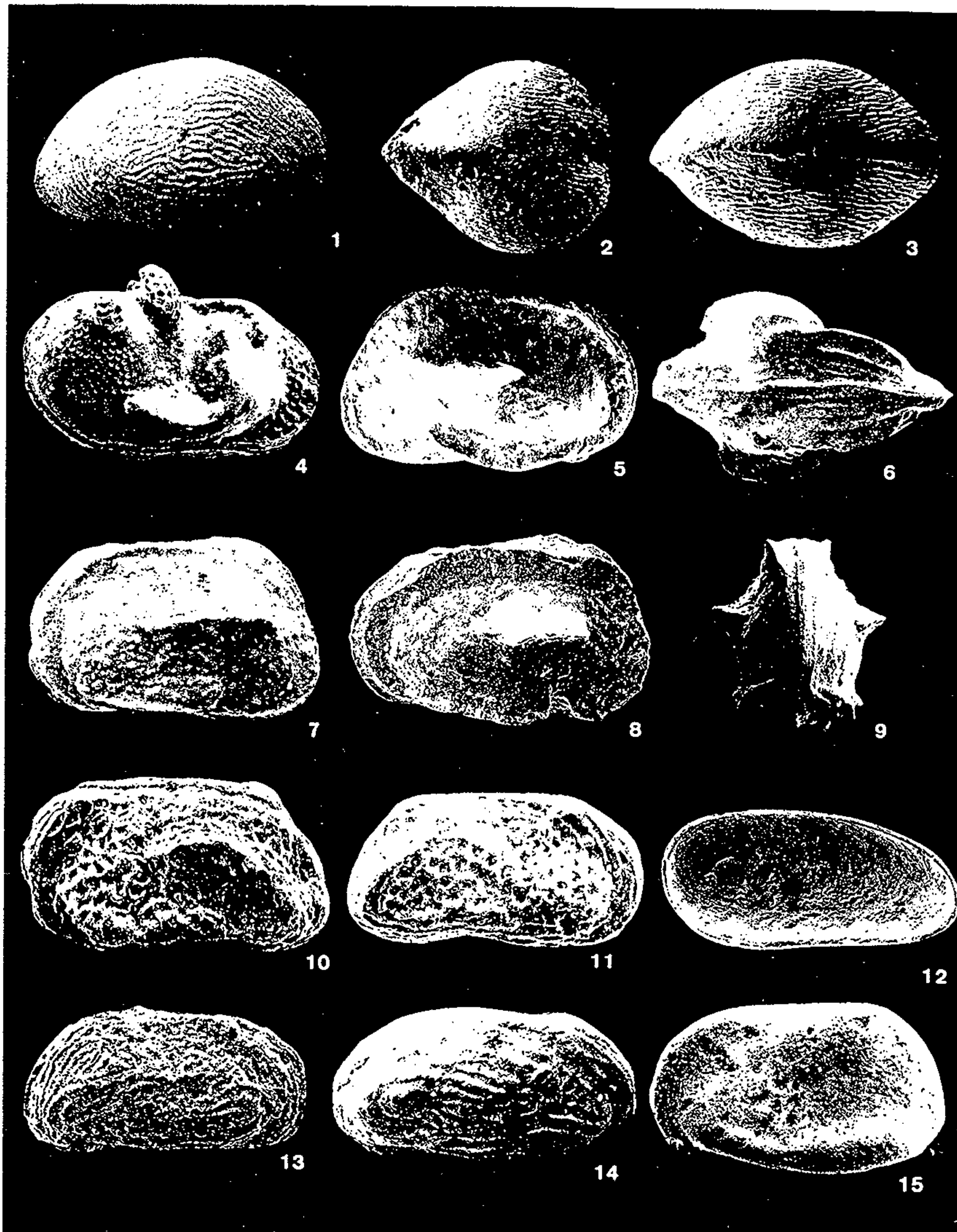


Plate 2.

Plate 3.—Fig. 1, Porochara arguta (Peck), MES 377, sample 1367-35-1+7 (x 95).
Fig. 2, Porochara kimmeridgensis (Mädler), MES 378, sample P-91-6 (x 70).
Fig. 3, Porochara fusca (Mädler), MES 379, sample 1398-5+1 (x 120).
Fig. 4, Porochara minima (Mädler), MES 380, sample 1346-24+16 (x 175).
Fig. 5, Latochara bellatula Peck, MES 381, sample 1392-6 (x 120).
Fig. 6, Latochara concinna Peck, MES 382, sample 1346-24+6.5 (x 106).
Fig. 7, Latochara latitruncata (Peck), MES 383, sample 1388-1+5 (x 85).
Fig. 8, Peckisphaera verticillata (Peck), MES 384, sample P-91-6 (x 127).
Fig. 9, Mesochara voluta (Peck), MES 385, sample 1392-6 (x 110).
Fig. 10, Aclistochara obovata Peck, MES 386, sample 1346-28+17.5 (x 85).
Fig. 11, Aclistochara bransoni Peck, MES 387, sample 1346-24+6.5 (x 95).
Fig. 12, Aclistochara jonesi Peck, MES 388, sample 1346-28+19 (x 120).
Fig. 13, Aclistochara mädleri (Peck), MES 389, sample P-91-6 (x 185).
Fig. 14, Aclistochara latisulcata Peck, MES 390, sample 1346-32+1 (x 65).
Figs. 15–16, Echinochara pecki (Mädler), silicified material from Peck's collection, U.S.G.S. Paleobotanical Loc. D282, Garfield County, Colorado (see Peck 1957: 12); 15, internode, MES 391 (x 41); 16, utricle, MES 392 (x 70).

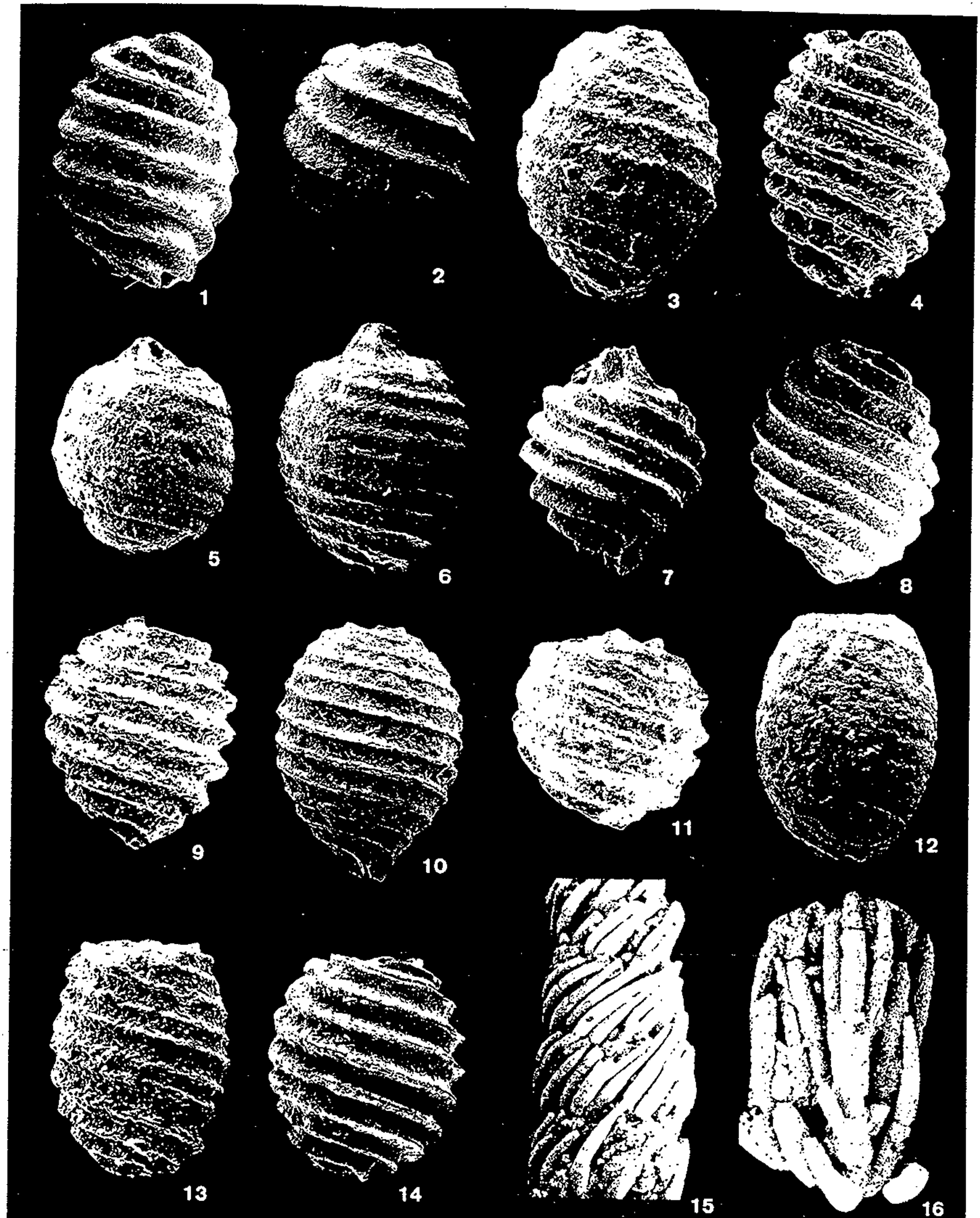


Plate 3.

CHARACTERIZATION AND PALEOENVIRONMENTAL INTERPRETATION OF PEDOGENIC CARBONATE AT THE JURASSIC-CRETACEOUS BOUNDARY, EAST-CENTRAL UTAH AND WEST-CENTRAL COLORADO; FINAL REPORT

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Denver, CO 80225

ABSTRACT

This study has concentrated on determining the conditions of calcrete formation at the Jurassic-Cretaceous (K-1) unconformity. Calcretes located in the northern Colorado Plateau were formed in a semi-arid and temperate climate. These calcretes formed under a variety of precipitational environments. The calcretes are nodular to massive in outcrop and are classified petrographically as alpha-type calcretes. Vadose calcrete is the most abundant, with lesser amounts of subaerial and water table calcretes present in the study area.

Five measured sections and six other locations were sampled for mineralogic, petrographic, and isotopic studies. Mineralogy of the calcretes was determined by x-ray diffraction, and the dominant minerals are calcite, quartz, and clays. Minor mineral constituents are feldspars, dolomite, gypsum, and mica. Clay minerals of the calcrete consist of, in order of decreasing relative abundance, illite, mixed-layer illite/smectite, chlorite, and kaolinite. The mixed-layer illite/smectite is dominantly >80% illite. Clay mineralogy probably reflects the calcrete host sediments rather than products of calcrete formation.

There is evidence that the vadose type calcretes are pedogenic in origin. Direct evidence is the presence of roots and burrows. Calcrete peloids, laminations, brecciation, and host sediment mottling are observed in these calcretes and are present in most pedogenic calcretes. Host sediments lack sedimentary structures and contain paleovertisolic

structures, shrink-swell features, and clay slicks. Petrographically, calcretes show root hairs, micro-brecciation, meniscus, and pendant structures. These collectively support a pedogenic origin for most of the calcretes.

Stable carbon and oxygen isotope compositions average -5.14‰ and -7.6‰ (PDB), respectively, and fall within a range typical for most calcretes. Carbon and oxygen isotopic profiles of measured sections reveal variations on the order of 2‰ to 3‰. Positive shifts in carbon and oxygen isotopes are for the most part interpreted as subaerially related. The variations in carbon isotopes are interpreted to represent slight changes in vegetation-respired CO_2 or changes in atmospheric $P(CO_2)$. Slight changes in oxygen isotopes reflect changes in the meteoric water supply, air temperature, or evaporation. No correlation between measured sections and isotopic values are observed with the exception that isotopic averages between sections are similar. Calculated atmospheric paleo-$P(CO_2)$ levels, using the carbon isotopic composition of pedogenic calcretes, reveal an atmosphere 6 to 12 times greater than the present atmospheric $P(CO_2)$. Carbon isotopes also indicate that the carbon isotopic composition of paleo-vegetation organic matter averaged -23‰ to -19.6‰ (PDB). The oxygen isotopic composition of waters from which the calcrete formed ranged between -5‰ to -15‰ (SMOW) and is comparable to modern continental meteoric isotopic compositions of similar geographic settings. Paleotemperatures of calcrete formation calculated from the oxygen isotopes average 27.5° C, a temperature not unreasonable for soils.

A high concentration of kaolinite and a corresponding light $\delta^{13}C$ (-7.4‰ PDB) in several easternmost locations indicate, in the northern part of the Colorado Plateau, there may have been a climatic gradient from drier in the west to wetter in the east. Known rates of calcrete accumulation are applied to calcretes of this study and the rates ranged between 9 million years and 56,000 years for the time of formation.

INTRODUCTION

The stratigraphic boundary between the Morrison Formation (Jurassic) and the Burro Canyon/Cedar Mountain Formations (Lower Cretaceous) in east-central Utah and west-central Colorado has been difficult to determine and has long been described as either interbedded, intertonguing, or gradational throughout the Colorado Plateau (Craig et al., 1955; Simmons, 1957; Ekren and Houser, 1959; Lohman, 1965). Previous studies have chosen the contact at the lowermost conglomeratic channel sandstone (Stokes, 1952; Carter, 1957; Ekren and Houser, 1959). Where a basal sandstone channel is not present, the boundary is defined as a textural difference in the weathered mudstone (Ekren and Houser, 1959). The Brushy Basin Member at the top of the Morrison Formation throughout the central and northern parts of the Colorado Plateau is identified by the "frothy" weathering appearance of its mudstones (more smectitic in composition) whereas the Burro Canyon/Cedar Mountain Formations tend to weather to a "hackly" or "fissile" appearance (more illitic in composition).

The Burro Canyon and Cedar Mountain Formations are considered to be time correlative (Tschudy et al., 1984; Figs. 1, 2). The Colorado River separates the two formations; the Cedar Mountain Formation is west and the Burro Canyon Formation is east of the Colorado River (Stokes, 1952).

It has recently been proposed that a more practical boundary between the Morrison and Burro Canyon/Cedar Mountain Formations is at or near the first calcic, nodular to bedded limestone unit (hereafter called "calcrete zone"; W.A. Aubrey, oral commun., 1994; F. Peterson, oral commun., 1994; B.C. Curry, oral commun., 1995). This is a soil-developed nodular calcrete (see below) that probably represents a subaerially exposed surface representing at least some of the missing time at the Jurassic-Cretaceous boundary (K-1 boundary) in the study area. The calcrete zone is typically located 3 to 12 m (10-40 ft) above the original boundary pick throughout the Colorado Plateau region.

In order to help reconcile differences in the present stratigraphic boundary placement and the proposed boundary, this study characterizes the calcrete zone and interprets the conditions under which it formed.

This report consists of selected parts from a larger report by Skipp (1997).

INTERPRETATION AND DISCUSSION

Before a paleoclimatic interpretation can be made, a paleoenvironmental evaluation of the calcretes must be addressed. A paleoenvironment interpretation will be accomplished by using the above results and field relations. A paleoenvironment interpretation using isotopes can only be made if: 1) no secondary carbonates are included in the sample; 2) no post-burial replacement or exchange has occurred; and 3) no detrital contamination (lithogenic carbonate) is included (Cerling, 1984). Once an interpretation of the calcrete has been reached, an evaluation of the paleo-$P(CO_2)$, paleo-$\delta^{18}O$ composition of the meteoric water, and regional paleoprecipitation can be made. This will be accomplished by using standard fractionation factors, a soil diffusion model (Cerling, 1984) and mineralogical comparisons. Any reference to $P(CO_2)$ in this thesis will be defined as parts per million by volume (ppmV). While I recognize these units do not define partial pressure (i.e., in conventional pressure units) this is the conventional notation used in the literature (Magaritz et al., 1981; Cerling, 1984).

Establishing the Origin of the Carbonates

Calcretes

To establish that these carbonates are calcretes other possible origins must first be rule out . Because the Morrison Formation is terrestrial, marine carbonates can immediately be ruled out; however, the Morrison Formation is known to have lacustrine carbonate beds (Turner and Fishman, 1991), and it is possible that the carbonates of this study may have a similar origin, especially the massive and bedded carbonate accumulations. There is much evidence suggesting that this is not the case. First, primary features including the development of weak soil horizons, color mottling, paleovertisolic structure, irregular shaped nodules, clotted fabric, and meniscus and pendant structures are indicative of calcretes. Second, lack of regular and continuous laminations, lack of evidence of gravity flows, lack of interbedded siliciclastic material due to high run-off, (floods at high seasonal flow), lack of seasonal precipitation of calcium carbonate (varved laminae), and lack of remains of lacustrine organisms such as charophytes, mollusks or fish are evidence against a lacustrine origin. The shape and stratigraphic relation to surrounding sediments, such as calcrete cross-cutting local stratigraphy, destruction of primary sedimentary structures and development of calcrete-type structures without regard to sediment type, and lateral gradation of most of the massive and bedded carbonates into nodular type calcretes that have soil horizons associated with them are all very good evidence refuting a lacustrine origin.

Pedogenic Calcretes

In addition to the features mentioned above, the sharp boundaries between carbonate accumulation and surrounding mudstone are generally abrupt on a small scale, but from a distance they appear more diffuse because of the chaotic boundaries between the carbonate and surrounding rock. This is a common feature of pedogenic calcretes (Joeckel, 1991). Blodgett (1988) suggested that sharp nodule boundaries with host material indicate movement within the soil profile (pedoturbation). Roots and burrows are observed in all the measured sections. This also is consistent with the interpretation that portions of the sections are pedogenic calcrete.

Some of the measured sections (Figures 9-14) exhibit the "typical" pedogenic calcrete profiles grading upwards from slightly calcareous sediments to nodular to coalesced or bedded carbonate that may or may not be capped by a thin laminated or peloidal zone; generally carbonate content increases upward. Purvis and Wright (1991) suggested that rimmed detrital grains, micrite peloids and clumps with spar and microspar have a vadose origin and therefore, possibly are pedogenic in origin. This rimming of spar is very common in the calcretes of this study.

The carbon and oxygen isotopes are also very similar to other calcretes, both modern and ancient (Salomons et al., 1978; Goudie, 1983; Talma and Netterberg, 1983; Cerling and Hay, 1986; Joeckel, 1991; Purvis and Wright, 1991; Rossinsky and Swart, 1993; Figure 27). Finally, much of the previous Results section contains additional information supporting this interpretation. This is all good evidence that some of these calcretes are of pedogenic origin.

Water Table-Related Calcretes

Not all the calcretes of this study were formed by pedogenic processes. Some calcretes in the measured sections (0.5-2.5 m SVA, Figure 9; and 12-13.5 m PR, Figure 13) are distinctly different from the pedogenic calcretes and are probably water table-related calcretes. According to Wright and Tucker (1991) and Arakel and McConchie (1982), a typical water table or capillary-fringe calcrete grades upwards through a sequence of zones including: a mottled nodular zone, a massive zone, a brecciated zone, and a thin cap-forming laminated zone. Because of the dynamics involved in the formation of calcrete, these horizons may overlap and/or may be totally missing. None of the sections in this study displays the typical zoning but they do have varying combinations of these zones. Also, opaline silica, which is a major component of modern massive calcretes in the phreatic zone (Arakel and McConchie, 1982), is present in the form of chert, and is both a major (SVA and DC sections, Figures 9 and 10) and a minor component (DC and PR sections, Figures 10 and 13) of these sections. However, only the SVA and PR sections have silica associated with those calcretes interpreted as water table related calcretes. Slate et al. (1996) observed hydromorphic paleosols that are mixed Bw/Bk horizons that are mottled with brown/red in the upper part and gray/green in the lower part. They interpreted hydromorphic paleosols as water table type paleosols. The SVA (0.5-2.0 m), PR (12-13.5 m), and RRR (2-5 m) sections have similar color characteristics.

There are two types of ground water related calcretes, some produced by fluvial processes and some produced by ground water. Fluvial processes involve deposition within channels or valleys or deposition from sheet floods (Goudie, 1983). These two types are very similar in morphology and hard to distinguish in the rock record without detailed stratigraphic and sedimentologic study. A recent ground water related calcrete study by Semeniuk and Searle (1985), observed a positive correlation among development of vegetation, wetness and the thickness of calcretes. Additionally, water pumping of phreatophytes, in the zone of capillary rise can result in the formation of massive and laminated calcrete sheets directly above the water table (Semeniuk and Meagher, 1981). No attempt was made in this study to distinguish between the two types of ground water calcretes.

Subaerial Calcretes

Subaerial calcretes were recognized mostly based on their isotope signatures. The near surface environment usually involves evaporation which fractionates the oxygen isotopes, giving an upward positive shift in $\delta^{18}O$. Therefore, the carbonate formed at the near surface will be more $\delta^{18}O$ enriched than carbonate formed at depth. Additionally, the near surface carbon isotopic composition is positive in comparison to soil carbon isotopic composition at depth. This is because the soil carbon isotope composition is lighter than the atmospheric carbon isotope composition due to plant respiration of isotopically light $CO_{2\,(gas)}$. At the near surface (<20 cm) there would be a mixing of the soil gas and atmosphere end members, setting up a concentration gradient (Cerling,1984) resulting in an upward positive shift of $\delta^{13}C$. Therefore, carbonate formed near the surface has more positive $\delta^{13}C$ than carbonate formed at a greater depth. Others have observed this positive covariance of the carbon and oxygen isotopes in soil carbonates (Salomons et al., 1978; Suchecki et al., 1988; Cerling and Quade, 1993). Therefore, positive shifts of >3‰ were scrutinized for inclusion in a paleoenvironmental interpretation, especially if the shift was abrupt (sample 96-3-RH). Subaerial calcretes also were identified, based on the presence of desiccation features such as mud cracks and clastic dikes.

PETROGRAPHY

Petrographic analysis of thin sections confirmed that the calcrete samples contained large quantities of micrite or microspar, which is the optimal texture for isotopic sampling for paleoenvironmental interpretations. Most isotope samples fill this criterion. Secondly, identification of related pedogenic features confirm soil-precipitated carbonate. Thin sections to some degree aided to distinguish pedogenic calcrete versus water table calcrete.

Identification of calcite replaced volcanic glass is important for two reasons. First, it means that the host micrite is probably not diagenetically altered; hence, it records the original isotopic signature. Second, carbonate formation and glass incorporation had to be early in the depositional history to preserve the glass shard morphology. Also, this is good evidence that volcanic activity and its subsequent material probably made large contributions to the sediment budget and the resultant calcrete host mudrocks.

Almost all the thin sections studied confirmed that the calcrete types studied can be interpreted as disruptive and displacive with minor amounts of replacement and that there are multiple generations of carbonate accumulation. This is important for recording the climate over an extended time period.

In order to evaluate carbon and oxygen isotopes as environmental indicators from these calcretes, burial conditions need to be considered to insure that original isotopic compositions are preserved. Petrographic analysis can indirectly aid in understanding the burial conditions. The average porosity of sandstones studied above and below the calcrete zone was determined to be 14%. This average porosity is greater than that predicted by

Baldwin and Butler (1985) (0 to 10%) for sandstones with similar burial conditions. Additionally, long average grain contacts and low grain contact index (2.47) show that burial conditions had minimal effect on these sediments. Petrographic analysis of the calcrete indicates very little recrystallization or replacement. Therefore, it is safe to conclude that burial conditions had little effect on these sediments, and therefore, little effect on altering carbon and oxygen isotopic composition of calcretes at these localities.

Brief Discussion of the Measured Sections

Ruby Ranch Road (RRR)

The RRR section is unique from the other measured sections in this study in that it is massive, thick, and lacks many vadose pedogenic characteristics (2-12 m, Figure 11). Characteristics of this section include: 1) the thickness (10 m) is unlike typical calcretes in paleosol horizons (typically <3 m; Slate et al., 1996); ground water related calcretes can typically reach thickness of 10 m or more (Wright and Tucker, 1991); 2) it is an alpha type calcrete (in itself not diagnostic but very common of water table-related calcretes) and densely crystalline (Wright and Tucker, 1991); 3) it is massive in appearance; 4) the lower boundaries are typically sharp and upper boundaries may be sharp or diffuse, typical of water table calcretes (Slate et al., 1996); 5) lack of well developed soil features and horizons; 6) encapsulation of alluvium (Mann and Horwitz, 1979); 7) lack of abundant trace fossils (roots and burrows) in upper portion of the massive calcrete; and 8) stage IV carbonate development of Retallack (1988)(see page 87). These are taken to indicate that the RRR location may have developed as a water table-related calcrete.

There is sufficient evidence, however, that suggests that the calcrete is instead pedogenic. According to Purvis and Wright (1991), sparry calcite rimming of voids and micrite and detrital grains suggests a vadose origin. Many of the RRR thin sections exhibit this sparry rimming. Furthermore, there are trace fossils in the lower portion of the section (Figure 11). Alveolar septal structures present in thin section 95-12-RRR also may be evidence for a pedogenic origin. The carbon and oxygen isotopes do not have unusual positive shifts observed in water table calcretes by Slate et al. (1996), nor do they exhibit the negative $\delta^{13}C$ shifts observed by Talma and Netterberg (1983). In fact, both the carbon and oxygen isotope values are comparable to the other vadose calcretes in the other sections (Figures 20-24). These observations suggest that this section is pedogenic and will be further treated as one.

Interestingly, no subaerial surfaces have been identified in the RRR section indicating possible removal of sediments that formed earlier. The carbon isotope profile has the least variation of all the sections (which might be predicted in a section lacking exposure surfaces), and actually shows a slight positive increase up section. This increase possibly may reflect a decrease in biogenic influence, increased sedimentation rate or gradual increase in atmospheric P(CO_2) during its accumulation (Figure 22). The oxygen isotope profile also shows the least variation of all the sections, with only a 0.32 standard deviation. This indicates fairly consistent geochemical conditions during calcrete formation and isotopically homogeneous source waters.

Disappointment Creek (DC)

The DC section probably had 6 to 8 episodes of calcrete development based mostly on field relations and some isotope data (Figures 10 and 21). The first episode occurs between 0-1 m in the measured section. Root halos and burrows in this interval are good evidence for a pedogenic origin. The 7-14 m interval could possibly have 4 to 6 individual episodes of calcrete development based on the "typical" calcrete profile discussed above. From 18-20 m, 2 to 3 individual calcrete accumulations are evident.

The enigmatic sample 95-20-DC, that has a $\delta^{18}O$ of -13.4‰, is difficult to interpret given that most world calcretes range between -8.5‰ and -1‰ $\delta^{18}O$ PDB (Goudie, 1983; Talma and Netterberg, 1983; Joeckel, 1991). Cerling and Quade (1993) observed $\delta^{18}O$

values from modern soil carbonates as depleted as -14‰ PDB in Saskatchewan. The environment for these $\delta^{18}O$ depleted soil carbonates is that of a boreal prairie and is probably an unreasonable comparison. Because the bed from which this sample was taken is also composed of silcrete and contains iron nodules (neither of which are found at any of the other locations), a different depositional or diagenetic environment is likely.

A stacked nodule set sampled at 13.6 to 13.8 m shows a 1.5‰ increase in carbon isotopic composition over a considerably small distance, possibly indicating an upward approach to a subaerial exposure surface. Increases at the subaerial surface results from heavier atmospheric CO_2 compared with light soil-gas CO_2. This suggests that sampling density may be an important limiting factor. Two positive bimodal isotope shifts at 17 and 20 m are most certainly subaerially related. Both units have abundant peloids and laminations, good indicators of near surface upper calcrete horizon development.

Riggs Hill (RH)

Nodular calcrete at the base of the RH section is truncated at its top by a channel sandstone, indicating that sedimentation terminated pedogenesis at this locality (Figure 12). This 4.5 m thick sandstone bed is laterally discontinuous and is composed of several channel sands which have incorporated calcrete nodules. These nodules, however, are probably the result of fluvial channel downcutting of pre-existing calcretes rather than in situ formation. In places, bedding and lamination within this sandstone have been disrupted. Although bioturbation can result in similar disruption, it is likely that pedogenesis and calcrete formation was responsible.

The RH location also has the lightest $\delta^{13}C$ (-7.4‰) and the heaviest $\delta^{18}O$ (-4.0‰) of all the sections, indicating the varied conditions under which RH calcretes formed. Goodfriend and Magaritz (1988) suggested that carbon isotopes are also controlled by the amount of rainfall which, in turn, is responsible for the amount of vegetative cover. The lowest $\delta^{13}C$ value corresponds to the greatest abundance of kaolinite in the section and may reflect more plant activity associated with more rainfall. Furthermore, the greater abundance of spar and flower structures in some of the RH thin sections (95-2-RH and 95-4-RH) in the basal section is indicative of beta-type calcretes, which in general reflect increased biologic activity and moister conditions (Wright and Tucker, 1991).

The lower few meters of the Riggs Hill section has a similar upward increase in carbon isotopes as the RRR, except over a much more condensed section; 1.5 m comparedto 13.5 m of the RRR section (Figures 11 and 22). This similar record likely indicates similar conditions of formation.

Salt Valley Anticline (SVA)

The SVA section is the most unusual of the five measured sections. The most noticeable difference with the other sections is the heavy average $\delta^{13}C$ values (Table 2). The oxygen isotopes are also heavier than the other sections, however, only slightly. A brecciated microsparite calcrete was sampled to determine the isotopic change from a breccia fragment to the sparry calcite fracture fill (Figure 31). The change in the oxygen isotope values either reflects an increase in recrystallization temperature or decrease in the $\delta^{18}O$ content of the meteoric water responsible for the precipitation of the fracture fill. The carbon isotope composition shows a -3.3‰ shift that probably represents an increased organic influence after brecciation.

Another noticeable difference is the very chaotic morphology of the outcrop from 1.9 to 2.5 m (Figure 9) and the thickness of the lower part of the section (3.5 m) which is much thinner than the other sections (Figures 10-13). This may in part be evidence that there was active Permian salt movement (Peterson, personal communication) during calcrete accumulation.

Upward movement of the salt structure may have resulted in a condensed section or inhibition of calcrete development due to a slightly higher topography. This type of setting may also be ideal for overprinting and karstification which may explain some of the chaotic features at 1.9 to 2.5 m and the generally heavier isotope values. Other supporting evidence that this section was diagenetically overprinted is that the carbonate texture is mostly microspar and spar (Table 1). The above evidence was sufficient to exclude most of the data from a paleoclimatic interpretation.

Price River (PR)

The PR section is composed of the largest number of cycles of calcrete formation, possibly 10 or more, and is the thickest calcrete zone. The calcrete is hosted dominantly by mudstone, which lacks the sandstone lenses, small channels, and the minor amounts of sand included in the other sections (Figure 13). Therefore, this section probably has the lowest permeability of all the sections. Geochemically, the average carbon and oxygen isotopes values are not unlike those of the other sections. The carbon and oxygen isotope profiles, however, have a greater variation from sample to sample in the upper half of the section than in other sections. This could be explained by lower permeability causing carbonate accumulation to be restricted to the near surface reaches of each cycle in the profile. However, no direct evidence, such as desiccation cracks, was found in association with positive isotope shifts.

The PR section also has calcite replaced volcanic glass shards in the upper half. The presence of volcanic material in this section does not seem unreasonable, given that the location of this section is the most proximal of all sections to a volcanic arc to the west. Inclusion of glass shards may indicate relatively rapid calcrete development. If the rate of calcrete formation is rapid, then it is sampling carbon and oxygen from a relatively short time span. Therefore, the carbon and oxygen isotopes of the calcrete may only represent an extended drought or an uncommon wet spell, rather than slower calcrete formation that would attenuate many of these cycles with respect to the record of carbon and oxygen isotopes. So, another possible explanation for the fluctuation of isotopes in the upper half of the section is rapid calcrete formation.

Paleoenvironmental Interpretation

Clay Minerals

Few trends and relationships among clay minerals within a measured section or between sample locations were identified. For the most part, the clay mineralogy of these calcretes is probably representative of the calcrete host material (Table 1). The fact that weathering tends to drive illite to smectite (Moore and Reynolds, 1989), and illite and mixed-layer illite/smectite are the dominant clay minerals in the study area, suggest that weathering was not extensive enough to make this alteration. This may indicate hotter, drier conditions than paleosols with developed smectite horizons.

The presence of abundant kaolinite at the RH, LPR, and DH location is the only anomaly of the clay mineral assemblages observed. This could imply a regional change from dominantly illite and mixed-layer illite/smectite in the west to kaolinite in the east. Kaolinite is the most common mineral in soils formed in warm, moist regions, occurring as a weathering product of aluminosilicates (Moore and Reynolds, 1989). Generally, this would suggest wetter conditions from west to east and may account for the lack of calcrete development farther east. Another interpretation is that the kaolinite is a detrital host material.

Other minerals found in mature to juvenile calcretes, such as sepiolite, palygorskite, chabazite and clinoptilolite (Goudie, 1983; Hay and Wiggins, 1980; Watts, 1980; Hay and Reeder, 1978; Wang et al., 1994) were not observed in any of the locations sampled. These minerals generally increase in abundance upward in soil horizons and are products of weathering (Moore and Reynolds, 1989; Hay and Wiggins, 1980) or seasonal wet-dry cycles (Wang et al., 1994). The lack of these minerals may mean several things: 1) soil development did not proceed long enough (e.g., increased sedimentation rates) for formation of these minerals, 2) upper horizons were removed before soil preservation, 3) replacement type calcretes are not prevalent in the sections (Wang et al., 1994) or, 4) conditions of soil formation were not favorable for the formation of these minerals.

Paleoclimate Interpretation from Calcrete Carbon and Oxygen Isotopes

In making a paleoclimatic interpretation from the isotopic composition of pedogenic carbonates, several conditions must be met: 1) no over-printing has occurred during carbonate formation, such as a fluctuating climate; 2) no post-burial diagenesis has taken place or at least minimal exchange has taken place (see below); 3) no detrital contamination is present (Cerling, 1984). Another assumption is that soil carbonate is closely associated with the CO_2 from plant respiration and therefore reflects the $\delta^{13}C$ of the vegetation (Talma and Netterberg, 1983; Cerling, 1984; Cerling and Hay, 1986).

Diagenesis can change carbonate $\delta^{18}O$ due to the different $\delta^{18}O$ water compositions involved in the dissolution-reprecipitation processes. This was observed from Holocene paleosol nodules in Wyoming, but the $\delta^{13}C$ was relatively unchanged (Cerling, 1991).

Vegetation can be grouped into three groups that have distinctive carbon isotopic values resulting from different photosynthetic pathways used by the plants: C_3 plants, C_4 plants, and CAM (crassulacean acid metabolism) plants. C_3 plants are the most primitive of the three and typically have values between -22‰ and -34‰ with an average of -26 to -27‰ PDB and are represented by most trees, shrubs, herbs, and some grasses. C_4 plants range from -6‰ to -25‰ with an average of -13‰ and CAM plants have $\delta^{13}C$ values intermediate to C_3 and C_4 plants. Maize, sorghum, most prairie and savanna grasses, and succulents are examples of C_4 and CAM plants (Cerling and Quade, 1993; Faure, 1986).

New interpretations of isotopic data suggest that C_4 photosynthetic plants have existed since Mississippian time or at least that pulses or local environments that supported C_4 or CAM type organic development were present (Wright and Vanstone, 1991). If this were true, the diffusion model used for paleoclimate interpretations would be much more difficult to apply when determining paleo-P(CO_2) (Cerling, 1991).These interpretations, while intriguing, are not supported by a majority of other workers. Quade et al. (1989b) indicated that the oldest C_4 grasses first appeared only as recently as in the late Miocene, at approximately 7 Ma. This is in accordance with most paleovegetation interpretations. Therefore, only the isotopic average of C_3 photosynthetic plants is considered using Cerling's diffusion model below.

The isotopic influence of the parent material on calcrete isotopic compositions also needs to be considered. However, Quade et al. (1989a) have shown that the host material generally does not affect the isotopic compositions of soil-formed carbonate in volcanic and limestone host terranes. The host sediments of the present study are dominantly silty mudstones, small sandstone channels and stringers with varying amounts of volcanic sediments. It seems likely that these sediments would be benign with respect to their influence on carbon isotopes. Many researchers (Magaritz et al., 1981; Talma and Netterberg, 1983; Cerling, 1984; Cerling et al., 1989; Quade et al., 1989a) have shown that $\delta^{18}O$ in soil-formed carbonate is a reflection of the local meteoric water, fresh water table (Slate et al., 1996) or saline water table (Salomons and Mook, 1976; Mack et al., 1991). It has also been shown that water-table type calcretes should be disregarded when making paleoclimatic or paleoecological interpretations (Slate et al., 1996). The problem with using water table calcretes is that the isotopic composition and contribution of the ground water is unknown, so it is recommended that only vadose formed carbonate be used (Wright and Vanstone, 1991; Slate et al., 1996).

The rate of calcrete formation also influences the stable isotopic composition. Slower rates will reflect time-averaged isotopic values, whereas faster rates will represent shorter time increments (Purvis and Wright, 1991).

Carbon Isotopes

An attempt was made to determine environments of formation (see above) for calcretes in the measured sections using criteria of Retallack (1988), Wright and Tucker (1991) and Slate et al. (1996). These criteria are color, morphology, and trace fossils of the host material, and variation in isotopes and adjacent stratigraphic relations of the calcrete. This enabled a segregation of carbon isotope samples into two groups; ground water or subaerial and vadose-type calcrete. Only those calcretes that were interpreted as vadose were used for paleoclimate interpretations (Figures 20-24).

Application of Carbon Isotopic Fractionation to Calcretes

Applying known carbon isotope fractionation behavior to the calcrete accumulations will enable us to determine average CO_2 soil-gas content, $\delta^{13}C$ and the nature of the associated vegetation. Theoretical $\delta^{13}C$ fractionation at 20°C for carbon dioxide gas-bicarbonate is $10^3\ln\alpha_{CO_2\text{-}HCO_3}=8.38‰$ and for bicarbonate-calcium carbonate is $10^3\ln\alpha_{HCO_3\text{-}CaCO_3}=1.85‰$ (Emrich et al., 1970). Therefore, the fractionation of $\delta^{13}C$ from CO_2 gas to $CaCO_3$ is $10^3\ln\alpha_{CaCO_3\text{-}CO_2}=10.17‰$. Soil-gas CO_2 is generally 5‰ more enriched than soil organic matter (vegetation composition). Therefore, soil carbonate is ~15.2‰ more enriched relative to vegetation composition. Empirical observations have shown that soil carbonate $\delta^{13}C$ is 14-17‰ more enriched than the vegetation because of various fractionation effects; temperature, isotope diffusion, atmosphere CO_2 diffusion, etc. (Wright and Vanstone, 1991).

Using the range of average $\delta^{13}C$ values for vadose pedogenic calcrete derived from this study, -6‰ to -4‰ (Table 2), the calculated soil-gas composition would be -16‰ to -14‰. Using these same average carbonate values and the empirical range for carbonate enrichment relative to the vegetation, a $\delta^{13}C$ vegetation composition would be -18‰ to -23‰. The most enriched $\delta^{13}C$ value (-4‰) is from the SVA location, low in comparison to the majority of the data, and is probably suspect. Neglecting this average value and using -5.6‰ for the lowest value, the range becomes much narrower and lighter: soil CO_2 between -16‰ and -15.6‰ and vegetation between -23‰ and -19.6‰.

Today's average $\delta^{13}C$ of C_3 vegetation is -26 and has a range of -22‰ to -34‰. The results above are 5‰ to 6‰ more enriched than the average modern C_3 vegetation. Several explanations could be possible: 1) sparse vegetation or, 2) average Jurassic/Cretaceous C_3 vegetation was heavier than today.

Application of Cerling's "Diffusion Model"

The diffusion model for determining paleo-$P(CO_2)$ using the carbon isotopic composition of paleosol carbonate, as presented by Cerling (1991), predicts that: 1) the soil $P(CO_2)$ of paleosols will vary with depth and approach atmospheric levels at very shallow depths (<20 cm), 2) soil carbonate formation is in isotopic equilibrium with soil CO_2, and 3) the isotopic composition of the soil carbonate can be used to predict $P(CO_2)$ of the paleoatmosphere. These relations have been confirmed in numerous field studies (Cerling, 1984; 1991; 1992; Cerling and Hay, 1986; Quade et al., 1989a; Cerling and Quade, 1993

There are some important conditions that must be mentioned before calcretes can be interpreted in terms of $P(CO_2)$ in parts per million (ppmV). Carbonates must have been formed below 20 cm to negate direct atmospheric influence (Cerling, 1991). This is difficult to assess in the study area profiles because no complete soil profiles were observed, so absolute depth of carbonate formation is unknown. Therefore, only samples interpreted as vadose (see above) were used in the model. Soils must have a relatively high free-air porosity (Cerling, 1991). This is a property that is difficult to determine because of the types of host material and timing of compactive forces. If a comparison is made between the $\delta^{13}C$ of calcretes formed in sandy mudstone to sandstone (Figure 21, samples 95-8-DC through 95-12-DC) and those formed in dominantly mudstone (Figure 21, samples 95-2-DC to 95-4-DC, 95-16-DC, and 95-17-DC), it seems that the free-air porosity at the time of calcrete formation may have been at least similar for the two rock types. Gleying of soils (Retallack, 1988) is indicative of low porosities and these soils should be avoided in modeling $P(CO_2)$ in the atmosphere. No obvious gleying was observed in any of the sections; however, samples 95-8-PR through 95-10-PR were suspect and disregarded (Figure 24).

Another test that can help verify that these are vadose pedogenic carbonates is a comparison of the isotopic composition of the calcretes and the coexisting organic material. This difference should range between 13.5‰ and 17‰ depending on temperature (Cerling et al., 1989). Because no organic matter was analyzed in relation to the sections or locations studied, the nearest organic matter analyzed is from the adjacent Morrison Formation from the Colorado Plateau (Cerling and Ekart, 1995) and is used for a rough estimate. Their data range from -24.3‰ to -22‰ PDB for organic material. Using the same $\delta^{13}C$ calcrete averages as in the previous section (-6‰ to -5.6‰) gives a difference between organic and carbonate $\delta^{13}C$ of 18.7‰ to 16‰. This is on the high end of the comparison but still within the range. Nevertheless, given the grossly removed source of organic material and the uncertainties associated with vegetation types, the range partially overlaps with that acceptable for a vadose pedogenic interpretation. Also, in response to low rates of organic respiration, soil CO_2 can differ greatly from that of the vegetation; therefore, it could be reflected in the soil carbonate (Cerling, 1984).

An important aspect to the diffusion model is that it predicts a 4.4‰ soil CO_2 enrichment of $\delta^{13}C$ relative to soil-respired CO_2 at all depths in the soil profile. There are many other variables that affect soil carbonate accumulation and application of the diffusion model. A very comprehensive discussion is presented by Cerling (1991) of the various effects of each variable and in the interest of brevity, the reader is referred to that reference.

The general equation for the diffusion model of Cerling (1991) is as follows, followed by defining terms:

Most parameters above are those used by Cerling (1984, 1991) to evaluate Cenozoic and Mesozoic paleosols. The reason for this is to keep as many variables as consistent as possible for making comparisons to other interpretations. The SVA data are not included in this evaluation. The total average vadose data (-5.8‰) and a -1σ (-6.5‰) are plotted on the model (Figure 32). A -1σ is a conservative estimate used because many of the parameters involved in the model tend to overestimate $P(CO_2)$ (Cerling, 1991). Cerling (1991) and Mora et al. (1991) plot their isotope data in a range of 5000 to 10,000 ppmV on the model; these values correspond to a temperate and tropical climate, respectively. The above range of 5000 ppmV is somewhat arbitrary (Cerling, 1991), but it will be used for comparative purposes.

The calculated $P(CO_2)$ range for soil carbonate from this study corresponds to 3100 to 4900 ppmV for atmospheric $P(CO_2)$. This range estimate may be too high given that much of the above evidence from this study points to a semi-arid to sub-humid temperate depositional environment and that Cerling (1991) and Mora et al. (1991) used the range of 5000 to 10,000 ppmV for modern temperate to tropical climates.

$$\delta_s(z) = \left\{ \frac{1}{R_{PDB}} \left[\frac{S(z)\dfrac{D_s^*}{D_s^{13}}\delta_\phi^* + C_a^*\delta_a^*}{S(z)\left(1 - \dfrac{D_s^*}{D_s^{13}}\delta_\phi^*\right) + C_a^*(1 - \delta_a^*)} \right] - 1 \right\} \times 1000$$

and:

$$\delta_i^* = \left[\frac{R_{PBD}\left(\dfrac{\delta_i}{1000} + 1\right)}{1 + R_{PDB}\left(\dfrac{\delta_i}{1000} + 1\right)} \right]$$

Where:

$$\frac{D_s^{12}}{D_s^{13}} = \sqrt{\left[\left(\frac{M(air) + M(^{12}CO_2)}{M(air) * M(^{12}CO_2)}\right)\left(\frac{M(air) * M(^{13}CO_2)}{M(air) + M(^{13}CO_2)}\right)\right]}$$

TERM DEFINITIONS:

$R_{PDB} = \frac{^{13}C}{^{12}C}$ in isotopic reference standard PDB=0.0112372 (Craig, 1957)

D_s^*=diffusion coefficient for CO_2 in soil (0.00746496 m^2/hr) where: $D_s^* = D_{air}\varepsilon\rho$

ε=free air porosity (0.24, Cerling,1984)

ρ=tortuosity factor (0.6, Cerling,1984)

D_{air}=diffusion coefficient for CO_2 in air (m^2/sec) where: $D_{air} = D°_{air}\left(\frac{P°T}{PT°}\right)^{1.823}$

(from Bird et al., 1960)

P°=standard pressure (1 bar)

P=ambient pressure (bars)

T°=standard temperature (298.15°K)

T=temperature (°K)

$D°_{air}$=diffusion coefficient for CO_2 in air (cm^2/sec) under standard conditions (STP)=0.144 cm^2/sec

D_s^{13}=diffusion coefficient for $^{13}CO_2$

D_s^{12}=diffusion coefficient for $^{12}CO_2$

S(z)=solution to the following equation:

$$S(z) = \frac{\phi_s^* z_z^2}{D_s^*}\left(1 - e^{-(z/z_z)}\right)$$

$\phi_s^*(z)$=production rate of CO_2 (8 moles/m^3/sec) as a function of depth (1 m) @ -26 ‰ PDB

z_z=the production depth of CO_2 in the soil (1 m)

z=the depth in the soil (10 cm)

M(air)=atomic mass of air

$M(^{12}CO_2)$=atomic mass of $^{12}CO_2$

$M(^{13}CO_2)$=atomic mass of $^{13}CO_2$

δ_ϕ^*=per mil value of soil-respired CO_2

δ_a^*=per mil value of atmospheric CO_2

δ_s=per mil value of soil CO_2

C_a^*=concentration of CO_2 in the atmosphere (300 ppmV) @ -6.5‰ PDB pre-industrial value

ppmV= parts per million by volume

Therefore, a range more appropriate to the interpretation of the data in this study would be a range skewed towards drier soils say, 3000 to 7000 ppmV (Figure 33). This gives a calculated atmospheric $P(CO_2)$ range of 1900 to 3500 ppmV. Berner (1990; 1991) modeled atmospheric CO_2 for this particular time period. He concluded that early Cretaceous $P(CO_2)$ was 2 to 9 times (600 to 2700 ppmV) modern $P(CO_2)$ (300 ppmV=pre-industrial). These values are in agreement with values calculated for this study. Additionally, calcrete results from the lower Cretaceous (Berriasian) from Texas paleosols have similar interpretations (1600-2600 ppmV)(Cerling, 1991). From the above interpretation, during K-1 unconformity time, atmospheric $P(CO_2)$ ranged between 6 and 12 times modern $P(CO_2)$ (1900 to 3500 ppmV), considerably higher than modern.

A consequence of this elevated $P(CO_2)$ would be a more acidic rain. Elevated atmospheric $P(CO_2)$ (1900 to 3500 ppmV) estimated from the above model is equilibrated at a pH of approximately 4 for the paleo-rain water compared to modern $P(CO_2)$ (350ppmV) which is pH=5.66. This lower ph could have serious environmental consequences and possibly affect mineral reactions near the land surface. Future studies will need to reconcile this dramatic consequence of higher paleo-$P(CO_2)$.

Oxygen Isotopes

The three main variables that affect $\delta^{18}O$ of calcretes are: 1) the original $\delta^{18}O$ composition of meteoric water (rainfall and ground water), 2) $\delta^{18}O$ enrichment of the waters during evaporation prior to calcium carbonate precipitation, and 3) temperature (Mack et al., 1991). Other minor effects on the $\delta^{18}O$ of calcretes are elevation and differential infiltration of $\delta^{18}O$ enriched waters due to evaporation or seasonal variation (Quade et al., 1989a; Cerling and Quade, 1993). Relief in the study area was probably minor (Peterson, 1986) and no studies on differential infiltration of $\delta^{18}O$ enriched waters have been documented.

Workers have documented a positive shift in soil carbonate $\delta^{18}O$ as the soil-atmosphere surface is approached (Salomons et al., 1978; Magaritz et al., 1981). This results from Raleigh fractionation during evaporation and/or temperature increase at the surface. The evaporation and probable temperature influence is clearly shown in the RH section sample 96-3-RH and in the lower section of RH with a progressive increase upward to 96-1-RH (Figure 23). Sample 96-3-RH is derived from an interval containing desiccation cracks. All oxygen isotope profiles show abrupt several per mil increases in the section profiles, with the exception of the RRR section. These most likely indicate subaerial exposure surfaces (Figures 20-24).

The greatest degree of oxygen isotope fluctuation is recorded in the PR section. This isotope variability could be due to many factors: 1) the sampling density was fine enough to resolve subaerial surfaces, 2) slow sedimentation rates (not likely being proximal to the western highlands) in combination with the following factor, and 3) finer sediments in the section forcing more calcrete development nearer to the sediment-atmosphere interface. In addition to the identification of possible subaerial surfaces, oxygen isotopes can give important information on the temperature and $\delta^{18}O$ composition of the waters from which the carbonate formed. Paleotemperature will be discussed in a later section. Calculations of the possible $\delta^{18}O$ water compositions were made for all the isotopic data for calcite precipitation temperature ranges of 20°, 25°, 30° and 35°C (Appendix A). Calculation of water $\delta^{18}O$ is based on the calcite-water fractionation equation of O'Neil et al. (1969). If we assume that the calcite precipitated at 25°C, then the average $\delta^{18}O$ water composition for the septarian nodule, DC, PR, and RRR locations is approximately -6‰ SMOW.

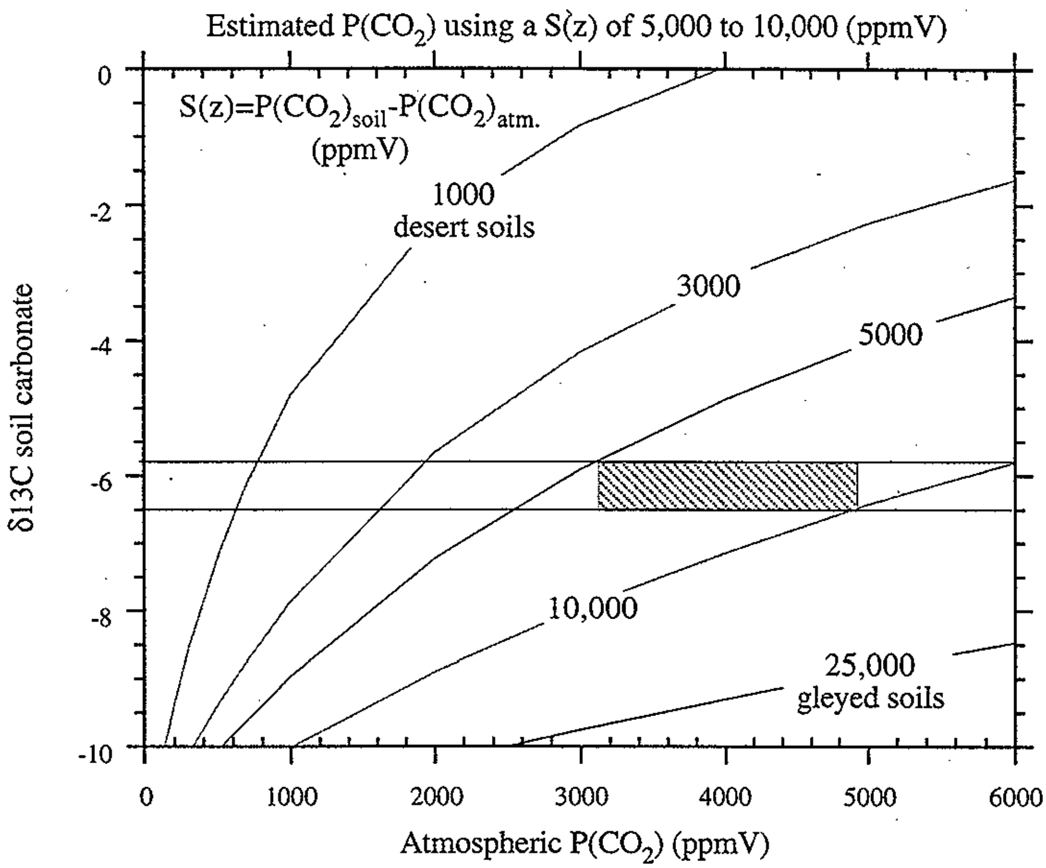

Figure 32. Atmospheric $P(CO_2)$ inferred from early Cretaceous pedogenic calcrete using Cerling (1991) diffusion model. Range of soil carbonate is the total average of sample locations RH, RRR, PR, and DC and a -1 sigma.

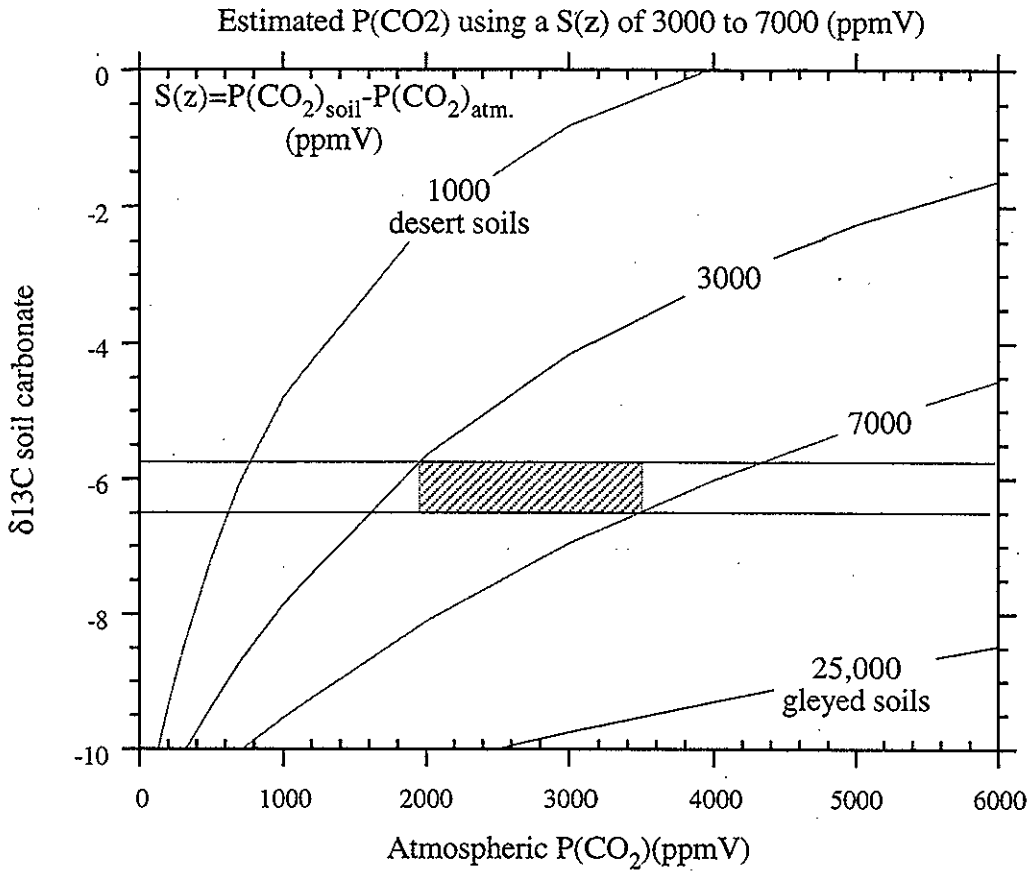

Figure 33. Atmospheric $P(CO_2)$ inferred from early Cretaceous pedogenic calcrete using Cerling (1991) diffusion model. Range of soil carbonate is the total average of sample locations RH, RRR, PR, and DC and a -1 sigma.

The RH and SVA location average is approximately -4.7‰ SMOW. RH is approximately 1.2‰ greater than the other sections, even disregarding its heaviest value (-1.6 @ 25°C). As discussed earlier, the isotopic compositions at the SVA location are probably a result of diagenesis, and are not representative.

A comparison to modern pedogenic carbonates and the associated modern meteoric water can also be useful in determining paleowater $\delta^{18}O$ composition. Modern $\delta^{18}O$ carbonate and water data from Cerling and Quade (1993) are plotted in Figure 34. The soil carbonates are grouped into similar climatic conditions under which they were formed. A crude trend emerges; warmer, milder climates are more positive and variable climates more negative. If the K-1 calcretes from this study are plotted and compared to this trend, a range of possible $\delta^{18}O$ water compositions is determined to be -5‰ to -15‰ SMOW. If this type of comparison is valid, then calcretes of this study formed in climates that were slightly more stressful or possibly drier than calcretes formed in equatorial regions.

Comparing the above estimated $\delta^{18}O$ water compositions derived from the modern data to the calculated fractionation results shows that modern soil carbonate and water compositions can be applied to the ancient. The calcrete $\delta^{18}O$ of this study had an average calculated value of -6‰ SMOW at 25°C for the formation waters (Figure 35). This is on the heavier end of the estimated range of paleowater compositions in Figure 34.

Talma and Netterberg (1983) measured the $\delta^{18}O$ of 155 worldwide calcrete samples of varying ages. The average $\delta^{18}O$ of these calcretes are -5‰ PDB. This calculates to $\delta^{18}O$ formation waters that are -4.5‰ SMOW. Talma and Netterberg (1983) also calculated expected $\delta^{18}O$ carbonate values for their calcretes using mean annual temperatures and $\delta^{18}O$ rainfall content of each area. Their calculated calcrete $\delta^{18}O$ values were almost always lighter than the actual calcretes. Therefore, lighter actual $\delta^{18}O$ formation waters might be expected over calculated $\delta^{18}O$ formation waters.

The calculated average $\delta^{18}O$ of the formation waters for the calcretes of the K-1 boundary is -6‰ SMOW (at 25°). Given that the actual $\delta^{18}O$ formation waters are probably lighter than calculated $\delta^{18}O$ formation waters, then skewing the data arbitrarily -1‰ towards lighter $\delta^{18}O$ values would give a value of approximately -7‰ SMOW. This value is well within the range predicted from Quade and Cerling's (1993) empirical data (Figure 34).

Finally, assuming that paleolatitude of the K-1 calcrete and many of the other variables affecting $\delta^{18}O$ distribution were approximately the same as today a comparison can be made to the worldwide modern $\delta^{18}O$ distribution of precipitated meteoric waters of Yurtsever (1975, his Figure 1-12). This results in a range of -6‰ to -10‰ SMOW. This is very comparable to ranges generated from this study.

Comparison of Carbon and Oxygen Isotopes

All the $\delta^{13}C$ and $\delta^{18}O$ data from this study are plotted in Figure 36. A general range of $\delta^{13}C$ and $\delta^{18}O$ of worldwide calcretes ranging in age from the Permian to the present are plotted in Figure 27. There is some overlap, but a majority of the data from the present study is more depleted in $\delta^{18}O$. The main factors that affect $\delta^{18}O$ in calcrete have been mentioned above. To try to account for this slightly more depleted $\delta^{18}O$, the source of the meteoric water needs to be discussed.

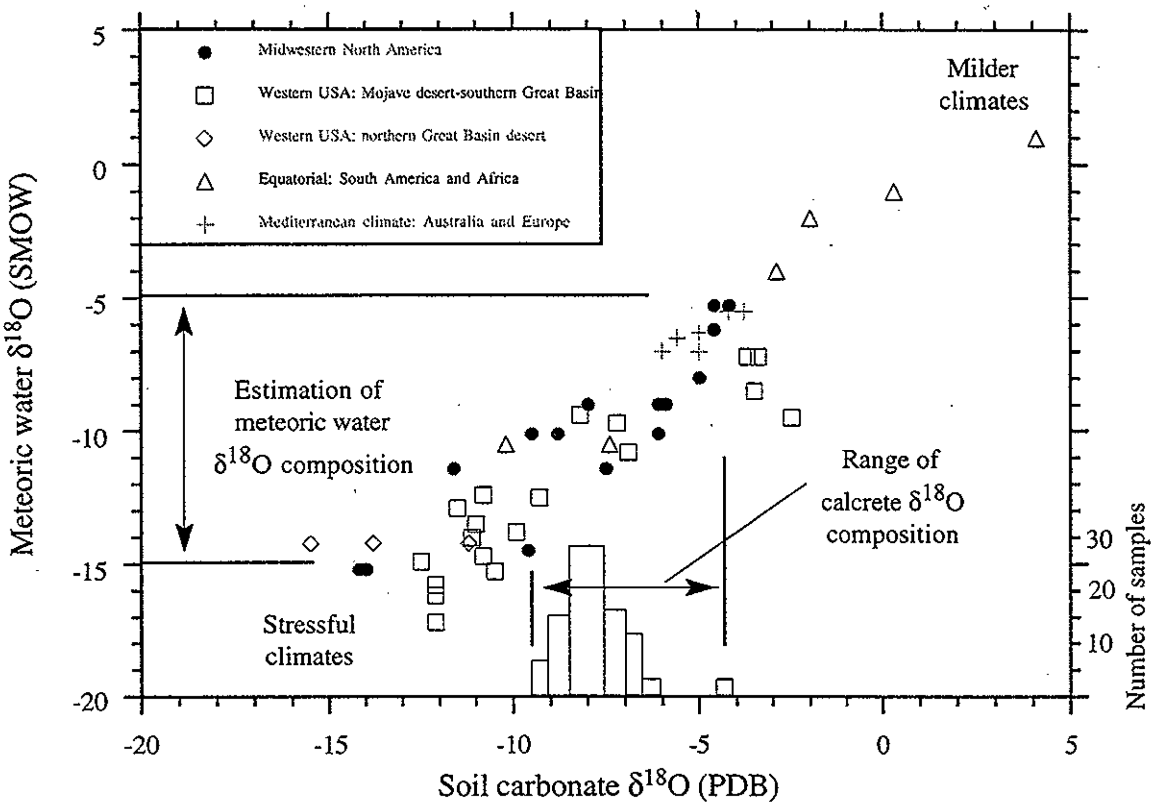

Figure 34. Isotopic composition of soil carbonate and associated meteoric water. Bars indicate number of samples and carbon isotopic composition of calcretes from this study. Plotted data from Cerling and Quade (1993).

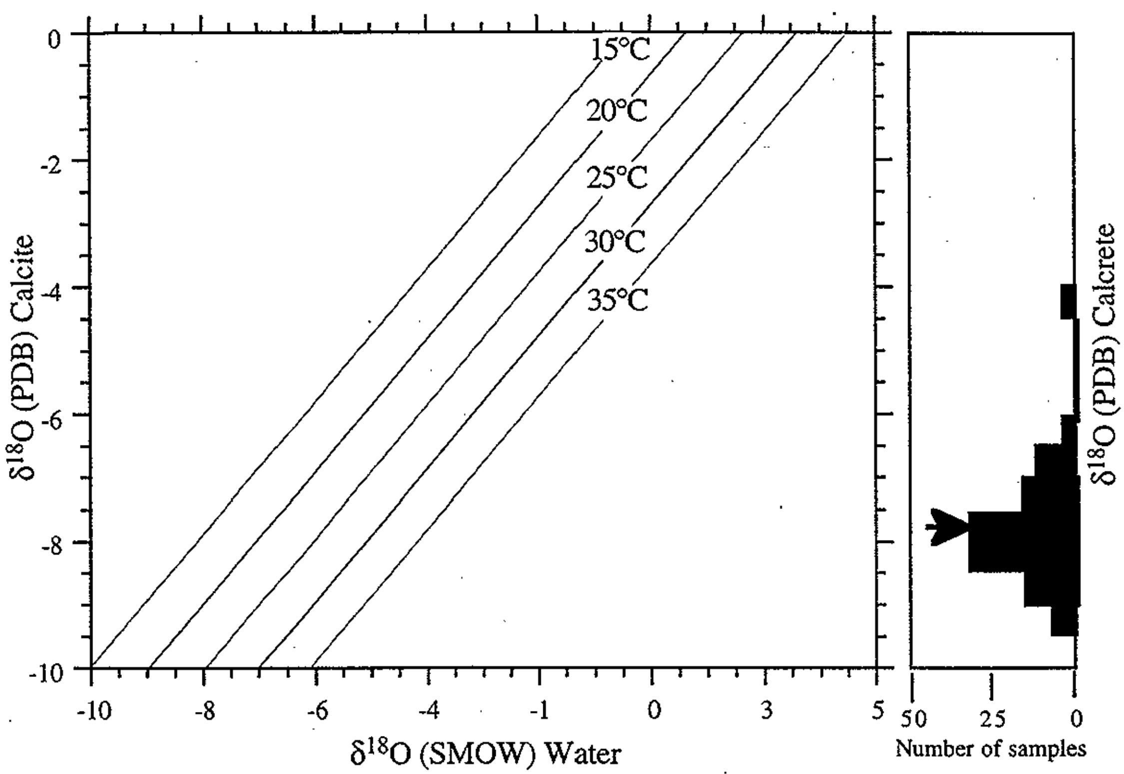

Figure 35. Equilibrium relationship between the $\delta^{18}O$ of carbonate and water for various temperatures. The fractionation equation is from O'Neil et al. (1969). Arrow is the average for the data. Data for calcretes of this study are shown on the right.

The Sevier highlands were directly west of the study area and paleowinds in the late Jurassic were consistently from the west to southwest (Poole, 1962). If these trade winds continued through the time of calcrete deposition, then there could be an orographic effect on depleting $\delta^{18}O$ in the meteoric water before reaching the study area. This may be analogous to the rain shadow effect of the Sierra Nevada Range of California. Another possibility is that the temperature of formation may have been elevated (see below).

Cerling and Quade (1993) made the observation that there is a high correlation between carbon and oxygen isotope composition of soil carbonates in regions that favor the C_3 photosynthetic pathway. This is because cooler temperatures favor C_3 vegetation and because meteoric waters are more depleted in $\delta^{18}O$ in cooler temperatures. No obvious enrichments or depletions of $\delta^{13}C$ or $\delta^{18}O$ are observed in transects from north to south or east to west (Figures 21-24). As mentioned earlier however, there is a slight depletion of the $\delta^{13}C$ at RH in comparison to DC, RRR, and PR. This could imply a cooler, wetter environment of calcrete formation at the RH location.

It was hoped that correlations between the individual sections could be drawn using carbon and oxygen isotopes from this study. Correlations looked for were similar positive or negative shifts in either $\delta^{13}C$ or $\delta^{18}O$ in the form of abrupt or gradual changes. These changes might indicate similar changes in conditions of formation regionally. No definitive correlations can be made from the isotopic profiles of this study (Figures 20-24). This could be due to lack of sample density within each section or, more likely, because the distance between sample localities is too great (Figure 1). Consequently, local environments are recorded rather than the regional environment. It may be possible to correlate enriched isotopes as subaerial exposure surfaces, but much more work would be involved to verify this. Nevertheless, most of the isotope data collected from this study are grouped around -6‰ $\delta^{13}C$ and -8‰ $\delta^{18}O$ ±2‰ (Figure 32). This relatively narrow range of carbon and oxygen isotopes over such a broad geographic region, and within diverse parent materials, suggests an overall consistent paleoclimate.

It was also hoped that the septarian nodule would reveal a carbon and oxygen isotopic change from its initial accumulation to its terminal growth, recording a change in climatic conditions. The carbon and oxygen isotope record that the nodule has retained is internally consistent and is also consistent with isotope values from the other sections. Isotopic composition for the septarian nodule averages -5.7‰ and -8.1‰ for carbon and oxygen, respectively. Although internal isotopic variability is limited, it can be said that conditions of nodule formation were relatively uniform and this observation corroborates that similar conditions existed at the measured sections.

Calcrete Paleotemperature

Paleotemperatures of calcrete formation have been calculated for the $\delta^{18}O$ isotope data (Appendix A). The paleotemperatures were calculated from an equation derived from the O'Neil et al. (1969) temperature and isotopic equilibrium equation. The equation derived by Hays and Grossman (1991) is used here for inland temperatures. The variables are the $\delta^{18}O$ composition of meteoric calcite and the $\delta^{18}O$ composition of sea water at the time of calcite formation. A $\delta^{18}O$ SMOW of the early Cretaceous paleocean is assumed to be 0‰ (Hays and Grossman, 1991). Because the equation developed by Hays and Grossman (1991) is a second order regression, it has two possible solutions for a given estimation of sea water at latitudes approximately between 0° and 45° (Hays and Grossman, 1991, their Figure 2). The paleolatitude of the study area was roughly that of its location today, 35° to 40° (Park, 1988); therefore, both solutions for paleotemperature must be considered.

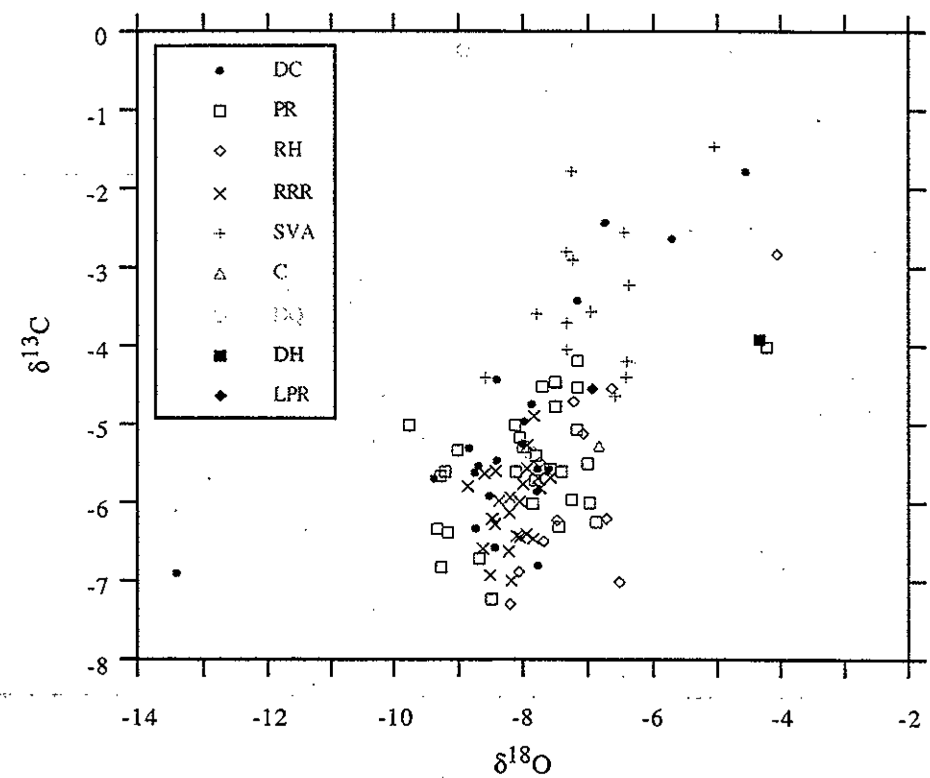

Figure 36. Carbon and oxygen stable isotope composition of calcretes from measured sections and other locations of this study.

Values calculated for Appendix A give average ranges for warm temperatures around 27° to 28°C and cooler temperatures around 7°C. Given that temperatures for the Cretaceous are generally thought to have been warmer than today and that modern soil temperatures for similar latitudes and climatic conditions are 20° to 30°C (Mack et al., 1991; Cerling and Quade, 1993), it would not be prudent to consider the cooler temperature for carbonate formation. The average for all samples is 27.5°C and is not unreasonable.

The next obvious step in paleoclimatic reconstruction would be to predict the average mean atmospheric paleotemperature. However, as others have observed (Talma and Netterberg, 1983; Cerling and Quade, 1993), the modern system needs to be studied further before these relationships can be applied to the past. Modern calcretes that form in semi-arid environments, and having comparable textures and features to those in this study, have developed in areas with a mean atmospheric temperature range of 16° to 25°C (Hay and Reeder, 1978; Hay and Wiggins, 1980; Watts, 1980; Semeniuk and Meagher, 1981; Semeniuk and Searle, 1985).

Applying the average temperature for carbonate formation (27.5°C) calculated above to the diffusion model increases the robustness of the paleoatmospheric $P(CO_2)$ model. All variables in this application of the model are kept the same as previously defined except temperature (27.5°C). If the $P(CO_2)$ range (5000 to 10,000 ppmV) for a temperate and tropical climate of Cerling (1991) and Mora et al. (1991) is used, an estimated paleo-$P(CO_2)$ of 3400 to 5400 ppmV (11 to 18 times modern $P(CO_2)$ is predicted (Figure 37). This is considerably higher than that predicted by Berner (1990; 1991); 2 to 9 times modern $P(CO_2)$. If the range previously chosen for a more arid soil (3000 to 7000 ppmV) is applied to the diffusion model, a range of 2200 to 3900 ppmV is predicted for paleoatmospheric $P(CO_2)$ (Figure 38). This is 7 to 13 times more than modern $P(CO_2)$, only slightly higher than the previous interpreted concentrations of 6 to 12 times modern $P(CO_2)$ using a temperature of 25°C. The later values (2200 to 3900 ppmV) are comparable but slightly higher than ranges predicted by Berner (1990; 1991) and Cerling

(1991) for the lower Cretaceous. A $P(CO_2)$ range of 1900 to 3500 ppmV (6 to13 times modern) predicted by a 25°C to 27.5°C temperature range is probably a reasonable estimation of paleoatmospheric $P(CO_2)$ for the lower Cretaceous calcretes of this study.

Applying Rates of Carbonate Accumulation to Calcrete

The presence of calcrete in any stratigraphic record indicates low sedimentation rates (Goudie, 1983). In continental environments, it is difficult to determine time elapsed during conditions of slow sedimentation or non-deposition. Calcretes are geologically significant because it is possible to estimate time elapsed during their formation. Calcrete rates are estimated by various methods, some of which are: radiocarbon dating (Robbin and Stipp, 1979; Magaritz et al., 1981); K-Ar dating, tephrochronology, vertebrate paleontology, and regional soil studies (Machette, 1978). Also, models for estimating calcrete formation rates using variables such as flood basin accretion rates, calcrete thickness, carbonate precipitation rates, carbonate content, water influx, carbonate influx and time have been developed (Leeder, 1975; Goudie, 1983). The type of climate and availability of calcium are probably the most important factors that influence the rate of calcrete formation (Goudie, 1983).

Some factors related to climate that influence the rates of calcrete formation are the type and amount of vegetative cover, (Klappa, 1979; 1980), and annual and/or seasonal precipitation (Leeder, 1975). Very little is known regarding the rates of formation of specific types of calcrete (e.g., ground water versus vadose, massive versus laminar); different types potentially could have widely divergent rates of formation.

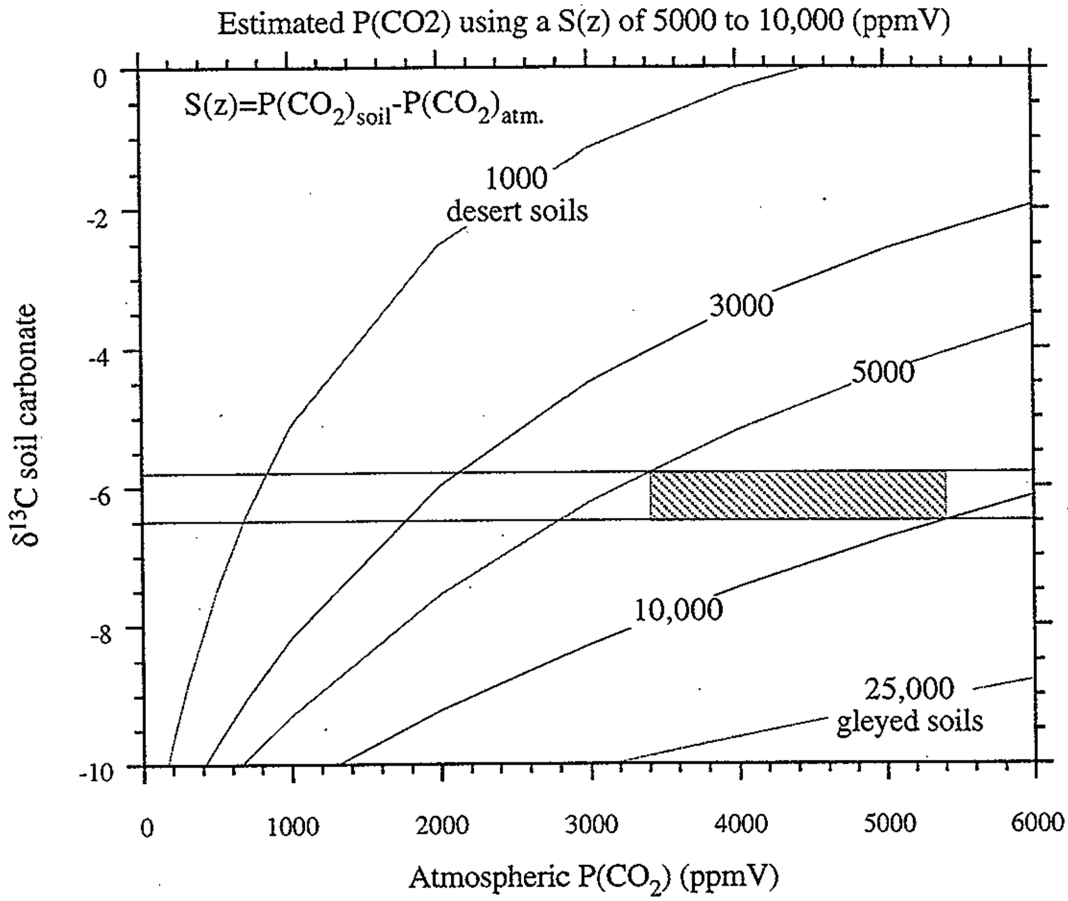

Figure 37. Atmospheric $P(CO_2)$ inferred from early Cretaceous pedogenic calcrete using Cerling (1991) diffusion model with a formation temperature of 27.5°C. Soil carbonate range is the total average and a -1 sigma.

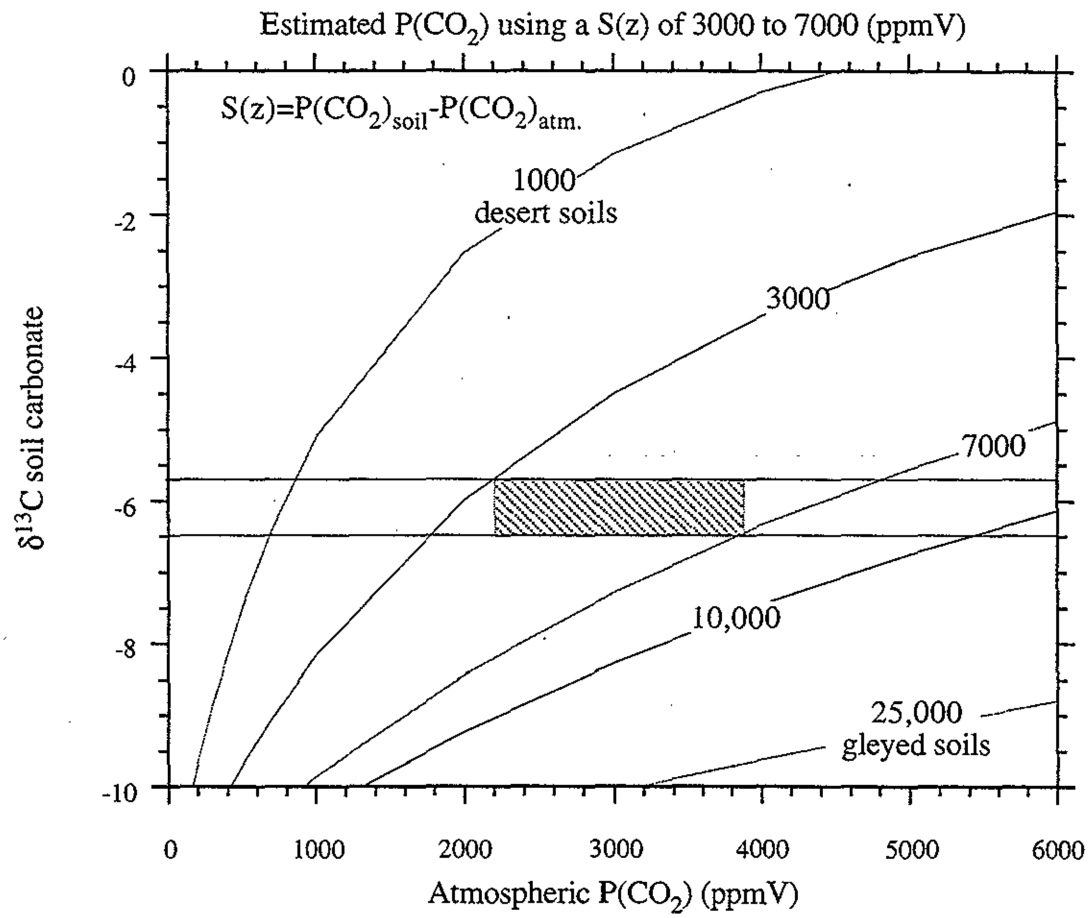

Figure 38. Atmospheric $P(CO_2)$ inferred from early Cretaceous pedogenic calcrete using cerling diffusion model with a formation temperature of 27.5°C. Soil carbonate range is the total average and a -1 sigma.

The duration of K-1 unconformity is not known precisely, but a time span of ~15 myr is presently accepted (Tschudy et al., 1984; Turner and Peterson, 1996). This duration gives an upper limit to the amount of time available for calcrete formation if we assume its development occurred during this hiatus. If general rates of calcrete accumulation are applied to total thicknesses of calcrete in the measured sections, an approximate time for formation can be calculated (Table 3). The SVA section is left out of the comparisons because it is believed to have dissolution associated with it, possibly altering the original calcrete thickness.

Table 3. Rates of calcrete formation applied to thicknesses of measured section calcretes to estimate the time required for formation. Rates are derived from: Machette, 1978; Robbin and Stipp, 1979; Magaritz et al., 1981 and; Goudie, 1983.

Location	Thickness (m)	Minimum rate 2.5×10^{-3} m/ kyr	Maximum rate 5.0×10^{-3} m/ kyr
DC	12.5	5.0 myr	2.5 myr
RRR	11.4	4.5 myr	2.3 myr
RH	2.3	920 kyr	460 kyr
PR	14	5.6 myr	2.8 myr

Another approach to determine the duration of carbonate accumulation is to assess each calcrete unit as determined by the stage of carbonate development and then add all the units within a section for a total amount of accumulated time. A description of each stage of carbonate accumulation from Retallack (1988) is as follows:

Stage I	Dispersed powdery and filamentous carbonate.
Stage II	Few to common carbonate nodules and veinlets.
Stage III	Carbonate forming a continuous layer formed by coalescing nodules and isolated nodules.
Stage IV	Upper part of solid carbonate layer with a weakly developed platy or lamellar structure, capping less pervasively calcareous parts of the profile.
Stage V	Platy or lamellar cap to the carbonate layer strongly expressed; in places brecciated and with pisolites of carbonate.

There are a few problems with this approach, however. Assigning a stage of carbonate development is subjective and not exact. Picking the boundaries of a particular stage may be difficult due to many factors, including overlapping of calcrete development, dissolution of calcrete, diffuse boundaries, erosion, etc. Estimated times for carbonate development stages are from Leeder (1975) and Wright (1990) and are as follows: stage II 3,500-7000 yr; stage III 6,000-40,000 yr; stage IV 10,000-1,000,000 yr. Stage I was not identified in any section. A conservative estimate of 10,000 to 1,000,000 yr for stage V is used because no estimated or calculated ranges for stage V were found. Maxima and a minima were assigned to each of the stages in a measured section and totaled. Figures 10, 11, 12, and 13 give the interpreted stages of carbonate development. The calculated maxima and minima for the sections are shown in table 4.

Table 4. Calculated formation times for calcretes in the study area using estimated stages of carbonate development (Figures 10-13). Stages of carbonate development are from Leeder (1975) and Wright (1990).

Location	Maximum	Minimum
DC	7.4 myr	100 kyr
RRR	9.2 myr	102 kyr
RH	1.6 myr	31 kyr
PR	1.7 myr	56 kyr

Given the variability of the factors that affect rates of carbonate accumulation, a less conservative range is more appropriate. The RH section probably represents a minimum duration because of erosion due to channeling. The RRR and PR sections do not include any channel sandstones and are probably the most complete records of calcrete development. The maximum and minimum durations from PR and RRR are 56 ky to ~9 my, respectively (Tables 3 and 4). This range is less than the upper limit of ~15 my that approximates the K-1 unconformity and greater than the minimum estimated by the RH calcrete (31 ky) and therefore, a reasonable estimate. The difference in the estimated range of 56 ky to 9 my is a 160 fold difference. To emphasize the variability of carbonate accumulation, a rate of 3 m/1000 yr for a ground water calcrete in a semi-arid climate of southern Africa was calculated by Goudie (1983). This would mean if the thickest calcrete section of this study was interpreted as a ground water type calcrete, it would only take 4,700 yr to form, greatly underestimating the time for its formation.

Rates of calcrete accumulation have also recently been determined by replacement geochemical modeling (Wang et al., 1994) and can be modeled for any type of host material. However, the model includes the presence of mineral phases such as sepiolite or attapulgite for the removal of silica. Because these minerals were not observed and the fact that these calcretes are interpreted to be mostly displacive not replacive, no attempt was made to use this type of geochemical modeling for determining rates of calcrete accumulation.

SUMMARY AND CONCLUSIONS

This study has taken a detailed approach to understanding calcrete development in a complex regional setting. One advantage of this study is that the depositional environment occurs in a consistently widespread fluvial setting, unlike other calcrete studies that bridge several depositional environments (Mack and James, 1986; Joeckel, 1991; Mack et al., 1991). A difficulty with this study was determining the specific precipitation environment of the calcrete (water table, vadose, or subaerial), which is instrumental in the interpretation of data. This difficulty may serve as a primary focus of subsequent studies.

Calcrete at the Jurassic-Cretaceous Boundary

Calcrete at each of the study locations is quite varied in its morphology and occurrence. It occurs as thin nodular zones, coalesced nodules, and massive beds of calcrete. Laminated calcretes are thin and their occurrence is rare. Sediments associated with the calcrete zone lack stratification and retain soil textures and fabrics. In general, fully developed soil horizons are lacking; Bk, Bkm, or K are the only paleosol horizons identified.

These calcretes are, in general, characterized as alpha calcretes. Their primary composition is micrite and microspar forming a clotted fabric. Peloids, circumgranular cracks, fracturing, flower structures, floating detrital grains, and few root tubes are present in calcretes studied. Secondary brecciation, dissolution and reprecipitation as blocky and bladed spar is common. The dominant clay minerals associated with the calcretes are illite and mixed-layer illite/smectite. Less abundant clay minerals are kaolinite, chlorite, and smectite. Parts of all the sections studied have emplacement of late silica, probably mobilized from volcanic ash.

The lack of developed soil horizons and few biogenic structures leads to the interpretation that sedimentation was probably frequent and/or climatic conditions were relatively dry. The DC, RRR, and PR sections are probably the most complete calcrete records, and each shows many cycles of calcrete development. None of these cycles had obvious correlations to one another using all available data, probably due to the large distance separating the locations. The timing and emplacement of each calcrete cycle was probably relatively rapid based on the deposition and preservation of calcite replaced volcanic glass at the PR location.

As mentioned above, determining the exact environment of precipitation for each type of calcrete was difficult in some cases. Calcrete of this study is complex regionally and in stratigraphic section. It is interpreted to represent water table-related, vadose, and subaerial types. No evidence indicates that the carbonates of this study are lacustrine. Because of over-printing due to sediment accumulation and erosion and eventual water table rise, individual types are difficult to recognize. Lateral and proximal studies may help refine the origin of each calcrete cycle.

The SVA section probably represents a condensed or amalgamated section, in relation to the other sections. This may be due to a slightly elevated topography resulting from upward salt movement and/or karstification (all of which may be interrelated). The evidence for salt movement during K-1 unconformity time is probably the most important outcome at this location.

Paleoclimate Interpretation

The climate during the formation of this regional calcrete was probably semi-arid and temperate based on minimal soil development and its associated minerals, desiccation cracks, alpha-type calcretes, lack of abundant rhizoliths, and comparison to modern calcretes of similar climates (Hay and Reeder, 1978; Hay and Wiggins, 1980; Watts, 1980; Semeniuk and Meagher, 1981; Semeniuk and Searle, 1985). Data and observations may also indicate times of sparse vegetation. Using the diffusion model, the atmospheric $P(CO_2)$ was probably elevated from 6 to 11 times that of the present atmosphere. This is probably a reliable estimate given the large number of isotope samples that are both closely grouped and also from regional locations. The oxygen isotopic composition of the meteoric water was probably between -5‰ to -15‰ (SMOW), consistent with this continental setting and location.

There is evidence that a possible climatic gradient was present during early calcrete development. This is based on differences identified at the RH location (Figure 9 and 22; Table 1). The dominant clay mineral at RH, PR and DH (all eastern sections) is kaolinite. The oxygen isotopes are slightly more enriched at these sections than at the other locations (Figure 32). Furthermore, petrographic observations from the RH location indicate wetter conditions of calcrete formation. Calculated paleotemperatures of calcrete formation are generally lower here than at the other locations. Therefore, in general, it was probably drier to the west and wetter to the east. Additionally, semi-correlative sediments of the Plainview Member of the Dakota Group (middle Albian?) east of the study area, are interpreted as wetter climate sediments (Weimer et al., 1990).

Average rainfall for modern calcrete development is 400-600 mm/yr, with exceptional cases in the range of 1000-1500 mm/yr and 175 mm/yr; however, the latter are closely associated with gypsum precipitation (Goudie, 1983). Because the western calcretes of this study are interpreted as semi-arid, annual precipitation may be slightly less than the above average range. Those calcretes on the eastern edge of the study area likely experienced slightly wetter conditions.

The paleo-carbon isotopic composition of the vegetation is -23‰ to -19.6‰. Vegetation with this carbon isotopic composition most likely follows the C_3 photosynthetic pathway. These average values may also support the interpretation that the study area was only sparsely vegetated. This is because sparse vegetation produces less available light carbon ($^{12}CO_2$) for the precipitation of calcium carbonate.

Rates of Calcrete Accumulation

Calculating durations of calcrete formation at present is not very reliable (Wright, 1990); nevertheless, an attempt was made. The duration of formation determined here (9 myr to 56,000 yr.) were deliberately conservative and therefore probably encompass the actual period of formation, whatever that may have been. This type of data may, at present, only serve as a comparison for future studies.

Potential for Mapping Paleohydrologic Surface

Because the calcrete in this study is laterally extensive, it may offer a great opportunity to map a geomorphic surface associated with the K-1 unconformity. Massive and laminar sheet-type calcretes (Quaternary) have been observed to develop parallel to the water table (Semeniuk and Meagher, 1981). Other indirect evidence for determining depth to water table can be estimated from the depth of burrow casts, assuming that they terminate at or near the water table (Hasiotis and Brown, 1992). Smith (1990) observed burrow casts, in Permian paleosols at a minimum depth of 1.5 m from the upper bounding paleosol.

Therefore the potential exists for mapping the paleo-water table related to the calcrete of the study area.

REFERENCES CITED

Amundson, R.G., Chadwick, O.A., Sowers, J.M., and Donner, H.E., 1988, Relationship between climate and vegetation and the stable carbon isotope chemistry of soils in the Eastern Mojave, Nevada: Quaternary Research, v. 29, p. 245-254.

Arakel, A.V., 1982, Genesis of calcrete in Quaternary soil profiles, Hutt and Leeman Lagoons, western Australia: Journal of Sedimentary Petrology, v. 52, p. 109-126.

Arakel, A.V., and McConchie, D., 1982, Classification and genesis of calcrete and gypsite lithofacies in paleodrainage systems of inland Australia and their relationship to carnotite mineralization: Journal of Sedimentary Petrology, v. 52, p. 1149-1170.

Aubrey, W.M., 1992, New interpretations of the stratigraphy and sedimentology of the uppermost Jurassic to lowermost Upper Cretaceous strata in the San Juan Basin of Northwestern New Mexico: U.S. Geological Survey Bulletin 1808-J, 17 p.

Baldwin, B., and Butler, C.O., 1985, Compaction curves: American Association of Petroleum Geology Bulletin, v. 69, p. 622-626.

Beier, J.A., 1987, Petrographic and geochemical analysis of caliche profiles in a Bahamian Pleistocene dune: Sedimentology, v. 34, p. 991-998.

Berner, R.A., 1990, Atmospheric carbon dioxide levels over Phanerozoic time: Science, v. 249, p. 1382-1386

Berner, R.A., 1991, A model for atmospheric CO_2 over Phanerozoic time: American Journal of Science, v. 291, p. 339-376.

Bird, R.B., Stewart, W.E., and Lightfoot, E.N., 1960, Transport Phenomena: John Wiley Publishing, New York, 780 p.

Blodgett, R.H., 1988, Calcareous paleosols in the Triassic Dolores Formation southwestern Colorado; in, Reinhardt, J., and Sigleo, W.R., (eds.), Paleosols and Weathering Through Geologic Time: Principles and Applications: Geological Society of America Special Paper 216, p. 103-122.

Brewer, R., 1976, Fabric and mineral analysis of soils: Krieger Publishing, Huntington, New York, 482 p.

Carter, W.D., 1957, Disconformity between Lower and Upper Cretaceous in western Colorado and eastern Utah: Geological Society of America Bulletin, v. 68, p. 307-314.

Cerling, T.E., 1984, The stable isotopic composition of modern soil carbonate and its relationship to climate: Earth and Planetary Science Letters, v. 71, p. 229-240.

Cerling, T.E., 1991, Carbon dioxide in the atmosphere: Evidence from Cenozoic and Mesozoic paleosols: America Journal of Science, v. 291, p. 377-400.

Cerling, T.E., 1992, Use of isotopes in paleosols as an indicator of the $P(CO_2)$ of the paleoatmosphere: Global Biogeochemical Cycles, v. 6, p. 307-314.

Cerling, T.E., and Hay, R.L., 1986, An isotopic study of paleosol carbonates from Olduvai Gorge: Quaternary Research, v. 25, p. 63-78.

Cerling, T.E., Quade, J., Wang, Y., and Bowman, J.R., 1989, Carbon isotopes in soils and paleosols as paleoecologic indicators: Nature, v. 341, p. 138-139.

Cerling, T.E., and Quade J., 1993, Stable carbon and oxygen isotopes in soil carbonates; in, Swart, P.K., Lohmann, K.C., Mckenzie, J., and Savin, S., (eds.), Climate Change in Continental Isotopic Records: American Geophysical Union, Geophysical Monograph 78, p. 217-231.

Cerling, T.E., and Ekart, D.D., 1995, Summary of Activities; in, Turner, C.E., and Peterson, F., (eds.), Semiannual Report: The Morrison Formation Extinct Ecosystems Project: U.S. Geological Survey Administrative Report, December 1, 1995, p. 13-17.
Chafetz, H.S., and Butler, J.C., 1980, Petrology of recent caliche pisolites, spherulites and speleothem deposits from central Texas: Sedimentology, v. 27, p. 497-518.
Craig, H., 1957, Isotopic standards for carbon and oxygen and correction factors for mass-spectrometer analysis of carbon dioxide: Geochemica et Cosmochimica Acta, v. 12, p. 133-149.
Craig, L.C., Holmes, C.N., Cadigan, R.A., Freeman, L.V., Mullens, T.E., and Weir, W.G., 1955, Stratigraphy of the Morrison and related Formations, Colorado Plateau region, a preliminary report: U.S. Geological Survey Bulletin 1009-E, p. 125-168.
Craig, L.C., and Shawe, D.R., 1975, Jurassic rocks of east-central Utah; in, Fasett, J.E., (ed.), Canyonlands Country: Four Corners Geological Society Guidebook, 8th Field Conference, , p. 157-165.
Deines, P., Langmuir, D., and Harmon, R.S., 1974, Stable carbon isotope ratios and the existence of a gas phase in the evolution of carbonate ground waters: Geochemica et Cosmochimica Acta, v. 38, p. 1147-1164.
Drever, J.I., 1973, The preparation of oriented clay mineral specimens for x-ray diffraction analysis by filter-membrane peel technique: American Mineralogist, v. 58, p. 553-554.
Ekren, E.B., and Houser, F.N., 1959, Relations of Lower Cretaceous and Upper Jurassic rocks, Four Corners area Colorado: American Association of Petroleum Geologists Bulletin, v. 43, p. 190-201.
Emrich, K, Ehhalt, D.H., and Vogel, J.C., 1970, Carbon isotope fractionation during the precipitation of calcium carbonate: Earth and Planetary Science Letters v. 8, p. 363-371.
Esteban, M., and Klappa C.F., 1983, Subaerial exposure; in, Scholle, P.A, Bebout, D.G., and Moore, C.H., (eds.), Carbonate Depositional Environments: American Association of Petroleum Geologists Memoir 33, p. 1-54.
Fahraeus, L.E., Slatt, R.M., and Nowlan, G.S., 1974, Origin of carbonate pseudopellets: Journal of Sedimentary Petrology, v. 44, p. 27-29.
Faure, G., 1986, Carbon: Principles of Isotope Geology, John Wiley and Sons Publications.
Ferguson, K.M., 1991, C- and O-isotopes of pedogenic nodules from two sections spanning the K-T transition in west Texas: Geological Society of America Abstracts With Programs, v. 23, p. 203.
Goldbery, R., 1982, Paleosols of the Lower Jurassic Mishhor and Ardon Formations ('laterite derivative facies'), Makhtesh Ramon, Israel: Sedimentology, v. 29, p. 669-690.
Goodfriend, G.A., and Magaritz, M., 1988, Palaeosols and late Pleistocene rainfall fluctuations in the Negev Desert: Nature, v. 332, p. 144-146.
Goudie, A.S., 1983, Calcrete; in, Goudie, A.S., and Pye, K., (eds.), Chemical Sediments and Geomorphology: Precipitates and Residua in the Near-Surface Environment: Academic Press, Inc., New York, p. 93-131.
Guthrie, R.L., and Witty, J.E., 1982, New designations for soil horizons and layers and the New Soil Survey Manual: Soil Science Society of America Journal, v. 46, p. 443-444.
Hasiotis, S.T., and Brown, T.M., 1992, Invertebrate trace fossils: the backbone of continental ichnology; in, Maples C.G., and West, R.R., (eds.), Trace Fossils: Short Courses in Paleontology, Number 5, The Paleontological Society, p. 64-104.
Hay, R.L., and Reeder, R.J., 1978, Calcretes of Olduvai Gorge and the Ndolanya beds of northern Tanzania: Sedimentology, v. 25, p. 649-673.
Hay, R.L., and Wiggins, B., 1980, Pellets, ooids, sepiolite and silica in three calcretes of the southwestern United States: Sedimentology, v. 27, p. 559-576.

Hays, P.D., and Grossman, E.L., 1991, Oxygen isotopes in meteoric calcite cements as indicators of continental paleoclimate: Geology, v. 19, p. 441-444.
Humphrey, J.D., and Ferring, C.R., 1994, Stable isotope evidence for latest Pleistocene and Holocene climate change in north-central Texas: Quaternary Research, v. 41, p. 200-213.
James, N.P., and Choquette, P.W., 1984, Diagenesis 9. Limestones-The meteoric diagenetic environment: Geoscience Canada, v. 11, p. 161-194.
Joeckel R.M., 1991, Paleosol stratigraphy of the Eskridge Formation; Early Permian pedogenesis and climate in southeastern Nebraska: Journal of Sedimentary Petrology, v. 61, p. 234-255.
Kelly, E.F., Yonker, C., and Marino, b., 1993, Stable carbon isotope composition of paleosols: An application to Holocene; in, Swart, P.K., Lohmann, K.C., Mckenzie, J., and Savin, S., (eds.), Climate Change in Continental Isotopic Records: American Geophysical Union, Geophysical Monograph 78, p. 233-239.
Klappa, C.F., 1979, Calcified filaments in Quaternary calcretes: organo-mineral interactions in the subaerial vadose environment: Journal of Sedimentary Petrology, v. 49, p. 955-968.
Klappa, C.F., 1980, Brecciation textures and tepee structures in Quaternary calcrete (caliche) profiles from eastern Spain: The plant factor in their formation: Geological Journal, v. 15, p. 81-90.
Klappa, C.F., 1983, A process-response model for the formation of pedogenic calcretes; in, Wilson, R.C.L., (ed.), Residual Deposits: Surface Related Weathering Processes and Materials: Blackwell Scientific Publications, London, p. 211-220.
Knox, G.F., 1977, Caliche profile formation, Saldanha Bay (South Africa): Sedimentology, v. 24. p. 657-674.
Lohman, S.W., 1965, Geology and artesian water supply, Grand Junction area Colorado: U.S. Geological Survey Professional Paper 451, 149 p.
Leeder, M.R., 1975, Pedogenic carbonate and flood sediment accretion rates: a quantitative model for alluvial arid-zone lithofacies: Geological Magazine, v. 112, p. 257-270.
Machette, M.N., 1978, Dating Quaternary faults in the southwestern United States by using buried calcic paleosols: Journal of Research, U.S. Geological Survey, v. 6, p. 369-381.
Machette, M.N., 1985, Calcic soils of the southwestern United States; in, Weide, D.L., (ed.), Soils and Quaternary Geology of the southwestern United States: Geological Society of America Special Paper 203, p. 1-21.
Mack, G.H., and James, W.C., 1986, Cyclic sedimentation in the mixed siliciclastic-carbonate Abo-Hueco transitional zone (Lower Permian), southwestern New Mexico: Journal of Sedimentary Petrology, v. 56, p. 635-647.
Mack, G.H., Cole, D.R., Giordano, T.H., Schall, W.C., and Barcelos, J.H., 1991, Paleoclimatic controls on stable oxygen and carbon isotopes in caliche of the Abo Formation (Permian), south-central New Mexico, U.S.A.: Journal of Sedimentary Petrology, v. 61, p. 458-472.
Mann, A.W., and Horwitz, R.C., 1979, Groundwater calcrete deposits in Australia: Some observations from Western Australia: Journal of the Geological Society of Australia, v. 26, p. 293-303.
Magaritz, M., Kaufman, A., and Yaalon, D.H., 1981, Calcium carbonate nodules in soils: $^{18}O/^{16}O$ and $^{13}C/^{12}C$ ratios and ^{14}C contents: Geoderma, v. 25, p. 157-172.
Moore, D.M., and Reynolds, R.C., 1989, X-ray diffraction and the identification and analysis of clay minerals: Oxford University Press, 332 p.
Mora, C.I., Driese, S.G., and Seager, P.G., 1991, Carbon dioxide in the Paleozoic atmosphere: Evidence from carbon-isotopic compositions of pedogenic carbonate: Geology, v. 19, p. 1017-1020.

Naylor, H., Turner, P., Vaughan, D.J., and Fallick, A.E., 1989, The Cherty Rock, Elgin: A petrographic and isotopic study for a Permo-Triassic calcrete: Geological Journal, v. 24, p. 205-221.

O'Neil, J.R., Clayton , R.N., and Mayeda, T.K., 1969, Oxygen isotope fractionation in divalent metal carbonates: Journal of Chemical Physics, v. 51, p. 5547-5558.

Owen, D.E., 1982, Correlation and paleoenvironments of the Jackpile Sandstone (Upper Jurassic) and intertongued Dakota Sandstone-Lower Mancos Shale (Upper Cretaceous) in west-central New Mexico; in, Grambling, J.A. and Wells, S.G., (eds.), Albuquerque County II: New Mexico Geological Society 33rd Annual Field Conference, Guidebook, p. 267-270.

Park, P.G., 1988, Geological Structures and Moving Plates: Chapman and Hall, New York, 337 p.

Peterson, F., 1986, Jurassic paleotectonics in the west-central part of the Colorado Plateau, Utah and Arizona; in, Peterson, J.A., (ed.), Paleotectonics and Sedimentation in the Rocky Mountain Region, United States: American Association of Petroleum Geologists Memoir 41, p. 563-596.

Peterson, F., and Turner-Peterson, C.E., 1987, The Morrison Formation of the Colorado Plateau: Recent advances in sedimentology, stratigraphy, and paleotectonics: Hunteria, v. 2, p. 1-18.

Pollastro, R.M., 1982, A recommended procedure for the preparation of oriented clay-mineral specimens for X-ray diffraction analysis: Modifications to Drever's filter-membrane peel technique: U.S. Geological Survey, Open-File Report 82-71, 10 p.

Poole, F.G., 1962, Wind directions in Late Paleozoic to Middle Mesozoic time on the Colorado Plateau: Short papers in Geology, Hydrology, and Topography, Articles 120-179, U.S. Geological Survey Professional Paper 450-D, p. D147-D151.

Purvis, K., and Wright, V.P., 1991, Calcretes related to phreatophytic vegetation from the Middle Triassic Otter Sandstone of southwest England: Sedimentology, v. 38, p. 539-551.

Quade, J., Cerling, T.E. and Bowman, J.R., 1989a, Systematic variations in the carbon and oxygen isotopic composition of pedogenic carbonate along elevation transects in the southern Great Basin, United States: Geological Society of America Bulletin, v. 101, p. 464-475.

Quade, J., Cerling, T.E. and Bowman, J.R., 1989b, Development of Asian monsoon revealed by marked ecological shift during the latest Miocene in the northern Pakistan: Nature, v. 342, p. 163-166.

Retallack, G.J., 1988, Field recognition of paleosols; in, Reinhardt, J., and Sigleo, W.R., (eds.), Paleosols and Weathering Through Geologic Time: Principles and Applications: Geological Society of America Special Paper 216, p. 1-20.

Robbin, D.M., and Stipp, J.J., 1979, Depositional rate of laminated soilstone crusts, Florida Keys: Journal of Sedimentary Petrology, v. 49, p. 175-180.

Rossinsky, V., Jr., and Swart, P.K., 1993, Influence of climate on the formation and isotopic composition of calcretes; in, Swart, P.K., Lohmann, K.C., Mckenzie, J., and Savin, S., (eds.), Climate Change in Continental Isotopic Records: American Geophysical Union, Geophysical Monograph 78, p. 67-75.

Salomons, W., and Mook, W.G., 1976, Isotope geochemistry of carbonate dissolution and reprecipitation in soils: Soil Science, v. 122, p. 15-24.

Salomons, W., Goudie, A., and Mook, W.G., 1978, Isotopic composition of calcrete deposits from Europe, Africa, and India: Earth Surface Processes, v. 3, p. 43-57.

Semeniuk, V., and Meagher, T.D., 1981, Calcrete in Quaternary coastal dunes in southwestern Australia: A capillary-rise phenomenon associated with plants:

Semeniuk, V., and Searle, D. J., 1985, Distribution of calcrete in Holocene coastal sands in relationship to climate, southwestern Australia: Journal of Sedimentary Petrology, v. 55 p. 86-95.

Siesser, W.G., 1973, Diagenetically formed ooids and intraclasts in South African calcretes: Sedimentology, v. 20, p. 539-551.
Simmons, G.C., 1957, Contact of the Burro Canyon Formation with the Dakota Sandstone, Slick Rock District, Colorado, and correlation of the Burro Canyon Formation: American Association of Petroleum Geologists Bulletin, v. 41, p. 2519-2529.
Skipp, G.L., 1997, Characterization and paleoenvironmental interpretation of pedogenic carbonate at the J-K boundary, east-central Utah and west-central Colorado: Unpublished M.S. thesis, Colorado School of Mines, Golden, 113 p.
Slate, J.L., Smith, G.A., Wang, Y., and Cerling, T.E., 1996, Carbonate-paleosol genesis in the Plio-Pleistocene St. David Formation, southeastern Arizona: Journal of Sedimentary Research, v. 66, p. 85-94.
Smith, R.M.H., 1990, Alluvial paleosols and pedofacies sequences in the Permian Lower Beaufort of the southwestern Karoo Basin, South Africa: Journal of Sedimentary Petrology, v. 60, p. 258-276.
Sobecki, T.M., and Wilding, L.P., 1983, Formation of calcic and argillic horizons in selected soils of the Texas coastal prairie: Soil Science Society of America Journal, v. 47, p. 707-715.
Stokes, L.W., 1952, Lower Cretaceous in the Colorado Plateau: American Association of Petroleum Geologists Bulletin, v. 36, p. 1766-1776.
Stokes, L.W., 1986. Geology of Utah: Utah Museum of Natural History, University of Utah and Utah Geological and Mineral Survey Department of Natural Resources, Salt Lake City, Utah, 308 p.
Suchecki, R.K., Hubert, J.F., and Birney-de Wet, C.C., 1988, Isotopic imprint of climate and hydrogeochemistry on terrestrial strata of the Triassic-Jurassic Hartford and Fundy Rift Basins: Journal of Sedimentary Petrology, v. 58, p. 801-811.
Talma, A.S., and Netterberg, F., 1983, Stable isotope abundances in calcretes; in, Wilson, R.C.L., (ed.), Residual Deposits: Surface Related Weathering Processes and Materials: Blackwell Scientific Publications, p. 221-233.
Tschudy, R.H., Tschudy, B.D., and Craig, L.C., 1984, Palynological evaluation of Cedar Mountain and Burro Canyon Formations, Colorado Plateau: U.S. Geological Survey Professional Paper 1281, 24 p.
Turner, C.E., and Fishman, N.S., 1991, Jurassic Lake T'oo'dichi': A large alkaline, saline lake, Morrison Formation, Eastern Colorado Plateau: Geological Society of America Bulletin v. 103, no. 4, p. 538-558.
Turner, C.E., and Peterson, F., 1996, Introduction; in, Turner, C.E., and Peterson, F., (eds.), Semiannual Report: The Morrison Formation Extinct Ecosystems Project: U.S. Geological Survey Administrative Report, December 1, 1996, p. 5-9.
Wang, Y., Nahon, D., and Merino, E., 1994, Dynamic model of the genesis of calcretes replacing silicate rocks in semi-arid regions: Geochimica et Cosmochimica Acta, v. 58, p. 5131-5145.
Watts, N.L., 1977, Pseudo-anticlines and other structures in some calcretes of Botswana and South Africa: Earth Surface Processes, v. 2, p. 63-74.
Watts, N.L., 1980, Quaternary pedogenic calcretes from the Kalahari (southern Africa): mineralogy, genesis and diagenesis: Sedimentology, v. 27, p. 661-686.
Wieder, M., and Yaalon, D.H., 1982, Micromorphological fabrics and development stages of carbonate nodular forms related to soil characteristics: Geoderma, v. 28, p. 203-220.
Wright, V.P., 1990, Estimating rates of calcrete formation and sedimentation accretion in ancient alluvial deposits: Geological Magazine, v. 127, p. 273-276.
Wright, V.,P. and Vanstone, S.D., 1991, Assessing the carbon dioxide content of ancient atmospheres using palaeo-calcretes: Theoretical and empirical constraints: Journal of the Geological Society, London, v. 148, p. 945-947.

Wright, V.P., and Tucker, M.E., 1991, Calcretes: An Introduction; in, Wright , V.P., and Tucker, M.E., (eds.), Calcretes: Blackwell Scientific Publications, Boston, Mass., p. 1-23.

Weimer, R., Dolson, J., Ethridge, F., and Warme, J., 1990, Two-Day Field Trip Sequence Stratigraphy—Lower K, Fort Collins-Boulder-Morrison Area: Rocky Mountain Section, American Association of Petroleum Geologists, 130 p.

Yurtsever, Y., 1975, Worldwide survey of stable isotopes in precipitation: Section of Isotope Hydrology, International Atomic Energy Agency, Vienna, 53 p.

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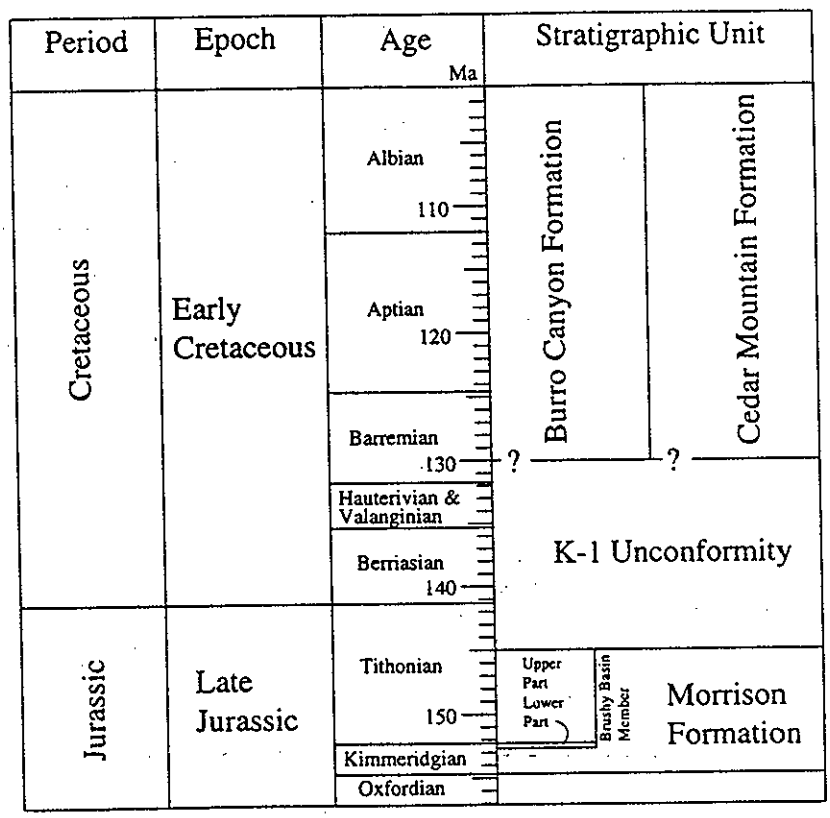

Figure 1. The age relations of the formations discussed in the text (modified from Turner and Peterson, 1996).

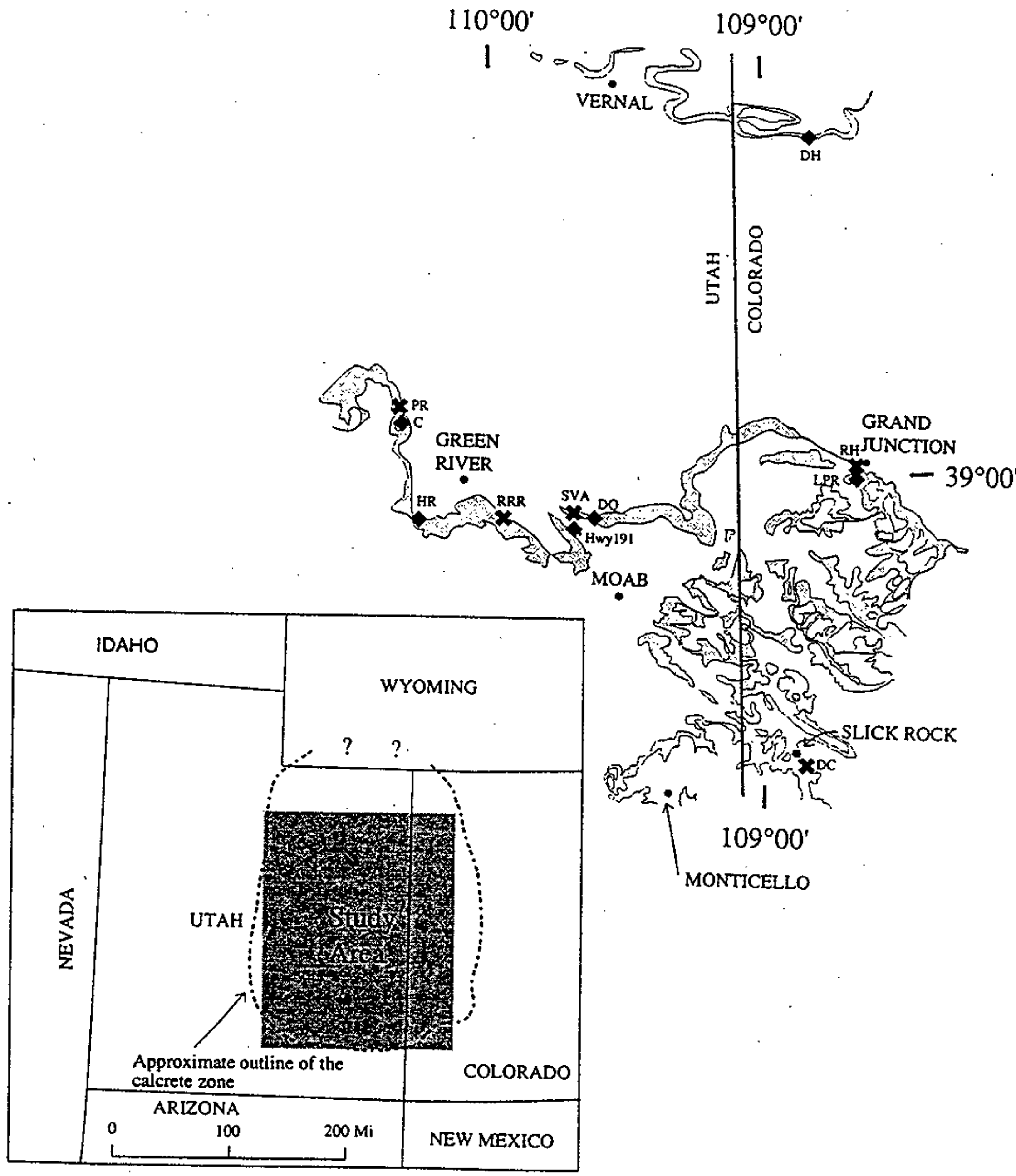

Figure 2. Location map of the study area. Outlined are the rocks of the Upper Jurassic and the Lower Cretaceous. Location of sampled sections are indicated by ✖: Price River (PR), Ruby Ranch Road (RRR), Salt Valley Anticline (SVA), Riggs Hill (RH), and Disappointment Creek (DC). Additional areas sampled for thin section and x-ray diffraction are indicated by ◆: Dinosaur Headquarters (DH), Dinosaur Quarry (DQ), Highway 191 (Hwy 191), Little Park Road (LPR), Cedar (C), and Hat Ranch (HR).

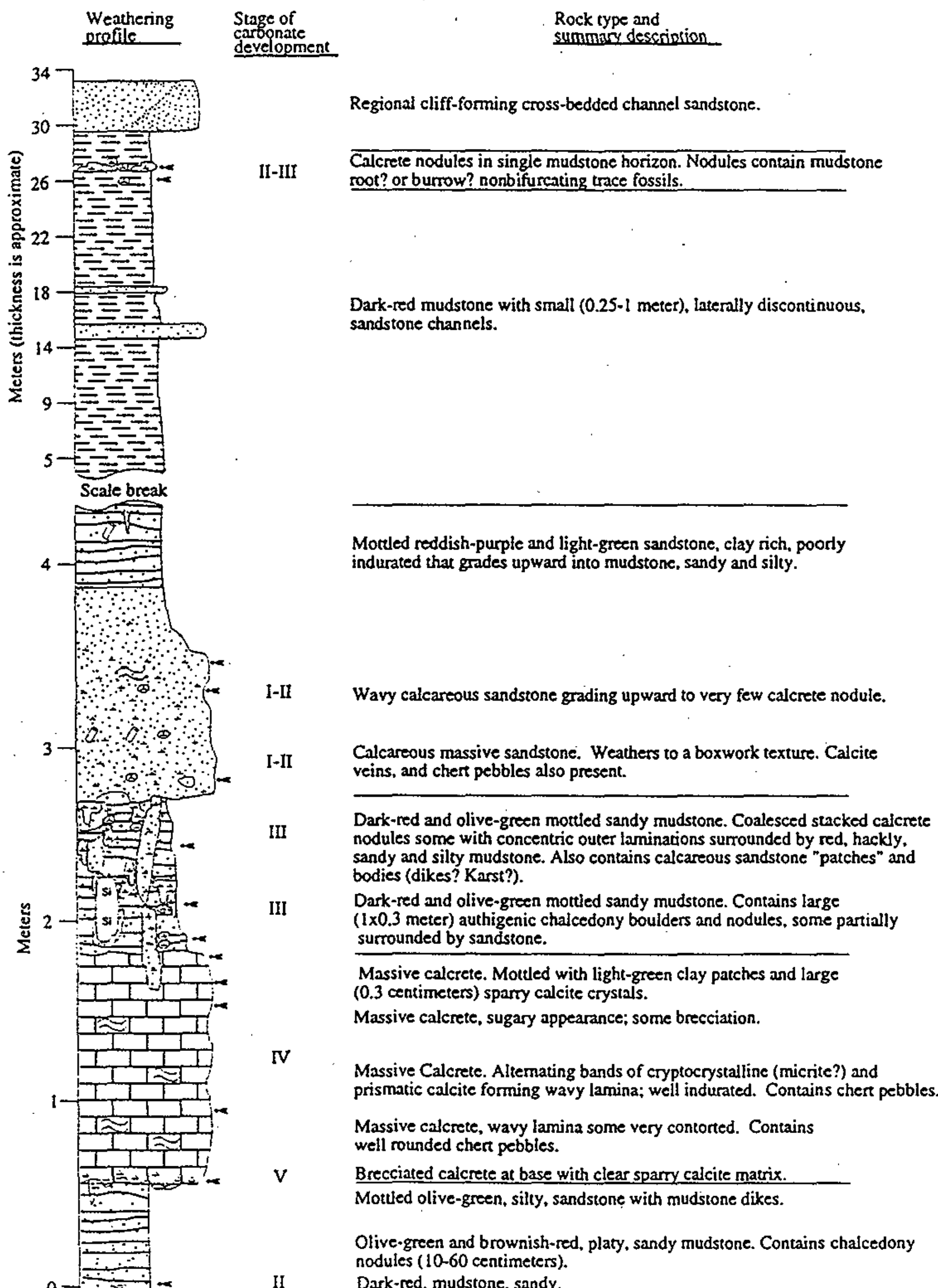

Figure 9. Salt Valley Anticline measured section.

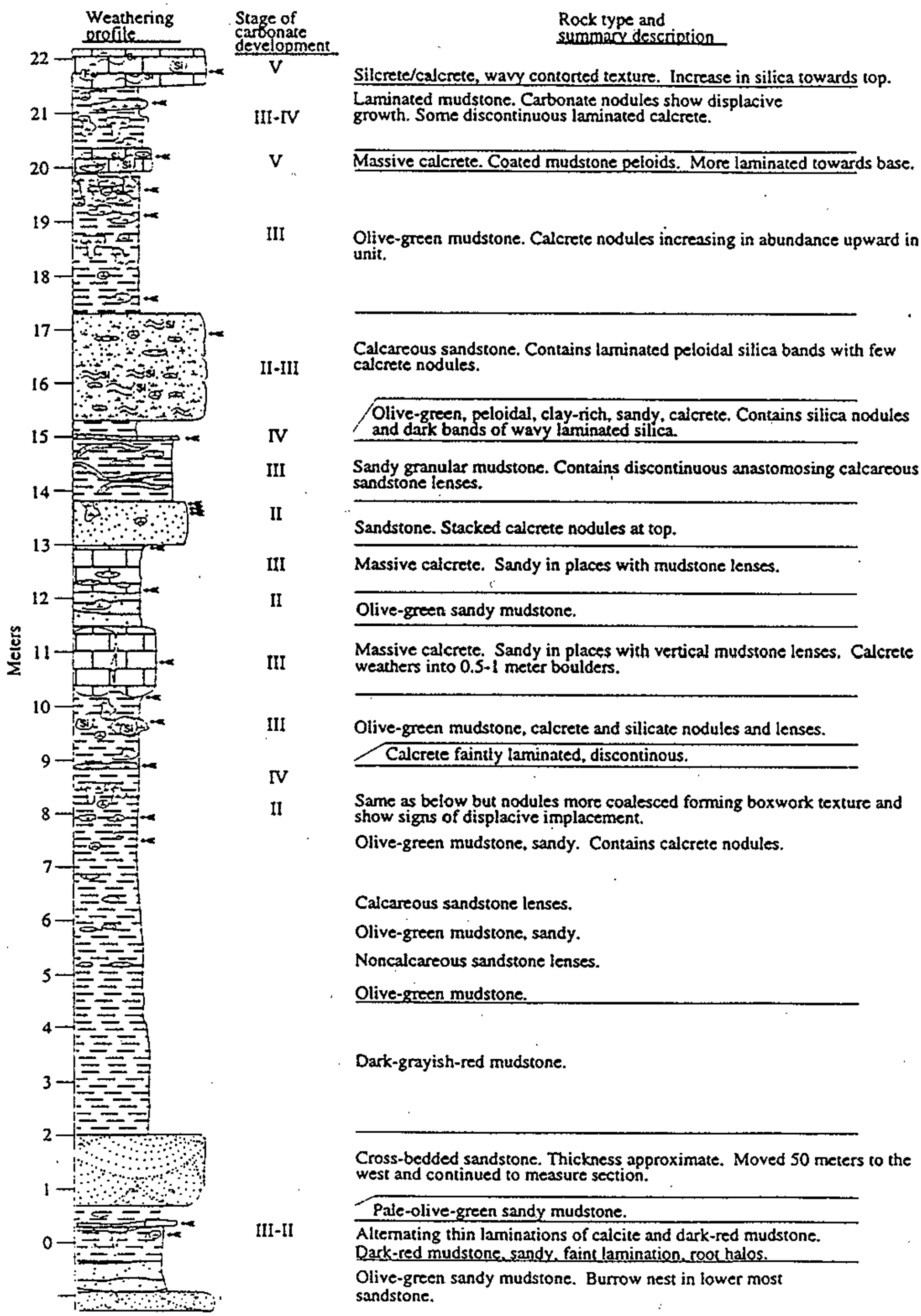

Figure 10. Disappointment Creek measured section.

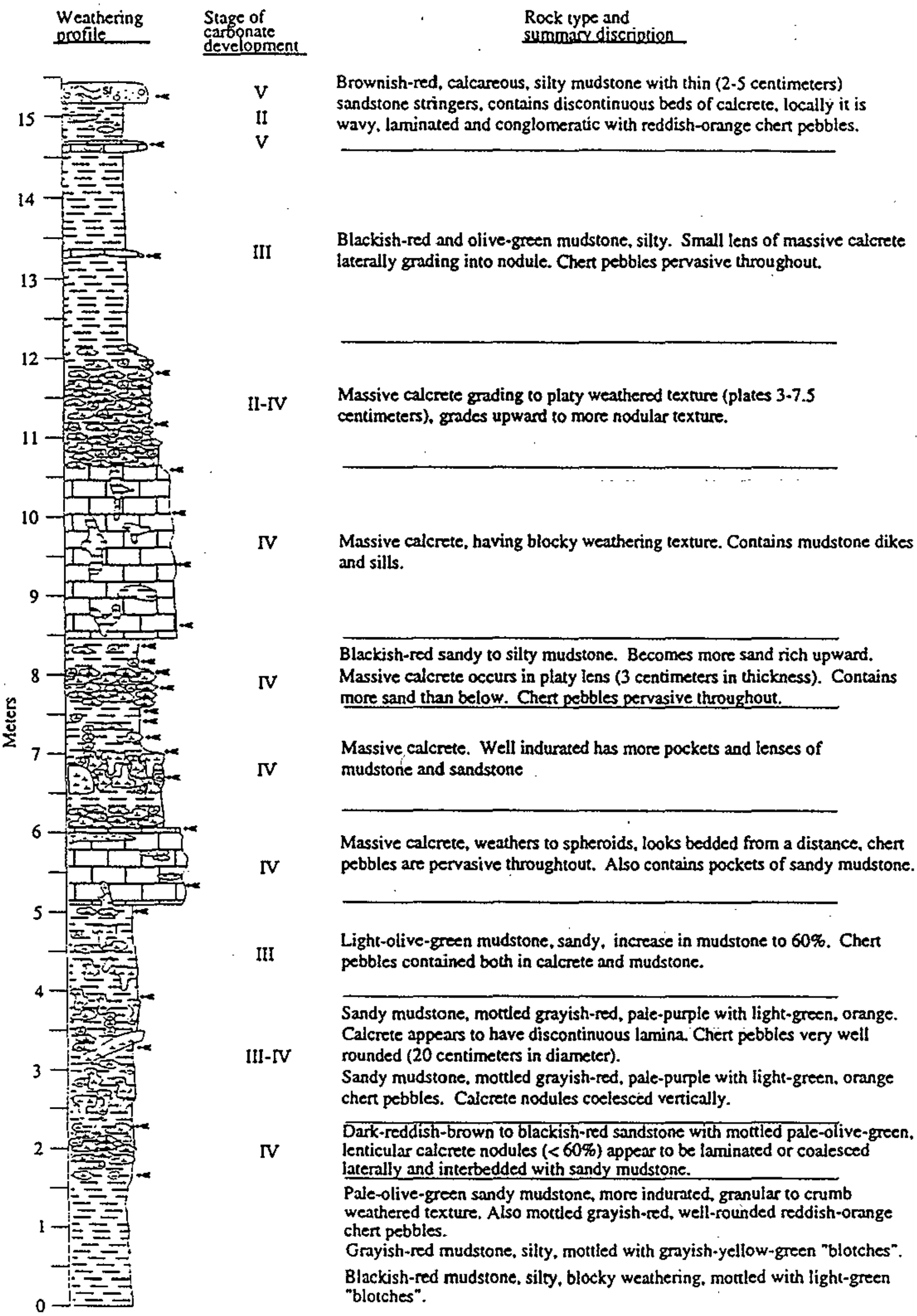

Figure 11. Ruby Ranch Road measured section.

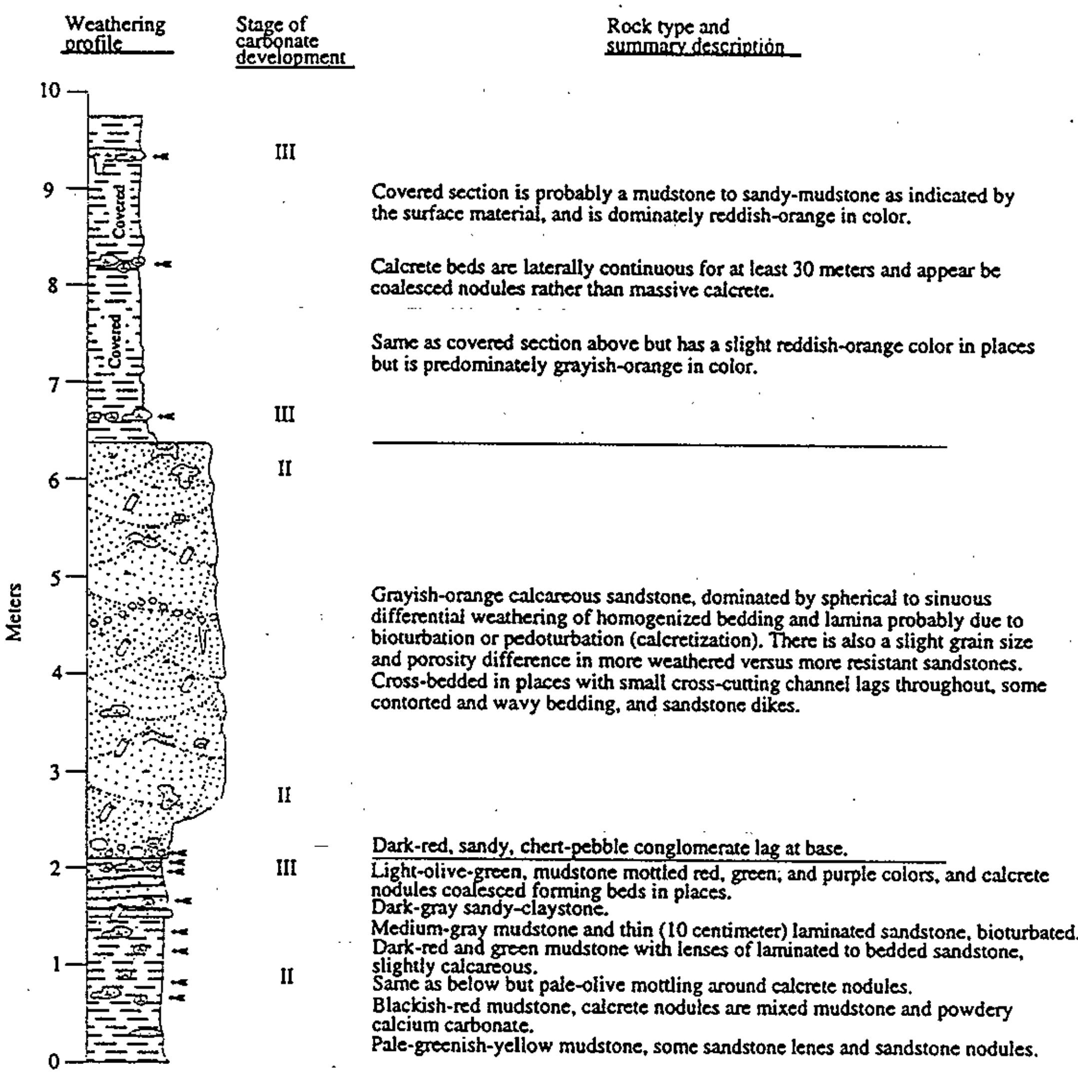

Figure 12. Riggs Hill measured section.

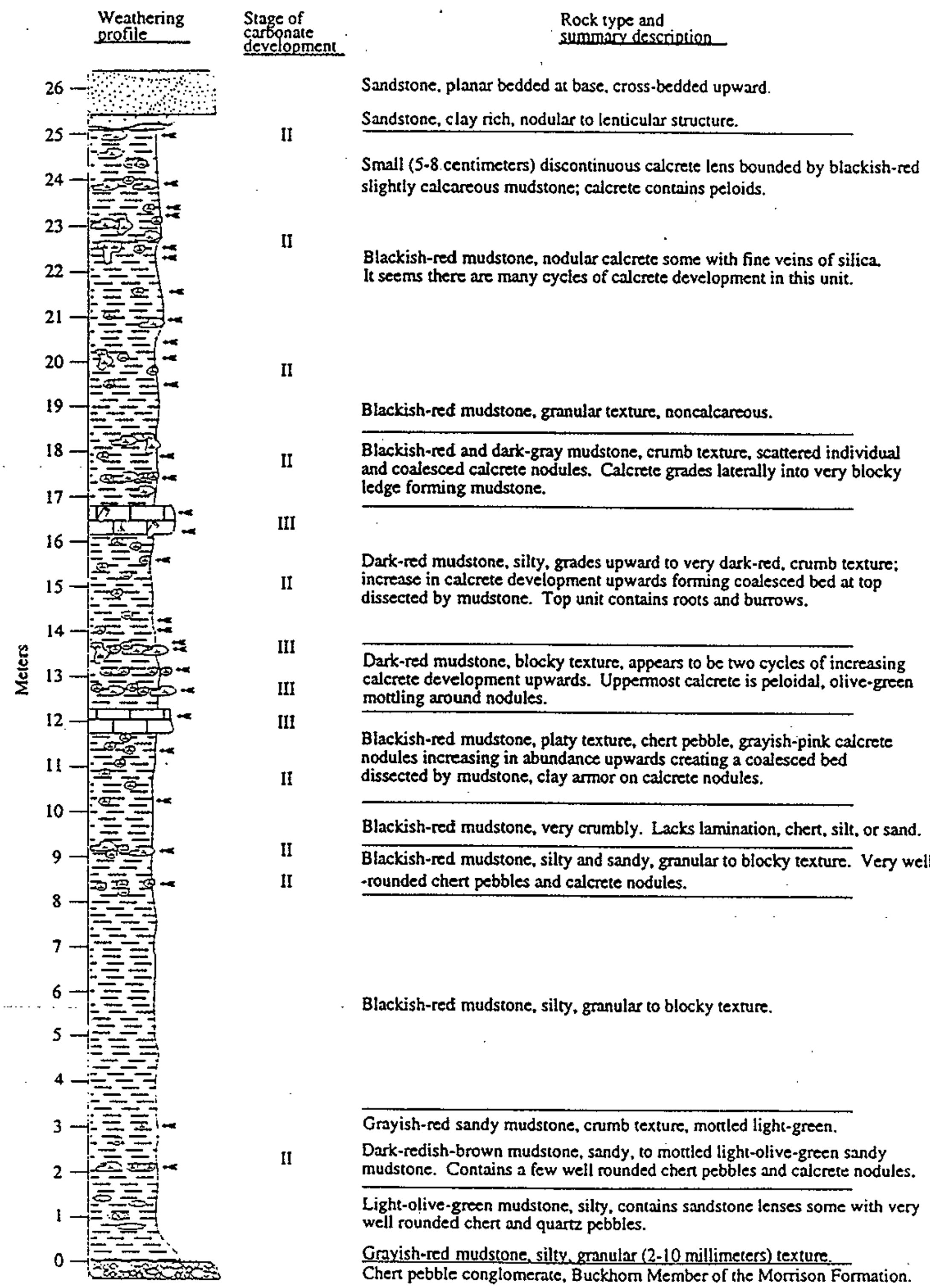

Figure 13. Price River measured section.

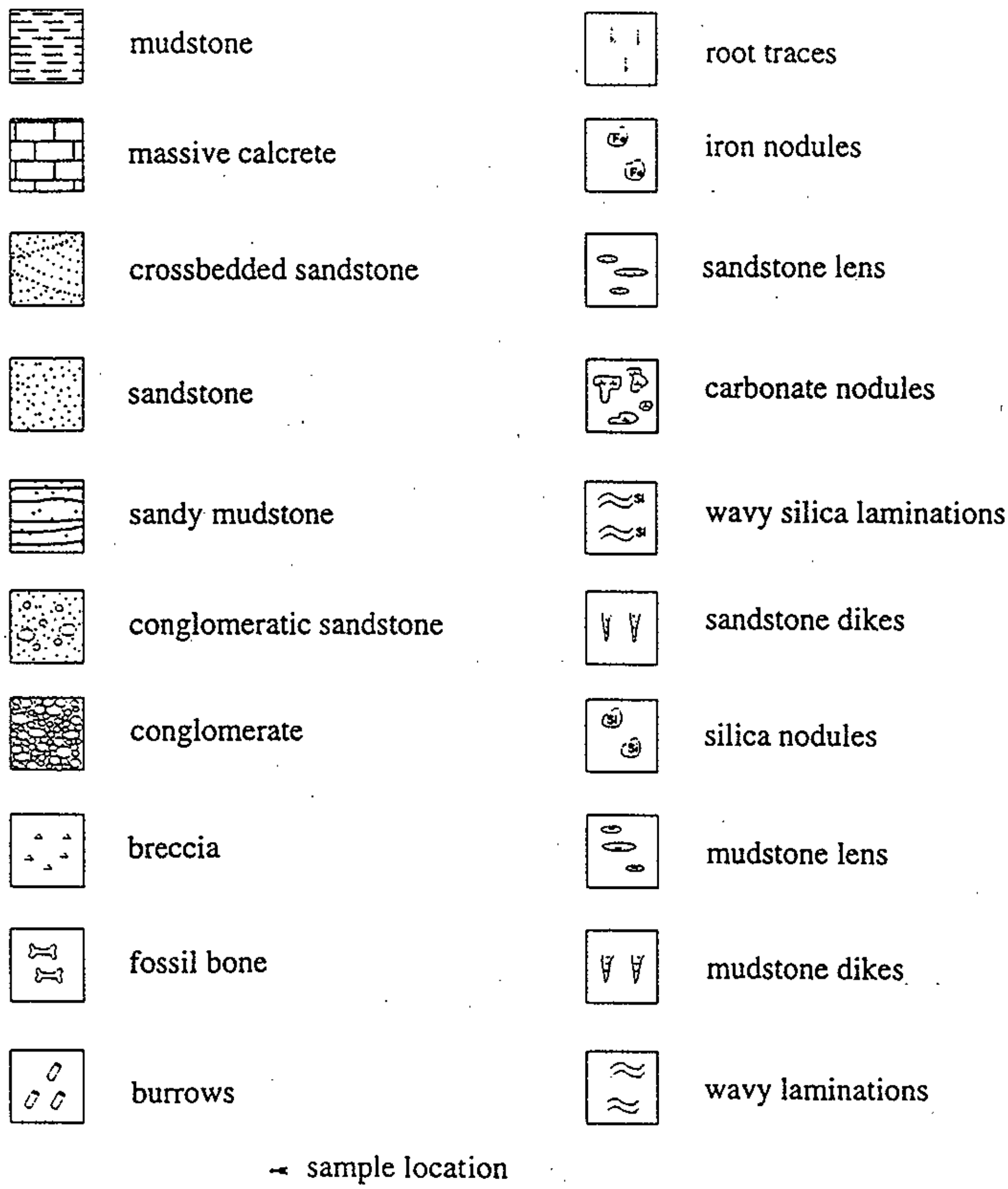

Figure 14. Explanation of symbols and patterns used in Figures 9, 10, 11, 12, and 13.

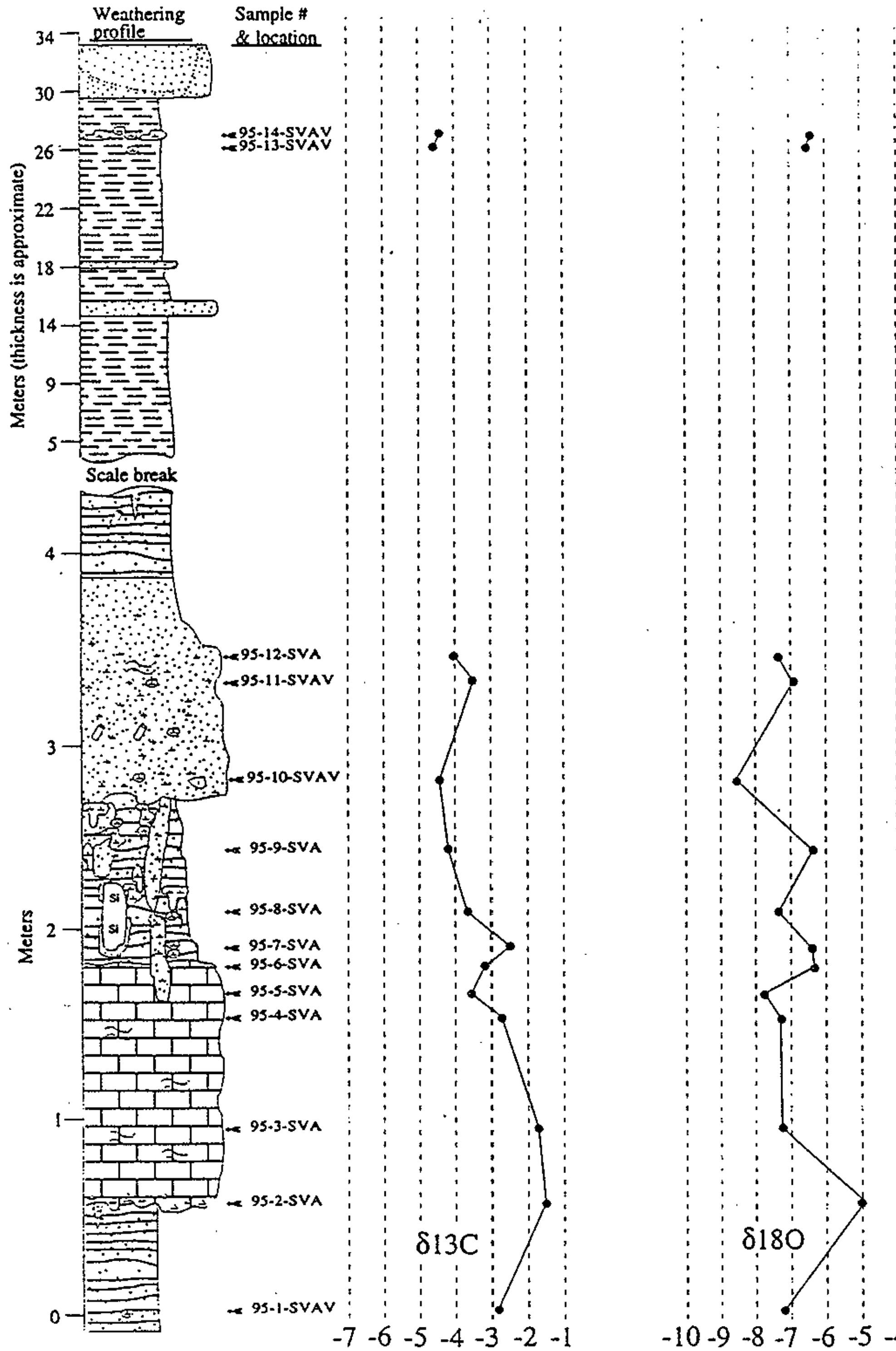

Figure 20. Salt Valley Anticline stable isotope data (PDB). Sample number followed by (V) is calcrete interpreted as vadose in origin.

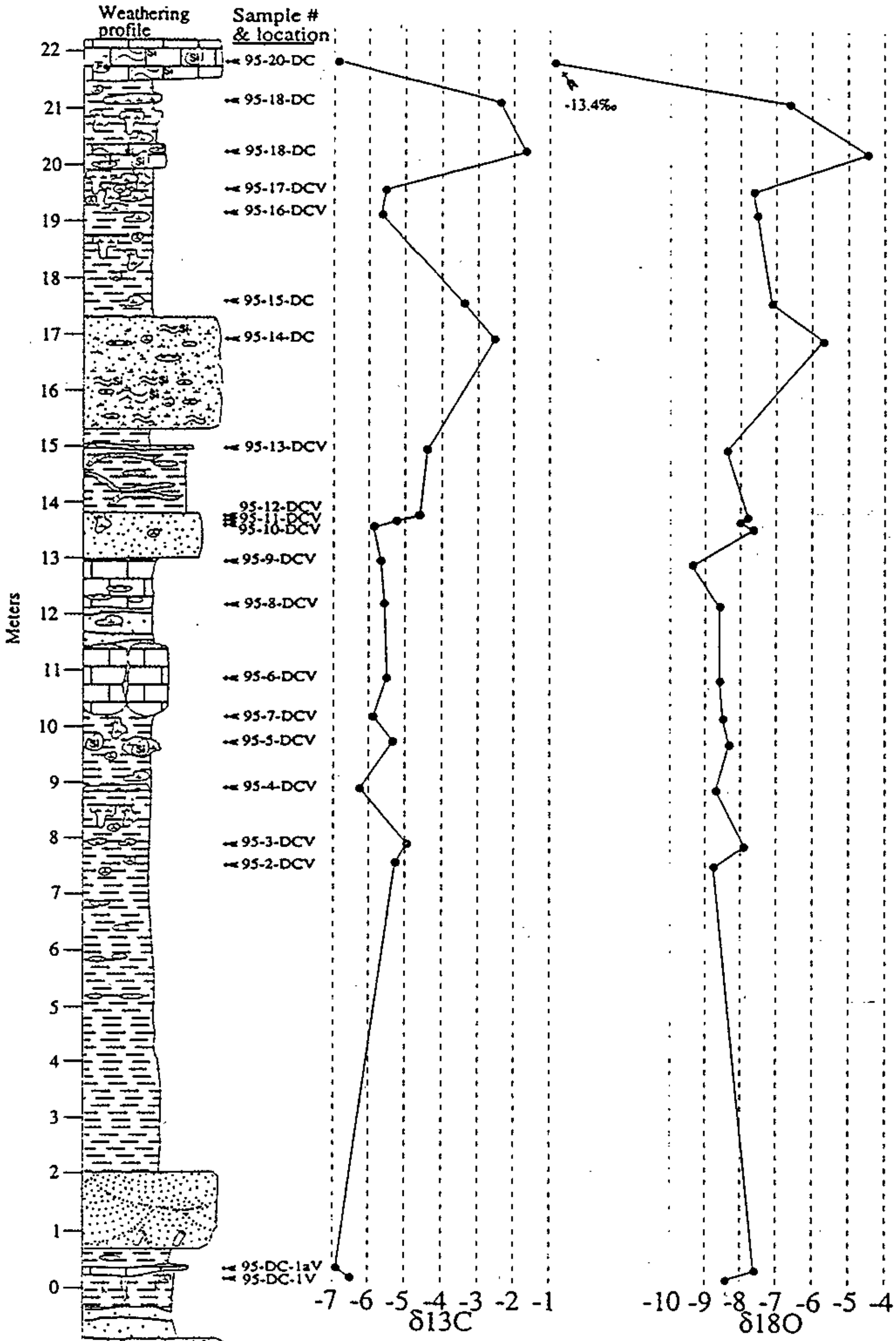

Figure 21. Disappointment Creek isotope data (PDB). Sample number followed by (V) is calcrete interpreted as vadose in origin.

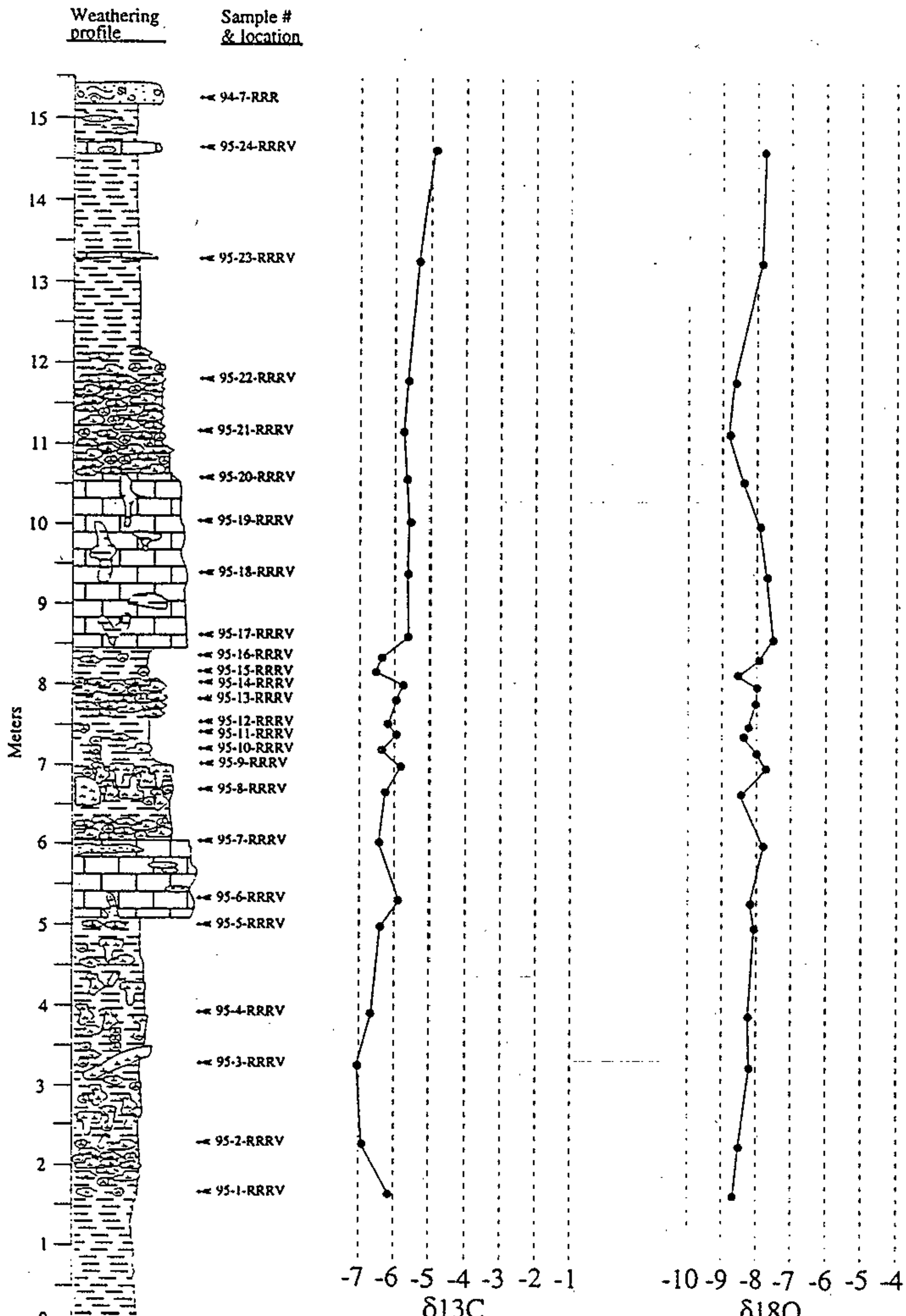

Figure 22. Ruby Ranch Road stable isotope data (PDB). Sample number followed by (V) is calcrete interpreted as vadose in origin.

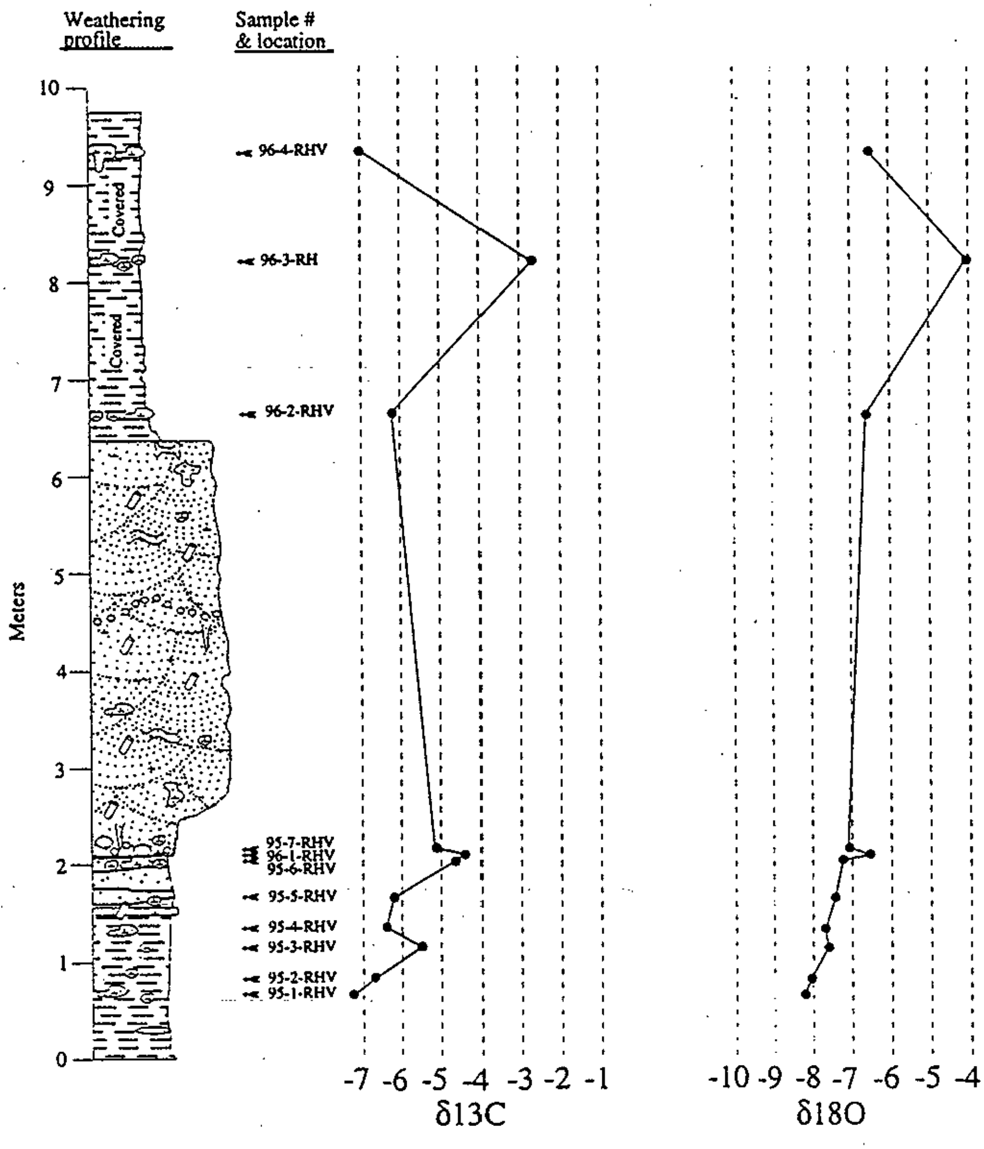

Figure 23. Riggs Hill stable isotope data (PDB). Sample number followed by (V) is calcrete interpreted as vadose in origin.

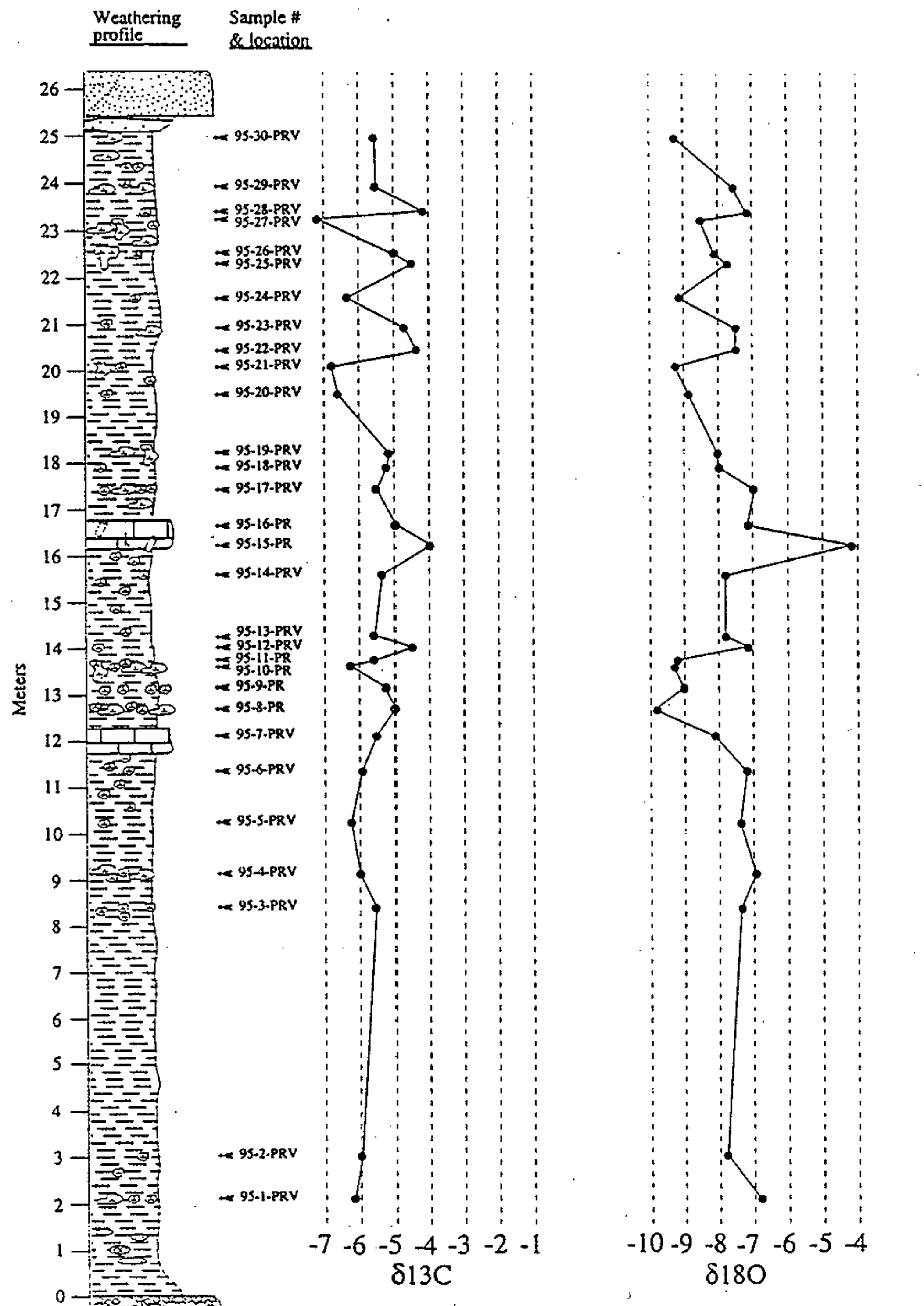

Figure 24. Price River stable isotope data (PDB). Sample number followed by (V) is interpreted as vadose in origin.

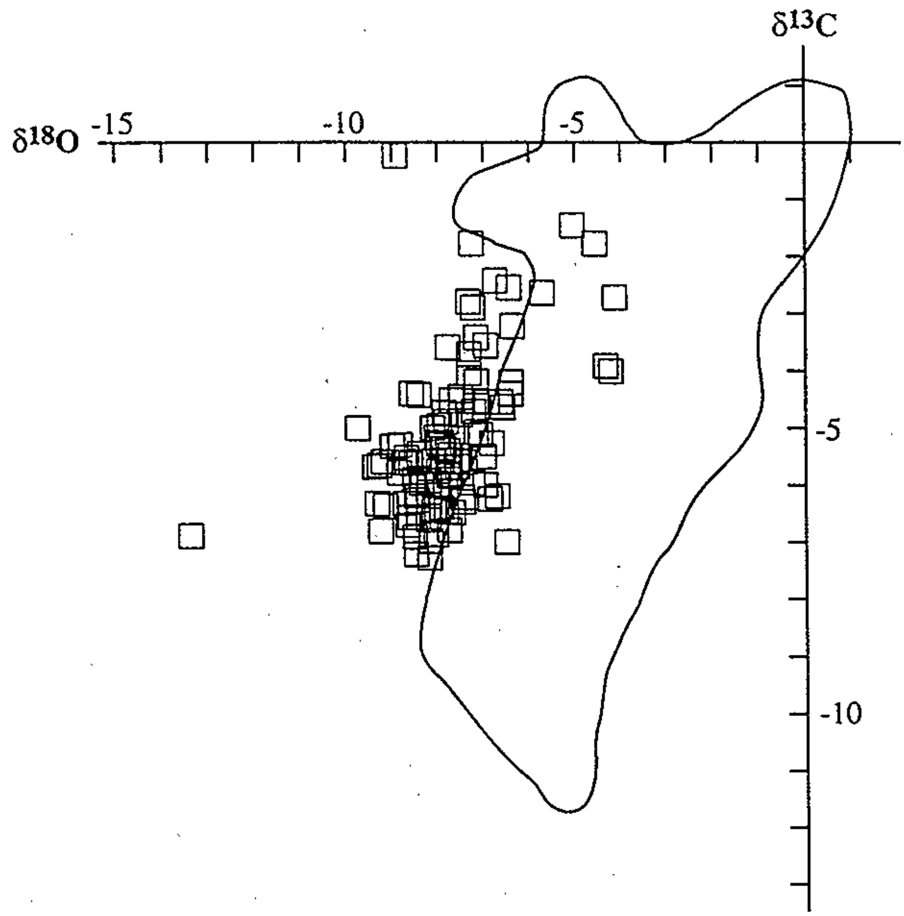

Figure 27. Carbon and oxygen isotope values for calcretes from the Colorado Plateau Jurassic-Cretaceous boundary (open squares). Field outlined is calcrete data from the Permian to the present. Data from: Salomons et al. (1978), Goudie (1983), Talma and Netterberg (1983), Cerling and Hay (1986), Naylor et al. (1989), Joeckel (1991), Purvis and Wright (1991), Wright and Vanstone (1991), Rossinsky and Swart (1993).

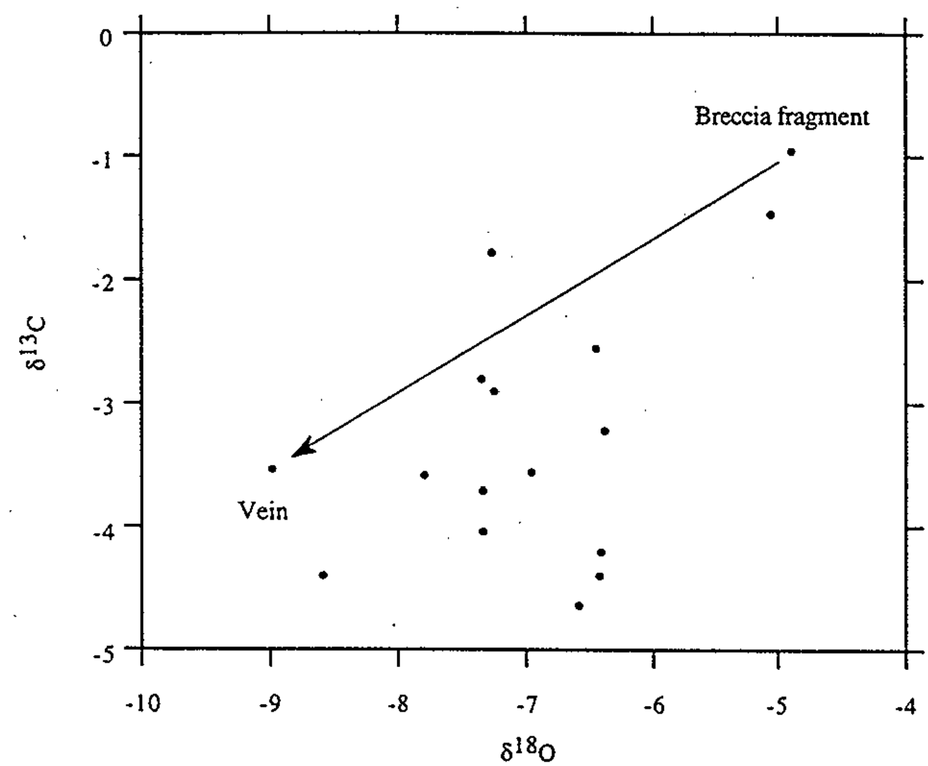

Figure 31. Carbon and oxygen isotopes for the SVA measured section. Arrow indicates isotopic change from microspar breccia fragment to adjacent clear sparry fracture fill.

STRATIGRAPHY OF THE MORRISON FORMATION AND RELATED BEDS IN THE WESTERN INTERIOR; FINAL REPORT

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INTRODUCTION

The Morrison Formation is a rock-stratigraphic unit that was deposited over much of the Western Interior of the United States during the Late Jurassic Epoch. It consists largely of terrestrial deposits, but it also includes some marine beds at the base in the middle and northern parts of the region and some other marine strata higher in the formation in the northernmost part of the region in northern Montana. Throughout most of this region the Morrison Formation extends vertically from the J-5 surface at the base to the sub-Cretaceous unconformity (either the K-1 or K-2 unconformities) at the top (the J-5 surface is an unconformity in some places and a conformable surface in other localities).

The only exception is in the Front Range foothills just west of Denver, Colorado, where the Ralston Creek Formation, about 34 m (110 ft) thick, occupies the interval from the J-5 surface up to the basal sandstone beds of the Morrison. Elsewhere in the region, the Ralston Creek is not recognized and strata that correlate with the Ralston Creek are considered part of the Morrison Formation. Because the Front Range foothills area is the type locality of both of these formations, and because various interpretations have been made in the literature concerning the age of the Ralston Creek and its relationship to the Morrison, it was critical to understand the stratigraphy of both formations at and near their type localities in the Front Range foothills. For this reason, a study was made of both formations in this critical area so that reliable correlations throughout the region could be made.

This chapter is divided into three parts in order to explain the complex stratigraphic relationships of the various parts of the Morrison Formation and related beds throughout the Western Interior as they are currently understood.

The first part by Peterson and Turner discusses the stratigraphy of the Morrison and Ralston Creek Formations at and near their type localities in the Front Range foothills. The Ralston Creek is shown to correlate with the lower part of the Morrison elsewhere, and that fossils indicating Middle Jurassic age that came from strata mistakenly considered the Ralston Creek actually came from beds that are more properly assigned to the Middle Jurassic Bell Ranch Formation. This part also shows the basis for correlations elsewhere in the Western Interior by concentrating on correlations to three critical areas: 1, The Cañon City-Garden Park area about 130 mi south of Denver, which is fairly representative of the eastern facies of the Morrison Formation, 2, Western Dinosaur National Monument in northeastern Utah, which is fairly representative of the stratigraphy of the Morrison on the Colorado Plateau, and, 3, The Como Bluff area in south-central Wyoming, which is fairly representative of the Morrison in the central part of the Western Interior. All three of these areas are well known for their excellent dinosaur quarries, and one of the objectives of this project is to establish the stratigraphic position of as many Morrison dinosaur quarries as reasonably possible.

The second part by Turner and Peterson discusses the stratigraphy of the Morrison and related beds throughout the Western Interior. This provides the basis for positioning the various dinosaur quarries in their stratigraphic context, that is, with respect to time. An important part of this report shows the stratigraphic or vertical (or time) ranges of the various dinosaurs that have been recovered and identified from the formation and provides the fundamental basis for comparing and interpreting Late Jurassic dinosaur evolution with respect to biogeographic differentiation.

The third part is the report by Turner and Fishman that discusses the paleohydrology of the Morrison Formation, which contains many beds deposited in small to large, freshwater to hypersaline lakes and ponds. The report suggests that geologic information can be used to infer some aspects of paleohydrology associated with fluvial and lacustrine rocks and that this geologic information, although not sufficient to permit precise reconstructions of paleohydrology, provides significant constraints for paleohydrologic modeling. The paleohydrology is important for understanding the Morrison ecosystem because it appears that the ground water supplied much of the moisture that sustained the vegetation in the region, and the vegetation, in turn, furnished the basis for the food chain that maintained the complex animal communities that lived in the region during the Late Jurassic.

STRATIGRAPHY OF THE UPPER JURASSIC RALSTON CREEK AND MORRISON FORMATIONS NEAR DENVER, COLORADO

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ABSTRACT

The Ralston Creek and Morrison Formations were reexamined at and near their type localities west of Denver, Colorado, in the area between Ralston Reservoir and Weaver Gulch, to determine the stratigraphy of the various units within them, to determine and clarify their contact relationships, to provide a basis for correlations to other important outcrop areas, and to clarify misconceptions about these and other related rock units.

The Ralston Creek Formation consists largely of variegated mudstone with lesser quantities of limestone and sandstone. A predominantly mudstone facies is present at the type locality that grades into a largely gypsiferous facies south of Morrison. The Morrison Formation is divided into three informal members: the lower member consists of a laterally discontinuous series of sandstone beds, the middle member consists largely of mudstone with lesser quantities of thin limestone or rare dolomite beds, and the upper member consists of sandstone and mudstone.

The base of the Ralston Creek is the regional J-5 unconformity and the top of the Morrison is the regional K-1 unconformity. The contact between the two formations is not an unconformity; interfingering of upper Ralston Creek mudstone beds with lower Morrison sandstone beds was documented at several localities. The upper contact with the Lower Cretaceous Lytle Formation can be identified most readily by several criteria, the most useful of which include: more interstitial clay, calcareous cement, and brown iron oxide spots in Morrison sandstone beds; Morrison siliceous pebbles tend to be smaller, more angular, and contain more black, red, and orange chert clasts than the Lytle; and a fairly thick paleosol is locally present at the top of the Morrison. Studies of microfossils

elsewhere in this volume demonstrate that the Ralston Creek and Morrison are entirely Late Jurassic in age.

Regional correlations of both formations to the entire Morrison Formation in other areas at Garden Park, Colorado; western Dinosaur National Monument, Utah; and Medicine Bow (Como Bluff), Wyoming, are accomplished by means of the various stratigraphic markers and the micropaleontological data. The most important of the physical stratigraphic criteria include the distinctive grit- and granule-bearing Bed A at the base of the Ralston Creek, a zone of colorful authigenic chert known as the welded chert in the lower part of the same formation, and a sharp vertical transition about a third of the way up in the type Morrison from predominantly non-smectitic clays below to predominantly smectitic clays above.

INTRODUCTION

Approximately 50 years have elapsed since the last detailed examination was made of the Morrison Formation at and near its type locality west of Denver (Waldschmidt and LeRoy, 1944). Since then, a considerable body of knowledge about the formation has accumulated, especially in areas other than the type locality at Alameda Parkway. However, few studies have been made that add to our knowledge of the stratigraphic relations of the Morrison and related beds in the vicinity of the type locality. Thus, the purpose of this report is to reexamine the Morrison Formation and the closely related

Ralston Creek Formation at and near their type localities in the outcrop belt west of Denver (Fig. 1), to gain an understanding of the contact relations, and to clarify the distinction between these formations and the adjacent rocks.

The Ralston Creek and Morrison Formations are closely related because they interfinger at their mutual boundary, consist largely of similar lithologies, for the most part were deposited in similar depositional environments, and both formations correlate with the entire Morrison Formation farther west, north, and south. For these reasons, the Ralston

Creek and Morrison must be considered together in any discussion concerning Upper Jurassic strata in eastern Colorado. Although they are closely related, we make no revision in the present nomenclatural status of these rock units.

Both the Ralston Creek and Morrison are largely concealed by soil, vegetation, slumped material, artificial fill, or faulting in the Front Range foothills and only rarely can the contacts be physically traced out between closely spaced measured sections. In addition, the quality of exposures may change from time to time. LeRoy (1946) was able to measure some of these beds in places where they are no longer exposed and we were able to measure the rocks at new road cuts or to find a more completely exposed section of the type Ralston Creek along the shoreline of Ralston Reservoir than LeRoy found when he did his field work in the early 1940's. Because of the rather extensive cover, stratigraphic markers are of considerable importance in establishing the stratigraphic framework between the measured sections. For the same reason, some of the measured sections are composites of partial sections measured in the same general area and correlated by local stratigraphic markers to make a single composite measured section.

A brief discussion of lithologic terms is appropriate. We tend to prefer rock terms that are useful in the field because some lithologic distinctions require laboratory procedures that appear unnecessary. There is little, if any, shale in these formations because the clay-rich rocks are not fissile and may contain varying but locally considerable quantities of silt- and sand-size material. Some of the finer-grained rocks appear to be composed of rather pure clay and may be classified as claystone. However, we found that distinguishing between mudstone and claystone in the field is rather challenging so we consider all of the clay-rich rocks mudstone. Rocks previously called marlstone by some workers are more appropriately called limestone (or dolomite where applicable) as a field term. Marlstone contains about 35-65 percent clay and complementary quantities of carbonate materials (Pettijohn, 1957, p. 369), but determining the content of those constituents in all of the rocks requires extensive laboratory work that does not seem merited for the purposes of this study. X-ray diffraction analyses of some of these rocks by G.L. Skipp indicate that they are limestone or dolomite.

RALSTON CREEK FORMATION

The Ralston Creek Formation was originally named the Ralston Formation by LeRoy (1946) but it was changed to the present name by Van Horn (1957a) when it was discovered that the name Ralston Formation was preoccupied. Cross (1894) appears to have included beds now recognized as the Ralston Creek within his Morrison Formation when he originally named the Morrison near the end of the last century. He listed gypsum as one of the main constituents of the Morrison, but little of that lithology is present in what is currently known as the Morrison in the area he studied (Pikes Peak 1:125,000 scale quadrangle and the area at or near Morrison) whereas it is locally abundant in the Ralston Creek, especially in the southeastern part of the Pikes Peak quadrangle.

Type Locality

The type locality of the Ralston Creek Formation is on the south side of Ralston Reservoir (Figs. 1, 2). There, the formation is exposed in two areas. One area is in artificial cuts along Long Lake Ditch, which is a small canal that carries water around the south side of Ralston Reservoir to Long Lake. The other area where the formation now is well exposed is about 34 m (110 ft) below and 60 m (200 ft) farther north in a wave-cut terrace along the south side of the reservoir. Exposures at the shoreline are excellent and readily accessible when the water level is low, usually in the early spring. LeRoy's (1946) type measured section is a composite of measurements made at both localities. This may have been because exposures at both places had concealed intervals in the early 1940's, but today the entire formation is well exposed along the shoreline. The lower part of the formation is partly concealed by soil and slope wash at Long Lake Ditch but can be dug out. For these reasons, we here propose that the section exposed on the south side of Ralston Reservoir be used as the sole type locality for the Ralston Creek Formation. The formation is not exposed on the north side of the reservoir.

At Ralston Reservoir, the Ralston Creek Formation consists largely of variegated mudstone that is non-smectitic or largely non-smectitic and does not swell or swells very little when moistened. The formation consists of the four units described below (Fig. 3).

Bed A. At the base of the formation is a unit of very thin- to thin-bedded, fine-grained, grit- and granule-bearing sandstone approximately 1.5 m (5 ft) thick. Scattered coarse to very coarse grains, granules, or small pebbles of chert or quartz distinguish it from other sandstone beds higher in the Ralston Creek or in the underlying Lykins Formation. Because this is an excellent marker bed immediately above the J-5 unconformity and is lithologically similar to Bed A at the base of the Morrison Formation farther west on the Colorado Plateau, we here name this Bed A of the Ralston Creek Formation. This bed and the overlying red unit were not included in the original Ralston Formation by LeRoy (1946), who placed the base of his new formation at the base of the yellow unit 3.7 m (12 ft) above the top of Bed A. Van Horn (1957ab) lowered the basal contact to the base of Bed A. Van Horn (1967, p. 44) did not find this bed along Long Lake Ditch. We found it there but it is soft and friable and must be dug out. This bed must be dug out or at least scraped clean to be identified clearly at all localities in the study area other than the southern shoreline of Ralston Reservoir and U.S. Highway I-70.

Red unit. The red unit is about 3.7 m (12 ft) thick at the southern shoreline of Ralston Reservoir and consists largely of dark red mudstone. In areas of poor exposures, this unit is difficult to distinguish from similar red mudstone beds in the Lykins Formation (Permian-Triassic). In many places, Bed A must be identified first in order to be certain that the unit is indeed part of the Ralston Creek. Color also is a helpful guide to distinguish red beds of the two formations. Mudstone in the Lykins tends to be bright red or brick red whereas mudstone in the Ralston Creek tends to be dull red or grayish red.

Yellow unit. The yellow unit is about 7.6 m (25 ft) thick and contains interbedded grayish-yellow or gray mudstone and lesser quantities of dark red mudstone or calcareous mudstone that include several thin limestone beds, mostly less than 15 cm (6 in) thick. The unit is persistent throughout the study area and is another valuable stratigraphic marker.

Upper unit. At the top of the formation is a series of variegated mudstone beds 22.4 m (73.5 ft) thick that is mostly gray, moderate to dark reddish brown, grayish purple, and light grayish green. About 2.4 m (8 ft) above the base is another grayish-yellow mudstone bed 0.8 m (2.5 ft) thick that is similar to those in the yellow unit. The upper unit also contains a few thin beds of light gray limestone, some of which contain charophytes. Sandstone is scarce; we only found three thin sandstone beds in this interval that were 0.3-0.5 m (1-1.5 ft) thick.

Welded chert. An almost inconspicuous but important stratigraphic marker in the Ralston Creek is a zone containing small blebs of authigenic red, yellow, gray, or white chert that is a replacement of some of the mudstone or limestone in the lower part of the formation. This is the "welded chert" of Ogden (1954) that is present in the lower part of the Ralston Creek or near the base of the Morrison Formation at many other localities in the southern part of the Western Interior where Ralston Creek is not recognized. The zone of beds containing the chert is 10.2-13.7 m (33.5-45 ft) above the base of the formation at the southern shoreline of Ralston Reservoir and 7-10.8 m (23-35.5 ft) above the base at Long Lake Ditch. Thus, the zone is not present at precisely the same stratigraphic position everywhere and the chert commonly is present within a stratigraphic interval several centimeters to several meters thick. The authigenic chert has been found throughout a large part of the central and southern Rocky Mountains region as well as on the Colorado Plateau (Eldridge, 1896, p. 56; Lee, 1902, p. 44-46, 1920, p. 184; Gilluly and Reeside, 1928, p. 92, 100; Ogden, 1954; Frederickson and others, 1956, p. 2132; Scott, 1963, p. 92; O'Sullivan, 1980; Petersen and Roylance, 1982, p. 11, unit 8; Lucas and others, 1985, 231-235; Peterson, 1988a, p. 40). In many places, the chert blebs are minute (1 mm or less in diameter), inconspicuous, and not readily apparent on the outcrop without a diligent search.

With the obvious qualification that the zone containing the welded chert is not a perfectly isochronous entity, it is, nevertheless, valuable as a widespread and crudely isochronous stratigraphic marker. Within the relatively small study area in the Front Range foothills, the yellow unit is a better stratigraphic marker, but that unit has not been found farther afield. However, the welded chert is much more widespread so it is especially helpful in establishing correlations to more distant localities.

Facies. Two facies of the Ralston Creek were recognized by LeRoy (1946), a shale-marlstone facies at the type locality and a gypsiferous facies that is present south of Morrison. We consider these as a mudstone facies and a gypsiferous facies (Fig. 3). In his unpublished field notes for 1885, G.H. Eldridge noted the presence of a thin bed of gypsum 0.3 m (1 ft) thick in these beds at Morrison at or within a few hundred meters south of measured section 8 (Fig. 3). The area is now covered by fill for Jefferson County Highway 93 so the presence of this lithology at Morrison cannot be confirmed. We found no gypsum at our nearest measured section several hundred meters farther north (measured section 7, Fig. 3). The thin gypsum bed noted by Eldridge is the northernmost occurrence of gypsum in the Ralston Creek Formation in the foothills outcrop area.

Contacts. The basal contact of the Ralston Creek is placed at the base of Bed A—the light gray sandstone bed at the base of the formation that contains scattered coarse and very coarse grains and granules. The yellow unit and the welded chert are especially helpful guides to finding Bed A where it is partly concealed. Thus, where the yellow unit and (or) the welded chert is encountered, Bed A should be a few meters below. In good exposures, the light gray color of Bed A contrasts markedly with the bright red mudstone beds in the underlying Lykins Formation. At poor exposures, however, red slope wash from the overlying unit may discolor Bed A so much that the bed is not readily identifiable unless the surficial debris is removed.

The upper contact of the Ralston Creek Formation is placed at the base of the lowest thick or moderately thick (generally 1-10 m or 3-30 ft) sandstone bed in the lower member of the Morrison Formation (Fig. 3). At Ralston Reservoir, this member consists of five vertically stacked fluvial sandstone beds in which the lower three beds pinch out southward into the uppermost mudstone beds of the Ralston Creek in the wave cut terrace (Fig. 2). In Figure 2, the beds labelled b and c in the lower member of the Morrison Formation pinch out southward into mudstone beds in the upper part of the Ralston Creek Formation. Another bed stratigraphically below bed b is largely covered by rubble and cannot be identified in this view.

Thickness. The Ralston Creek Formation is 35.2 m (115.5 ft) thick along the south shoreline of Ralston Reservoir, but this is a maximum thickness that includes the part of the Ralston Creek that interfingers with the lower sandstone beds of the Morrison Formation. The interfingering zone of Ralston Creek and Morrison is 7.6 m (25 ft) thick so the thickness of the Ralston Creek up to the base of the lowest Morrison sandstone bed is only 27.6 m (90.5 ft). The measurements compare reasonably well with LeRoy's (1946, p. 51-52) thickness of 30.5 m (100 ft) for the Ralston Creek when the thicknesses of Bed A and the overlying red unit are added to his measured section. We obtained a thickness of 39.3 m (129 ft) for the formation at Long Lake Ditch. From Ralston Reservoir to Weaver Gulch, the Ralston Creek Formation ranges in thickness from a minimum of 20.7 m (68 ft) at Highway I-70 to a maximum of about 42.1 m (138 ft) at Bergen Ditch. The average of the six sections measured from Ralston Reservoir to Bergen Ditch is 33.7 m (110.5 ft).

MORRISON FORMATION

The Morrison Formation was first named by Cross (1894) in his discussion of the Pikes Peak Folio, which covers a topographic quadrangle south of the town of Morrison but that does not include the town. He stated (Cross, 1894, p. 2): "The name [Morrison formation] is given from the classic locality at Morrison, near Denver, where the first gigantic Dinosaurs from this formation were obtained." He described the new formation as consisting of "...prevailingly greenish, pinkish or gray shales and marls. Sandstone occurs at the base and is also intercalated at numerous horizons in the upper part of the section...Gypsum is locally developed and becomes prominent to the east. A thin limestone often forms the base of the formation." Thus, gypsum was recognized as a constituent of the formation by the original author.

Because the original description was so brief and because the type locality was not in the area of Cross' study (his 1894 report covered the Pikes Peak quadrangle, 72-130 km or 45-80 mi south of Morrison), some workers apparently thought that Eldridge (1896) first named the formation and that Cross' 1894 report merely got into print first. In part, this misunderstanding might have come about because Eldridge gave a much better description of the new formation, and his field area and report included the type locality.

Two facts dispel this misunderstanding and demonstrate that Cross (1894) deserves credit for first naming the Morrison Formation. First, in a later publication concerning the La Plata quadrangle in southwestern Colorado, Cross (in Cross and others, 1899, p. 4) explicitly stated that he had named the formation in his 1894 report: "The name Morrison was given by the writer to the vertebrate-bearing formation of the eastern foothills [of the Front Range] because it seemed best not to correlate it too closely with the Gunnison beds of the Elk Mountains, in which no fossils were known (Pikes Peak folio, No. 7, U. S. Geol. Survey)." (The reference cited is Cross' 1894 report.) Second, a statement by Eldridge (1896, p. 60) refers to the assignment of the formation name in the past tense, as though the naming had been done earlier: "Morrison Formation...To this formation has been assigned the name "Morrison," from the town near which it is typically developed." Had Eldridge intended to have named the formation in his report; one would expect him to have substituted "is" for "has been", or some other similar wording.

The measured section along Alameda Parkway that was proposed as the type section for the Morrison Formation by Waldschmidt and LeRoy (1944) is acknowledged as such by most geologists today. Since 1944, the lower middle part of their measured section has become partly concealed by soil, vegetation, and debris but the entire formation now is well exposed about 2.4 km (1.5 mi) farther north in deep road cuts along the south side of U.S. Highway I-70. Poor exposures between the road cuts require that the lateral relations between the measured sections be worked out by means of the stratigraphic markers.

Type Locality

Waldschmidt and LeRoy (1944) divided their type section at Alameda Parkway into six units. The four mudstone-dominated units that they recognized in the middle of the formation weather to a covered slope and change character in short lateral distances; hence, they are not readily distinguished away from Alameda Parkway. For this reason, we here divide the Morrison into the three informal members described briefly below.

Lower member. At the base of the Morrison at the type locality is a sandstone unit 2.1 m (7 ft) thick that is very light-brown, fine grained, and crossbedded to very thin bedded that locally contains mudstone rip-up clasts at the base. The bed tends to weather dark brown or dark reddish brown, largely by slope wash from overlying red mudstone beds. Where soil and vegetation prevent slope wash, beds assigned to this member commonly weather to very light brown or light gray. Where two or more sandstone beds are present, thin red, gray, or grayish-green mudstone beds separate the sandstone beds. Walking these beds out, where exposures permit, reveals that they are thin, laterally amalgamated, locally vertically stacked, ribbon-type, fluvial channel sandstone beds. The separate channels appear to be no more than about several hundred meters wide perpendicular to paleostream flow, which was approximately to the east or perpendicular to the north-south outcrop trend in the Front Range foothills. Interfingering is common with these types of fluvial deposits and was documented at several localities (Fig. 3).

The lower member of the Morrison at Highway I-70 is a fluvial sandstone bed that scours down into underlying Ralston Creek red mudstone beds. The deepest part of the scour contains scattered small pebbles as much as 1.4 cm (0.5 in) long of chert and quartz as well as dinosaur bones, one of which measured 41 cm (16 in) in length. Several other sandstone beds lie above the lowest bed and one thins northward almost to a wedge edge in the exposure, again supporting the interpretation that lower Morrison fluvial sandstone beds are laterally discontinuous.

The bottom surface of the basal sandstone bed of the lower member was designated as the basal contact of the Morrison Formation by Waldschmidt and LeRoy (1944, p. 1100), who considered it a disconformity. Because the basal sandstone bed has no lateral continuity, we believe the underlying surface is nothing more than a scour surface such as one typically finds at the base of most fluvial sandstone beds. Interfingering was clearly identified and documented at several places (Figs. 2, 3).

Middle member The middle member is 59.1 m (194 ft) thick at Alameda Parkway where it consists mostly of mudstone interbedded with thin limestone or scarce dolomite beds. Grayish-green or gray colors dominate in the middle and dark reddish-brown colors are more common near the base and top. The carbonate beds are most abundant in the middle and are fewer in number toward the base and top. Waldschmidt and LeRoy (1944, p. 1105, 1108-1110) reported a small amount of anhydrite in thin sections of three or four of the limestone beds (they are unclear as to the precise number), and they also noted a small amount of pyrite in these beds. The basal contact of the middle member is at the base of the lowest mudstone bed and at the top of the highest sandstone bed of the lower member. In the last century but before the Morrison Formation had been named, strata belonging to the middle member were termed the "Atlantosaurus clays" from the abundant large and impressive dinosaur bones that had been recovered from these beds.

Most of the limestone beds are less than about 0.6 m (2 ft) thick. However, a somewhat thicker unit consisting largely of limestone beds about 1-3 m (3-9 ft) thick is present in the lower part of the middle member (Fig. 3). Keller (1953) found a change in dominant clay minerals at the top of this limestone unit, from kaolinitic and illitic clays below to smectitic clays above. The combination of the thick limestone unit and the change in dominant clay minerals at the top make the limestone unit a helpful stratigraphic marker to aid in correlating between measured sections in the Front Range foothills and is used where possible as a datum for the stratigraphic section (Fig. 3).

A sandstone bed in the middle of the middle member at Alameda Parkway was quarried for dinosaur bones in 1877. The bed apparently pinches out laterally and is not present farther north or south (Fig. 3). Elsewhere, the middle member locally contains similar sandstone beds, all of which appear to be local ribbon-type fluvial channel sandstone beds.

Waldschmidt and LeRoy (1944) found that some of the mudstone and limestone beds contain charophytes, which have proven useful for age and environmental interpretations (Schudack and others, this volume). In some of the limestone beds, they also reported the presence of "numerous blade-shaped objects" that they tentatively identified as fresh-water sponge spicules (Waldschmidt and LeRoy, 1944, p. 1101). We suggest, however, that these are shards of volcanic ash replaced by calcium carbonate that preserved the original morphology of the shards.

Upper member. Interbedded sandstone and mudstone comprise the upper member, which is 16.2 m (53 ft) thick at Alameda Parkway. Strata within the member have been the subject of considerable discussion in the literature concerning the position of its upper contact. The sandstone beds are very light brown, fine grained, tend to have crossbedding that is faint or obscure, and contain scattered small pebbles of chert or scarce quartz in many but not all localities. The lowest sandstone beds pinch out locally so the basal contact has an interfingering relation with the uppermost mudstone beds of the middle member. The mudstone beds in the upper member are dark reddish brown, light grayish green, or gray and tend to be noncalcareous. Some beds that appear to be composed of hard siliceous mudstone actually consist of dolomite (determined by X-ray diffraction) but limestone is rare. Mudstone is the dominant lithology in many places but the presence of sandstone is what distinguishes the upper member from the underlying middle member.

Upper contact. The upper contact of the Morrison at Alameda Parkway is placed by us at the top of a fairly thick (2 m or 6 ft) series of paleosols at the top of the upper member. The contact is beneath sandstone bed 6 (Fig. 3) and at the base of the Lower Cretaceous Lytle Formation at Alameda Parkway (Fig. 4). It is a difficult contact to identify in many places but the features listed below are fairly reliable guides to distinguishing between sandstone beds of the two formations. Some of these features have been discussed by Waagé (1955, p. 23).

Distinguishing Features of Morrison and Lytle Sandstone Beds.

1. Morrison sandstone beds contain a fair amount of interstitial clay and may be classified as wackes as they appear to contain more than 10 percent clay- or silt-size material. Lytle sandstone beds contain very little clay- or silt-size material and may be classified as quartz arenites. We have not done point counts in thin sections and our percentages are estimated in the field with a hand lens. The interstitial clay seems to be the best feature to use in distinguishing sandstone beds of the two formations and has been noted as a helpful guide by Waagé (1955, p. 23) and Van Horn (1976, p. 15). However, we have found that this feature is not everywhere diagnostic. We caution that fresh samples must be analyzed because Quaternary weathering, even in road cuts such as at Alameda Parkway, might allow clay-sized material from surficial processes to fill the pore spaces.
2. Morrison sandstone beds contain fairly common small brown spots 1-6 mm in diameter of some form of iron oxide. These have been called yellow pulverulent concretions of iron oxide, brown polka-dots, rusty dots, small limonitic concretions, ferruginous specks, or limonite nodules by Cannon (1893), Eldridge (1888), Eldridge (1896), Waldschmidt and LeRoy (1944), Waagé (1955), and Van Horn (1957) respectively. They are absent or scarce in the Lytle.

3. Morrison sandstone beds contain a moderate amount of feldspar whereas Lytle sandstone beds contain very little feldspar. Diagenetic alteration of the feldspar may partly account for the relatively large amount of clay-size material in Morrison sandstones. Other workers who have done the petrography and noted this in other regions include Owen and others (1984) and Holbrook and others (1987) in New Mexico and May (1993) in Wyoming.
4. Morrison sandstone beds have calcareous cement and effervesce with dilute (10 percent) hydrochloric acid whereas Lytle sandstone beds have very little, if any, calcareous cement.
5. Morrison sandstone beds contain a slightly more varied siliceous pebble suite than the Lytle. Both formations contain a suite of light to dark gray, white, and scarce tan chert and scarce light gray quartz pebbles, but the Morrison also includes a small but readily apparent amount of black chert clasts (roughly 1-3 percent by field estimate) and smaller quantities of red or orange chert (less than 1 percent). Samples from both formations should be compared to distinguish the shades of black as we would consider most Lytle "black" clasts closer to dark gray or very dark gray rather than black. The distinction is subtle and does not always hold up, but it is a helpful guide.
6. Morrison siliceous pebbles tend to be significantly smaller than Lytle pebbles. Most Morrison clasts are less than about 1 cm (0.4 in) in length although we did find a single exceptionally large chert clast about 2.5 cm (1 in) in diameter at Highway I-70. Lytle pebbles tend to be larger. Clasts 1 cm (0.4 in) long are fairly common and the maximum pebble length noted in several pebble suites is 3 cm (1.2 in).
7. Morrison siliceous pebbles tend to be more angular than those of the Lytle. We would classify Morrison pebbles as well rounded to angular and Lytle pebbles as well rounded to subrounded. Angular pebbles are rare in the Lytle.
8. Crossbedding in upper Morrison sandstone beds tends to be faint, or at least much more obscure than crossbedding in Lytle sandstone beds, and does not etch out well by

natural weathering processes. Crossbedding tends to be much easier to see in Lytle sandstone beds, especially in natural exposures.

9. According to Waagé (1955, p. 23), upper Morrison variegated beds have somewhat darker hues compared to those in the Lytle. This is a subtle but fairly consistent distinction; we would add that the red color of Lytle mudstone seems to be a somewhat brighter shade of red than that of Morrison mudstone.

10. A zone of paleosols about 1.2-1.8 m (4-6 ft) thick is present at the top of the highest mudstone bed in the Morrison at Alameda Parkway lateral to the pinchout of the basal Lytle sandstone bed (Fig. 4; Fig. 3, sec. 6). Other but thinner paleosols are locally present lower in the Morrison or in the Lytle Formation (T.M. Demko, oral commun., 1996) so identification of the paleosol zone marking the contact is based largely upon its exceptional thickness and its lateral relationship to sandstone bed 6 (Fig. 3), as well as the other criteria enumerated above that serve to identify bed 6 as a Lytle sandstone bed. The following description of the paleosols at the top of the Morrison at Alameda Parkway was kindly contributed by T.M. Demko (Colorado State Univ., written commun., 1995).

> "A fairly thick paleosol is present here and is underlain by a thinner one that is only locally present."
>
> "The upper or main paleosol consists of an upper or A/E_2 horizon 40 cm (16 in) thick consisting of light gray leached sandy mudstone that contains moderate quantities of very fine to medium sand-size grains of quartz and chert. It has blocky fractures that produce peds about 0.5-1.5 cm (0.2-0.6 in) long. The lower or B_T horizon is about 75 cm (30 in) thick and consists of dark reddish-brown sandy mudstone that also contains moderate quantities of very fine to medium sand-size grains of quartz and chert. It has blocky fractures that produce peds about 0.5-1.5 cm (0.2-0.6 in) long with cutans or clay-covered surfaces that superficially

resemble slickensides. It also contains highly irregular grayish-green root casts, adhesive meniscate burrows, and other unidentified burrows that may be called "planolites" as a rather loose term."

"The lower paleosol contains, at the top, another A/E_1 horizon about 40 cm (16 in) thick of light gray sandy mudstone that is locally mottled dark reddish brown from partial development of the B_T horizon from the overlying paleosol. It also has blocky peds of the same size as the upper paleosol. This is underlain by 0-33 cm (0-13 in) of a B_{T1} horizon consisting of yellow sandy mudstone containing blocky peds and cutans. A lower or C horizon consists of the leached upper part of the underlying fluvial sandstone bed [bed 5 in the local stratigraphic terminology of this report]."

Dark gray to black mudstone is rare in the Morrison but was found in two localities and may have some stratigraphic significance. A dark gray mudstone bed is at the top of the middle member at section 8 just north of Morrison in a small and poor exposure but it cannot be traced laterally for any distance owing to cover. This bed is poorly exposed in the floor of the old dinosaur quarry 10a (Fig. 3, sec. 8) but it is largely covered by blocks that have fallen from the overlying sandstone bed. We found thin dark gray to black mudstone and scattered plant impressions, some with carbonized films still preserved, along bedding planes in the basal sandstone bed of the upper member at Ralston Reservoir, which perhaps would suggest that the sandstone bed should be included in the Dakota Group. However, the relatively large amount of interstitial clay in the sandstone indicates that the upper contact of the Morrison should be placed higher in the section, and plant impressions are not characteristic of the Lytle either, so the position of the contact there must be based upon the other criteria. Although this type of mudstone is rare, it has been found at scattered localities in the upper part of the Morrison farther north in Wyoming and Montana. In Montana, the upper part of the formation contains dark gray to black mudstone as well as coal and carbonaceous mudstone beds, suggesting that these lithologies might be a crude correlation marker across an extensive part of the Western Interior.

Thickness. The Morrison Formation varies considerably in thickness across the study area. The greatest thickness is 112.6 m (369.5 ft) at the Bergen Ditch section and the thinnest section is 73.8 m (242.2 ft) at Alameda Parkway. The average of the seven complete sections between Ralston Reservoir and Bergen Ditch is 93.8 m (307.7 ft).

AGE OF THE FORMATIONS

The Ralston Creek Formation is largely if not entirely Kimmeridgian in age although the lowermost few meters could be as old as latest Oxfordian (Litwin and others, this volume; Schudack and others, this volume). The formation contains charophytes and ostracodes and Scott (1963, p, 92) recovered the late Oxfordian to Kimmeridgian charophyte *Echinochara pecki* from the Ralston Creek near Kassler. Lateral correlations to well dated lower Morrison strata at Owl Canyon about 105 km (65 mi) farther north, and elsewhere, also indicate that the Ralston Creek is largely if not entirely Kimmeridgian in age (Schudack and others, this volume).

The age of the Morrison Formation has been discussed considerably since it was first named, with various reasons presented favoring either a Late Jurassic or Early Cretaceous age. The problem arose from attempts to define the Jurassic-Cretaceous boundary by the earliest workers several decades before the formation was named. The upper contact of the Jura or Jurassic System of the earliest workers (Hayden, 1869; Marvine, 1874) apparently was placed at the base of today's Kassler Sandstone Member of the South Platte Formation in the Dakota Group (see Fig. 3), which placed strata now known to be Early Cretaceous in age within what they thought was Jurassic. Subsequently, Lee (1920) and Knowlton (1920), apparently under the mistaken impression that Eldridge also placed the upper contact of the Morrison at the higher stratigraphic position, discovered Early Cretaceous plant fossils below that contact and concluded that the Morrison was Cretaceous in age. In contrast, it is noteworthy that Eldridge (1896, and unpublished field notes in the archives of the U.S. Geological Survey) placed the upper contact of the Morrison Formation well below the Kassler and at or very close to the stratigraphic position that is used in this report.

More recently, opinions favoring a Cretaceous age for some part of the Morrison stem largely from different interpretations of the age significance of the fauna, flora, and isotopic dates, or from incorrect positioning of the upper contact. The new information on isotopic dates (Kowallis and others, this volume), palynomorphs (Litwin and others, this volume), and charophytes and ostracodes (Schudack and others, this volume) all support an entirely Late Jurassic age for the formation as its upper contact is presently understood. More specifically, the microfossil evidence indicates a Kimmeridgian-Tithonian age for the formation in the Front Range foothills and most likely the age there is early Kimmeridgian to early Tithonian. Several thin bentonite beds were found in the middle member of the Morrison above the limestone marker at Highway I-70 but they proved too deeply weathered to be useful for isotopic dating.

Paleomagnetic studies by Steiner and others (1994) indicate an early Tithonian age for the uppermost part of the Morrison. There are several problems with the basic stratigraphy and correlation of magnetic polarity chron sequences in the lower and middle parts of the Morrison in their report. However, there is general agreement that the highest part of the Morrison magnetostratigraphic sequence correlates best with the lower part of magnetic polarity chron M22 in the magnetic polarity time scale of Ogg and others (1991). The Jurassic-Cretaceous boundary is placed at or very near the base of polarity chron M18, suggesting that about three and a half latest Jurassic magnetic polarity chrons are not present in the Morrison. This suggests that Morrison deposition ended several million years before the end of the Jurassic Period, a conclusion also indicated from the isotopic dates of Kowallis and others (this volume).

STRATIGRAPHY

The ultimate goal of the stratigraphic studies is to be able to place the formations in a chronostratigraphic framework for the purpose of making regional syntheses. We feel that the best way to accomplish this is to use stratigraphic markers, coupled with any other available paleontologic, paleomagnetic, and isotopic age information. Because the age information is not everywhere available and has inherent limitations, the stratigraphic markers must, of necessity, be relied upon to relate the strata over broad geographic areas. Any regional picture obtained without using the markers would be poorly constrained, confused, or overly simplistic.

Correlations Within the Study Area

An understanding of the stratigraphic relations of beds in the Ralston Creek and Morrison Formations in the study area is based largely upon the various stratigraphic markers described earlier in this report. We used the thick limestone marker unit in the Morrison as a datum throughout most of the study area although lower horizons were used locally where necessary. This presents a better understanding of the stratigraphy of the rock units within the formations and it also presents a more realistic arrangement that shows reasonably well the depth of scour at the unconformities. The stratigraphic section (Fig. 3) only extends 23.3 km (14.5 mi) but it shows important features for understanding these formations.

Ralston Creek Formation Southward gradation of Ralston Creek strata into the gypsiferous facies is clearly apparent, and the various stratigraphic markers within the formation demonstrate that the gypsum is not part of the Permo-Triassic Lykins Formation. The maximum depth of erosion at the J-5 unconformity at the base of the Ralston Creek is about 12.2 m (40 ft) at the south end of the study area. It may be more in the vicinity of Ralston Reservoir but this could not be documented well because we could not find an exposure of the limestone marker unit at the Long Lake Ditch section. Consequently, we are not entirely confident that the reference datum we used at the top of the lower member of the Morrison gives a proper representation of the depth of erosion on the J-5 unconformity. Considerable interfingering is apparent at the Ralston Creek-Morrison contact, and is well documented at several places although extensive cover requires interpretations between other sections.

Exposures are especially poor south of Weaver Gulch although Scott (1963) was able to to obtain several incomplete measured sections of the Ralston Creek about 16 km (10 mi) farther south near Kassler (Fig. 1). These sections were not examined by us and the presence there of the basal marker—Bed A—is uncertain. The yellow unit and welded chert can be distinguished in Scott's (1963, p. 91-92) measured section 5 at Kassler. Gypsum is absent at Kassler but it is present at Perry Park, 30 km (18 mi) farther southeast, demonstrating that the gypsum is only locally present in the outcrop belt along the Front Range foothills. Subsurface studies by Blair (1951) show gypsum or anhydrite at the base of the Morrison Formation north and northeast of Denver that appear to correlate with the gypsiferous facies of the Ralston Creek Formation. Farther afield, gypsum has been found by us at or a short distance above the base of the Morrison between Bed A and the welded chert at Garden Park near Cañon City and in southeastern Colorado although the yellow zone is not present at these localities. The presence of gypsum in these areas suggests that it was deposited in a large hypersaline marine embayment or inland evaporite basin that may have been a Late Jurassic precursor to the Denver-Julesburg structural basin (O'Sullivan, 1992, p. 14, Fig. 7).

Morrison Formation The three members that comprise the Morrison Formation are present throughout the area covered by the stratigraphic section, which shows considerable interfingering among the three members (Fig. 3). Although there is considerable interfingering between these members, the formation does not undergo broader facies changes across the study area. The lower member is composed of laterally discontinuous fluvial sandstone bodies with interfingering contact relations between strata in the upper part of the Ralston Creek Formation as well as strata in the lower part of the middle member of the Morrison. Interfingering is indicated at the top of the middle member based upon the different stratigraphic positions of the lowest sandstone beds of the upper member of the Morrison with respect to the limestone marker unit lower in the formation. None of this could be confirmed by lateral tracing owing to extensive cover. However, sandstone bed 3 at Alameda Parkway and the basal sandstone bed of the upper member at the Morrison-1 section (Fig. 3, secs. 6, 8) are similar and consist largely of horizontally-laminated to very thin-bedded, fine-grained sandstone that lacks siliceous pebbles. These similarities suggest the possible correlation of this bed between the two measured sections shown in Figure 3.

The limestone marker unit in the middle member apparently extends the full 23.3 km (14.5 mi) length of the study area (Fig. 3). Other limestone beds are present in the middle member throughout the area, but it cannot be determined if any of these correlate between even the closest of measured sections.

A maximum depth of erosion of about 36 m (120 ft) on the K-1 unconformity at the base of the Lytle Formation is indicated between the Turkey Creek and Bergen Ditch sections, but there are other deep erosional scours or possible paleovalleys elsewhere in the study area (Fig. 3).

Thickness Variations. Because of interfingering between the Ralston Creek and Morrison Formations, there is little value in comparing the thickness variations for each formation along the outcrop trend. However, some trends are apparent when the thicknesses of both formations are combined. The combined Ralston Creek-Morrison unit is thinnest at Highway I-70 (118.6 m or 389 ft); it thickens northward to 143.7 m (471.5 ft) at Ralston Reservoir and it thickens southward to 154.7 m (507.5 ft) at the Bergen Ditch section. This might reflect a broad paleotopographic and possibly structural high with its crest at or near Highway I-70 and with lows farther north and south. In contrast, Weimer and others (1990, p. 71) interpreted a paleostructural high centered about Turkey Creek and a structural low near Alameda Parkway and Highway I-70 during late Early Cretaceous time. The Ralston Creek-Morrison thickness data only cover a short distance. Additional information would be desirable, but the thickness variations may be a hint that the vertical movement on these paleostructures reversed between Late Jurassic and Early Cretaceous time.

Duration of the Unconformities The unconformities at the base of the Ralston Creek and top of the Morrison represent significant time spans. The upper beds of the Lykins Formation are considered Early Triassic in age (Maughan, 1980) and the basal strata of the Ralston Creek are earliest Kimmeridgian or possibly latest Oxfordian in age (Litwin and others, this volume; Schudack and others, this volume). Using the geologic time scale of Harland and others (1990), approximately 85 million years is represented by the J-5 unconformity in the Front Range foothills area. The top of the Morrison is about 147 Ma or middle Tithonian in age (Kowallis and others, this volume) and the Lytle Formation is thought to be about middle to late Albian in age through rather long-distance correlations with the Cheyenne Sandstone of south-central Kansas (Kues and Lucas, 1987, p. 178). This suggests that the K-1 unconformity spans about 40 my.

Correlations to other areas

The physical stratigraphy and the new biostratigraphic and isotopic age control (Kowallis and others, this volume; Litwin and others, this volume; Schudack and others, this volume) permit correlation of the Ralston Creek and Morrison Formations from near their type localities to other well-known Morrison areas to the south, west, and northwest (Fig. 5). The section at Highway I-70 is used as the primary reference section for the

Morrison-Ralston Creek area because it contains all of the stratigraphic units and is exceptionally well exposed.

The basis for the regional correlations presented here requires some explanation. The change in clay minerals is thought to be an isochronous or nearly isochronous horizon. The J-5 and K-1 unconformities are considered correlative surfaces but their precise age and duration most likely changes from place to place, as might be expected with unconformities. An additional problem with the J-5 unconformity is derived from recent studies of trace fossils and sedimentology by T.M. Demko and S.T. Hasiotis (oral commun., 1994) at Dinosaur National Monument in northeastern Utah. At that locality, an unconformity does not appear to be present at the base of the Windy Hill Member of the Morrison Formation. It is possible that the basal surface of the Windy Hill at Dinosaur National Monument is a conformable contact that correlates with the J-5 unconformity elsewhere; that is, it could be a correlative conformity. Another possibility, however, is that the position of the J-5 unconformity at the Monument has been misidentified and, instead, is higher or lower in the section. The nature of this surface at Dinosaur National Monument and elsewhere is currently being studied. Locally angular truncation of beds beneath the Windy Hill has been documented elsewhere by Pipiringos (1972) and Pipiringos and O'Sullivan (1976).

All of the other regional correlations probably are reasonably reliable, based upon the new information of this report as well as the new age information presented by Kowallis and others (this volume), Litwin and others (this volume), and Schudack and others (this volume). Bed A and the Windy Hill Member both lie on the J-5 unconformity but their precise relations to each other is unclear. They are shown as correlative but Bed A is nonmarine in origin whereas the Windy Hill is a marine unit deposited during a marine transgressive-regressive cycle. Thus, the surface at the base of Bed A and the Windy Hill most likely have different origins. The surface at the base of Bed A probably is a lowstand surface of erosion whereas the surface at the base of the Windy Hill is a transgressive surface of erosion.

Several other stratigraphic markers help with the regional correlations. The welded chert is a persistent stratigraphic marker and occurs in a zone that has a restricted stratigraphic position although the boundaries of the zone are not necessarily isochronous surfaces. The upper boundary of the smectitic mudstone interval is difficult to determine in some localities, partly because of the influx of fluvially transported nonsmectitic clays near the top of the Morrison but also because of the various processes that produced the smectitic clays. One of these processes is gradual reduction in the volcanism farther west that produced the windblown ash deposits that later altered to the Morrison bentonite and smectitic beds. Another is the downwind or northeastward regional loss of the windblown ash, which accounts for fewer bentonite beds and less smectitic material in the Morrison of the Front Range foothills than farther west on the Colorado Plateau. A third factor is that the volcanoes along the west coast of Late Jurassic North America apparently had limited northward extent (Saleeby and Busby-Spera, 1992). As a consequence, the northeast-directed prevailing winds (Peterson, 1988b) did not deposit ash at more northerly latitudes, thereby accounting for the lack of smectite in the Morrison in northern Wyoming and Montana.

The lower boundary of the upper member of the Morrison is known to change stratigraphic position from place to place (Fig. 3). Despite the extensive interfingering at the base, the member nevertheless constitutes a helpful stratigraphic guide to the upper part of the Morrison.

Garden Park, Colorado

Garden Park is about 127 km (79 mi) south of the Highway I-70 reference section near Morrison and 10 km (6 mi) north of Cañon City, Colorado (Fig. 1). Various beds have been assigned to the Ralston Creek Formation in this area but paleontological evidence indicates that some of these beds are Middle Jurassic in age and therefore are older than the type Ralston Creek west of Denver. The nearest appropriate name for these beds that is consistent with the lithologies is the Bell Ranch Formation, which is the name applied to Middle Jurassic strata in southeastern Colorado and northeastern New Mexico.

All of the rocks above the Bell Ranch and beneath the Cretaceous System in Garden Park are best considered Morrison because lithologically they more closely resemble the Morrison in outcrop areas farther south, southeast, and west. In all of these areas, the upper contact of a "Ralston Creek Formation" would have to be determined by the presence of a thick or moderately thick sandstone bed at the base of a restricted Morrison Formation. But where a reasonably thick sandstone bed is absent, the similarity of limestone-bearing red and green mudstone in both formations would make it difficult if not impossible to establish a contact between the two formations. Also, Bed A and the welded chert are recognized in the Morrison of many areas, with the exception of the study area where they are included in the Ralston Creek (Fig. 5). For these reasons, we only recognize the Ralston Creek Formation in the Front Range foothills area west of Denver.

The Bell Ranch Formation at Garden Park consist of light reddish brown, very fine- to fine-grained, laminated to thin-bedded sandstone and silty sandstone and includes some reddish-brown or light gray mudstone as well variable quantities of limestone and gypsum. Conglomeratic or pebbly sandstone also is locally common. Morrison strata directly above the Bell Ranch in Garden Park are somewhat similar in containing several pebbly sandstone beds (especially the basal Bed A), red or grayish-green mudstone, scarce gypsum, and thin limestone, but there is considerably more mudstone in the Morrison, the welded chert marker zone is present in lower Morrison strata, and the thin limestone beds contain charophytes and ostracodes that have not, to our knowledge, been found in the Bell Ranch in the Garden Park area.

Strata here assigned to the Bell Ranch Formation near Cañon City and Garden Park most likely are entirely Middle Jurassic in age and therefore should not be included in the

Morrison Formation. The Bell Ranch Formation at Garden Park contain two species of actinopterygian fish that suggest it is Middle Jurassic in age. These are Todiltia schoewei (Dunkle, 1942) and Hulettia americana (Eastman, 1899) as reported by Dunkle (1942) and Schultze and Enciso (1983). T. schoewei and H. americana have been found in the Todilto and Pony Express Limestone Members of the Wanakah Formation in southwestern Colorado and northern New Mexico (Schaeffer and Patterson, 1984). The Todilto and Pony Express are thought to be middle Callovian (latest Middle Jurassic) in age because they correlate with upper beds of the Entrada Sandstone, which is thought to be middle Callovian in age (Imlay, 1980). However, Imlay's age assignment depends largely upon correlations of the Entrada with Middle Jurassic strata in Wyoming and adjacent areas that are included in the Sundance Formation, which contains age-diagnostic marine fossils. Hence, the age of the Bell Ranch fish beds depends entirely upon the age of correlative Wyoming marine strata that contain the same species of fish.

Only part of the Middle and Upper Jurassic Sundance Formation of Wyoming and South Dakota contains strata that correlate with the Bell Ranch Formation. The various members of the Sundance Formation in Wyoming and nearby areas are listed below in their proper stratigraphic order. Locally, there is interfingering between some of the members.

Sundance Formation:
- Redwater Shale Member (Youngest)
- Pine Butte Sandstone Member
- Lak Member
- Hulett Sandstone Member (Contains Hulettia americana)
- Stockade Beaver Shale Member (Contains Hulettia americana)
- Canyon Springs Sandstone Member (Contains Hulettia americana) (oldest)

The fish Hulettia americana has been reported from South Dakota and Wyoming only in the lower part of the Sundance Formation (Canyon Springs Sandstone Member, Stockade Beaver Shale Member, and Hulett Sandstone Member) according to Schaeffer and

Patterson (1984). Other marine fossils that indicate a late Bathonian to early Callovian age have been recovered from these beds (Imlay, 1980). Thus, correlations based upon this single species of fish may be interpreted to suggest an age within this time span. However, the complete biostratigraphic range of H. americana is unknown because it or its evolutionary precursors or descendents have not been recovered from stratigraphically lower or higher strata than the lower three members of the Sundance Formation listed above. For this reason, the span of geologic time in which the species lived is unclear. It must therefore be assumed that the presence of the same species of fish indicates that the Bell Ranch is the same age as some part or all of the lower three members of the Sundance Formation in Wyoming and South Dakota.

Correlation of the Bell Ranch Formation at Garden Park with the Canyon Springs Sandstone, Stockade Beaver Shale, and (or) Hulett Sandstone Members of the Sundance suggests the Bell Ranch was deposited sometime during the late Bathonian to early Callovian time interval. This is significantly older than the Kimmeridgian or possibly latest Oxfordian age for basal strata of the Morrison at Garden Park or for basal strata of the Ralston Creek Formation west of Denver. Hence, age determinations based upon the fossil fish support the lithologic determination that strata in the Bell Ranch Formation at Garden Park should not be included in either the Ralston Creek or Morrison Formation.

Correlation of the type Ralston Creek and Morrison Formations near Denver with the lower part of the Garden Park Morrison is accomplished by means of some of the stratigraphic markers that are present near Morrison. From base up, these include Bed A, the zone of welded chert, the clay change and overlying smectitic clay interval, and the upper member (Fig. 5). We did not uncover all of the bentonite beds within the smectitic interval at the Garden Park measured section but better exposures through that interval elsewhere in Garden Park suggest that perhaps a dozen or so bentonite beds are present there. The charophyte and ostracode biostratigraphy of Schudack and others (this volume) indicates a Kimmeridgian to about early Tithonian age for the Morrison in Garden Park and supports the correlations based upon the physical stratigraphy.

Dinosaur National Monument, Utah The Ralston Creek and Morrison Formations of the Front Range foothills can be correlated reasonably well with the Morrison 357 km (222 mi) west-northwest of Morrison near the Carnegie Quarry on the west side of Dinosaur National Monument in northeastern Utah (Fig. 1). The locality is about 407 km (253 mi) northwest of Garden Park, Colorado.

The Morrison is considerably thicker at the Monument (188.5 m or 618.5 ft) than farther east (Fig. 5) but it contains many of the stratigraphic markers that permit correlation between the two widely separated areas. These markers are the Windy Hill Member, the welded chert, the clay change and overlying smectitic interval in the Brushy Basin Member, and the K-1 unconformity at the top of the formation. The Tidwell and Salt Wash Members at Dinosaur National Monument are homotaxial equivalents to the Ralston Creek and lower member of the Morrison in the Front Range foothills. However, because of interfingering between the Tidwell and Salt Wash at the Monument and between the Ralston Creek and lower Morrison in the Front Range foothills, as well as other complications, the pair of members at the two localities do not necessarily correlate in all details. The lateral relations based on the microfossils and stratigraphic markers suggest that some of the Salt Wash Member at the Monument was deposited contemporaneously with the lower member of the Morrison in the Front Range foothills. However, the lower member of the type Morrison should not be considered an eastern extension of the Salt Wash Member. The angularity and moderately large to large size of some of the Morrison clasts in the Front Range foothills indicate that the lower member of the Morrison at and near the town of Morrison was derived largely if not entirely from a local source area, probably in a topographically reduced but somewhat hilly remnant of the ancestral Front Range. The upper part of the Brushy Basin Member at Dinosaur National Monument contains numerous bentonite beds but we only found three in the same interval at Highway I-70. This reflects the eastward or downwind loss of volcanic ash derived from volcanoes southwest of the Colorado Plateau.

The microfossil biostratigraphy derived from palynomorphs, charophytes, and ostracodes (Litwin and others, this volume; Schudack and others, this volume) indicates a Kimmeridgian to about early Tithonian age for the Morrison at Dinosaur National Monument and therefore support correlations based on physical stratigraphy. In addition, an isotopic date of 154.8±0.6 Ma. from near the base of the Tidwell Member at Dinosaur National Monument (Kowallis and others, this volume) indicates a latest Oxfordian or earliest Kimmeridgian age for the base of the formation (time scale of Harland and others, 1990), which is compatible with the other correlations based upon the physical stratigraphy and age interpretations gained from the microfossils.

Medicine Bow (Como Bluff), Wyoming Part or all of the Ralston Creek Formation near Denver has been miscorrelated with the Sundance Formation of southeastern Wyoming, which has led some to the erroneous conclusion that the Ralston Creek is Middle Jurassic in age. Part of the confusion results from lithologic correlations along the Front Range foothills to southeastern Wyoming (Lee, 1920, 1927; Pipiringos and O'Sullivan, 1976). A contributing factor to this misconception arose from the Middle Jurassic fossil fish in the Bell Ranch Formation of the Garden Park area, which was earlier thought to be Ralston Creek.

The last attempt at correlating the Sundance Formation southward into northeastern Colorado was by Pipiringos and O'Sullivan (1976). They correlated the lower 5.2 m (17 ft) of the Ralston Creek Formation at Ralston Reservoir, which includes Bed A and the overlying lower red unit with the Canyon Springs Sandstone Member of the Sundance Formation. Lithologically, the lower red unit of the type Ralston Creek is not at all similar to the Canyon Springs farther north, which consists dominantly of crossbedded sandstone.

Although work is still in progress on the lateral relationships of the type Ralston Creek to the Sundance farther north, we tentatively conclude that the Canyon Springs Sandstone Member is beveled out southward beneath the J-5 unconformity and is not present at Ralston Reservoir.

The correlations shown in Figure 5 are to the Morrison Formation exposed at Ninemile Hill, which is about 8 km (5 mi) northeast of Medicine Bow and about 261 km (162 mi) north-northwest of Morrison. The Ninemile Hill section is only about 10 km (6 mi) northwest of the numerous dinosaur quarries at Como Bluff and the section is closely representative of the Morrison at Como Bluff. Correlations to Ninemile Hill therefore allow correlation of the world famous Como Bluff bone beds with the type Morrison and Ralston Creek Formations and also allows the Como Bluff strata and vertebrate fossils to be dated on a much finer scale than had been accomplished before (Litwin and others, this volume; Schudack and others, this volume). The correlations are based upon several stratigraphic markers including the Windy Hill Member approximately correlating with Bed A of the Ralston Creek, the clay change and overlying smectitic interval, and the K-1 unconformity at the top of the Morrison. In addition, the thin charophyte and ostracode-bearing freshwater limestone beds in an interval 6.1 m (20 ft) thick just above the Windy Hill near Medicine Bow suggest correlation with the largely nonmarine Tidwell Member of the Morrison at Dinosaur National Monument and with some of the limestone-bearing strata in or closely adjacent to the yellow unit of the Ralston Creek Formation in the Front Range foothills (Fig. 3; Schudack and others, this volume).

The correlations suggest that the smectitic interval in southern Wyoming is part of the Morrison Formation and not part of the Lower Cretaceous Cloverly Formation, as had been thought by some workers. This is also supported by the age of Morrison strata in Wyoming as determined from studies of the palynomorphs (Litwin and others, this volume) and the charophytes and ostracodes (Schudack and others, this volume). This contrasts with the interpretation of DeCelles and Burden (1992) who placed the lower boundary of the Lower Cretaceous Cloverly Formation at the base of the smectitic interval at Como Bluff in south-central Wyoming, which is near our Ninemile Hill section.

DEPOSITIONAL ENVIRONMENTS

The Ralston Creek is a dominantly continental deposit in the foothills study area west of Denver. Freshwater fossils indicate that the mudstone facies was deposited largely in lacustrine and mudflat environments. Near the top of the formation are overbank floodplain deposits that were marginal to stream channels represented by the fluvial channel sandstone beds at the base of the Morrison that interfinger with upper Ralston Creek mudstone strata. The gypsiferous facies was deposited in an evaporite basin that may have been either an entirely landlocked inland basin or, more likely, a broad hypersaline marine embayment that had its connection with more normal marine waters to the north in northeastern Colorado and southeastern Wyoming.

The Morrison is entirely nonmarine in the foothills study area. Fluvial strata below and above the middle member that contains freshwater limestone and mudstone beds indicate two fluvial episodes separated by a fairly long interval in which lacustrine and mudflat environments prevailed throughout the region. Scarce ribbon-type fluvial channel sandstone beds in the middle member demonstrate that streams occasionally entered the lacustrine system. The lake delimited by the limestone marker unit may have been quite large. The unit extends the full 23.3 km (14.5 mi) distance of the study area (Figs. 1, 3), suggesting that the lake in which it was deposited probably was at least that long in a north-south direction. Aside from a fairly long concealed interval 14 km (8.7 mi) long between Long Lake Ditch and Highway I-70 where the limestone marker unit could be missing, this appears to be the only known instance where some idea of the minimum size of a fairly large Morrison lake in eastern Colorado may be obtained. The lateral extent of any associated peripheral lacustrine mudstone facies to the lacustrine limestone deposit needs additional detailed research that is beyond the scope of the present study. Other limestone beds are present in the middle member throughout the foothills study area, but their lateral relations between even the closest of measured sections is uncertain, which makes it difficult to estimate the size of the lakes represented by these beds.

The lacustrine limestone beds in the Ralston Creek and Morrison Formations of eastern Colorado contain charophytes and ostracodes that indicate fresh-water habitats (Schudack and others, this volume). This contrasts with Morrison strata farther west on the east side of the Colorado Plateau that were deposited in a large saline-alkaline lake (Turner and Fishman, 1991). Our tentative conclusion is that the two highly dissimilar lacustrine systems were isolated from each other, presumably by a drainage divide that followed Late Jurassic remnants of the ancestral Rocky Mountains.

The angular nature of some of the small pebbles in the upper member of the Morrison suggests a nearby source that most likely was erosional remnants of the ancestral Rockies, which were perhaps 10-150 km (6-90 mi) farther west. The only other possibility is that the pebbles came from source areas approximately 650 km (400 mi) or more away in eastern Nevada and western Utah or in southern Arizona (Peterson, 1994). It seems unlikely that the pebbles could have survived fluvial transport for such distances without becoming well rounded. Almost all of the sandstone beds at Garden Park contain angular grains or small pebbles of pink feldspar that must have been derived from Precambrian crystalline rocks nearby. Consequently, the angularity of many of the Morrison pebbles demonstrates a nearby source of at least some and quite likely all of the material in these beds. Most likely Morrison fluvial strata in the foothills study area are not extensions of fluvial sandstone units farther west or southwest on the Colorado Plateau.

ACKNOWLEDGEMENTS

The South Boulder Division of the Denver Water District granted permission to study the rocks at Ralston Reservoir. The landowners of the area including the Bergen Ditch and Weaver Gulch sections graciously allowed us to study the formations on their property.

T.M. Demko kindly furnished the description of the paleosols at the top of the Morrison at Alameda Parkway. R.T. Bakker suggested the locality at Ninemile Hill near Medicine Bow for a well-exposed section that would be representative of the Morrison Formation throughout that part of Wyoming.

REFERENCES CITED

Blair, R.W., 1951, Subsurface geologic cross sections of Mesozoic rocks in northeastern Colorado: U.S. Geological Survey Oil and Gas Investigations Chart OC-42.

Cannon, G.L., Jr., 1893, The geology of Denver and vicinity: Colorado Scientific Society, Proceedings, v. 4, p. 235-270.

Cross, Whitman, 1894, Pikes Peak Folio, Colorado: U.S. Geological Survey Folio 7, 5 p., 4 maps, scale 1:125,000.

Cross, Whitman, Spencer, A.C., and Purington, C.W., 1899, La Plate Folio, Colorado: U.S. Geological Survey Folio 60, 14 p., 4 maps, scale 1:62,500.

DeCelles, P.G., and Burden, E.T., 1992, Non-marine sedimentation in the overfilled part of the Jurassic-Cretaceous Cordilleran foreland basin: Morrison and Cloverly Formations, central Wyoming, USA: Basin Research, v. 4, nos. 3/4, p. 291-313.

Dunkle, D.H., 1942, A new fossil fish of the Family Leptolepidae: Cleveland Museum of Natural History, Scientific Publications, v. 8, no. 5, p. 61-64.

Eastman, C.R., 1899, Some new American fossil fishes: Science, new series, v. 9, p. 642-643.

Eldridge, G.H., 1888, On some stratigraphical and structural features of the country about Denver, Colorado: Proceedings of the Colorado Scientific Society, v. 3, pt. 1, p. 86-118.

Eldridge, G.H., 1896, Chapter II, Mesozoic Geology; in, Emmons, S.F., Cross, Whitman, and Eldridge, G.H., Geology of the Denver Basin in Colorado: U.S. Geological Survey Monograph 27, p. 51-150.

Frederickson, E.A., De Lay, J.M., and Saylor, W.W., 1956, Ralston Formation of Cañon City embayment, Colorado: American Association of Petroleum Geologists Bulletin, v. 40, no. 9, p. 2120-2148.

Gilluly, James, and Reeside, R.B., Jr., 1928, Sedimentary rocks of the San Rafael Swell and some adjacent areas in eastern Utah: U.S. Geological Survey Professional Paper 150-D, p. 61-110.

Harland, W.B., Armstrong, R.L., Cox, A.V., Craig, L.E., Smith, A.G., and Smith, D.G., 1990, A Geologic Time Scale 1989: Cambridge University Press, New York, 263 p.

Hayden, F.V., 1869, Geological Report; in, Hayden, F.V., Preliminary Field Report of the United States Geological Survey of Colorado and New Mexico: Government Printing Office, Washington, p. 1-99.

Holbrook, J.M., Wright, Robyn, and Kietzke, K.K., 1987, Stratigraphic relationships at the Jurassic-Cretaceous boundary in east-central New Mexico; in, Lucas, S.G., and Hunt, A.P., (eds.), Northeastern New Mexico: New Mexico Geological Society Guidebook, 38th Field Conference, p. 161-165.

Imlay, R.W., 1980, Jurassic paleobiogeography of the conterminous United States in its continental setting: U.S. Geological Survey Professional Paper 1062, 134 p.

Keller, W.D., 1953, Clay minerals in the type section of the Morrison Formation: Journal of Sedimentary Petrology, v. 23, no. 2, p. 93-105.

Knowlton, F.H., 1920, A dicotyledonous flora in the type section of the Morrison Formation: American Journal of Science, 4th series, v. 49, no. 291, art. 14, p. 189-194.

Kowallis, B.J., Christiansen, E.H., Deino, A.L., Peterson, F., Turner, C.E., Kunk, M.J., and Obradovich, J.D., 1998, The age of the Morrison Formation: Modern Geology, v. 22, nos. 1-4, p. 235-260.

Kues, B.S., and Lucas, S.G., 1987, Cretaceous stratigraphy and paleontology in the Dry Cimarron Valley, New Mexico, Colorado and Oklahoma; in, Lucas, S.G., and Hunt, A.P., (eds.), Northeastern New Mexico: New Mexico Geological Society Guidebook, 38th Annual Field Conference, p. 167-198.

Lee, W.T., 1902, The Morrison shales of southern Colorado and northern New Mexico: Journal of Geology, v. 10, no. 1, p. 36-58.

Lee, W.T., 1920, Type section of the Morrison Formation: American Journal of Science, 4th series, v. 49, no. 291, art. 13, p. 183-188.

Lee, W.T., 1927, Correlation of geologic formations between east-central Colorado, central Wyoming, and southern Montana: U.S. Geological Survey Professional Paper 149, 80 p.

LeRoy, L.W., 1946, Stratigraphy of the Golden-Morrison area, Jefferson County, Colorado: Quarterly of the Colorado School of Mines, v. 41, no. 2, 115 p.

LeRoy, L.W., and Weimer, R.J., 1971, Geology of the Interstate 70 road cut, Jefferson County, Colorado: Professional Contributions of the Colorado School of Mines, No. 7. 1 sheet.

Litwin, R.J., Turner, C.E., and Peterson, Fred, 1998, Palynological evidence on the age of the Morrison Formation, Western Interior, U.S.: Modern Geology, v. 22, nos. 1-4, p. 297-320.

Lucas, S.G., Kietzke, K.K., and Hunt, A.P., 1985, The Jurassic System in east-central New Mexico; in, Lucas, S.G., (ed.), Santa Rosa-Tucumcari Region: New Mexico Geological Society Guidebook, 36th Field Conference, p. 213-242.

Marvine, A.R., 1874, Report of Arch. R. Marvine, Assistant Geologist directing the Middle Park Division; in, Hayden, F.V., Annual Report of the United States Geological and Geographical Survey of the Territories, embracing Colorado, being a report of progress of the exploration for the year 1873: Government Printing Office, Washington, p. 83-192.

Maughan, E.K., 1980, Permian and Lower Triassic geology of Colorado; in, Kent, H.C., and Porter, K.W., (eds.), Colorado Geology: Rocky Mountain Association of Geologists, p. 103-110.

May, M.T, 1993, Petrographic characteristics of Morrison-Cloverly Formations and equivalent rocks in west central and central Wyoming—Implications for tectonic complexity in the early Sevier foreland; in, Keefer, W.R., Metzger, W.J., and Godwin, L.H., (eds.), Oil and Gas Resources of the Wind River Basin, Wyoming: Wyoming Geological Association Special Symposium, p. 49-70.

Ogden, Lawrence, 1954, Rocky Mountain Jurassic time surface: American Association of Petroleum Geologists Bulletin, v. 38, no. 5, p. 914-916.

Ogg, J.G., Hasenyager, R.W., Wimbledon, W.A., Channell, J.E.T., and Bralower, T.J., 1991, Magnetostratigraphy of the Jurassic-Cretaceous boundary interval—Tethyan and English realms: Cretaceous Research, v. 12, p. 455-482.

O'Sullivan, R.B., 1980, Stratigraphic sections of Middle Jurassic San Rafael Group from Wilson Arch to Bluff in southeastern Utah: U.S. Geological Survey Oil and Gas Investigations Chart OC-102.

O'Sullivan, R.B., 1992, The Jurassic Wanakah and Morrison Formations in the Telluride-Ouray-western Black Canyon area of southwestern Colorado: U.S. Geological Survey Bulletin 1927, 24 p.

Owen, D.E., Walters, L.J., and Beck, R.G., 1984, The Jackpile Sandstone Member of the Morrison Formation in west-central New Mexico—A formal definition: New Mexico Geology, v. 6, no. 3, p. 45-52.
Petersen, L.M., and Roylance, M.M., 1982, Stratigraphy and depositional environments of the Upper Jurassic Morrison Formation near Capitol Reef National Park, Utah: Brigham Young University Geology Studies, v. 29, pt. 2, p. 1-12.
Peterson, Fred, 1988a, Stratigraphy and nomenclature of Middle and Upper Jurassic rocks, western Colorado Plateau, Utah and Arizona: U.S. Geological Survey Bulletin 1633-B, p. 13-56.
Peterson, Fred, 1988b, Pennsylvanian to Jurassic eolian transportation systems in the western United States: Sedimentary Geology, v. 56, p. 207-260.
Peterson, Fred, 1994, Sand dunes, sabkhas, streams, and shallow seas: Jurassic paleogeography in the southern part of the Western Interior Basin; in, Caputo, M.V., Peterson, J.A., and Franczyk, K.J., (eds.), Mesozoic Systems of the Rocky Mountain Region, USA: Rocky Mountain Section of SEPM (Society for Sedimentary Geology), p. 233-272.
Pettijohn, F.J., 1957, Sedimentary Rocks: Harper and Brothers, New York, 718 p.
Pipiringos, G.N., 1972, Upper Triassic and pre-Morrison Jurassic rocks; in, Segerstrom, Kenneth, and Young, E.J., General geology of the Hahns Peak and Farwell Mountain quadrangles, Routt County, Colorado: U.S. Geological Survey Bulletin 1349, p. 18-29.
Pipiringos, G.N., and O'Sullivan, R.B., 1976, Stratigraphic sections of some Triassic and Jurassic rocks from Douglas, Wyoming, to Boulder, Colorado: U.S. Geological Survey Oil and Gas Investigations Chart OC-69.
Saleeby, J.B., and Busby-Spera, C., with contributions by Oldow, J.S., Dunne, G.C., Wright, J.E., Cowan, D.S., Walker, N.W., and Allmendinger, R.W., 1992, Early Mesozoic tectonic evolution of the western U.S. Cordillera; in, Burchfiel, B.C., Lipman, P.W., and Zoback, M.L., (eds.), The Cordilleran Orogen: Conterminous U.S.: Geological Society of America, The Geology of North America, v. G-3, chapter 4, p. 107-168.
Schaeffer, Bobb, and Patterson, Colin, 1984, Jurassic fishes from the western United States, with comments on Jurassic fish distribution: American Museum Novitates, no. 2796, p. 1-86.
Schudack, M.E., Turner, C.E., and Peterson, F., 1998, Biostratigraphy, paleoecology, and biogeography of charophytes and ostracodes from the Upper Jurassic Morrison Formation, Western Interior, USA: Modern Geology, v. 22, nos. 1-4, p. 379-414.
Schultze, H.-P., and Enciso, Gonzalo, 1983, Middle Jurassic age of the fish-bearing horizon in the Cañon City embayment, Colorado: Journal of Paleontology, v. 57, no. 5, p. 1053-1060.
Scott, G.R., 1963, Bedrock geology of the Kassler Quadrangle, Colorado: U.S. Geological Survey Professional Paper 421-B, p. 71-125.
Steiner, M.B., Lucas, S.G., and Shoemaker, E.M., 1994, Correlation and age of the Upper Jurassic Morrison Formation from magnetostratigraphic analysis; in, Caputo, M.V., Peterson, J.A., and Franczyk, K.J., (eds.), Mesozoic Systems of the Rocky Mountain Region, USA: Rocky Mountain Section, SEPM (Society for Sedimentary Geology), Denver, CO, p. 315-330.
Trimble, D.E., and Machette, M.N., 1979, Geologic map of the greater Denver area, Front Range urban corridor, Colorado: U.S. Geological Survey Miscellaneous Investigations Map I-856-H, scale 1:100,000.
Turner, C.E., and Fishman, N.S., 1991, Jurassic Lake T'oo'dichi': A large alkaline, saline lake, Morrison Formation, eastern Colorado Plateau: Geological Society of America Bulletin, v. 103, no. 4, p. 538-558.

Van Horn, Richard, 1957a, Ralston Creek Formation, new name for Ralston Formation of LeRoy (1946): American Association of Petroleum Geologists, Bulletin, v. 41, no. 4, p. 755-756.

Van Horn, Richard, 1957b, Bedrock geology of the Golden quadrangle, Colorado: U.S. Geological Survey Geologic Quadrangle Map GQ-103, scale 1:24,000.

Van Horn, Richard, 1967, Paleozoic and Mesozoic sedimentary rocks; in, Sheridan, D.M., Maxwell, C.H., and Albee, A.L., Geology and uranium deposits of the Ralston Buttes District, Jefferson County, Colorado: U.S. Geological Survey Professional Paper 520, p. 39-51.

Van Horn, Richard, 1976, Geology of the Golden Quadrangle, Colorado: U.S. Geological Survey Professional Paper 872, 116 p.

Waagé, K.M., 1955, Dakota Group in northern Front Range foothills, Colorado: U.S. Geological Survey Professional Paper 274-B, 51 p.

Waagé, K.M., 1959, Stratigraphy of the Dakota Group along the northern Front Range foothills, Colorado: U.S. Geological Survey Oil and Gas Investigations Chart OC-60.

Waldschmidt, W.A., and LeRoy, L.W., 1944, Reconsideration of the Morrison Formation in the type area, Jefferson County, Colorado: Geological Society of America Bulletin, v. 55, no. 9, p. 1097-1114.

Weimer, Bob, Dolson, John, Ethridge, Frank, and Warme, John, 1990, Sequence stratigraphy—Lower K, Fort Collins-Boulder-Morrison area: American Association of Petroleum Geologists, Rocky Mountain Section, 2-Day Geology Field Trip, September 20-21, 1990, 130 p.

APPENDIX

LOCATION 0F MEASURED SECTIONS

Measured by Fred Peterson and Christine E. Turner except where noted otherwise.

1. Ralston Reservoir North: On the north side of Ralston Reservoir in the N½ SW¼ SE¼ NW¼, SE¼ NW¼ SE¼ NW¼ Sec. 5, T. 3 S., R. 70 W., Jefferson County, Colorado. Morrison Formation from LeRoy (1946, p. 58, section 1), Dakota Group from Waagé (1959, sec. 8). Ralston Buttes 7.5' quadrangle.
2. Ralston Reservoir: Along the high water shoreline on the south side of Ralston Reservoir in the N½ NW¼ NW¼ NE¼ SW¼ Sec. 5, T. 3 S., R. 70 W., Jefferson County, Colorado. Ralston Buttes 7.5' quadrangle.
3. Long Lake Ditch: Along the southeast side of Long Lake Ditch in the SW¼ NW¼ NW¼ NE¼ SW¼ Sec. 5, T. 3 S., R. 70 W., Jefferson County, Colorado. Ralston Buttes 7.5' quadrangle.
4. Highway I-70: On the southeast side of U.S. Interstate Highway I-70 in the NW¼ SW¼ NW¼ SW¼, SE¼ NW¼ NW¼ SW¼, SW¼ NE¼ NW¼ SW¼ Sec. 14, T. 4 S., R. 70 W., Jefferson County, Colorado. Morrison 7.5' quadrangle. South Platte Formation from LeRoy and Weimer (1971) and Weimer and others (1990, sec. 4).
5. Mount Vernon Canyon Mouth: Measured east of the mouth of Mount Vernon Canyon along a road to an abandoned clay mine adit just east of Colorado State Highway 26 in the SE¼ SE¼ SE¼ SE¼ Sec. 15, W½ SW¼ SW¼ SW¼ Sec. 14, T. 4 S., R. 70 W., Jefferson County, Colorado. Morrison 7.5' quadrangle. From LeRoy (1946, p. 52, section 2).
6. Alameda Parkway: Along northeast side of Alameda Parkway or Colorado State Highway 26 in the SE¼ NW¼, NE¼ SW¼, SW¼ SE¼, NE¼ NW¼ Sec. 26, T. 4 S., R, 70 W., Jefferson County, Colorado. Morrison 7.5' quadrangle. Modified from Waldschmidt and LeRoy (1944, p. 1103-1106) and LeRoy (1946, p. 61-64, section 2). This was proposed as the type section of the Morrison Formation by Waldschmidt and LeRoy (1944). The locality was given in the wrong cadastral survey section on pages 1100 and 1101 of that report but was later corrected by LeRoy (1946, p. 61). The South Platte Formation is from Waagé (1959, sec. 10) as modified by Weimer and others (1990, sec. 5).
7. Morrison-2: Just east of Jefferson County Highway 93 in the SW¼ SW¼ SW¼ NE¼ Sec. 35, T. 4 S., R. 70 W., Jefferson County, Colorado. Morrison 7.5' quadrangle.
8. Morrison-1: Just east of Jefferson County Highway 93 heading about east-southeast from an abandoned clay mine adit, in the SE¼ SE¼ SW¼ NW¼ SE¼, SW¼ SW¼ SE¼ NW¼ SE¼, N½ NE¼ NE¼ SW¼ SE¼ Sec. 35, T. 4 S., R. 70 W., Jefferson County, Colorado. Morrison 7.5' quadrangle. The part 6.7-28.4 m (22-93 ft) above the top of the limestone marker unit was concealed at the time we measured this section; that part is modified from LeRoy (1946, p. 58, sec. 3), who did not describe the colors of the rocks. The Dakota Group is modified from Waagé (1959, sec. 11) and Weimer and others (1990, sec. 6).
9. Glennon Canyon-1: On northeast side of Glennon Canyon and southwest slopes of Mount Glennon in the NE¼ SE¼ NW¼ NW¼, SE¼ SE¼ NE¼ NW¼ NW¼, SW¼ NW¼ NE¼ NW¼ Sec. 12, T. 5 S., R. 70 W., Jefferson County, Colorado. Morrison 7.5' quadrangle. (Glennon Canyon is not named on the Morrison 7.5' topographic map.)
10. Glennon Canyon-2: Upper Ralston Creek Formation and basal Morrison Formation measured about 90 m (300 ft) southeast of measured section 9 on the northeast side of Glennon Canyon and southwest slopes of Mount Glennon in the

C-W½ W½ SW¼ NE¼ NW¼ Sec. 12, T. 5 S., R. 70 W., Jefferson County, Colorado. Morrison 7.5' quadrangle.

11 Glennon Canyon-3: Morrison Formation measured about 120 m (400 ft) southeast of measured section 10 in the SE¼ SW¼ NE¼ NW¼ Sec. 12, T. 5 S., R. 70 W., Jefferson County, Colorado. Morrison 7.5' quadrangle.

12. Turkey Creek: Most of section was measured on the north side of Turkey Creek and U.S. Highway 285 in the SE¼ NW¼ SW¼ NE¼, SW¼ NE¼ SW¼ NE¼, NE¼ NE¼ SW¼ NE¼ Sec. 12, T. 5 S., R. 70 W., Jefferson County, Colorado. Morrison 7.5' quadrangle. The limestone marker unit and 6.4 m (21 ft) of underlying strata were measured on the southeast side of Turkey Creek in the NE¼ NW¼ SE¼ SW¼ NE¼ Sec. 12. The part 0-10.7 m (0-35 ft) above the top of the limestone marker unit was concealed at the time we measured this section; that part is modified from LeRoy (1946, p. 65, sec. 4). The South Platte Formation is modified from Waagé (1959, sec. 12) and Weimer and others (1990, sec. 7).

13. Bergen Ditch-N: About 30 m (100 ft) north of measured section 14 and about 2-5 m (6-16 ft) south of a conspicuous fence line. Same locality as measured section 14.

14. Bergen Ditch: On southwest side of unnamed hogback ridge capped by Dakota Group on opposite side of a small valley from Bergen Ditch and about 30-90 m (100-300 ft) east of a fence line in the SW¼ NE¼ SE¼ Sec. 12, T. 5 S., R. 70 W., Jefferson County, Colorado. Morrison 7.5' quadrangle.

15. Weaver Gulch: On the southwest side of the same unnamed hogback ridge capped by the Dakota Group as locality 14. The precise locality where the section was measured by LeRoy (1946, p. 66, section 5) is unclear but judging from the nature of exposures in the area, his section probably was measured in a small reentrant in the E½ E½ SE¼ SW¼ NE¼ SE¼ Sec. 12, T. 5 S., R. 70 W., Jefferson County, Colorado. Morrison 7.5' quadrangle. Modified by the authors.

16. Dinosaur National Monument, Utah: On the west side of a small valley informally known as Douglass Draw by the National Park Service and about 600 m (2,000 ft) west of the Carnegie dinosaur quarry in western Dinosaur National Monument. Measured in the W½ NW¼ NW¼ SW¼ Sec. 26, SE¼ NE¼ NE¼ SE¼, NE¼ SE¼ NE¼ SE¼ Sec. 27, T. 4 S., R. 23 E., Uintah County, Utah. Dinosaur Quarry 7.5' quadrangle.

17. Garden Park, Colorado: The section is on the bluffs west of and overlooking Fourmile Creek (formerly Oil Creek) in the southern part of Garden Park. It was measured south to a small hill locally known as Copes Nipple, thence northwest to the northeast side of a larger hill locally known as North Fort. In the E½ SE¼ SE¼ SW¼, W½ SE¼ SE¼ SW¼, SE¼ NW¼ SE¼ SW¼ Sec. 21, N½ NW¼ NE¼ NW¼ Sec. 28, T. 17 S., R. 70 W., Fremont County, Colorado. Cooper Mountain 7.5' quadrangle.

18. Medicine Bow, Wyoming: On the northwest side of Ninemile Hill in the NE¼ NW¼ NW¼, W½ NE¼ NW¼, C-N½ SE¼ NW¼ Sec. 23, T. 23 N., R. 78 W., Carbon County, Wyoming. Medicine Bow 7.5' quadrangle.

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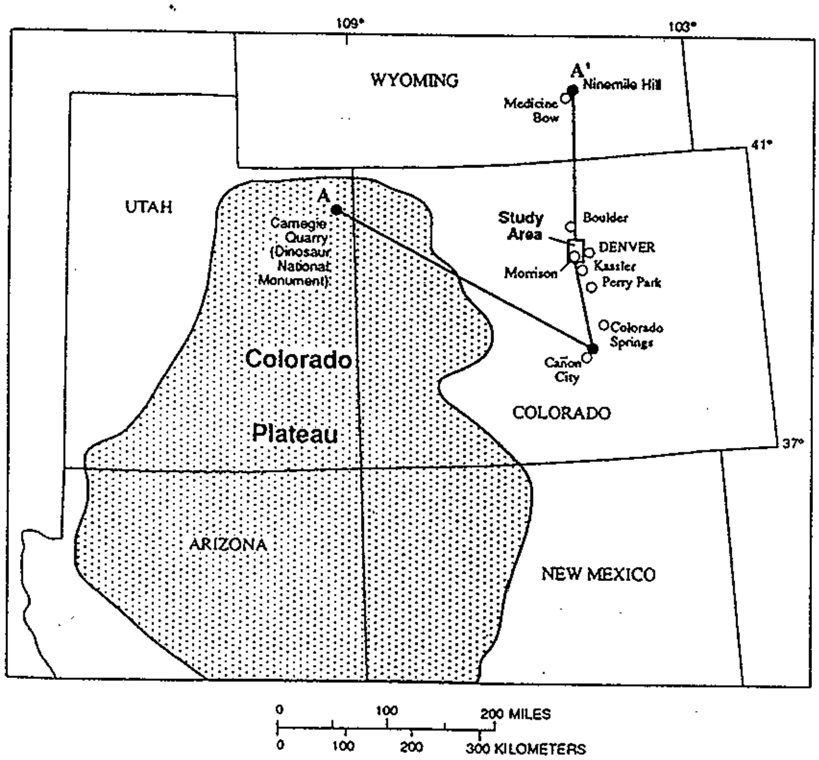


109°
103°
WYOMING
A'
Ninemile Hill
Medicine Bow
41°
UTAH
A
Carnegie Quarry (Dinosaur National Monument)
Study Area
Boulder
DENVER
Morrison
Kassler
Perry Park
Colorado Springs
Cañon City
Colorado
Plateau
COLORADO
37°
ARIZONA
NEW MEXICO
0 100 200 MILES
0 100 200 300 KILOMETERS

FIGURE 1-L

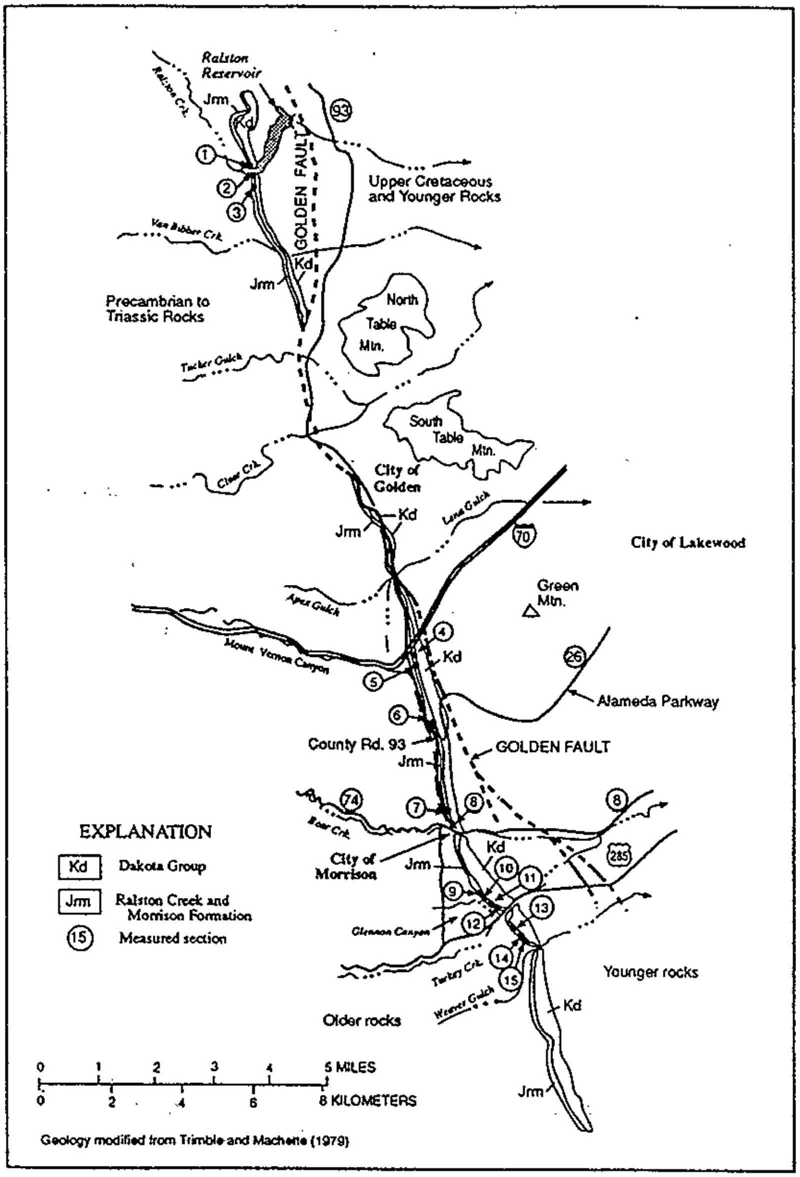


FIGURE 1-R

FIGURE 1 Geologic sketch map showing the outcrop trace of the Morrison and Ralston Creek Formations along the eastern foothills of the Colorado Front Range west of Denver. The numbers indicate the measured sections in Fig. 3. The geology is modified from Trimble and Machette (1979). The small map shows the location of sections in Fig. 5. Detailed locations are in the Appendix.

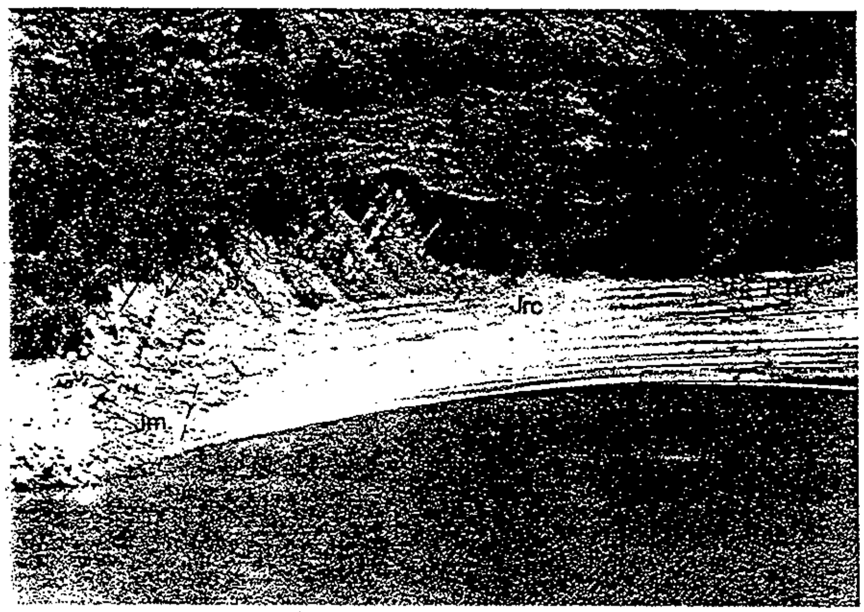
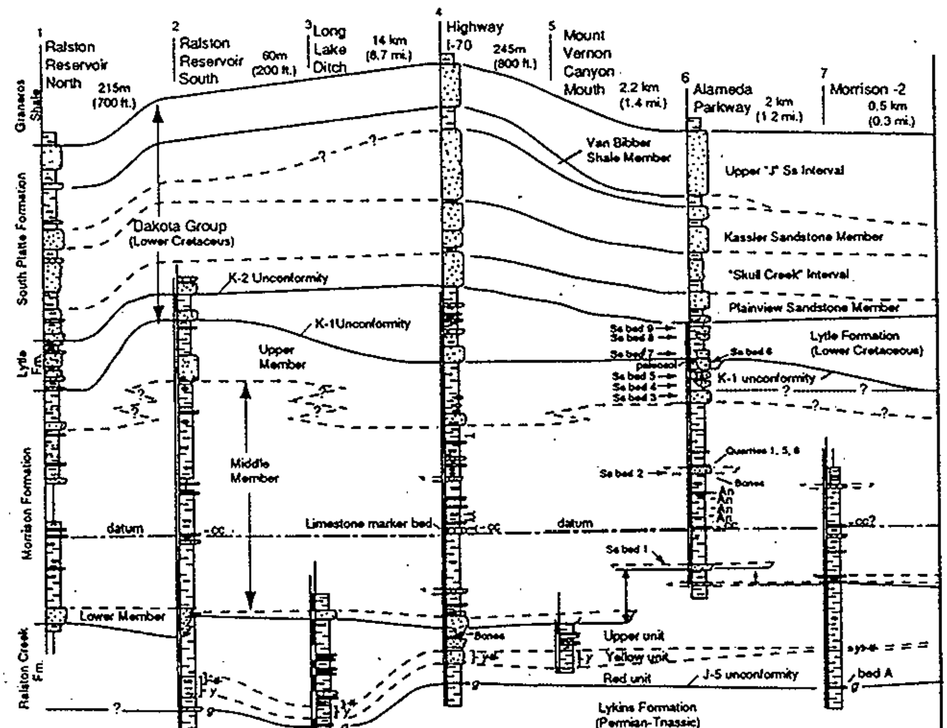


FIGURE 2 View south toward the south side of Ralston Reservoir showing Ralston Creek Formation (Jrc). For scale, the Ralston Creek is 27.6–35.2 m (90.5–115.5 ft) thick to the base or top, respectively, of the zone of interfingering with the Morrison Formation (Jm). See text for additional discussion. a, J-5 unconformity at bottom of Bed A. PTrl, Lykins Formation.



EXPLANATION

- Sandstone
- Pebbly or conglomeratic sandstone
- Mudstone, includes claystone
- Calcareous mudstone and thin limestone beds
- Limestone
- Gypsum
- y — Yellow
- Welded chert zone
- — cc Clay change
- — An Anhydrite in thin section
- Bentonite bed
- g Grit and granules

m 30 – 0; ft 100 – 0

FIGURE 3-L

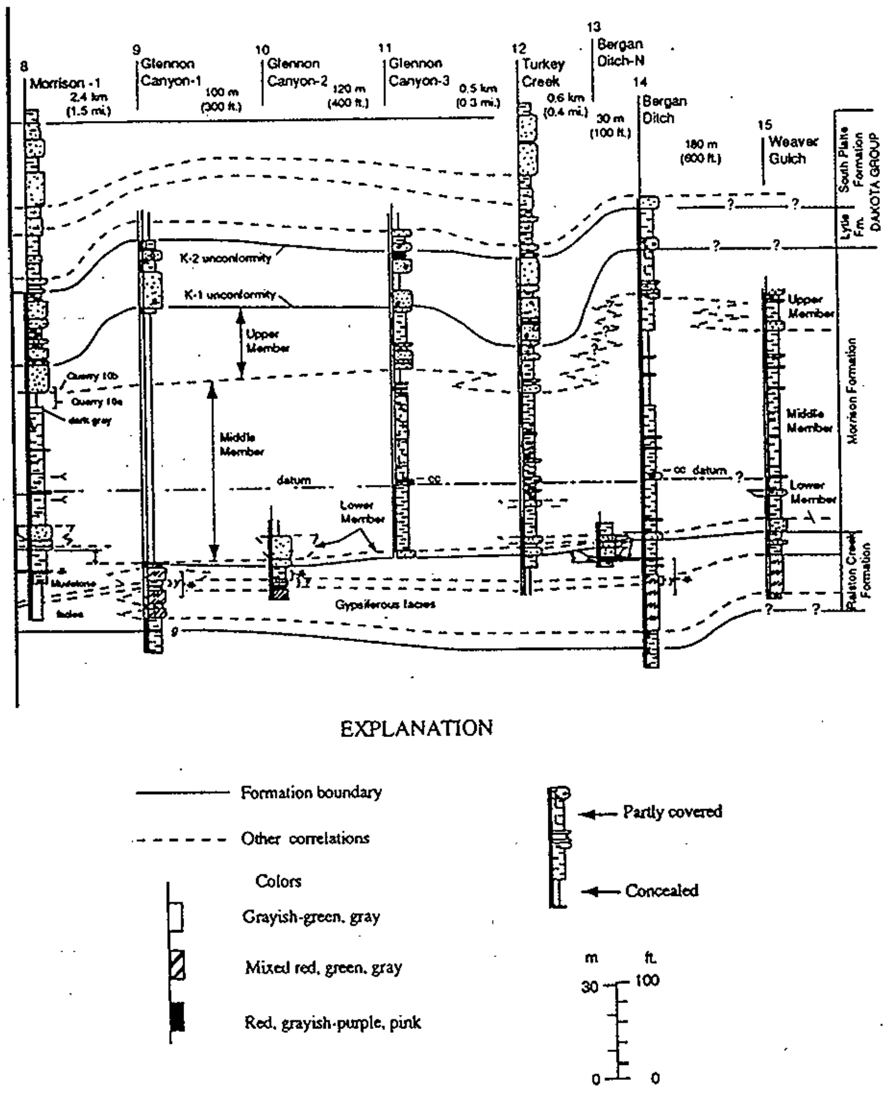


FIGURE 3-R

FIGURE 3 Stratigraphy of the Ralston Creek and Morrison Formations in the Front Range foothills, eastern Colorado.

FIGURE 4 Upper contact of the Morrison Formation (Jm) at Alameda Parkway marked by a zone of paleosols (p) that is about 2 m (6 ft) thick. 4–6 are the sandstone beds in Fig. 3. Kl, Lytle Formation.

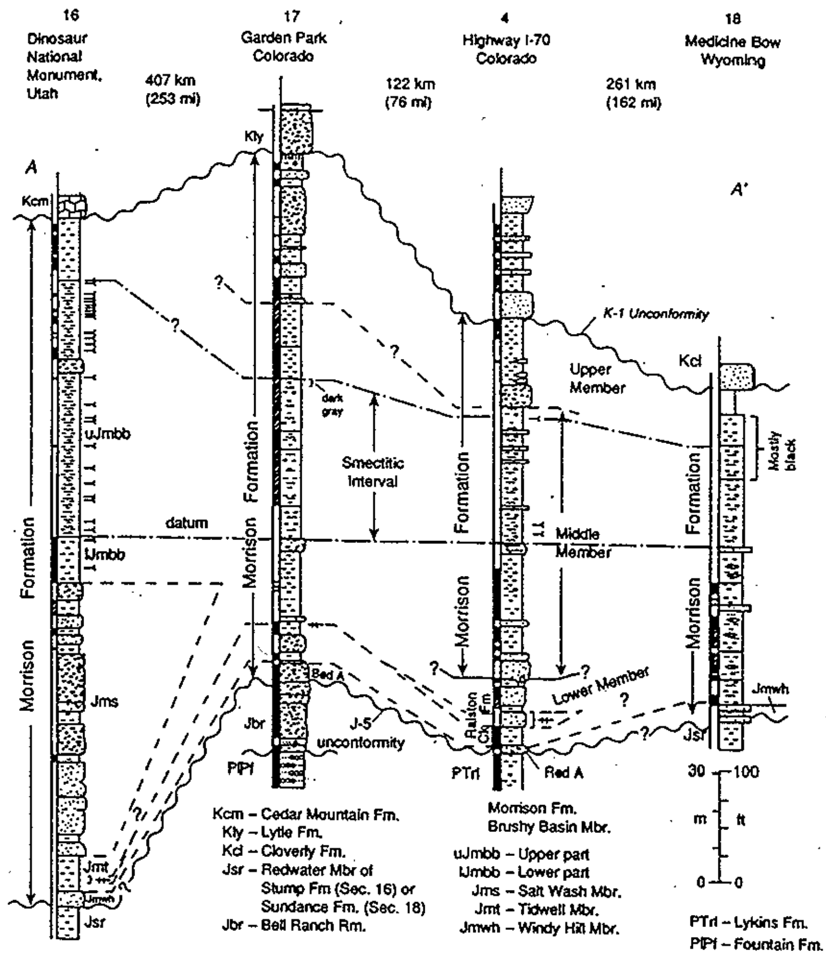


FIGURE 5 Correlation of the Ralston Creek and Morrison Formations from the Interstate-70 roadcut section in the Front Range foothills to other areas in the southern part of the Western Interior. For locations see Fig. 1 (inset map) and Appendix, for explanation of lithologic symbols see Fig. 3.

BIOSTRATIGRAPHY OF DINOSAURS IN THE UPPER JURASSIC MORRISON FORMATION OF THE WESTERN INTERIOR, USA

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ABSTRACT

The biostratigraphy of dinosaur remains in the Upper Jurassic Morrison Formation and related beds was studied throughout the Western Interior in an effort to place as many dinosaur localities as possible in their relative chronostratigraphic positions. First, we established a regional stratigraphic framework for the Morrison Formation throughout the Western Interior. Three primary stratigraphic markers in the formation aided in regional correlations. An important marker in about the middle or upper middle part of the formation, known as the clay change, marks the abrupt transition from predominantly non-smectitic clays below to predominantly smectitic clays above. This surface, as well as the J-5 unconformable to conformable surface at the base of the Morrison and the K-1 unconformity at the top of the Morrison, comprise the basis for most of the correlations.

After the stratigraphic framework was established, a total of 128 dinosaur sites were placed in the stratigraphic framework and then were correlated to a primary reference section (DQW) near the Carnegie Quarry at Dinosaur National Monument in northeastern Utah. Where the clay change is not evident (Black Hills and Montana), the correlations are more tenuous so the 13 localities in these areas are treated separately, even though other evidence from the regional stratigraphy and calcareous microfossils help relate these sites to the primary reference section.

The biostratigraphic distribution of the dinosaurs allows the Morrison Formation and related beds to be divided into four biozones, numbered one through four from oldest to youngest. The zones are based on the stratigraphic (vertical) distribution of long-ranging taxa (mostly genera and species), which are taxa that extend through two or more different

stratigraphic positions in the formation. Single-site taxa that are only found at one locality in one stratigraphic level are not used in the zonation. Dinosaur Zone 1 extends from the base of the formation to the middle of the Salt Wash Member. Dinosaur Zone 2 extends upward to about 30 ft (9.1 m) above the clay change in the primary reference section (DQW). Dinosaur Zone 3 extends up to about the middle of the upper part of the Brushy Basin Member. Dinosaur Zone 4 extends to the top of the formation. Based on age information from palynomorphs, charophytes and ostracodes, isotopic dates, and paleomagnetic studies, Dinosaur Zones 1, 2, and 3 are Kimmeridgian in age and the Kimmeridgian-Tithonian boundary is in the lower part of Dinosaur Zone 4.

The biostratigraphic distribution shows a vertical trend of increasing faunal diversity followed by decreasing diversity during deposition of the Morrison Formation. First, it is noteworthy that dinosaurs were scarce during earliest Morrison deposition—the earliest fauna consists of only a few taxa (Zone 1, Tidwell and lower Salt Wash Members). Diversity increased dramatically near the middle of the Salt Wash Member (low in Zone 2) and continued to increase, reaching a peak in diversity just above the clay change (high in Zone 2, near the base of the upper part of the Brushy Basin Member) where the first of the long-ranging taxa began to die out. Diversity continued to decrease gradually to about the middle of the upper Brushy Basin Member where a fairly sharp decline occurred (high in Zone 3). Another fairly sharp decline in diversity occurred higher in the same member (middle of Zone 4), followed by a gradual decline, with the few remaining taxa dying out toward the end of Morrison deposition.

The changes in diversity low in Zone 2, high in Zone 3, and toward the middle of Zone 4 coincide fairly well with similar changes in the diversity of charophytes and ostracodes. This suggests that any environmental changes that occurred at these stratigraphic positions were ubiquitous and of sufficient character to exert a strong influence on markedly different types of organisms.

The scarcity of dinosaurs at the beginning of Morrison deposition may reflect a continuation of the harsh conditions that persisted during Middle Jurassic time. Dinosaurs were scarce just before Morrison deposition, or at least only sparse footprint evidence exist in Middle Jurassic rocks. It is likely that the arid climate that persisted during deposition of the eolian ergs and evaporites of the Middle Jurassic was inimical to the dinosaurs. Conditions during earliest Morrison deposition may have remained inhospitable to the dinosaurs, judging from the presence of eolian and evaporite deposits in the lowermost part of the Morrison. The development of the extensive river systems of the Salt Wash Member may have established a more equable habitat, enticing dinosaurs into the area. They seem to have flourished and and reached their heyday at about the middle of the Morrison. The change from greater to lesser diversity occurs just above the clay change and thus coincides with the tremendous increase in the output of volcanic ash in the source area. What role the increase in volcanic ash may have played in dinosaur diversity, either direct or indirect, is uncertain.

Taken together with the biostratigraphic data from some of the other organisms in the Morrison ecosystem (for example, charophytes and ostracodes), the newly established biostratigraphic synthesis forms the basis for evaluating widespread paleoecological changes in the Western Interior during the Late Jurassic. Moreover, this synthesis provides, for the first time, a biostratigraphic foundation for the evaluation of taxonomic lineages and evolutionary trends among the dinosaurs in the Morrison Formation.

INTRODUCTION

Two of the more perplexing problems related to the numerous dinosaur remains recovered from the Upper Jurassic Morrison Formation of the Western Interior (Fig. 1) have been their age in terms of the standard geologic time scale and their relative age with respect to each another. The age of the formation has been resolved rather well in several recent publications (Kowallis and others, 1998; Litwin and others, 1998; Schudack and others, 1998), but the relative stratigraphic position of the numerous dinosaur quarries and sites that are scattered throughout seven of the Western Interior states remained an enigma. Recent advances in understanding the stratigraphy of the Morrison Formation and related beds as well as its lower and upper boundaries (Peterson and Turner, 1998) now allow many of the quarries and sites to be placed in a relative stratigraphic framework. Although new sites are discovered with each field season,

we estimate that perhaps as many as about 30 presently known and mostly minor sites remain to be positioned stratigraphically and the data from most if not all of these probably would not significantly change the findings given in the present report. Thus, for this investigation, we present the results of data thus far accumulated in which 141 dinosaur quarries and sites throughout the Western Interior are positioned within the formation and with respect to each other. The information presented here may prove helpful in understanding and distinguishing evolutionary relationships and biogeographic diversity, as well as in making paleoecological reconstructions.

METHODOLOGY

The goal of positioning Morrison dinosaur localities is hampered considerably by the numerous facies changes that are common in continental deposits, by the scarcity of reliable and widespread isochronous or nearly isochronous stratigraphic markers, and by the lack of abundant micropaleontological material that could aid in establishing a detailed microfossil-based biostratigraphy of the formation. Although there are a fair number of local stratigraphic markers in the formation (Peterson and Turner, 1998), most of these vary too much in stratigraphic position or are regionally too discontinuous to be useful for positioning the quarries and were only used where other means of correlation were not available. The primary stratigraphic markers that we used are the J–5 surface (Pipiringos and O'Sullivan, 1978) and the K–1 unconformity (Peterson, 1988cd, 1994) at the base and top, respectively, of the Morrison Formation (and related beds where other stratigraphic units are involved) and a prominent vertical change in clay mineralogy at or near the middle of the formation (Owen and others, 1989; Turner and Fishman, 1991). The J–5 surface is an unconformity in some localities and its correlative conformity in other places; the K–1 surface is an unconformity at the base of Lower Cretaceous rocks, but in some places, Lower Cretaceous rocks are missing and the K–2 unconformity at the base of uppermost Lower Cretaceous or lowermost Upper Cretaceous strata must be used. The vertical change in clay mineralogy within the Morrison is from largely nonsmectitic mudstone below to predominantly smectitic mudstone above (Owen and others, 1989). X-Ray analyses indicate that the clay minerals below the clay change may include some swelling (smectitic) clays but, if present, they are much less abundant and generally do not produce the "popcorn" texture in soils that typically develop on claystones and mudstones that contain abundant smectite-rich clays. An additional stratigraphic marker found by Demko and others (1996) is a persistent and well developed paleosol zone in the lowermost strata of the lower part of the Brushy Basin Member and in correlative strata in other areas. Because it was discovered after many of the dinosaur localities had been positioned, it has not been used extensively in this report although it has considerable potential as another widespread stratigraphic marker that could aid in extending correlations into areas where the clay change is not present.

For convenience of discussion, we refer to the entire assemblage of strata between the J–5 surface and the K–1 unconformity (or the K–2 unconformity in some places) as the Morrison package of beds or the Morrison Formation and related beds. Also for convenience, all strata between the J–5 surface and the clay change are herein referred to informally as the lower Morrison and all strata between the clay change and the K–1 unconformity are referred to informally as the upper Morrison. We use the term "site" for a place where a few bones identifiable to genus level were picked up or otherwise easily extracted from the rock with minimal digging, or in rare cases where bones were identified in place by a competent paleontologist, and we use the term "locality" for either a site or a quarry where moderate to considerable excavation has occurred.

Complete or partial sections of the Morrison Formation were measured at each of the locations we recovered. In rare cases, dinosaur localities were adequately located geographically and stratigraphically in the published literature so no additional work was required; those sections not measured by us are cited in Appendix 1. Throughout most of the region where the clay change is present, we measured a complete section of the Morrison, or at least a partial section from the clay change to the appropriate upper or lower contact of the part of the formation that included the dinosaur locality. Where it was only possible to measure a partial section, the locality was positioned with respect to one of the three key marker surfaces or, rarely, to some other stratigraphic marker and then correlated to the nearest available measured section. The nearest available measured section with the correlated dinosaur locality was then tied to the nearest local reference section that was more complete or representative of the local area. The local reference sections are shown in Figures 2-6.

Correlating the various quarries in the local reference sections to the primary reference section at Dinosaur National Monument (designated as the DQW or Dinosaur Quarry West section) was accomplished by positioning the quarries in proportion to their stratigraphic positions within the lower Morrison or upper Morrison units. This was done largely by graphic correlation methodology (Shaw, 1964), which is simply a way of doing it proportionately. Because we employ the proportional method of correlating the localities, it does not matter that some of the measured sections on various figures in this report are plotted at different scales.

There are obvious shortcomings in the methodology we used in trying to correlate the dinosaur localities to a single master reference section, but, given that the thickness of the Morrison was influenced by slight but nevertheless significant crustal movements, and that widespread stratigraphic markers are scarce, it is the best that can be accomplished at present.

At the base, the lowermost strata of the Morrison onlap paleotopographic highs in some places, which could lead to incorrect positioning of a locality. Fortunately, the areas where this occurs are fairly well known and appropriate measures can be taken to correct for it. A good example of this is the Cabin Creek Quarry (CO-48) near Gunnison, Colorado, where the Morrison onlapped Precambrian crystalline rocks and only the upper strata of the lower Morrison are present and exposed. The quarry is in the Salt Wash Member. The overlying Brushy Basin Member is concealed by a deep cover of alluvium so that the locality could not be positioned with respect to the clay change and could only be positioned with respect to the Salt Wash elsewhere. Because of the known onlap in this area and known pinchout of the lower part of the Salt Wash Member farther west (up the depositional slope) of the Gunnison area, we knew that the lowermost strata of the Salt Wash were not present there, and therefore only the uppermost beds of the Salt Wash Member were present. With this knowledge, we could position the quarry with respect to the upper contact of the Salt Wash Member and then we correlated that contact to the local reference section.

The upper contact of the Morrison is more intractable for a variety of reasons, depending on the locality. It is difficult to estimate the amount of scour beneath Lower Cretaceous rocks. An important clue is the thick, locally present, paleosol zone at the top of the Morrison Formation that is most likely at places where deep scour did not occur (T.M. Demko, oral communication, 1996). This suggests that the areas with the paleosols retained the greatest original thickness of the upper Morrison. Because we tried to refer the localities to the thickest local reference sections, an area that has a thick paleosol at the top of the formation was considered ideal. These were also the areas where we felt most confident in our identification of the upper contact.

The "Breakfast Bench beds" at the top of the upper Morrison in the Como Bluff region of Wyoming deserve special mention because of their important dinosaur fauna and the thought that they could be Early Cretaceous in age (Bakker and others, 1990). The beds are as much as 71 ft (21.6 m) thick and consist largely of black mudstone that is smectitic to nonsmectitic and carbonaceous or noncarbonaceous. We found that the carbonaceous mudstone strata (zero to about 15 ft or zero to about 4.6 m thick) locally present at the top of the Morrison Formation in the Como Bluff area interfinger with the basal fluvial sandstone bed of the Lower Cretaceous Cloverly Formation and therefore are Early Cretaceous in age and not part of the Morrison Formation. However, we also found a paleosol beneath the carbonaceous black mudstone beds that separates them from noncarbonaceous black mudstone below. This suggests that the black noncarbonaceous mudstone beds are Late Jurassic in age and part of the Morrison Formation whereas the black carbonaceous mudstone beds above are Early Cretaceous in age and more closely allied to the Cloverly Formation. Because the Breakfast Bench fauna is restricted to the noncarbonaceous strata below the paleosol, we suggest that the Breakfast Bench fauna is Late Jurassic in age. Black mudstone beds are locally present at or near the top of the Morrison at scattered localities from Montana south through Wyoming and into central Colorado near the town of Morrison so their occurrence at Como Bluff is not unusual. An important clarification here is that black carbonaceous mudstone does occur locally in beds that we consider Morrison, even though noncarbonaceous black mudstone is more commonly found at the top of the Morrison. This is based on other criteria, mentioned earlier in this report, that are used to identify the upper contact of the Morrison Formation.

Another problem with the upper contact is abrupt regional beveling to the east and west beneath Lower Cretaceous rocks. No dinosaur localities are close to the western edge of the Upper Jurassic Western Interior depositional basin and thus westward beveling is not a problem. However, localities in westernmost Oklahoma and in the Black Hills are near the eastern limit of the Morrison depositional basin and the degree of eastward beveling at the top of the formation in some of those areas, especially the Black Hills, is difficult to evaluate.

In western Oklahoma, a fairly thick series of fluvial sandstone beds is present at the top of the Morrison above a thick series of smectitic mudstone beds. The fluvial beds appear to correspond in stratigraphic position to an interval in the uppermost Morrison farther west that also includes several thick fluvial sandstone beds, such as the Jackpile Sandstone Member in the southern San Juan Basin of northwestern New Mexico and the fairly thick sandstone unit at the top of the undifferentiated Morrison in northeastern New Mexico (Holbrook and others, 1987). This suggests that the entire Morrison thins eastward in the western Oklahoma area and that no inordinate amount of beveling has occurred at the top of the formation near the dinosaur localities.

Regional eastward thinning of the Morrison in the Black Hills is more difficult to evaluate. Thick fluvial sandstone beds generally are lacking at the top of the formation there, so sandstone petrology cannot be used as a guide. Furthermore, the clays throughout the formation in the Black Hills area lack smectite, so that the most reliable stratigraphic marker in the middle of the formation—the clay change—is absent. However, another basis for stratigraphic correlation permits evaluation of Morrison stratigraphy in the Black Hills area. Eolian sandstone units are fairly common in the Morrison of Wyoming and especially on the Colorado Plateau; thus far they have only been found in lower Morrison strata and not above the clay change. This suggests that the eolian Unkpapa Sandstone Member of the Morrison in the Black Hills also is entirely within the lower Morrison and that the horizon in the Black Hills that is equivalent to the clay change elsewhere should be above the Unkpapa. Thus, we speculate that the Morrison is reasonably complete on the east side of the Black Hills where the Wonderland local reference section was measured (Fig. 5) and that the distinct thinning of the formation on the west side of the Black Hills is a local phenomenon.

The ostracode Theriosynoecum wyomingense apparently is restricted to Morrison strata below the clay change (Sohn and Peck, 1963). More recent studies by Schudack and others (1998) support this conclusion and indicate that this species occurs in their charophyte/ostracode Zones 1-3 below the clay change. The stratigraphically highest known occurrence of this species in the Black Hills is in the northeastern part of that region where it was estimated to be about 45 ft (13.7 m) below the top of the Morrison (Sohn and Peck, 1963, p. A8, Locality 11) in the lower part of the first "limy" unit. Based on correlation to a nearby measured section of the Morrison about 3 mi (5 km) southeast of the fossil locality (Foster, 1996a, Fig. 4, Sturgis Area section), the lowest limestone unit is about 60 ft (18.3 m) below the top of the formation. When projected into our Wonderland local reference section (Fig. 11), that position is about 3 ft (1 m) above the projected position indicated for dinosaur locality WY-11 and, therefore, within uppermost strata of the Unkpapa Sandstone Member. (It should be noted that the thickness of the Wonderland section reported by Foster [1996a, Fig. 4] is in error [J.R. Foster, oral commun., 1997]. We measured the Morrison Formation at the same locality (Fig. 5) and obtained 176 ft (53.6 m) for the entire Morrison, including the Unkpapa Sandstone and Windy Hill Members.)

The foregoing suggests that the horizon equivalent to the clay change elsewhere is above the top of the Unkpapa Sandstone Member in the Black Hills area, but how much higher is uncertain. We collected two samples for calcareous microfossils 1 ft (0.3 m) and 11 ft (3.4 m) above the top of the Unkpapa at the Wonderland section. These samples yielded an excellent suite of 9 charophyte and ostracode species (Schudack, 1994) that indicate charophyte/ostracode Zone 3 or the lower part of Zone 4 (see Fig. 7). Neither sample contained Theriosynoecum wyomingense, which suggests that the samples most likely indicate the lower part of charophyte/ostracode Zone 4, the base of which is at the clay change elsewhere in the Western Interior (Schudack and others, 1998). This interpretation also suggests that the top of the calcareous strata there is within and not at the base of the upper Morrison. As discussed in a later section, the biostratigraphy of the dinosaur fauna of the Black Hills, when compared with the biostratigraphy of the dinosaur fauna elsewhere in the Western Interior, also tends to support these correlations. If correct, our analysis suggests that the top of the Morrison is not excessively beveled on the east side of the Black Hills.

Szigeti and Fox (1981, p. 344) reported Theriosynoecum wyomingense from the level of the Wonderland Quarry (SD-4), which is higher stratigraphically than reported by Schudack and others (1998). If correctly identified, this would suggest that the stratigraphic horizon equivalent to the clay change is higher in the Black Hills area and perhaps at the level of the highest calcareous beds. This may also suggest that there was some significant amount of eastward regional beveling at the top of the Morrison in the Black Hills region. This contrast with the tentative conclusions of our research cannot be resolved without further study.

Our tentative analysis of Morrison stratigraphy on the west side of the Black Hills suggests that the uppermost part of the formation was rather deeply eroded prior to deposition of Lower Cretaceous strata. The Windy Hill Member is present at the base of the Morrison there, which indicates that thinning of the Morrison cannot be attributed to onlap against a significant paleotopographic high. The top of the calcareous mudstone strata appears to correlate with the top of the calcareous mudstone beds farther east at the Wonderland section (Fig. 5), which suggests that this horizon is above the base of upper Morrison strata. We arbitrarily positioned the horizon of the clay change at the top of the thin sandstone bed near the upper-middle part of the Morrison at Little Houston Creek (Fig. 5) because sandstone is more commonly found below the clay change than just above it in other areas. If our tentative assignment is correct, based largely on correlation of the top of the calcareous strata, a significant amount of Pre-Cretaceous erosion occurred at the top of the Morrison on the west side of the Black Hills, which would largely but not entirely account for the considerable thinning of the formation there. These correlations suggest that some degree of internal thinning also occurred within the Morrison in this area. Accordingly, we correlated all of the dinosaur localities on the west side of the Black Hills to the Little Houston Creek local reference section (Fig. 5) and suggest that the top of the formation was truncated more there than elsewhere. The dinosaur localities were then correlated to the Wonderland local reference section on the east side of the Black Hills (Fig. 11).

A somewhat similar problem exists in Montana, but that area lacks the charophyte and ostracode information that helps to determine the internal stratigraphy of the Morrison Formation. The localities we studied are near the middle of the depositional basin where regional beveling at the top of the formation is most likely minimal. We also found a thick zone of paleosols in the upper-middle part of the formation in the section near Bridger, Montana, which most likely correlates with the middle Morrison paleosol zone farther south. Another guide to the stratigraphy in Montana is that most of the thick fluvial sandstone beds in the middle of the formation tend to occur below the clay change in areas where the clay change is present. A final guide is that black, carbonaceous mudstone beds associated with the coal deposits in the Great Falls-Lewistown Coal Field appear to correlate reasonably well with black carbonaceous and(or) black noncarbonaceous mudstone beds that are locally present at or near the top of the Morrison elsewhere in Montana and Wyoming, and as far south as Morrison, Colorado. Although the dinosaur fauna in Montana has not yet been well analyzed or described, the biostratigraphy of those genera that have been identified also supports the conclusion that the formation is more or less complete there and is neither significantly older nor younger than elsewhere in the Western Interior.

Several illustrations in this report show the stratigraphic positions of the dinosaur localities as correlated to the primary reference section DQW at Dinosaur National Monument (Figs. 7-9). We plotted the localities as the methodology dictated, but the close vertical spacing of the localities on some of those illustrations implies a greater accuracy in stratigraphic positioning than is merited by the methodology. Although it is difficult to evaluate the degree of error that is involved in the methodology, we estimate that the error should be less than about plus or minus 20 ft (6 m) in most cases. The error should be less for those localities near the clay change, but it could be more in Montana and the Black Hills where the clay change is not present.

Quite often, where numerous bones are present, they are within an interval as much as 3-6 ft (1-2 m) in stratigraphic thickness. For this study, we used the lowest level of the bones or the quarry floor as the quarry level. In some cases, such as Cope's Quarries 2-8 at Cope's Nipple in Garden Park near Cañon City, Colorado (CO-2), we grouped all of the quarries into a single locality because the quarries are at the same stratigraphic level adjacent to each other. In other cases, such as the Bone Cabin Quarries in Wyoming where two quarries are present at the same stratigraphic level but separated laterally by a few hundred feet (about a hundred meters), we gave each quarry a separate designation, in this case WY-78 and WY-79, because they were excavated at significantly different times by entirely different parties.

One source of error that could not be compensated for adequately, but may not be a serious concern, is the stratigraphic position of the quarries in the lowermost parts of fluvial channel sandstone beds, such as the Dry Mesa and Carnegie Quarries. We positioned these and similar quarries where they occurred in the overall stratigraphy of the formation, but to be more accurate, one would have to position them with respect to a slightly higher stratigraphic level because the fluvial channels had scoured down into preexisting strata, generally overbank floodplain beds. In many cases, the depth of scour is unknown, either because the upper half or more of the fluvial channel sandstone bed is missing or concealed, as at the Carnegie Quarry, or detailed correlation of the bone-bearing strata within the channel with overbank floodplain strata outside the channel cannot be determined precisely, as at the Dry Mesa Quarry. We estimate that in most of these situations, the resulting error in positioning the quarry floor could be as much as 10 ft (3 m) too low stratigraphically.

The Carnegie Quarry (UT-18) deserves special mention because it is well known to be within a fluvial sandstone bed and this aspect is not indicated on the master reference section (Fig. 10), which was measured nearby but not directly at the quarry. The master reference section (DQW) was measured about 2,000 ft (610 m) west of the Carnegie Quarry in a small drainage locally known as "Douglass Draw". Although the quarry is in a fluvial channel sandstone bed, that bed is not the same fluvial channel sandstone bed that is present at "Douglass Draw" at the higher stratigraphic level shown on Figure 10. We positioned the quarry with respect to its true stratigraphic position as correlated to the master reference section DQW in "Douglass Draw" despite the fact that there is no fluvial sandstone bed at the precise level of the quarry in the master reference section.

Some of the localities are on private land and, in most cases, access was freely given by the landowners. Unfortunately, we were denied access to the land that includes the two quarries on the Red Fork of the Powder River, which accounts for why those important localities were not included in this study.

The location of the famous Stego 99 Quarry in the Como Bluff region of Wyoming has been lost, according to R.T. Bakker (oral commun., 1993). Several more recently opened quarries are in the vicinity and one of these could be the site of the old quarry.

An alphabetical list of all the dinosaur species included in this study is in Appendix 2. A complete listing of the quarries and sites with their faunas and credits for the identifications are in Appendix 3. Tables 1 and 2 contain a checklist of the dinosaur genera and species (including some higher taxonomic categories where necessary) found at the localities and arranged as closely as possible in their stratigraphic order.

The figure showing diversity of genera and species (Fig. 13) requires an explanation because both formally named species and informally named species (for example, Allosaurus sp.) were included in the count. If the range of a genus extended vertically across any particular locality, that locality was considered to represent a species even though the first occurrence of a formally named species was above that locality (for example, Allosaurus sp. below the lowest horizon of A. fragilis was considered as a species). In contrast, if a formally named species is present at any particular locality, no additional count was given for an identification only to genus level (for example, if a locality includes dinosaurs identified as Allosaurus sp. and A. fragilis, only the latter was counted).

In many cases, it is inappropriate to publish a scientific report without locations, but we follow procedures established by the vertebrate paleontology community by not publishing the detailed locations of the sites because of the possibility that bone hunters, rock hounds, or vandals would recover the locations and either remove any remaining material or destroy it. Also, many people freely contributed the site locations with the provision that those locations would not be published. Accordingly, no locations other than state and county are given in this report. Following accepted procedures, the locations have been given to responsible institutions or appropriate Federal land-holding agencies so that responsible researchers can contact those institutions or agencies for this information.

STRATIGRAPHY

The Upper Jurassic Morrison Formation is recognized throughout most of the Western Interior of the United States (Fig. 1), extending from central New Mexico northward into Canada where correlative strata exist but are given different names. The formation consists predominantly of sandstone and mudstone, but it also includes a wide variety of other lithologies including conglomerate, claystone, tuff (including bentonite beds), limestone, dolomite, gypsum, anhydrite, and coal. The formation has been divided into members or other stratigraphic units in several areas. Thus far ten formally named members have been proposed on the Colorado Plateau (Brushy Basin, Bluff Sandstone, Fiftymile, Jackpile Sandstone, Junction Creek, Recapture, Salt Wash, Tidwell, Westwater Canyon, and Windy Hill Members). Along the east side of the Black Hills in South Dakota, Szigeti and Fox (1981) recognize the Unkpapa Sandstone Member at the base of the Morrison. Three other members were proposed for central Wyoming (from oldest to youngest these are the Lake Como, Talking Rocks, and Indian Fort Members of Allen, 1996) but, for the present, they must be considered informal units because type localities were never specified, type measured sections were not given, and because the publication medium has a highly restricted distribution.

Lower Contact

The lower contact of the sequence of beds that includes the Morrison Formation and related beds is the J-5 unconformity of Pipiringos and O'Sullivan (1978) or an equivalent conformable surface where evidence suggests that deposition was continuous. On the Colorado Plateau, slightly angular truncation of underlying strata has been documented at this contact in several places by Gilluly and Reeside (1928, p. 81), Pipiringos (1972), Pipiringos and O'Sullivan (1976, 1978), and Peterson (1988a). Broadly angular southward beveling of strata beneath the J-5 unconformity along the east front of the Rocky Mountains in eastern Colorado and Wyoming was documented by Pipiringos and O'Sullivan (1976). Near Denver, the J-5 unconformity separates the Upper Jurassic Ralston Creek Formation, which correlates with basal Morrison strata elsewhere, from the underlying Triassic(?) and Permian Lykins Formation. We thus include the Ralston Creek Formation in the Morrison package of beds (Peterson and Turner, 1998).

Upper Contact

The upper contact has been enigmatic ever since the Morrison Formation was established by Cross in 1894. Under ideal circumstances, this contact is placed at the top of a thick paleosol zone (Demko and others, 1996). Because this zone was removed by erosion prior to deposition of overlying Lower Cretaceous beds at many localities, the position of the contact is based largely on a combination of other characteristics summarized by Peterson and Turner (1998).

In many places, especially northeastern New Mexico and eastern Colorado, the upper contact of the Morrison is between sandstone beds and is difficult to identify for those not familiar with the distinguishing characteristics of these lithologies. We follow Holbrook and others (1987) who showed that upper Morrison sandstone beds tend to be clay-rich, feldspathic sandstones, more properly called feldspathic wackes, whereas basal Cretaceous sandstone beds tend to be quartz rich with little feldspar or interstitial clay and may be classified as quartz arenites. The feldspar in Morrison sandstones tends to weather to clay, thereby filling the pore spaces in upper Morrison sandstone beds with clay, whereas basal Cretaceous sandstone beds tend to have considerably less interstitial clay and are more porous and permeable. Locally, as at Garden Park near Cañon City, Colorado, the basal Cretaceous sandstone bed contains appreciable quantities of interstitial clay. However, this clay is white (kaolinite?) and contrasts markedly with the light brown color of interstitial clay in the Morrison Formation.

In Montana and northern Wyoming, the upper contact is traditionally placed at the base of the lowest thick and laterally continuous sandstone bed above Morrison mudstone strata, especially if the bed is a "salt and pepper" type sandstone bed containing abundant black chert grains. However, our studies suggest that this is not a valid criterion. For example, carbonaceous mudstone is a common component of the coal zone at the top of the Morrison in the Great Falls-Lewistown Coal Field of west-central Montana. At the town of Belt, which is about 20 mi (30 km) east of Great Falls, we found carbonaceous mudstone interbedded with sandstone beds that contain abundant black chert grains and the sandstone beds are beneath a prominent (15.0 ft or 4.6 m thick) paleosol that we consider to mark the upper contact of the Morrison Formation. Similar findings elsewhere have lead us to conclude that fluvial sandstone beds, with or without appreciable quantities of black chert grains, may be present at or near the top of the Morrison in Wyoming and Montana, similar to the upper Morrison farther south on the Colorado Plateau, and in eastern Colorado, northeastern New Mexico, and western Oklahoma.

Other Stratigraphic Units

Throughout most of the southern part of the study area, the J-5 and K-1 surfaces define the lower and upper limits of the Morrison Formation. However, locally, some units historically assigned to other formations now are recognized as part of the interval between the J-5 and K-1 surfaces, and thus are Morrison equivalents.

Near the type locality of the Morrison Formation just west of Denver, Colorado, the type Ralston Creek Formation lies above the J–5 unconformity. Age determinations for the Ralston Creek Formation in the Denver area that are based on calcareous microfossils (charophytes and ostracodes; Scott, 1963, p. 92; M.E. Schudack, unpublished data, written communication, 1996) indicate that the type Ralston Creek Formation is Kimmeridgian (middle Late Jurassic) in age. This age designation, together with recognition of stratigraphic markers found in the Ralston Creek and the lower part of the Morrison Formation elsewhere, suggests that the Ralston Creek Formation correlates with the lower part of the Morrison Formation elsewhere (Peterson and Turner, 1998).

South of Denver in the vicinity of Cañon City, and in southeastern Colorado, the term Ralston Creek has been misapplied to include Middle Jurassic strata. Instead, we assign the Middle Jurassic strata to the Bell Ranch Formation and the Upper Jurassic strata, which contain recognizable stratigraphic markers, to the Morrison Formation (Peterson and Turner, 1998).

The lowest beds of the Burro Canyon Formation, formerly considered entirely Early Cretaceous in age, interfinger in some localities in southwestern Colorado and southeastern Utah with the uppermost beds of the Morrison Formation (Ekren and Houser, 1959, 1965) and lie below stratigraphic markers that indicate the top of the Morrison elsewhere (Aubrey, 1996). Accordingly, some beds, traditionally included in the lowermost Burro Canyon, are here included in the Morrison.

North of northern Utah and northern Colorado, where lower Morrison beds include marine strata of the Windy Hill Member, it is unclear if an unconformity separates lower

Morrison beds from underlying strata. In many places, the marine beds of the lower Morrison appear to be part of a conformable sequence of a shoaling upward package of marine strata.

Because marine beds of the Swift Formation in Montana and northernmost Wyoming are thought to be conformable or interfinger with basal Morrison strata (Imlay, 1980, p. 82; Richards, 1955, p. 41; Way and others, 1994) and have an unconformity at their base (Imlay, 1980), we include the Swift in the Morrison package of beds and use the unconformity at the base of the Swift as the basal surface of the Morrison package of beds.

AGE

The age of the Morrison Formation and related beds has been debated considerably in the literature but is now rather well understood. One of the objectives of the recent research on the Morrison Formation and related beds by us and our associates was to determine the age of the formation independently from what the dinosaurs might suggest. The results of those studies are now published and are only briefly discussed below. In Figure 7, we show a summary of the various age-determination studies by using the same methodology that was employed for positioning the dinosaur localities.

Palynological studies by Litwin and others (1998) indicate that the Morrison Formation and related beds are largely Kimmeridgian in age and that only the uppermost part is early Tithonian in age (Fig. 7). The Kimmeridgian-Tithonian boundary is within the upper part of the Brushy Basin Member of the Morrison as shown in Figure 7.

The calcareous microfossils (charophytes and ostracodes) were studied by Schudack (1994, 1995) and Schudack and others (1998) who proposed five charophyte and ostracode zones shown in Figure 7. The age determined by these organisms is similar to that obtained from the palynomorphs. The calcareous microfossils indicate that Zones 1-4 of Schudack and others (1998), which comprise the bulk of the formation, are Kimmeridgian in age. The Kimmeridgian-Tithonian boundary could not be identified clearly but the calcareous microfossils indicate that charophyte and ostracode Zone 5 at the top of the Morrison is definitely not Cretaceous in age and therefore could only be Kimmeridgian and(or) Tithonian in age. Charophyte and ostracode Zone 5 was tentatively considered Tithonian(?) in age based on fairly close correspondence of its lower boundary with the Kimmeridgian-Tithonian boundary as determined by palynomorphs.

Isotopic age determinations on sanidine separates from bentonite beds were made by Kowallis and others (1998); these dates are shown in their correct stratigraphic position in Figure 7. Dating was by the single-crystal laser-fusion $^{40}Ar/^{39}Ar$ methodology, although the $^{40}Ar/^{39}Ar$ plateau methodology was used for a few duplicate samples. The dates indicate that the Morrison package of beds spans a period of time of about 8 m.y. and ranges in age from about 155 to 147 Ma (Fig. 7). The Jurassic-Cretaceous boundary is about 141 Ma (Bralower and others, 1990) so these studies indicate that the top of the Morrison is about 6 m.y. older than the end of the Jurassic Period.

Paleomagnetic data, when evaluated in light of recent paleontologic and isotopic age determinations as well as the regional stratigraphic correlations, can be reinterpreted to be consistent with the paleontologic data. That is to say, we find some of the paleomagnetic data useful when reinterpreted, but we disagree with some of the paleomagnetic age conclusions drawn in the literature because the earlier workers did not have the benefit of the most recent paleontologic age assignments.

Several magnetostratigraphic sections through parts or most of the Morrison Formation on or near the Colorado Plateau are given by Steiner and others (1994), the most important of which are those measured at Norwood and Slick Rock, Colorado. They interpret the approximately lower third of the formation as Oxfordian in age in these sections whereas the age evidence from palynomorphs and calcareous microfossils cited above demonstrates that the lower third of the formation is Kimmeridgian in age.

The inferred paleomagnetic age for approximately the upper fourth of the formation at Slick Rock is Tithonian (Steiner and others, 1994), which is consistent with the palynological age determinations by Litwin and others (1998). The magnetic anomaly at the top of the Morrison in the Slick Rock magnetostratigraphic section correlates best with the M-22 magnetochron in the marine magnetic anomaly sequence. Because the Jurassic-Cretaceous boundary (that is, the top of the Tithonian Age) is at or very near the base of magnetochron M-18, the paleomagnetic studies suggest that about three latest Jurassic magnetochrons are missing at the Slick Rock section and therefore that the top of the Morrison there is significantly older than the end of the Jurassic Period. It should be noted that the clay change within the Morrison Formation is about 486 ft (148 m) above the base of the Salt Wash Member in their Norwood section and about 535 ft (163 m) above the base of the Salt Wash in their Slick Rock section. Assuming, as we do, that the clay change marks an isochronous or nearly isochronous surface, the magnetostratigraphic correlations between the Norwood and Slick Rock sections as proposed by Steiner and others (1994) are not tenable. We suggest that the uppermost Morrison at the Norwood section is anomalously thin and has only Kimmeridgian strata remaining. This may be the result of any of several causes or combination of causes: the upper part of the Brushy Basin Member may have been more deeply eroded during development of the K-1 unconformity, the top of the Morrison may not have been sampled or included when the section was measured for paleomagnetic studies, or the upper Morrison there may be more compressed than is apparent.

Another paleomagnetic study of the Morrison Formation was undertaken in north-central Wyoming by Swierc and Johnson (1996) in which they concluded that the Morrison Formation there is entirely Tithonian in age. It appears that they were influenced by a fission-track date of 149 Ma near the base of the Morrison in one of their measured sections and this date is within the Tithonian Age according to the time scale of Harland and others (1990). Based on problems with fission-track dates in the Morrison Formation (B.J. Kowallis, oral commun., 1997) and the greater reliability of the $^{40}Ar/^{39}Ar$ dates (Kowallis and others, 1998), we discount the fission-track dates and rely, instead, on the $^{40}Ar/^{39}Ar$

dates elsewhere in the Morrison Formation, which are more consistent with the paleontological age designations. Furthermore, the clay change can be identified in most of Wyoming and permits correlation with the better dated Morrison on the Colorado Plateau. The clay change occurs in essentially the same measured section northeast of Greybull, Wyoming, (the Greybull NE section in Fig. 6) as one of the sections studied by Swierc and Johnson (1996, their South Sheep Mountain section SS). The clay change there is 95 ft (29.0 m) above the base of the Morrison and the entire Morrison is 175 ft (53.3 m) thick. The microfossil studies by Litwin and others (1998) and Schudack and others (1998) indicate that the clay change is about middle Kimmeridgian in age (Fig. 7), which conflicts considerably with the inferred Tithonian age for the entire Morrison that was suggested by Swierc and Johnson (1996) for strata in north-central Wyoming. Reevaluating the paleomagnetic studies in north-central Wyoming in light of the age and position of the clay change on the Colorado Plateau leads us to conclude that magnetochron M-22 is at the top of the formation in north-central Wyoming and that the Morrison in Wyoming includes both Kimmeridgian and lower Tithonian strata.

DEPOSITIONAL ENVIRONMENTS

The Morrison Formation was deposited in a wide variety of depositional environments. It is commonly thought of as an entirely nonmarine formation, but the presence of marine organisms and glauconite in Morrison strata suggests otherwise. Marine dinoflagellates were recovered from the Tidwell Member near the Carnegie Quarry in western Dinosaur National Monument, Utah (R.J. Litwin, oral communication, 1994). Glauconite occurs in sandstone beds in about the middle of the formation in northern Montana (Knechtel, 1959). The Windy Hill Member (Pipiringos, 1968; Peterson, 1994) locally contains glauconite, oolites, and brackish-water to marine bivalves that indicate deposition in shallow marine waters (this is member A of the Sundance Formation of Pipiringos, 1957). Most of the formation is interpreted to have been deposited in a variety of continental environments including eolian dune fields, sabkhas, fluvial channels, overbank floodplains, alluvial plains, saline-alkaline and freshwater lakes or ponds, evaporite basins, and coal swamps (Turner and Fishman, 1991; Turner-Peterson, 1986; Peterson, 1994). Summaries of the geology and paleogeography during deposition of the Morrison Formation and related beds were published recently by Turner and Fishman (1991), Peterson (1994) and Brenner and Peterson (1994). A good impression of the stratigraphy of the Morrison Formation and related beds throughout the region can be obtained from the various stratigraphic sections in this report (Figs. 2-6).

BIOSTRATIGRAPHY OF THE DINOSAURS

Localities Where the Clay Change is Present

The clay change within the Morrison Formation is recognizable in most of the Western Interior and thus in most of the areas that contain dinosaur quarries. The area in which the clay change is readily identified includes New Mexico, Colorado, Utah, and Wyoming excluding the northeast corner of that state around the Black Hills. Recognition of the clay change facilitates considerably the relative positioning of the dinosaur localities in these areas.

Although dinosaur bones have been recovered from nearly all stratigraphic levels in the Morrison Formation, the majority of the localities are in about the middle or upper middle half of the formation (Fig. 8). Ten quarries indicated on Figure 10 dominate Morrison biostratigraphy and are the quarries that contain, or at least appear to have the potential to contain, about a thousand or more bones, judging from an estimate by us or by our colleagues. For the most part, these are well-known and famous quarries that include, from lowest to highest stratigraphic position, Reed's Quarry 13 at Como Bluff (WY-46), Howe Quarry (WY-62), Bone Cabin Quarry (WY-78,79), Marsh-Felch Quarry (CO-3), Dry Mesa Quarry (CO-58), Mygatt-Moore Quarry (CO-21), Cleveland-Lloyd Quarry (UT-7), Carnegie Quarry (UT-18), Stovall's Pit 1 (OK-1), and Cope's Quarries at the Nipple in

Garden Park (CO-2). Additional work may demonstrate that two additional localities, the Poison Creek Quarries (WY-71, 73) and Mother's Day Quarry (MT-1), have the potential to also be included in this category. Although these ten quarries dominate Morrison biostratigraphy, there are approximately 131 other localities in the formation that have yielded bones identifiable to genus or species level. According to the numbers of dinosaur taxa recovered from each of the localities, about two-thirds of the localities contain only one or two taxa and nearly half contain only a single taxon (Fig. 9).

We divided the taxonomic units into several broad groupings to facilitate discussion: 1, Long-ranging taxa (mostly genera and species but also including the ankylosaurs), and 2, Single-locality species occurrences. Long-ranging taxa are those that range stratigraphically through two or more different stratigraphic levels in the master reference section (Fig. 7). Single-locality species are those that have only been reported from one locality and, hence, are rare and extremely restricted stratigraphically and geographically. The ankylosaurs (undivided) are also included in the long-ranging category because they are a fairly recent addition to the Morrison fauna and some have not yet been described to the genus or species level.

The stratigraphic distribution of the dinosaurs is divided most logically into four faunal zones (Fig. 10).

Zone 1

Zone 1 is poorly defined and marked by the beginning of the three long-ranging genera Allosaurus, Stegosaurus, and Haplocanthosaurus. It also includes the rare occurrence of Dystrophaeus viaemalae, the new allosaurid from Dinosaur National Monument (UT-20) that is currently under study by D.J. Chure (oral communication, 1997), and Haplocanthosaurus delfsi.

Zone 2

Zone two is marked by the abrupt beginning of many new long-ranging taxa and by the end of the ranges of several taxa toward the top of the zone. New taxa at the genus or higher level include: Torvosaurus, Coelurus, Diplodocus, Camptosaurus, Camarasaurus, Apatosaurus, Barosaurus, Brachiosaurus, the ankylosaurs, Dryosaurus, Elaphrosaurus, Othnielia, Ceratosaurus, Supersaurus, Marshosaurus, and Edmarka (Fig. 10). In addition, Zone 2 includes the lowest occurrences of 17 new long-ranging species and 14 single-site taxa shown in Figure 10. The highest known occurrences of several taxa in Dinosaur Zone 2 include those of Brachiosaurus, Elaphrosaurus, Supersaurus, Edmarka, and Edmarka rex. Thus, Zone 2 marks the addition of many new taxa to the Morrison dinosaur fauna and, toward the top, the beginning of a decline in the taxa.

Zone 3

Dinosaur Zone 3 contains several new additions to the dinosaur fauna but, more importantly, it includes the end ranges of many taxa. The new long-ranging higher taxa are Mymoorapelta and Drinker and the new species are Apatosaurus ajax, Mymoorapelta maysi, Marshosaurus bicentesimus, and Drinker nisti. The highest levels of the following long-ranging taxa are in the upper part of this zone: Haplocanthosaurus, Torvosaurus, Coelurus, Barosaurus, the ankylosaurs, Othnielia, Ceratosaurus, Marshosaurus, and Mymoorapelta. In addition, 17 species die out before the end of the zone and there are 5 single-site taxa within it (Fig. 10).

Zone 4

Zone 4 marks the end of the stratigraphic ranges of the remaining dinosaur genera and species in the Morrison. Amphicoelias is the only new long-ranging genus to appear in this zone. The genera whose ranges end in Zone 4 include Allosaurus, Stegosaurus, Diplodocus, Camptosaurus, Camarasaurus, Apatosaurus, Dryosaurus, Drinker, and Amphicoelias. Five single-site species are also present.

The Black Hills and Montana

Dinosaur material recovered from Montana and the Black Hills region of northeastern Wyoming and western South Dakota occurs where a lack of smectitic clays in the upper

Morrison does not permit accurate positioning with respect to the clay change. We attempted to determine a stratigraphic position that might correlate with the clay change elsewhere (Figs. 5, 6), but the result must be considered tentative.

The biostratigraphic distribution of the dinosaurs in areas where the clay change is present (Fig. 10, Table 1) offers clues to the dinosaur zonation in areas such as the Black Hills, where the clay change is not readily identified (Fig. 11). The ranges of the following genera in the Black Hills begin in Zone 2 in areas where the clay change is present: Dryosaurus, Apatosaurus, Camarasaurus, Barosaurus, and Diplodocus. Furthermore, Othnielia, present in the Black Hills (Fig. 11), is questionably identified low in Zone 2, although the first appearance where it is clearly identified is high in Zone 2. The highest occurrences of Othnielia and Barosaurus extend no higher than near the top of Zone 2 in areas that contain the clay change, and thus the top of Zone 3 in the Black Hills should be above the highest occurrence of these genera. Barosaurus extends highest in the Wyoming part of the Black Hills (locality WY-9) where it has been identified as cf. Barosaurus. Assuming the generic identification is satisfactory, Zone 3 in the Black Hills should extend upward to at least the position of that locality, which is why we tentatively place the upper boundary of Zone 3 as indicated on Figure 11. Such a correlation accords with our earlier conclusion that the top of the Morrison in the eastern part of the Black Hills has not been eroded more deeply than most of the other localities in the Western Interior. Hence, the positioning of the eastern Black Hills dinosaur localities with respect to the projected horizon of the clay change as well as to the upper or lower boundaries of the Morrison seems reasonable.

The zonal stratigraphy of the dinosaurs in Montana is more difficult to determine for several reasons: the clay change is absent, many of the dinosaur remains that have been recovered have not yet been identified, and there is a scarcity of age-diagnostic microfossils in much of the formation. All three of the dinosaur localities are in the lower half of the Morrison and below the stratigraphic level that we tentatively correlate with the clay change farther south (Fig. 12). The stratigraphically highest calcareous microfossil collection that we obtained came from at or very near the level of dinosaur locality MT-2 (Fig. 12). The most stratigraphically restricted charophyte species that this sample contained was Aclistochara obovata, which ranges from the upper half of dinosaur Zone 1 through dinosaur Zone 3 in the Morrison elsewhere in the Western Interior (Schudack and others, 1998). Most of the dinosaurs recovered from Montana are long ranging. However, the lowest dinosaur collection (MT-1) yielded one individual tentatively identified as either Diplodocus or Barosaurus, both of which range from dinosaur Zone 2 upward through Zone 3 (Barosaurus) or Zone 4 (Diplodocus). Taken together, the calcareous microfossils and dinosaurs could only coexist in dinosaur Zones 2 and 3, which are of Kimmeridgian age. The uppermost strata of the Morrison are Tithonian in age because the carbonaceous mudstone and coal unit at the top of the Cinnabar Mountain local reference section (Fig. 12) correlates with the Tithonian age palynomorph collections obtained from a similar carbonaceous mudstone and coal unit at the top of the Morrison about 37 mi (60 km) farther northeast at West Boulder Creek, Montana (Litwin and others, 1998). Putting all of this together, a tentative evaluation of the dinosaur zonation at Cinnabar Mountain is illustrated in Figure 12.

DISCUSSION AND CONCLUSIONS

The role of the major quarries in the biostratigraphy of the dinosaurs in the Morrison and related beds is considerable. Because most of these quarries have yielded numerous bones and have been studied extensively, they account for the dramatic increase in the taxonomic diversity at or near the base of Zone 2. The major quarries also account for significant increases in the faunal diversity higher in Zone 2 (Figs. 10, 13). The taxonomic diversity reaches a maximum high in Zone 2 (Fig. 13). The diversity begins to decline gradually near the top of Zone 2 and rather abruptly declines near the top of Zone 3 and again in the middle of Zone 4. Because the major quarries above the point of maximum diversity high in Zone 2 (Fig. 13) contain a substantial number of taxa, these quarries tend to confirm that the decline in diversity is real and probably is not biased by the numerous sites containing only one or a few taxa.

An important question is whether or not the dramatic increase in taxonomic diversity at or near the base of Zone 2 reflects a sharp change in the composition of the dinosaur fauna or if the change is largely if not entirely a function of the lack of major quarries below that level. Quite likely the marked increase in diversity largely reflects the lack of major quarries in Zone 1, but this is not necessarily the entire explanation. It seems noteworthy that the boundary between dinosaur Zones 1 and 2 coincides with the change in the calcareous microfossil assemblages at the boundary between charophyte and ostracode Zones 2 and 3 of Schudack and others (1998). Also noteworthy is a lithostratigraphic change in the Salt Wash Member at the boundary between dinosaur Zones 1 and 2. This is marked by the change from fluvial sandstone beds that lack pebbles or contain very few pebbles to overlying fluvial strata that contain pebbly or conglomeratic sandstone beds or conglomerate. This occurs in the Salt Wash throughout a large part of the Colorado Plateau and is present at measured section DQW at Dinosaur National Monument (Fig 10).

The lithologic change apparently correlates with the boundary between the middle and upper sequences of the Salt Wash Member farther south on the west side of the Colorado Plateau (Peterson, 1980, 1984). The lithologic change also coincides with the boundary between the upper sandstone-dominated interval and the middle mudstone-dominated interval of the Salt Wash on the east side of the Colorado Plateau (Peterson and Turner-Peterson, 1987). The coincidence of vertical sedimentologic changes with other biostratigraphic changes, such as with the charophytes and ostracodes, suggests that a marked evolutionary change may have occurred at this horizon. These evolutionary changes may have been in response to changes in habitat, depositional environment, climate, or a combination of these factors. The lithologic change at this horizon is thus far only recognized in the Salt Wash Member, which is restricted to the Colorado Plateau. An analogous lithologic change elsewhere in the Western Interior has not yet been recognized.

Another rather dramatic change in taxonomic diversity, one of upward decrease, is present at or near the upper boundary of Zone 3 (Figs. 10, 13). The vertical decrease in diversity occurs where there are a number of localities, including major quarries, above and below this stratigraphic horizon. Thus, the dinosaur fauna recovered to date from Zone 4 may be fairly representative of the original fauna that inhabited the region toward the end of Morrison deposition. The decrease in diversity of the dinosaur fauna at or near the top of Zone 3 coincides with the sharp change in calcareous microfossil assemblages between charophyte and ostracode Zones 4 and 5 of Schudack and others (1998), suggesting that the biotic changes at this stratigraphic horizon may be real and not a reflection of inadequate sampling. Locally, there are slight lithologic changes in the Morrison Formation at or near this horizon but they do not appear to be significant.

The stratigraphic distribution of the dinosaur localities shows a vertical trend of increasing diversity followed by decreasing diversity during deposition of the Morrison Formation and related beds. It seems noteworthy that dinosaur remains are scarce in lowermost Morrison deposits. Only a few dinosaur taxa were introduced to the ecosystem during deposition of dinosaur Zone 1. The scarcity of dinosaurs probably reflects the continuation of the harsh conditions that persisted during the Middle Jurassic, as suggested by the eolian sandstone beds and evaporite deposits in lower Morrison strata (O'Sullivan, 1992, p. 14; Peterson, 1994). Slightly later during deposition of the upper part of the Salt Wash Member, the development of an extensive alluvial plain fed by intermittent and possibly a small number of perennial streams may have established a more equable habitat that enticed dinosaurs into the region. The change from increasing to decreasing diversity a short distance above the clay change (about 10 ft or 3 m above the clay change in the master reference section at Dinosaur National Monument) does not coincide precisely with any obvious lithologic change but may reflect increasing environmental stress from the abundant volcanic ash that was carried into the region, either directly by airfall or indirectly by streams.

The remaining rather sharp declines in diversity near the top of dinosaur Zone 3 and in the middle of dinosaur Zone 4 do not coincide with any obvious lithologic changes. As nearly as we can determine, the top of charophyte and ostracode Zone 4 coincides with the top of dinosaur Zone 3 (Fig. 7). This suggests that the sharp decline in charophytes and ostracodes there (about 12 species dropping out at or near this level) may be related to environmental stresses that were not manifested in the lithologies but that did adversely affect other life forms (Schudack and others, 1998). In a somewhat similar fashion, the remaining charophytes and ostracodes drop out entirely in about the middle of dinosaur Zone 4, again suggesting an environmental stress that affected markedly different types of organisms but that are not clearly reflected in the rocks.

The data suggest that there was essentially no change in the dinosaur fauna at the Kimmeridgian-Tithonian boundary (Figs. 10, 13), but with so little Tithonian Age strata preserved in the Morrison, we cannot rule out the possibility that a change in the fauna would be apparent at this horizon if more specimens were available from dinosaur Zone 4.

The foregoing conclusions, based largely upon the biostratigraphic distribution of the entire dinosaur fauna throughout an extensive region (Fig. 10), are biased considerably by the faunas thus far recovered from the ten major quarries. In view of the well known biogeographic diversity of modern but pre-human faunas in a similarly large area, such as the Great Plains region of the United States, a single major quarry, no matter how large and diversified the recovered fauna, quite likely would contain a poor representation of the overall fauna that existed throughout the Western Interior during any specific time of Morrison deposition.

On the other hand, the fauna recovered from a major quarry could be fairly representative of a significant part of the overall fauna if the factors that were responsible for the demise of the animals encouraged them to congregate in a few places just before their deaths. The most plausible scenario for this would be the concentration of animals, who ordinarily ranged over a broad area, around the last of the waterholes before those too dried up during a major drought. Extensive droughts are plausible in light of the overall semi-arid interpretation for much of the Morrison Formation. Evidence of overall dryness includes extensive evaporite deposits (gypsum-anhydrite) in the lowermost part of the Morrison and related beds in the Colorado Plateau and eastern Colorado (O'Sullivan, 1992; Peterson and Turner, 1998), large eolian dune fields in the lower Morrison in the central and southern parts of the Colorado Plateau and smaller dune fields as far north as north-central Wyoming and western South Dakota (Szigeti and Fox, 1981; Blakey and others, 1988; Peterson, 1988b, 1994), and extensive saline-alkaline or playa lake deposits in the upper Morrison (Brushy Basin Member) on the east side of the Colorado Plateau (Turner and Fishman, 1991).

With additional study by paleontologists, it may become clear that some faunal trends in this report indicate evolutionary progressions, and other taxonomic relationships may come to light. For example, the biostratigraphic ranges of Stegosaurus stenops , S. ungulatus, and S. armatus are so similar as to suggest an unusually close relationship between the three species. Apparently sexual dimorphism does not appear to be a reasonable explanation for some of this (P.M. Galton, oral communication, 1997). Also, more work might establish that Hypsirophus is an evolutionary descendant of one of the Stegosaurs. Our study also shows an upward progression in the first occurrences of species in some of the genera, a progression that might reflect evolutionary lineages, which can only be clarified by further and more detailed examination by specialists. These include the vertical progression of first occurrences of the camarasaurs, including Camarasaurus lentus, C. grandis, C. supremus, and C. lewisi, (Fig. 10). Similarly, in the genus Diplodocus, the vertical progression is D. longus, and D. carnegii (the relative position of D. hayi is unknown because we were unable to obtain permission to enter the property containing the quarry that yielded that species). In the Allosaurs, the vertical progression is Allosaurus n.

sp. (from Dinosaur National Monument) followed by A. fragilis. In the genus Apatosaurus, the vertical progression of first appearances is A. excelsus, A. yahnapin, A. ajax, and A. louisae. "Apatosaurus" minimus is considered "a valid species, but not belonging to Apatosaurus" (J.S. McIntosh, written commun., 1997).

The ten major quarries, either singly or grouped, are positioned at about six different stratigraphic levels, which is intriguingly periodic. The various stratigraphic positions with their included major quarries are shown on Figure 10 and are, from oldest to youngest: 1, Reed's Quarry 13 (WY-46), Howe Quarry (WY-62), and Bone Cabin Quarries (WY-78, 79); 2, Marsh-Felch Quarry (CO-3); 3, Dry Mesa Quarry (UT-58), 4, Mygatt-Moore Quarry (CO-21) and Cleveland-Lloyd Quarry (UT-7); 5, Carnegie Quarry (UT-18), and Stovall Pit 1 (OK-1); and 6, Cope's Nipple Quarries (CO-2). The six stratigraphic positions marked by these groupings of the major quarries could mark periodic recurrences of prolonged or intermittent environmental stress. The periodicity may have been related to Milankovitch cycles (De Boer and Smith, 1994), but insufficient time resolution precludes drawing any conclusions along these lines. Clearly, further research on this aspect is necessary.

RECOMMENDATIONS

valuable contribution to understanding Morrison dinosaur faunas would be for more paleontologic research to be focused on Zone 1. Excavation of localities already known in that part of the formation and searching for more sites to enlarge the faunal base would be most helpful. The goal would be to enlarge the number of taxa to the extent that it would be sufficient to adequately represent that part of the formation. In this regard, the East Canyon (UT-4) and Meilyn (WY-83) Quarries seem most promising. A similar need exists for new sites or additional work on existing sites high in Zone 4, but the need is not as great as with Zone 1.

Additional paleontologic work is also needed in Montana, so that sufficient information becomes available to provide the basis for interpreting biogeographic diversity or paleolatitudinal variations in the overall fauna.

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REFERENCES CITED

Allen, Al, 1994, The dinosaur beds of the Morrison Formation (Jurassic), Alcova Lake, Wyoming: Tate Museum publication, Casper College, Wyoming, 35 p. (includes Cross Sections 1 and 2 as separates).

Allen, Al, 1996, Morrison Formation stratigraphy between the classic Como Bluff and Thermopolis areas, Wyoming; in, Hunter, R.A., (ed.), Tate '96—Paleoenvironments of the Jurassic: Tate Museum Guidebook No. 1, Tate Geological Museum, Casper, Wyoming, p. 19-28.

Anderson, O.J., and Lucas, S.G., 1996, Stratigraphy and depositional environments of Middle and Upper Jurassic rocks, southeastern San Juan Basin, New Mexico; in, Goff, F., Kues, B.S., Rogers, M.A., McFadden, L.D., and Gardner, J.N., (eds.), The Jemez Mountains Region: New Mexico Geological Society Guidebook, 47th Annual Field Conference, p. 205-210.

Armstrong, H.J., and McReynolds, E.S. 1987, Stratigraphic correlation of dinosaur quarries near Grand Junction, Colorado; in, Averett, W.R., (ed.), Paleontology and Geology of the Dinosaur Triangle: Grand Junction Geological Society, Guidebook, p. 103-106.

Aubrey, W.M., 1996, Stratigraphic architecture and deformational history of Early Cretaceous foreland basin, eastern Utah and southwestern Colorado; in, Huffman, A.C., Jr., Lund, W.R., and Godwin, L.H., (eds.), Utah Geological Association Guidebook 25, p. 211-220.

Bakker, R.T., Galton, Peter, Siegwarth, James, and Filla, James, 1990, A new latest Jurassic vertebrate fauna, from the highest levels of the Morrison Formation at Como Bluff, Wyoming, Part IV—The dinosaurs—A new Othnielia-like hypsilophodontoid: Hunteria, v. 2, no. 6, p. 8-19.

Bakker, R.T., Siegwarth, James, Kralis, Donald, and Filla, James, 1992, Edmarka rex, a new, gigantic theropod dinosaur from the middle Morrison Formation, Late Jurassic of the Como Bluff outcrop region, with comments on the evolution of the chest region and shoulder in theropods and birds, and a discussion of the five cycles of origin and extinction among giant dinosaurian predators: Hunteria, v. 2, no. 9., 24 p.

Bartleson, B.L., and Jensen, J.A., 1988, The oldest (?) Morrison Formation dinosaur, Gunnison, Colorado: The Mountain Geologist, v. 25, no. 3, p. 129-139.

Bilbey, S.A., and Hamblin, A.H., 1992, An articulated partial skeleton of Stegosaurus from the Salt Wash Member of the Morrison Formation near Jensen, Utah: Geological Society of America, Abstracts with Programs, v. 24, no. 6, p. 4.

Bjoraker, C.A., and Naus, M.T., 1996, A summary of Morrison Formation (Jurassic: Kimmeridgian-Tithonian) geology and paleontology, with notice of a new dinosaur locality in the Bighorn Basin (USA); in, Bowen, C.E., Kirkwood, S.C., and Miller, T.S., (eds.), Resources of the Bighorn Basin: Wyoming Geological Association, 47th Guidebook, p. 297-303.

Blakey, R.C., Peterson, Fred, and Kocurek, Gary, 1988, Synthesis of late Paleozoic and Mesozoic eolian deposits of the Western Interior of the United States: Sedimentary Geology, v. 56, p. 3-125.

Bollan, H.R., 1991, The Bollan Stegosaurus; in, Averett, W.R., (ed.), Guidebook for Dinosaur Quarries and Tracksites Tour: Grand Junction Geological Society, p. 53-54.

Bralower, T.J., Ludwig, K.R., Obradovich, J.D., and Jones, D.L., 1990, Berriasian (Early Cretaceous) radiometric ages from the Grindstone Creek section, Sacramento Valley, California: Earth and Planetary Sciences Letters, v. 98, no. 1, p. 62-73.

Brenner, R.L., and Peterson, J.A., 1994, Jurassic sedimentary history of the northern portion of the Western Interior Seaway, USA; in, Caputo, M.V., Peterson, J.A., and Franczyk, K.J., (eds.), Mesozoic Systems of the Rocky Mountain Region: Rocky Mountain Section of the SEPM (Society for Sedimentary Geology), p. 217-232.

Britt, B.B., 1991, Theropods of Dry Mesa Quarry (Morrison Formation, Late Jurassic), Colorado, with emphasis on the osteology of Torvosaurus tanneri: Brigham Young University Geology Studies, v. 37, p. 1-72.

Callison, George, 1987, Fruita—A place for wee fossils; in, Averett, W.R., (ed.), Paleontology and Geology of the Dinosaur Triangle: Grand Junction Geological Society, Guidebook, p. 91-96.

Carpenter, K., 1998, Vertebrate biostratigraphy of the Morrison Formation near Cañon City, Colorado: Modern Geology, v. 23, nos. 1-4, p. 407-426

Chenoweth, W.L., 1953, The variegated member of the Morrison Formation in the southeastern part of the San Juan Basin, Valencia County, New Mexico: Unpublished M.S. thesis, University of New Mexico, Albuquerque, 86 p.

Chenoweth, W.L., 1987, The Riggs Hill and Dinosaur Hill sites, Mesa County, Colorado; in, Averett, W.R., (ed.), Paleontology and Geology of the Dinosaur Triangle: Grand Junction Geological Society, Guidebook, p. 97-100

Chure, D.J., 1989. The fauna of the Morrison Formation in Dinosaur National Monument; in, Flynn, J.J., and McKenna, M.C., (leaders), Mesozoic/Cenozoic vertebrate paleontology—Classic localities, contemporary approaches: 28th International Geological Congress, Field Trip T-322, p. 8-14.

Chure, D.J., 1994, Koparion douglassi, a new dinosaur from the Morrison Formation (Upper Jurassic) of Dinosaur National Monument; the oldest troodontid (Theropoda: Maniraptora): Brigham Young University Geology Studies, v. 40, p. 11-15.

Chure, D.J., 1995, A reassessment of the gigantic theropod Saurophagus maximus from the Morrison Formation (Upper Jurassic) of Oklahoma, USA; in, Sun, A., and Wang, Y., (eds.), Sixth Symposium on Mesozoic Terrestrial Ecosystems and Biota, Short Papers: China Ocean Press, Beijing, p. 103-106.

Chure, D.J., Turner, C.E., and Peterson, F., 1994, An embryo of Camptosaurus from the Morrison Formation (Jurassic, Middle Tithonian) in Dinosaur National Monument, Utah; in, Carpenter, K., Hirsch, K.F., and Horner, J.R., (eds.), Dinosaur Eggs and Babies: Cambridge University Press, p. 298-311.

Cooley, J.T., 1993, Fluvial systems of the Upper Jurassic Morrison Formation, northern Beartooth and Gallatin Ranges, southwest Montana: Unpublished M.S. thesis, Montana State University, Bozeman, 55 p.

Cope, E.D., 1877, On a dinosaurian from the Trias of Utah: American Philosophical Society, Proceedings, v. 16, p. 579-584.

Craig, L.C., Holmes, C.N., Freeman, V.L., Mullens, T.E., and others, 1959, Measured sections of the Morrison and adjacent formations: U.S. Geological Survey Open-File Report.

Cross, Whitman, 1894, Pikes Peak Folio, Colorado: U.S. Geological Survey Folio 7, 5 p., 4 maps (1:125,000).

Curtice, B.D., and Wilhite, D.R., 1996, A re-evaluation of the Dry Mesa Dinosaur Quarry sauropod fauna with a description of juvenile sauropod elements; in, Huffman, A.C., Jr., Lund, W.R., and Godwin, L.H., (eds.), Geology and Resources of the Paradox Basin: Utah Geological Association Guidebook 25, p. 325-338.

De Boer, P.L., and Smith, D.G., 1994, Orbital forcing and cyclic sequences: International Association of Sedimentologists Special Publication 19, p. 1-14.

Demko, T.M., Currie, B.S., and Nicoll, K.A., 1996, Paleosols at sequence boundaries in the Upper Jurassic Morrison Formation, Colorado Plateau and Rocky Mountain regions, USA: Geological Society of America, Abstracts with Programs, v. 28, no. 7, p. A-185.

Dodson, P., Behrensmeyer, A.K., and Bakker, R.T., 1980, Taphonomy of the Morrison Formation (Kimmeridgian-Portlandian) and Cloverly Formation (Aptian-Albian) of the western United States: Mémoires de la Société Géologique de France (Nouvelle Série), Mémoire No. 139, Ecosystémes Continentaux du Mésozoïque, p. 87-93.

Ekren, E.B., and Houser, F.N., 1959, Relations of Lower Cretaceous and Upper Jurassic rocks in the Four Corners area, Colorado: American Association of Petroleum Geologists Bulletin, v. 43, no. 1, p. 190-201.

Ekren, E.B., and Houser, F.N., 1965, Geology and petrology of the Ute Mountains area, Colorado: U.S. Geological Survey Professional Paper 481, 74 p.

Filla, B.J., and Redman, P.D., 1994, Apatosaurus yahnahpin—A preliminary description of a new species of diplodocid dinosaur from the Late Jurassic Morrison Formation of southern Wyoming, the first sauropod dinosaur found with a complete set of "belly ribs"; in, Nelson, G.E., (ed.), The Dinosaurs of Wyoming: Wyoming Geological Association Guidebook, 44th Annual Field Conference, p. 159-178.

Fiorillo, A.R., and May, C.L., 1996, Preliminary report on the taphonomy and depositional setting of a new dinosaur locality in the Morrison Formation (Brushy Basin Member) of Curecanti National Recreation Area, Colorado; in, Morales, M., (ed.), The Continental Jurassic: Museum of Northern Arizona Bulletin 60, p. 555-561.

Foster, J.R., 1992, Fossil vertebrates of the Morrison Formation (Upper Jurassic) of the Black Hills, South Dakota and Wyoming: Unpublished M.S. thesis, South Dakota School of Mines and Technology, Rapid City, 178 p.

Foster, J.R., 1996a, Fossil vertebrate localities in the Morrison Formation (Upper Jurassic) of western South Dakota; in, Morales, M., (ed.), The Continental Jurassic: Museum of Northern Arizona Bulletin 60, p. 255-263.

Foster, J.R., 1996b, Sauropod dinosaurs of the Morrison Formation (Upper Jurassic), Black Hills, South Dakota and Wyoming: Contributions to Geology, University of Wyoming, v. 31, no. 1, p. 1-25.

Foster, J.R. and Martin, J.E., 1994, Late Jurassic dinosaur localities in the Morrison Formation of northeastern Wyoming; in, Nelson, G.E., (ed.), The Dinosaurs of Wyoming: Wyoming Geological Association Guidebook, 44th Annual Field Conference, p. 115-126.

Fraser, G.D., Waldrop, H.A., and Hyden, H.J., 1969, Geology of the Gardiner area, Park County, Montana: U.S. Geological Survey Bulletin 1277, 118 p.

Galton, P.M., 1990, Stegosauria; in, Weishampel, D.B., Dodson, Peter, and Osmólska, Halszka, (eds.), 1990, The Dinosauria: University of California Press, Berkeley, p. 435-455.

Galton, P.M., and Jensen, J.A., 1973, Small bones of the hypsilophodontid dinosaur Dryosaurus altus from the Upper Jurassic of Colorado: The Great Basin Naturalist, v. 33, no. 2, p. 129-132.

Gillette, D.D., 1991, Seismosaurus halli, gen. et sp. nov., a new sauropod dinosaur from the Morrison Formation (Upper Jurassic/Lower Cretaceous) of New Mexico, USA: Journal of Vertebrate Paleontology, v. 11, no. 4, p. 417-433.

Gilluly, James, and Reeside, J.B., Jr., 1928, Sedimentary rocks of the San Rafael Swell and some adjacent areas in eastern Utah: U.S. Geological Survey Professional Paper 150-D, p. 61-110.

Goodknight, C.S., Chenoweth, W.L., and Girdley, W.A., 1991, First day road log from Grand Junction to Moab; in, Averett, W.R., (ed.), Guidebook for Dinosaur Quarries and Tracksites Tour: Grand Junction Geological Society, p. 71-81.

Harland, W.B., Armstrong, R.L., Cox, A.V., Craig, L.E., Smith, A.G., and Smith, D.G., 1990, A Geologic Time Scale 1989: Cambridge University Press, New York, 263 p.

Holbrook, J.M., Wright, Robyn, and Kietzke, K.K., 1987, Stratigraphic relationships at the Jurassic-Cretaceous boundary in east-central New Mexico; in, Lucas, S.G., and Hunt, A.P., (eds.), Northeastern New Mexico: New Mexico Geological Society Guidebook, 38th Annual Field Conference, p. 161-165.

Holt, E.L., 1940, The Morrison and Summerville Formations of the Grand River Valley and their vertebrate and invertebrate fauna: Unpublished M.S. thesis, University of Colorado, Boulder, 71 p.

Imlay, R.W., 1980, Jurassic paleobiogeography of the conterminous United States in its continental setting: U.S. Geological Survey Professional Paper 1062, 134 p.
Jensen, J.A., 1985, Three new sauropod dinosaurs from the Upper Jurassic of Colorado: The Great Basin Naturalist, v. 45, no. 4, p. 697-709.
Jensen, J.A., 1987, New brachiosaur material from the Late Jurassic of Utah and Colorado: The Great Basin Naturalist, v. 47, no. 4, p. 592-608.
Jensen, J.A., 1988, A fourth new sauropod dinosaur from the Upper Jurassic of the Colorado Plateau and sauropod bepedalism: The Great Basin Naturalist, v. 48, no. 2, p. 121-145.
Kirkland, J.I., and Carpenter, K., 1994, North America's first pre-Cretaceous ankylosaur (Dinosauria) from the Upper Jurassic Morrison Formation of western Colorado: Brigham Young University Geology Studies, v. 40, p. 25-42.
Knechtel, M.M., 1959, Stratigraphy of the Little Rocky Mountains and encircling foothills, Montana: U.S. Geological Survey Bulletin 1072-N, p. 723-752.
Kolb, R.L., Davis, L.E., and Gillette, D.D., 1996, The theropod dinosaur Allosaurus Marsh from the upper part of the Brushy Basin Member of the Morrison Formation (Upper Jurassic) near Green River, Utah; in, Huffman, A.C., Jr., Lund, W.R., and Godwin, L.H., (eds.), Geology and resources of the Paradox Basin: Utah Geological Association Guidebook 25, 1996 field symposium, p. 339-349.
Kowallis, B.J., Christiansen, E.H., Deino, A.L., Peterson, Fred, Turner, C.E., Kunk, M.J., and Obradovich, J.D., 1998, The age of the Morrison Formation: Modern Geology, v. 22, nos. 1-4, p. 235-260.
Langston, Wann, Jr., 1989, A history of vertebrate paleontology at the University of Oklahoma: Unpublished document from the Museum of Paleontology at the University of Oklahoma, Norman, 92 p., plus Appendix IV of 24 p.
Litwin, R.J., Turner, C.E., and Peterson, Fred, 1998, Palynological evidence on the age of the Morrison Formation, Western Interior U.S: Modern Geology, v. 22, nos. 1-4, p. 297-320.
Lucas, S.G., and Hunt, Adrian, 1985, Dinosaurs from the Upper Jurassic Morrison Formation in New Mexico: New Mexico Journal of Science, v. 25, p. 1-12.
Lucas, S.G., Kietzke, K.K., and Hunt, A.P., 1985, The Jurassic System in east-central New Mexico; in, Lucas. S.G., (ed.), Santa Rosa—Tucumcari Region: New Mexico Geological Society Guidebook, 36th Annual Field Conference, p. 213-242.
Lull, R.S., 1919, The sauropod dinosaur Barosaurus Marsh: Connecticut Academy of Arts and Sciences, New Haven, v. 6, 42 p.
Madsen, J.H., Jr., 1976, Allosaurus fragilis—A revised osteology: Utah Geological and Mineral Survey Bulletin 109, 163 p.
Maxwell, C.H., 1976, Geologic map of the Acoma Pueblo quadrangle, Valencia County, New Mexico: U.S. Geological Survey Geologic Quadrangle Map GQ-1298, scale 1:24,000.
McIntosh, J.S., 1981, Annotated catalogue of the dinosaurs (reptilia, archosauria) in the collections of Carnegie Museum of Natural History: Bulletin of Carnegie Museum of Natural History, no. 18, 67 p.
McIntosh, J.S., 1990a, Sauropoda; in, Weishampel, D.B., Dodson, P., and Osmólska, H., (eds.), The Dinosauria: University of California Press, Berkeley, p. 345-401.
McIntosh, J.S., 1990b, The second Jurassic dinosaur rush: Earth Sciences History, v. 9, no. 1, p. 22-27.
McIntosh, J.S., Miller, W.E., Stadtman, K.L., and Gillette, D.D., 1996, The osteology of Camarasaurus lewisi (Jensen, 1988): BYU Studies in Geology, v. 41, p. 73-115.
Meyers, J.H., and Schwartz, R.K., 1994, Summary of depositional environments, paleogeography, and structural control on sedimentation in the Late Jurassic (Oxfordian) Sundance foreland basin, western Montana; in, Caputo, M.V., Peterson, J.A., and Franczyk, K.J., (eds.), Mesozoic Systems of the Rocky Mountain Region: Rocky Mountain Section of the SEPM (Society for Sedimentary Geology), p. 331-349.

Miller, W.E., Baer, J.L., Stadtman, K.L., and Britt, B.B., 1991, The Dry Mesa dinosaur quarry, Mesa County, Colorado; in, Averett, W.R., (ed. Guidebook for Dinosaur Quarries and Tracksites Tour: Grand Junction Geological Society, p. 31-46.
Miller, W.E., Horricks, R.D., and Madsen, J.H., Jr, 1996, The Cleveland-Lloyd Dinosaur Quarry, Emery County, Utah: A U.S. Natural Landmark (including history and quarry map): BYU Studies in Geology, v. 41, p. 3-24.
Molnar, R.E., Kurzanov, A.M., and Dong, Zhiming, 1990, Carnosauria; in, Weishampel, D.B., Dodson, Peter, and Osmólska, Halszka, (eds.), The Dinosauria: University of California Press, Berkeley, p. 169-209.
Norman, D.B., and Weishampel, D.B., 1990, Iguanodontidae and related ornithopods; in, Weishampel, D.B., Dodson, Peter, and Osmólska, Halszka, (eds.), 1990, The Dinosauria: University of California Press, Berkeley, p. 510-533.
Osborn, H.F., and Mook, C.C., 1921, Camarasaurus, Amphicoelias, and other sauropods of Cope: American Museum of Natural History, Memoir, New Series, v. 3, part 3, p. 247-387.
Ostrom, J.H., and McIntosh, J.S., 1966, Marsh's Dinosaurs—The Collections from Como Bluff: Yale University Press, New Haven, 388 p.
O'Sullivan, R.B., 1980, Stratigraphic sections of Middle Jurassic San Rafael Group from Wilson Arch to Bluff in southeastern Utah: U.S. Geological Survey Oil and Gas Investigations Chart OC-102.
O'Sullivan, R.B., 1992, The Jurassic Wanakah and Morrison Formations in the Telluride-Ouray-western Black Canyon area of southwestern Colorado: U.S. Geological Survey Bulletin 1927, 24 p.
Owen, D.E., Turner-Peterson, C.E., and Fishman, N.S., 1989, X-Ray diffraction studies of the <0.5-μm fraction from the Brushy Basin Member of the Upper Jurassic Morrison Formation, Colorado Plateau: : U.S. Geological Survey Bulletin 1808-G, p. G1-G25
Paul, G.S., 1988, The small predatory dinosaurs of the Mid-Mesozoic—The horned theropods of the Morrison and Great Oolite—Ornitholestes and Proceratosaurus—and the sickle-claw theropods of the Cloverly, Djadokhta and Judith River—Deinonychus, Velociraptor and Saurornitholestes: Hunteria, v. 2, no. 4, 9 p.
Peterson, Fred, 1980, Sedimentology of the uranium-bearing Salt Wash Member and Tidwell unit of the Morrison Formation in the Henry and Kaiparowits basins, Utah, in, Picard, M.D., (ed.), Henry Mountains Symposium: Utah Geological Association Publication 8, p. 305-322.
Peterson, Fred, 1984, Fluvial sedimentation on a quivering craton—Influence of slight crustal movements on fluvial processes, Upper Jurassic Morrison Formation, western Colorado Plateau: Sedimentary Geology, v. 38, no. 1/4, p. 21-49.
Peterson, Fred, 1988a, Stratigraphy and nomenclature of Middle and Upper Jurassic rocks, western Colorado Plateau, Utah and Arizona: U.S. Geological Survey Bulletin 1633-B, p. 17-56.
Peterson, Fred, 1988b, Pennsylvanian to Jurassic eolian transportation systems in the western United States: Sedimentary Geology, v. 56, p. 207-260.
Peterson, Fred, 1988c, A synthesis of the Jurassic System in the southern Rocky Mountain region; in, Sloss, L.L., (ed.), Sedimentary Cover—North American craton, U.S.: Geological Society of America, the Geology of North America, v. D-2, p. 65-76.
Peterson, Fred, 1988d, Sedimentologic and paleotectonic analysis of the Henry, Kaiparowits, and Black Mesa Basins, Utah and Arizona; in, Sloss, L.L., (ed.), Sedimentary Cover—North American craton, U.S.: Geological Society of America, the Geology of North America, v. D-2, p. 134-144.

Peterson, Fred, 1994, Sand dunes, sabkhas, streams, and shallow seas—Jurassic paleogeography in the southern part of the Western Interior Basin; in, Caputo, M.V., Peterson, J.A., and Franczyk, K.J., (eds.), Mesozoic Systems of the Rocky Mountain Region: Rocky Mountain Section of the SEPM (Society for Sedimentary Geology), p. 233-272.

Peterson, Fred, and Turner-Peterson, C.E., 1987, The Morrison Formation of the Colorado Plateau: Recent advances in sedimentology, stratigraphy, and paleotectonics: Hunteria, v. 2, no. 1, 18 p.

Peterson, Fred and Turner, C.E., 1998, Stratigraphy of the Ralston Creek and Morrison Formations (Upper Jurassic) near Denver, Colorado: Modern Geology, v. 22, nos. 1-4, p. 3-38.

Pillmore, C.L., and Mapel, W.J., 1963, Geology of the Nefsy Divide quadrangle, Crook County, Wyoming: U.S. Geological Survey Bulletin 1121-E, p. E1-E52.

Pipiringos, G.N., 1957, Stratigraphy of the Sundance, Nugget and Jelm Formations in the Laramie Basin, Wyoming: Geological Survey of Wyoming Bulletin No. 47, 63 p.

Pipiringos, G.N., 1968, Correlation and nomenclature of some Triassic and Jurassic rocks in south-central Wyoming: Professional Paper 594-D, p. D1-D26.

Pipiringos, G.N., 1972, Upper Triassic and pre-Morrison Jurassic rocks; in, Segerstrom, K., and Young, E.J., General geology of the Hahns Peak and Farwell Mountain Quadrangles, Routt County, Colorado: U.S. Geological Survey Bulletin 1349, p. 18-29.

Pipiringos, G.N., and O'Sullivan, R.B., 1976, Stratigraphic sections of some Triassic and Jurassic rocks from Douglas, Wyoming, to Boulder, Colorado: U.S. Geological Survey Oil and Gas Investigations Chart OC-69.

Pipiringos, G.N., and O'Sullivan, R.B., 1978, Principal unconformities in Triassic and Jurassic rocks, Western Interior United States—A preliminary survey: U.S. Geological Survey Professional Paper 1035-A, p. A1-A29.

Richards, P.W., 1955, Geology of the Bighorn Canyon–Hardin area, Montana and Wyoming: U.S. Geological Survey Bulletin 1026, 93 p.

Richmond, D.R., and Stadtman, K.L., 1996, Sedimentology of a Ceratosaurus site in the San Rafael Swell, Emery County, Utah: Brigham Young University Geology Studies, v. 41, p. 117-124.

Rigby, J.K., Jr., 1982, Camarasaurus cf. supremus from the Morrison Formation near San Ysidro, New Mexico—The San Ysidro dinosaur; in, Callender, J.F., (ed.) Albuquerque Country II: New Mexico Geological Society Guidebook, 33rd Annual Field Conference, p. 271-272.

Riggs, E.E., 1903, Brachiosaurus altithorax, the largest known dinosaur: American Journal of Science, v. 4, p. 15, p. 299-306.

Scheetz, R.D., 1991, Progress report of juvenile and embryonic Dryosaurus remains from the Upper Jurassic Morrison Formation of Colorado; in, Averett, W.R., (ed.), Guidebook for Dinosaur Quarries and Tracksites Tour: Grand Junction Geological Society, p. 27-29.

Schmude, D.E., and Weege, C.J., 1996, Stratigraphic relationship, sedimentology, and taphonomy of Meilyn, a dinosaur quarry in the basal Morrison Formation of Wyoming; in, Morales, Michael, (ed.), The Continental Jurassic: Museum of Northern Arizona Bulletin 60, p. 547-554.

Schudack, M., 1994, Die ostracoden und charophyten der Morrison-Formation (Oberjura, westliche USA)—Systematik, biostratigraphie, ökologie, biogeographie: Deutsche Forschungsgemeinschaft, Abschlußbericht zur DFG–Sachbeihilfe Schu 694/4-1, Institut für Paläontologie der Freien Universität Berlin, 139 s.

Schudack, M.E., 1995, Neue mikropälontologische beitrage (ostracoda, charophyta) zum Morrison–ökosystem (Oberjura des Western Interior, USA): Berliner Geowiss. Abh, E. 16, Gundolf-Ernst-Festschrift, s. 389-407.

Schudack, M.E., Turner, C.E., and Peterson, F., 1998, Biostratigraphy, paleoecology, and biogeography of charophytes and ostracodes from the Upper Jurassic Morrison Formation, Western Interior, USA: Modern Geology, v. 22, nos. 1-4, p. 379-414.
Schwartz, H.L., and Manley, Kim, 1992, Geology and stratigraphy of the Seismosaurus locality, Sandoval County, New Mexico: New Mexico Geology, v. 14, no. 2, p. 25-30.
Scott, G.R., 1963, Bedrock geology of the Kassler Quadrangle, Colorado: U.S. Geological Survey Professional Paper 421-B, p. 71-125.
Shaw, A.B., 1964, Time in Stratigraphy: McGraw-Hill Publishing Co., New York, 365 p.
Shepard, J.D., Galton, P.M., and Jensen, J.A., 1977, Additional specimens of the hypsilophodontid dinosaur Dryosaurus altus from the Upper Jurassic of western North America: Brigham Young University Geology Studies, v. 24, pt. 2, p. 11-15.
Sohn, I.G., and Peck, R.E., 1963, Theriosynoecum wyomingense (Branson, 1935), a possible guide ostracode to the Salt Wash Member of the Morrison Formation: U.S. Geological Survey Bulletin 1161-A, p. A1-A10.
Steiner, M.B., Lucas, S.G., and Shoemaker, E.M., 1994, Correlation and age of the Upper Jurassic Morrison Formation from magnetostratigraphic analysis; in, Caputo, M.V., Peterson, J.A., and Franczyk, K.J., (eds.), Mesozoic Systems of the Rocky Mountain Region: Rocky Mountain Section of the SEPM (Society for Sedimentary Geology), p. 315-330.
Swierc, J.E., and Johnson, G.D., 1996, A local chronostratigraphy for the Morrison Formation, northeastern Bighorn Basin, Wyoming; in, Bowen, C.E., Kirkwood, S.C., and Miller, T.S., (eds.), Resources of the Bighorn Basin: Wyoming Geological Association, 47th Guidebook, p. 315-327.
Sues, H.-D., and Norman, D.B., (1990), Hypsilophodontidae, Tenontosaurus, Dryosauridae; in, Weishampel, D.B., Dodson, Peter, and Osmólska, Halszka, (eds.), 1990, The Dinosauria: University of California Press, Berkeley, p. 498-509.
Szigeti, G.J., and Fox, J.E., 1981, Unkpapa Sandstone (Jurassic), Black Hills, South Dakota—An eolian facies of the Morrison Formation; in, Ethridge, F.G., and Flores, R.M., (eds.), Recent and Ancient Nonmarine Depositional Environments—Models for Exploration: Society of Economic Paleontologists and Mineralogists, Special Publication No. 31, p. 331-349.
Turner-Peterson, C.E., 1986, Fluvial sedimentology of a major uranium-bearing sandstone—A study of the Westwater Canyon Member of the Morrison Formation, San Juan Basin, New Mexico; in, Turner-Peterson, C.E., Santos, E.S., and Fishman, N.S., (eds.), A Basin Analysis Case Study—The Morrison Formation, Grants Uranium Region, New Mexico: American Association of Petroleum Geologists, Studies in Geology No. 22, p. 47-75.
Turner, C.E., and Fishman, N.S., 1991, Jurassic Lake T'oo'dichi'—A large alkaline, saline lake, Morrison Formation, eastern Colorado Plateau: Geological Society of America Bulletin, v. 103, no. 4, p. 538-558.
Ver Ploeg, A.J., 1991, Rare dinosaur skeleton found near Greybull: Wyoming Geo-Notes, no. 32, p. 40-41.
Way, J.N., O'Malley, P.J., Furer, L.C., Suttner, L.J., Kvale, E.P., and Meyers, J.H., 1994, Correlations of the Upper Jurassic–Lower Cretaceous nonmarine and transitional rocks in the northern Rocky Mountain foreland; in, Caputo, M.V., Peterson, J.A., and Franczyk, K.J., (eds.), Mesozoic Systems of the Rocky Mountain Region: Rocky Mountain Section of the SEPM (Society for Sedimentary Geology), p. 351-364.
Weege, Christopher, and Schmude, D.E., 1996, The stratigraphic relationship, sedimentology, and taphonomy of Meilyn—A dinosaur quarry in the basal Morrison Formation of Wyoming; in, Hunter, R.A., (ed.), Tate '96—Paleoenvironments of the Jurassic: Tate Museum Guidebook No. 1, Casper, Wyoming, p. 52-58.

West, E.S., 1978, Biostratigraphy and paleoecology of the lower Morrison Formation of Cimarron County, Oklahoma: Unpublished M.S. thesis, Wichita State University, Wichita, Kansas, 61 p.

APPENDIX 1

CREDITS FOR SECTIONS MEASURED BY OTHERS THAT WERE USED IN THE COMPILATION

Montana

The Cinnabar Mountain local reference section is from Fraser and others (1969, p. 93-95) and partly revised in further work by us.

The position of the T and J Quarry (MT-6) was correlated to a nearby section of the entire Morrison Formation that was measured by J.T. Cooley (unpublished data) and was used in Figure 6 as the Toston local reference section.

The Tithonian palynomorph samples were positioned in a partial section at the top of the Morrison Formation measured by us and tied in to a complete section of the Morrison measured in essentially the same area by Cooley (1993, p. 39, section B at West Boulder River).

New Mexico

The localities at Acoma (NM-1) and Concho Springs (NM-2) were correlated to measured sections in Chenoweth (1953) by Lucas and Hunt (1985), which were then correlated by us to the Cuchillo Arroyo local reference section of Craig and others (1959, section 49).

Oklahoma

A measured section through the lower part of the Morrison Formation by West (1978, measured section 1) was used along with our measured sections through the remainder of the Morrison Formation to help with the initial positioning of sites in western Oklahoma. These were then correlated to our Travesser Park local reference section in northeastern New Mexico.

South Dakota

Measured sections by Foster (1996ab) were used to initially position several sites in the eastern Black Hills. These were then correlated to our Wonderland local reference section.

Utah

The Green River Quarry (UT-9) was positioned in a measured section by Kolb and others (1996, p. 341, Fig. 2, section 3) and correlated by us to our nearby Hatt Ranch section.

Wyoming

The Thermopolis local reference section is from Bjoraker and Naus (1996, p. 303, Column 5).

We correlated the Little Houston Creek Quarry (WY-11) to a nearby and more complete local reference section in Pillmore and Mapel (1963, Pl. 2, section 42). Other sites on the west side of the Black Hills were related to measured sections by Foster (1992) and Foster and Martin (1994) and correlated by us to the Little Houston Creek local reference section.

The Meilyn (WY-83) and Lynn (WY-84) sites were positioned in measured sections by Weege and Schmude (1996, Fig. 2, sections A and B) and Schmude and Weege (1996, p. 550, Fig. 2, sections A and B) and correlated by us to our nearby measured section at Ninemile Hill.

APPENDIX 2

ALPHABETICAL LIST OF SPECIES

See Table 1 for a listing by numerical order that also includes selected genera.

Taxon Identity Number	Species
37	Allosaurus fragilis Marsh
62	Allosaurus n. sp. (N.A.A.)
87	Amphicoelias altus Cope
84	Amphicoelias fragillimus Cope
68	Ankylosaur n. gen & sp.
48	Apatosaurus ajax Marsh
38	Apatosaurus excelsus Marsh
81	Apatosaurus louisae Holland
69	Apatosaurus yahnapin Filla & Redman
65	"Apatosaurus" minimus Mook
80	Barosaurus lentus Marsh
77	Brachiosaurus altithorax Riggs
36	Camarasaurus grandis (Marsh)
32	Camarasaurus lentus (Marsh)
73	Camarasaurus lewisi (Jensen)
44	Camarasaurus supremus Cope
70	Camptosaurus amplus (Marsh)
64	Camptosaurus dispar (Marsh)
42	Ceratosaurus nasicornis Marsh
31	Coelurus fragilis Marsh
47	Diplodocus carnegii Hatcher
43	Diplodocus longus Marsh
51	Drinker nisti Bakker, Galton, Siegwarth & Filla
39	Dryosaurus altus (Marsh)
61	Dystrophaeus viaemalae Cope
74	Dystylosaurus edwini Jensen
76	Echinodon sp.
46	Edmarka rex Bakker, Siegwarth, Kralis, and Filla
40	Elaphrosaurus sp.
63	Haplocanthosaurus delfsi McIntosh & Williams
71	Haplocanthosaurus priscus (Hatcher)
83	Hypsirophus sp.
85	Koparion douglassi Chure
50	Marshosaurus bicentesimus Madsen
72	"Morosaurus" sp.
49	Mymoorapelta maysi Kirkland & Carpenter
66	Ornitholestes sp.

Taxon Identity Number	Species
67	Ornitholestes hermanni Osborn
41	Othnielia rex (Marsh)
82	Saurophaganax maximus Chure
78	Seismosaurus hallorum (Gillette)
35	Stegosaurus armatus Marsh
33	Stegosaurus stenops Marsh
34	Stegosaurus ungulatus Marsh
79	Stokesosaurus clevelandi Madsen
75	Supersaurus vivianae Jensen
45	Torvosaurus tanneri Galton & Jensen
86	Troodontid second sp.

APPENDIX 3

MORRISON DINOSAUR SITES AND FAUNAL LISTS

The various dinosaur sites are listed by state and general locality within that state. This is followed by a code having the accepted two-letter abbreviation for the state followed by an identifying number (for example, CO-11), the name(s) applied to the locality, and the county. The sites are listed sequentially by their identifying numbers but the numerical sequence may be broken to allow for flexibility in compilation. Credits for the identifications and faunal lists are included. Brief notes are added in places for clarity and understanding. Brackets [thus] enclose vague taxonomic groups of possible interest but not mentioned elsewhere in this report.

AMNH: American Museum of Natural History
CMNH: Cleveland Museum of Natural History
DMNH: Denver Museum of Natural History
DNM: Dinosaur National Monument
FPA: Fruita Paleontological Area
LACM: Los Angeles County Museum
RVRNA: Rabbit Valley Research Natural Area

COLORADO

CAÑON CITY (Garden Park area)

CO-1 Cope's Quarry 8 (about 500 ft southwest of Cope's Nipple)
Fremont Co., CO

Carpenter (1998)

According to K. Carpenter, (oral commun., 1997), this locality is Quarry 8 in Cope's original notes. Cope also referred to it as Camarasaurus Quarry No. 2. Osborn and Mook (1921) incorrectly called it Cope Quarry No. 1.

Sauropoda:
- Camarasaurus supremus

CO-2 Cope's Quarries 1-7 (At Cope's Nipple, or Saurian Hill)
Fremont Co., CO

Carpenter (1998); Osborn and Mook (1921) incorrectly called this Cope Quarry No. 2.

Theropoda:
- Allosaurus? sp

Sauropoda:
- Camarasaurus sp.
- Camarasaurus supremus
- Amphicoelias fragillimus
- Apatosaurus sp.

Thyreophora:
- Hypsirophus sp. (Stegosaur genus tentatively accepted pending further study; Carpenter, 1998)

Ornithopoda:
- Camptosaurus sp.

CO-3 Marsh-Felch Quarry 1
Fremont Co., CO
K. Carpenter (1998; oral commun., 1991, 1997), Ostrom and McIntosh (1966)
Theropoda:
Ceratosaurus nasicornis
Allosaurus fragilis
Elaphrosaurus sp.
Coelurus fragilis
Sauropoda:
Haplocanthosaurus priscus
Brachiosaurus sp.
"Morosaurus" sp.
Diplodocus longus
Apatosaurus sp.
Thyreophora:
Stegosaurus armatus
Stegosaurus stenops
Ornithopoda:
Othnielia rex
Dryosaurus altus

CO-4 Marsh-Felch Quarry 2
Fremont Co., CO
K. Carpenter (oral commun., 1991), J.S. McIntosh (written commun., 1997)
Theropoda:
Allosaurus sp.

CO-5 CMNH Quarry
(Delfs' Quarry)
Fremont Co., CO
K. Carpenter (oral commun., 1991)
Sauropoda:
Haplocanthosaurus delfsi

CO-6 DMNH Quarry 1
(Dall DeWeese's 1915 Quarry)
Fremont Co., CO
K. Carpenter (oral commun., 1991)
Sauropoda:
Diplodocus longus

CO-7 DMNH Quarry 2 (Kessler's 1937 Quarry)
Fremont Co., CO
K. Carpenter (1998; oral commun., 1991)
Theropoda:
Allosaurus sp.
Thyreophora:
Stegosaurus stenops

CO-8 DMNH Quarry 3 (Lindsey's 1977 Quarry)
Fremont Co., CO
K. Carpenter (1998; oral commun., 1991)
Theropoda:
Allosaurus fragilis
Sauropoda:
Camarasaurus grandis

CO-9 DMNH Quarry 4 (Carpenter's 1990 Quarry or Valley of Death 5 Quarry)
Fremont Co., CO
K. Carpenter (1998; oral commun., 1991)
Sauropoda:
Diplodocus sp.
Ornithopoda:
Othnielia rex

CO-10 DMNH Quarry 5 (Carpenter's 1991 Quarry, or Shaw's Park 1 Quarry)
Fremont Co., CO
K. Carpenter (1998; oral commun., 1992)
Sauropoda:
Haplocanthosaurus sp.

CO-11 DMNH Quarry 6 (Small's Quarry)
Fremont Co., CO
K. Carpenter (oral commun., 1992, 1997)
Theropoda:
Elaphrosaurus sp.
Sauropoda:
Apatosaurus excelsus
Thyreophora:
Stegosaurus stenops
?Mymoorapelta sp.
Ornithopoda:
Dryosaurus altus

DINOSAUR NATIONAL MONUMENT EAST

CO-16 Homestead Quarry
Moffat Co., CO
D.J. Chure (oral commun., 1993)
Theropoda:
Marshosaurus(?) sp.

CO-17 Wolf Creek Quarry
Moffat Co., CO
J.R. Foster (oral commun., 1997)
Theropoda:
Allosaurus sp.
Sauropoda:
Camarasaurus sp.
[Indeterminate diplodocid]
Thyreophora:
Stegosaurus sp.

GRAND JUNCTION-FRUITA AREA
(Rabbit Valley locality)

CO-21 Mygatt-Moore Quarry (M&M Quarry)
Mesa Co., CO
Kirkland and Carpenter (1994),
Theropoda:
Ceratosaurus sp.
Allosaurus sp.
Sauropoda:
Camarasaurus sp.
Diplodocus sp.
Barosaurus sp.
Apatosaurus sp.
Thyreophora:
Mymoorapelta maysi

CO-22 RVRNA-2 (Trail Through Time Stop 2)
Mesa Co., CO
Armstrong and McReynolds (1987)
Sauropoda:
Camarasaurus sp.

CO-23 RVRNA-13 (Trail Through Time Stop 13)
Mesa Co., CO
K. Carpenter (written commun., 1997)
Ornithopoda:
Camptosaurus sp.

CO-24 Lower Split Rock Site 1 (In lower sandstone bed)
Mesa Co., CO
J.I. Kirkland (oral commun., 1993)
Theropoda:
Allosaurus sp.
Sauropoda:
Brachiosaurus(?) sp.
Thyreophora:
Stegosaurus sp.
Stegosaurus stenops(?)
Ornithopoda:
Othnielia(?) sp.

CO-25 Upper Split Rock Site 2 (In upper sandstone bed)
Mesa Co., CO
J.I. Kirkland (oral commun., 1993)
Sauropoda:
Apatosaurus sp.
Ornithopoda:
Dryosaurus altus(?)

CO-26 Rabbit Valley-E Site
Mesa Co., CO
J.I. Kirkland (oral commun., 1993)
Sauropoda:
Supersaurus sp.

CO-27 Bollan's Site
Mesa Co., CO
Bollan (1991), J.I. Kirkland (oral commun., 1993)
Theropoda:
Allosaurus sp. (tooth)
Thyreophora:
Stegosaurus ungulatus

FRUITA PALEONTOLOGICAL AREA

CO-33 Callison's Quarries (Includes four sites at same stratigraphic level, all nearby)
Mesa Co., CO
Callison, 1987), J.I. Kirkland (oral commun., 1993, 1997)
Theropoda:
Ceratosaurus sp.
Allosaurus sp.
[Undetermined coelurosaur]
Sauropoda:
Brachiosaurus sp.
Camarasaurus sp.
Diplodocus sp.
Apatosaurus sp.
Thyreophora:
Echinodon sp.
Stegosaurus sp.

CO-34 FPA Dryosaur Nesting Site
Mesa Co., CO
J.I. Kirkland (oral commun., 1993)
Ornithopoda:
Dryosaurus sp.

CO-35 LACM Quarry (Clark's Quarry)
Mesa Co., CO
J.I. Kirkland (oral commun., 1993)
Thyreophora:
Stegosaurus sp.

CO-36 Riggs' Quarry 15 (Dinosaur Hill Quarry)
Mesa Co., CO
Chenoweth (1987), Goodknight and others (1991)
Sauropoda:
Diplodocus sp.
Apatosaurus excelsus

RIGGS HILL AREA

CO-45 Riggs' Quarry 13 (Riggs Hill)
Mesa Co., CO
Riggs (1903)
Sauropoda:
Brachiosaurus altithorax

CO-46 Holt's Quarry 1
Mesa Co., CO
Holt (1940)
Thyreophora:
Stegosaurus sp.

CO-47 Holt's Quarry 2
Mesa Co., CO
Holt (1940)
Theropoda:
Allosaurus sp.
Sauropoda:
Brachiosaurus(?) sp.

GUNNISON AREA

CO-48 Cabin Creek Quarry
Gunnison Co., CO
Bartleson and Jensen (1988)
Sauropoda:
Apatosaurus sp.

CO-49 Curecanti-Red Creek Quarry
Gunnison Co., CO
Fiorillo and May (1996)
Theropoda:
Allosaurus sp.
Sauropoda:
Apatosaurus(?) sp.

MORRISON AREA

CO-51 Lake's Quarries 1, 5, 8
Jefferson Co., CO
Ostrom & McIntosh (1966), J.S. McIntosh (written commun., 1997)
Sauropoda:
Camarasaurus sp.
Diplodocus sp.
Apatosaurus ajax
Thyreophora:
Stegosaurus armatus

CO-52 Lake's Quarry 10-L (In black mudstone bed)
Jefferson Co., CO
Ostrom & McIntosh (1966)
Theropoda:
Allosaurus sp.
Sauropoda:
Apatosaurus ajax

CO-53 Lake's Quarry 10-U (In buff sandstone bed)
Jefferson Co., CO
Ostrom & McIntosh (1966)
Sauropoda:
Apatosaurus ajax

UNCOMPAHGRE PLATEAU

CO-55 Cactus Park Quarry (Of J.A. Jensen)
Mesa Co., CO
J.R. Foster (written commun., 1997), J.S. McIntosh (written commun., 1997)
Sauropoda:
Camarasaurus sp.
Apatosaurus sp.
Thyreophora
Stegosaurus sp.

CO-56 Dominguez-Jones Quarry (Pit 1 of J.A. Jensen)
Mesa Co., CO
Jensen (1988), McIntosh and others (1996)
Sauropoda:
Camarasaurus lewisi

CO-57 Hups' Cactus Park Quarry
Mesa Co., CO
K. Carpenter (written commun., 1997), J.R. Foster (written commun., 1997)
Theropoda:
Allosaurus sp.
Thyreophora:
Mymoorapelta maysi

CO-58 Dry Mesa Quarry 1
Mesa Co., CO
Jensen (1985, 1987), Britt (1991), Miller and others (1991), W.E. Miller (oral commun., 1992), Curtice & Wilhite (1996), Curtice and others (1996)
Theropoda:
Ceratosaurus sp.
Allosaurus sp.
Torvosaurus tanneri
?Ornitholestes sp. and (or) Coelurus sp.
Marshosaurus sp.
Sauropoda:
Brachiosaurus sp.
Dystylosaurus edwini
Camarasaurus sp.
Diplodocus sp.
Apatosaurus sp.
Supersaurus vivianae
Thyreophora:
Stegosaurus sp.
Ankylosaur, undetermined
Ornithopoda:
Dryosaurus sp.
Camptosaurus sp.

CO-59 Dry Mesa Quarry 2 (Jones Hole Quarry)
Mesa Co., CO
W.E. Miller (oral commun., 1992), J.S. McIntosh, written commun., 1997)
Theropoda:
Allosaurus sp.
Sauropoda
Barosaurus sp.
Ornithopoda:
Camptosaurus sp.

CO-60 Potter Creek Quarry
Montrose Co., CO
Jensen (1985, 1987)
Sauropoda:
?Brachiosaurus altithorax

URAVAN AREA

CO-66 Sheetz' Quarry 1
Montrose Co., CO
Galton & Jensen (1973), Scheetz (1991)
Ornithopoda:
Dryosaurus altus (baby)

CAÑON CITY
(Garden Park area)
Additional localities donated by K. Carpenter after technical reviews, from Carpenter (1998)

CO-70 Shaw's Park 3
Fremont Co., CO
Theropoda:
Allosaurus sp.

CO-71 Cope's Quarry 12
Fremont Co., CO
Sauropoda:
Amphicoelias altus

CO-72 Egg Gulch
Fremont Co., CO
Ornithopoda:
Dryosaurus? sp.

CO-73 Meyer Sites 1 and 2
Fremont Co., CO
Theropoda:
Allosaurus sp.
Torvosaurus cf. T. tanneri

CO-74 Meyer Site 3
Fremont Co., CO
Sauropoda:
Diplodocus sp.

CO-75 Kenny's Stegosaur Site
Fremont Co., CO
Thyreophora:
Stegosaurus cf. S. stenops

CO-76 Cope's Quarry 15 (Oil Tract)
Fremont Co., CO
Stratigraphic position approximate
Sauropoda:
Camarasaurus sp.

CO-77 Gregg's Bone Site
Fremont Co., CO
Thyreophora:
Stegosaurus sp.

MONTANA

BRIDGER AREA

MT-1 Mothers Day Quarry
Carbon Co., MT
Kristi Curry (oral commun., 1996)
Theropoda:
Allosaurus sp.
[Dromeosaur tooth]
Sauropoda:
Diplodocus or Barosaurus (not Apatosaurus)
Thyreophora:
Stegosaurus(?) sp.

LIVINGSTON AREA

MT-2 Upper Strickland Creek Quarry
Park Co., MT
Matthew Smith (oral commun., 1992)
Theropoda:
Allosaurus sp.
Sauropoda:
[Family Diplodocidae (gen. & sp. undet.)]

TOSTON AREA

MT-6 T and J Quarry
(Ted and Jane Quarry)
Gallatin Co., MT
R.D. Scheetz (oral commun., 1995)
Theropoda:
Allosaurus? sp.
Sauropoda:
[Small mature sauropods]

NEW MEXICO

SE SAN JUAN BASIN AREA

NM-1 Acoma Quarry
Cibola Co., NM
Chenoweth (1953), Lucas and Hunt (1985)
Theropoda:
Allosaurus sp.

NM-2 Concho Springs Quarry
Cibola Co., NM
Chenoweth (1953), Lucas and Hunt (1985)
Thyreophora:
Stegosaurus sp.

NM-3 San Ysidro Camarasaur Quarry
Sandoval Co., NM
Rigby (1982), Lucas and Hunt (1985)
Theropoda:
Allosaurus sp. (teeth)
Sauropoda:
Camarasaurus supremus

NM-4 Seismosaur Quarry
Sandoval Co., NM
Gillette (1991), Schwartz and Manley (1992)
Theropoda:
cf. Allosaurus sp. (teeth)
Sauropoda:
Seismosaurus hallorum

NM-5 Boney Canyon Quarry
Bernalillo Co., NM
T.E. Williamson (oral commun., 1997)
Theropoda:
[Large allosaurid (partial skeleton)]
Sauropoda:
[Diplodocid (partial skull)]
Camarasaurus sp. (partial skull)

NM-6 Boney Canyon-NE Site
Bernalillo Co., NM
T.E. Williamson (oral commun., 1997)
Sauropoda:
Camarasaurus sp. (tooth)

NM-7 San Ysidro Diplodocid Quarry
Bernalillo Co., NM
Anderson and Lucas (1996), T.E. Williamson (oral commun., 1997).
Sauropoda:
Diplodocus sp.

NE NEW MEXICO AREA

NM-10 Bull Canyon Site
Guadalupe Co., NM
Lucas and others (1985)
Thyreophora:
?Stegosaurus sp.

OKLAHOMA

KENTON AREA

OK-1 Stovall's Pit 1
Cimarron Co., OK
Langston (1989), Chure (1995)
Theropoda:
Allosaurus sp.
Saurophaganax maximus
Sauropoda:
Diplodocus sp.
[Diplodocus or Barosaurus sp. (may pertain to Amphicoelias sp.)]
cf. Apatosaurus sp.
Apatosaurus? sp. or Camarasaurus? sp.
Thyreophora:
Stegosaurus sp.
Ornithopoda:
Camptosaurus sp.

OK-2 Stovall's Pit 5
Cimarron Co., OK
Langston (1989)
Theropoda:
Allosaurus sp.
Sauropoda:
Camarasaurus sp.
?Diplodocus sp.
?Apatosaurus sp.
Thyreophora:
?Stegosaurus sp.
Ornithopoda:
?Camptosaurus sp.

OK-3 Stovall's Pit 6
Cimarron Co., OK
Langston (1989)
Theropoda:
Allosaurus sp.
Sauropoda:
?Camarasaurus sp.
Diplodocus sp.
Apatosaurus sp.
Ornithopoda:
Camptosaurus sp.

OK-4 Stovall's Pit 8
Cimarron Co., OK
Langston (1989)
Theropoda:
[?Coelurosaurian dinosaur]
Ornithopoda:
?Camptosaurus sp.

SOUTH DAKOTA

BLACK HILLS EAST AREA

SD-1 Bear Butte Quarry
Meade Co., SD
Foster (1996ab)
Sauropoda:
Apatosaurus sp.

SD-2 Fuller's 351 (Spearfish) Quarry
Lawrence Co., SD
Foster (1996ab), J.R. Foster (written commun., 1997)
Theropoda:
Allosaurus sp.
Sauropoda:
Camarasaurus sp.
Apatosaurus sp.

SD-3 Piedmont Quarry
Meade Co., SD
Lull (1919), Dodson and others (1980)
Theropoda:
Allosaurus sp.
Sauropoda:
Barosaurus lentus

SD-4 Wonderland Quarry
Meade Co., SD
Foster (1996ab)
Theropoda:
Allosaurus sp.
[Unidentified theropod (illium, resembles Stokesosaurus or Marshosaurus)]
Sauropoda:
Camarasaurus sp. (teeth)
Barosaurus lentus

SD-5 Wonderland North Quarry
Meade Co., SD
Foster (1996ab)
Sauropoda:
Diplodocus sp.

UTAH

HANKSVILLE AREA

UT-1 Hanksville Quarry
Wayne Co., UT
J.S. McIntosh (written commun., 1997)
Theropoda
[Unidentified new(?) theropod]
Sauropoda:
Apatosaurus sp.
(Originally thought to be Camptosaurus sp. according to J.T. Gregory, written commun., 1992)

MOAB AREA

UT-4 East Canyon Quarry
San Juan Co., UT
Cope (1877), D.D. Gillette (oral commun., 1995)
Sauropoda:
Dystrophaeus viaemalae

SAN RAFAEL SWELL AREA

UT-7 Cleveland-Lloyd Quarry
Emery Co., UT
Madsen (1976), J.H. Madsen (written commun., 1994, oral commun., 1997), Miller and others (1996)
Theropoda:
Ceratosaurus sp.
Allosaurus fragilis
Stokesosaurus clevelandi
Ornitholestes?
Marshosaurus bicentesimus
Sauropoda:
Haplocanthosaurus sp.
Camarasaurus lentus
Barosaurus sp.
Amphicoelias? sp.
Thyreophora:
Stegosaurus stenops
Nodosaur, undetermined
Ornithopoda:
Camptosaurus cf. C. dispar

UT-8 Sand Bench Site
Emery Co., UT
Richmond & Stadtman (1996)
Theropoda:
Ceratosaurus nasicornis

UT-9 Green River Quarry
Emery Co., UT
Kolb and others (1996), L.E. Davis (oral commun., 1996)
Theropoda:
Allosaurus sp.
Sauropoda:
Camarasaurus(?) sp.
Thyreophora:
Stegosaurus(?) sp.

DINOSAUR NATIONAL MONUMENT WEST
(South of Green River)

UT-12 Jensen/Jensen Quarry
Uintah Co., UT
Jensen (1987), D.J. Chure (oral commun., 1993)
Sauropoda:
Brachiosaurus sp.
Camarasaurus sp.
Apatosaurus sp.

UT-13 Utah Field House of Natural History Quarry
Uintah Co., UT
Bilbey and Hamblin (1992), D.J. Chure (oral commun., 1993)
Thyreophora:
Stegosaurus sp.

UT-14 DNM-5
Uintah Co., UT
D.J. Chure (oral commun., 1993)
Theropoda:
Allosaurus sp.
Ornithopoda:
Dryosaurus sp.

DINOSAUR NATIONAL MONUMENT WEST
(Near Carnegie Quarry)

UT-17 DNM-15
Uintah Co., UT
D.J. Chure (oral commun., 1993)
Sauropoda:
Apatosaurus sp.

UT-18 Carnegie Quarry
Uintah Co., UT
D.J. Chure (written commun., 1991), J.S. Mcintosh (written commun., 1997)
Theropoda:
Ceratosaurus nasicornis
Allosaurus fragilis
Torvosaurus tanneri
Marshosaurus bicentesimus
Sauropoda:
Camarasaurus lentus
Diplodocus longus
Barosaurus lentus
Apatosaurus louisae
Thyreophora:
Stegosaurus ungulatus
Stegosaurus stenops
Ornithopoda:
Dryosaurus altus
[Ornithischian, unidentified]

UT-19 DNM-315
Uintah Co., UT
Chure and others (1994)
Ornithopoda:
Camptosaurus sp. (Embryo)

UT-20 DNM-116 (N.A.A. Quarry)
Uintah Co., UT
D.J. Chure (oral commun., 1997)
Theropoda:
Allosaurus n. sp. (possibly new genus)

DINOSAUR NATIONAL MONUMENT WEST
(Rainbow Park area)

UT-24 DNM-8 (Soft Sauropod Quarry)
Uintah Co., UT
D.J. Chure (oral commun., 1991)
Sauropoda:
Apatosaurus sp.

UT-25 DNM-94 (Quarry 94, Rainbow Park microsite)
Uintah Co., UT

Chure (1989; 1994), D.J. Chure (oral commun., 1997)

Theropoda:

- Allosaurus sp.
- Koparion douglassi
- Troodontid second sp.

Sauropoda:

- Camarasaurus sp.
- Diplodocus sp.

Thyreophora:

- Stegosaurus sp.

Ornithopoda:

- Dryosaurus sp.
- Camptosaurus sp.

UT-26 DNM-96 (Quarry 96, Rainbow Park microsite)
Uintah Co., UT

D.J. Chure (oral commun., 1997)

Theropoda:

- Allosaurus sp.

Sauropoda:

- Camarasaurus sp.
- Diplodocus sp.

Thyreophora:

- Stegosaurus sp.

Ornithischian:

- Dryosaurus sp.
- Camptosaurus sp.

WYOMING

ALCOVA AREA

WY-1 Cottonwood Creek Site-1
Natrona Co., WY
Allen (1994)
Ornithopoda:
cf. Dryosaurus sp.

WY-2 Cottonwood Creek Site-2
Natrona Co., WY
Allen (1994)
Sauropoda:
Camarasaurus sp.

WY-3 Cottonwood Creek Site-3
Natrona Co., WY
Allen (1994)
Sauropoda:
Diplodocus sp.

WY-4 Allen's (1994) Allosaur Site
Natrona Co., WY
Allen (1994)
Theropoda:
Allosaurus sp.

BLACK HILLS NORTHWEST

WY-8 Lower Dillon's Corner Site
Crook Co., WY
Foster and Martin (1994)
Theropoda:
?Allosaurus sp.

WY-9 Upper Dillon's Corner Site
Crook Co., WY
Foster and Martin (1994)
Sauropoda:
cf. Barosaurus sp.

WY-10 Lightning Rod Butte Quarry
Crook Co., WY
Foster and Martin (1994)
Ornithopoda:
Othnielia sp.

WY-11 Little Houston Quarry
Crook Co., WY
Foster and Martin (1994), Foster (1996ab)
Theropoda:
Allosaurus sp.
Sauropoda:
Camarasaurus sp.
Diplodocus or Barosaurus sp.
Apatosaurus sp.
Thyreophora:
Stegosaurus sp.
Ornithopoda:
Othnielia sp.
Dryosaurus sp.
[Ornithischian, indeterminate]

WY-12 MIA Quarry
Crook Co., WY
Foster and Martin (1994), J.R. Foster, written commun. (1997)
Sauropoda:
Barosaurus sp.

COMO BLUFF WEST
(West of Marshall Road)

WY-15 Reed's Quarry 9
Albany Co., WY
Ostrom and McIntosh (1966), Bakker and others (1990), Sues and Norman (1990)
Theropoda:
Allosaurus fragilis
Coelurus fragilis
Sauropoda:
Camarasaurus sp.
Thyreophora:
Stegosaurus sp.
Ornithopoda:
Othnielia rex (may not be from this quarry)
Drinker nisti
Dryosaurus sp.
Camptosaurus sp.

WY-16 Reed's Quarry 14
Albany Co., WY
Ostrom and McIntosh (1966)
Theropoda:
Allosaurus sp.

WY-17 Reed's Quarry 10
Albany Co., WY
Ostrom and McIntosh (1966)
Sauropoda:
Apatosaurus excelsus

WY-18 Reed's Quarry 11
Albany Co., WY
Ostrom and McIntosh (1966), Galton (1990), J.S. McIntosh (written commun., 1997)
Sauropoda:
Apatosaurus excelsus
Thyreophora:
Stegosaurus ungulatus

WY-19 Reed's Quarry 8
Albany Co., WY
Ostrom and McIntosh (1966)
Theropoda:
Allosaurus sp.
"Coelurus fragilis"
Sauropoda:
Camarasaurus sp.
Diplodocus sp.
Thyreophora:
Stegosaurus sp.

WY-20 Reed's Quarry 3
Albany Co., WY
Ostrom and McIntosh (1966), Molnar and others (1990)
Theropoda:
Allosaurus fragilis
Sauropoda:
Camarasaurus grandis

WY-21 Reed's Quarry 1
Albany Co., WY
Ostrom and McIntosh (1966), Molnar and others (1990)
Theropoda:
Allosaurus fragilis
Sauropoda:
Camarasaurus grandis
Diplodocus sp.

WY-22 Louise Quarry
Albany Co., WY
Bakker and others (1992), J. Filla (oral commun, 1993)
Theropoda:
Allosaurus sp.
Edmarka rex
Sauropoda:
Camarasaurus sp.
Apatosaurus sp.
Thyreophora:
Stegosaurus(?) sp.

WY-23 Reed's Quarry 2 (Fishplate Quarry)
Albany Co., WY
Ostrom and McIntosh (1966)
Sauropoda:
Apatosaurus sp.

WY-24 Drinker Nisti Quarry-L (Lower Big Nose Quarry?)
Albany Co., WY
Bakker and others (1990)
Ornithopoda:
Drinker nisti

WY-25 Drinker Nisti Quarry-U (Upper Big Nose Quarry?)
Albany Co., WY
Bakker and others (1990)
Ornithopoda:
Drinker nisti

WY-26 Reed's Quarry 5
Carbon Co., WY
Ostrom and McIntosh (1966)
Sauropoda:
Diplodocus sp.
Ornithopoda:
Dryosaurus altus

WY-27 Lake's Quarry 1A (Big Canyon Quarry)
Carbon Co., WY
Ostrom and McIntosh (1966)
Theropoda:
Allosaurus sp.
Sauropoda:
Camarasaurus sp.
Ornithopoda:
Camptosaurus amplus

WY-28 Reed's Quarry 7 (Three Trees Quarry)
Carbon Co., WY
Ostrom and McIntosh (1966)
Ornithopoda:
Othnielia rex

WY-29 Reed's Quarry 12
Carbon Co., WY
Ostrom and McIntosh (1966), (Galton (1990), J.S. McIntosh (written commun., 1997)
Theropoda:
Allosaurus sp.
Coelurus sp.
Sauropoda:
Camarasaurus sp.
Diplodocus sp.
Thyreophora:
Stegosaurus ungulatus
Ornithopoda:
Othnielia? sp. or Dryosaurus? sp.

WY-30 Reed's Quarry 1½
Carbon Co., WY
Ostrom and McIntosh (1966), Molnar and others (1990)
Theropoda:
Allosaurus fragilis
Sauropoda:
[Unidentified sp.]

WY-31 Cope's Quarry 3
Carbon Co., WY
J.S. McIntosh (oral commun., 1997)
Theropoda:
Allosaurus sp.

COMO BLUFF EAST
(East of Marshall Road)

WY-39 Nail Quarry
Albany Co., WY
Bakker and others (1992),
Theropoda:
Allosaurus sp.
Edmarka rex
Sauropoda:
Camarasaurus sp.
Diplodocus sp.
Apatosaurus sp.
Thyreophora:
Stegosaurus sp.

WY-40 Reed's Quarry 4 (Truckstop Quarry)
Albany Co., WY
Ostrom and McIntosh (1966)
Theropoda:
Allosaurus fragilis
Sauropoda:
Camarasaurus sp.
Barosaurus sp.
Apatosaurus sp.
Thyreophora:
Stegosaurus sp.

WY-41 Two Thigh Quarry
Albany Co., WY
R.T. Bakker (oral commun., 1993)
Ornithopoda:
Drinker nisti

WY-42 Bernice Quarry
Albany Co., WY
J. Filla (oral commun., 1993)
Sauropoda:
Diplodocus sp.

WY-43 Cam Bench Quarries (West, Middle, and East Sites)
Albany Co., WY
J. Filla (oral commun., 1993)
Sauropoda:
Camarasaurus sp.
Ornithopoda:
Camptosaurus(?) sp.

WY-44 Bertha Quarry
Albany Co., WY
J. Filla (oral commun, 1993), R.T. Bakker (oral commun., 1993),
Filla and Redmond (1994)
Sauropoda:
Apatosaurus yahnahpin
Ornithopoda:
Dryosaurus sp.

WY-45 Zippy Quarry
Albany Co., WY
J. Filla (oral commun., 1993)
Sauropoda:
Diplodocus? sp.

WY-46 Reed's Quarry 13
Albany Co., WY
Ostrom and McIntosh (1966), Norman and Weishampel (1990),
K. Carpenter (oral commun., 1997), J.S. McIntosh (written commun., 1997)
Theropoda:
Coelurus fragilis
Sauropoda:
Camarasaurus lentus
Diplodocus sp.
Thyreophora:
Stegosaurus armatus
Stegosaurus ungulatus
Ornithopoda:
Othnielia? sp. or Dryosaurus? sp.
Camptosaurus dispar

WY-47 E.P. Thompson's Quarry
Albany Co., WY
R.T. Bakker (oral commun., 1993)
Sauropoda:
Diplodocus carnegii
Thyreophora:
Stegosaurus sp.
Ornithopoda:
Camptosaurus sp.

GREYBULL-SHELL AREA

WY-61 Big Al Quarry
Big Horn Co., WY
D. Maxwell (oral commun., 1992), R. Harmon (oral commun., 1993), Ver Ploeg (1991)
Theropoda:
Allosaurus sp.
Sauropoda:
Diplodocus sp.
Thyreophora:
Stegosaurus(?) sp.

WY-62 Howe Quarry
Big Horn Co., WY
Dodson and others (1980)
Theropoda:
Allosaurus sp.
Sauropoda:
Camarasaurus sp.
Diplodocus sp.
Barosaurus sp.
Ornithopoda:
Camptosaurus sp.

WY-63 Little Butte Quarry (Smithsonian "Quarry-2")
Big Horn Co., WY
M. Brett-Surman (oral commun., 1997)
Sauropoda:
Barosaurus? sp. or Diplodocus? sp.

WY-64 Big Butte Quarry (Smithsonian "Quarry 4")
Big Horn Co., WY
M. Brett-Surman (oral commun., 1997)
Sauropoda:
Apatosaurus? sp.
Thyreophora:
Stegosaurus sp.

KAYCEE

WY-71 Poison Creek (Erickson) Quarry
Johnson Co., WY
B.R. Erickson (written commun., 1994), J.R. Foster (written commun., 1997)
Theropoda:
Allosaurus sp.
Elaphrosaurus sp.
Sauropoda:
Haplocanthosaurus sp.
Camarasaurus sp.
Diplodocus sp.
[Diplodocid, gen. & sp. undet.]
Barosaurus(?) sp.
Apatosaurus sp.
Thyreophora:
Stegosaurus sp.
Ornithopoda:
Camptosaurus sp.

WY-72 Poison Creek (Flynn) Quarry-1
Johnson Co., WY
J.R. Foster (written commun., 1997)
Theropoda:
Allosaurus sp.
Sauropoda:
Camarasaurus sp.
Diplodocus sp.
Apatosaurus sp.
Thyreophora:
?Stegosaurus sp.

WY-73 Poison Creek (Flynn) Quarry-2
Johnson Co., WY
J.R. Foster (written commun., 1997)
Theropoda:
[Large theropod, (huge tooth) possibly megalosaurid or large allosaur]
Sauropoda:
Camarasaurus sp.

WY-74 Poison Creek (Flynn) Quarry-3
Johnson Co., WY
J.R. Foster (written commun., 1997)
Theropoda:
Allosaurus sp.

MEDICINE BOW ANTICLINE
(Also called Flat Top Anticline)

WY-78 Bone Cabin Quarry
Albany Co., WY
Shepard and others (1977), Dodson and others (1980), McIntosh (1981, 1990a), Paul (1988)
Theropoda:
Allosaurus fragilis
Ornitholestes hermanni
Sauropoda:
Camarasaurus sp.
Diplodocus sp.
Apatosaurus excelsus
"Apatosaurus" minimus "...a valid species, but not belonging to Apatosaurus."
(J.S. McIntosh, 1990; written commun., 1997)
Thyreophora:
Stegosaurus stenops
Ornithopoda:
Dryosaurus altus
Camptosaurus sp.

WY-79 Bone Cabin Quarry-E (Eastward extension of old Bone Cabin Quarry)
Albany Co., WY
Jeff Parker (oral commun., 1997), K. Carpenter (written commun., 1997)
Theropoda:
Allosaurus fragilis
Sauropoda:
Brachiosaurus sp.
Camarasaurus grandis
Diplodocus sp.
Apatosaurus sp.
Thyreophora:
Stegosaurus stenops
Ankylosaur, new gen. & sp. (per K. Carpenter (oral commun. 1997)
Ornithopoda:
Dryosaurus sp.
Camptosaurus sp.

WY-80 Jeff Parker's Quarry (Near Stego 99 site)
Albany Co., WY
Jeff Parker (oral commun., 1992, 1997)
Theropoda:
Allosaurus sp. (teeth)
Sauropoda:
Camarasaurus sp.

WY-81 Pat McSherry's Quarry
Albany Co., WY
R.T. Bakker (oral commun., 1992)
Sauropoda:
Camarasaurus sp.

WY-82 Ninemile Hill Site
Carbon Co., WY
R.T. Bakker (oral commun., 1992)
Ornithopoda:
Drinker sp. (tooth)

WY-83 Meilyn Quarry
Carbon Co., WY
C.J. Weege (written commun., 1997),
Theropoda:
Allosaurus sp.
Thyreophora:
Stegosaurus sp.

WY-84 Lynn Quarry
Carbon Co., WY
C.J. Weege (written commun., 1997)
Theropoda:
Allosaurus sp.
Sauropoda:
Camarasaurus sp.
Diplodocus sp.
Ornithopoda:
Drinker? sp.

WY-85 Weege Boys Quarry
Carbon Co., WY
C.J. Weege (written commun., 1997)
Thyreophora:
Stegosaurus sp.

WY-86 Camarasaurus 1993 Quarry
Carbon Co., WY
C.J. Weege (oral commun., 1997)
Sauropoda:
Camarasaurus sp.
Diplodocus sp.
Barosaurus? sp.

SHEEP CREEK AREA

WY-91 AMNH Sheep Creek Quarry D
Albany Co., WY
McIntosh (1981, 1990b), J.S. McIntosh (written commun., 1997)
Sauropoda:
Camarasaurus grandis
Diplodocus carnegii
Apatosaurus excelsus
Thyreophora:
Stegosaurus ungulatus

WY-92 Zane Quarries 1-4
Albany Co., WY
R.T. Bakker (oral commun., 1992, 1993), Bakker and others (1992)
The quarries are at four stratigraphic levels within a 16.5 ft (5.0 m) thick interval; a faunal list for the individual quarries was not available.
Theropoda:
[Megalosaurid]
Sauropoda:
Apatosaurus sp.
Diplodocus sp.
Thyreophora:
Stegosaurus sp.
Nodosaur gen & sp. undet.

THERMOPOLIS AREA

WY-98 BS (Beside Sauropod) Quarry
Hot Springs Co., WY
Bjoraker and Naus (1996), C.A. Naus (written commun., 1997)
Theropoda:
Allosaurus sp. (teeth)
Sauropoda:
Camarasaurus sp.
?Diplodocus sp.
?Apatosaurus sp.

WY-99-102 RB (RoadBone) Quarries
Hot Springs Co., WY
The name applies to the locality as well as to one of the producing stratigraphic levels.
Bjoraker and Naus (1996), C.A. Naus (written commun., 1997)

WY-99 PL Site
Thyreophora:
?Stegosaurus sp.
Ornithopoda:
?Camptosaurus sp.

WY-100 AD Site
Sauropoda:
?Diplodocus sp.

WY-101 RB Site
Sauropoda:
?Camarasaurus sp.,

WY-102 TH Site
Sauropoda:
?Diplodocus sp.

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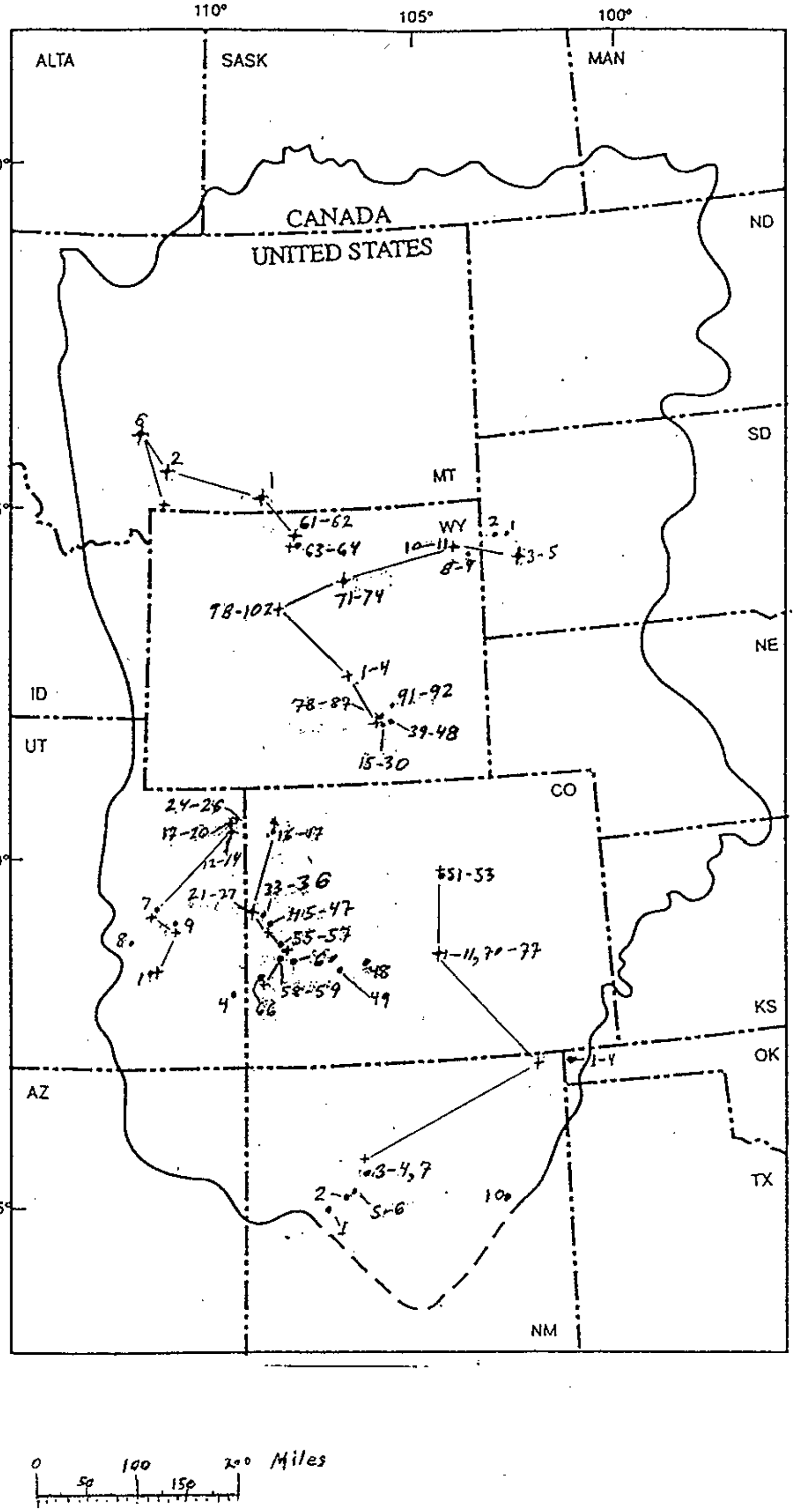

Figure 1.—Index map of the Western Interior showing dinosaur localities (dots), local reference sections (crosses), and lines of stratigraphic sections.

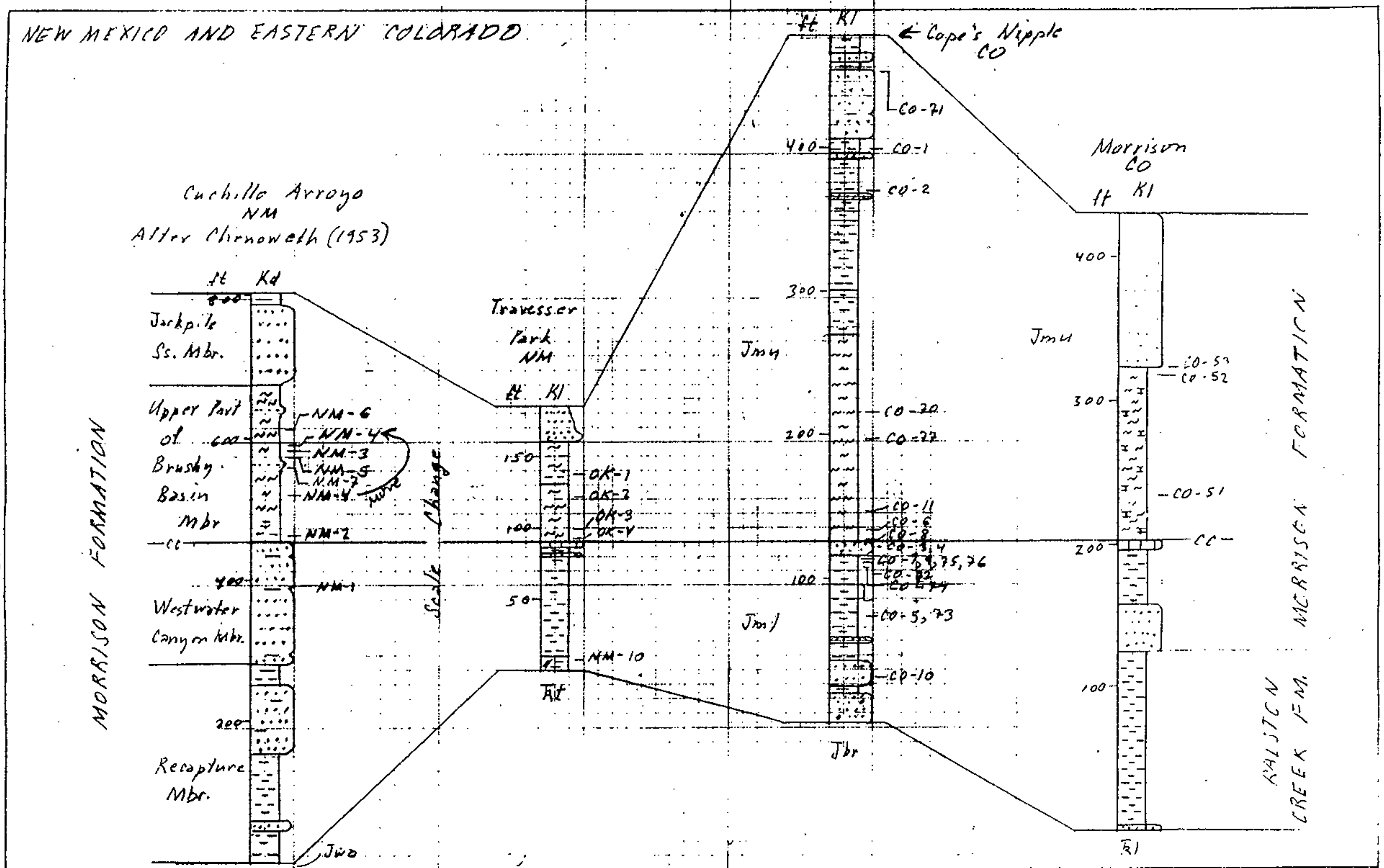

Figure 2.—A, Stratigraphic section showing stratigraphic position of dinosaur localities in New Mexico, Oklahoma, and eastern Colorado. Line of section shown on Figure 1.
B, The Explanation applies to this and Figures 3, 4, 5, 6, 7, 10, 11, 12, and 13.

EXPLANATION

- Pebbly sandstone
- Sandstone
- Eolian sandstone
- Nonsmectitic mudstone
- Smectitic mudstone
- Calcareous mudstone with thin limestone beds
- Limestone nodules
- Limestone
- Gypsum
- Partly covered
- Concealed

Kd	Dakota Formation
Kl	Lytle Formation
Kcm	Cedar Mountain Formation
Kbc	Burro Canyon Formation
Kcl	Cloverly Formation
Kla	Lakota Formation
Kk	Kootenai Formation

	Morrison Formation
Jmu	Upper Part
Jml	Lower Part
	Brushy Basin Member
uJmbb	Upper Part
lJmbb	Lower Part
Jms	Salt Wash Member
Jmt	Tidwell Member
Jmwh	Windy Hill Member
Jmuk	Unkpapa Member
Jbr	Bell Ranch Formation
Jwa	Wanakah Formation
Js	Summerville Formation
	Sundance Formation
Jsr	Redwater Member
Jr	Rierdon Formation
℞t	Travesser Formation
℞l	Lykins Formation

Figure 2B

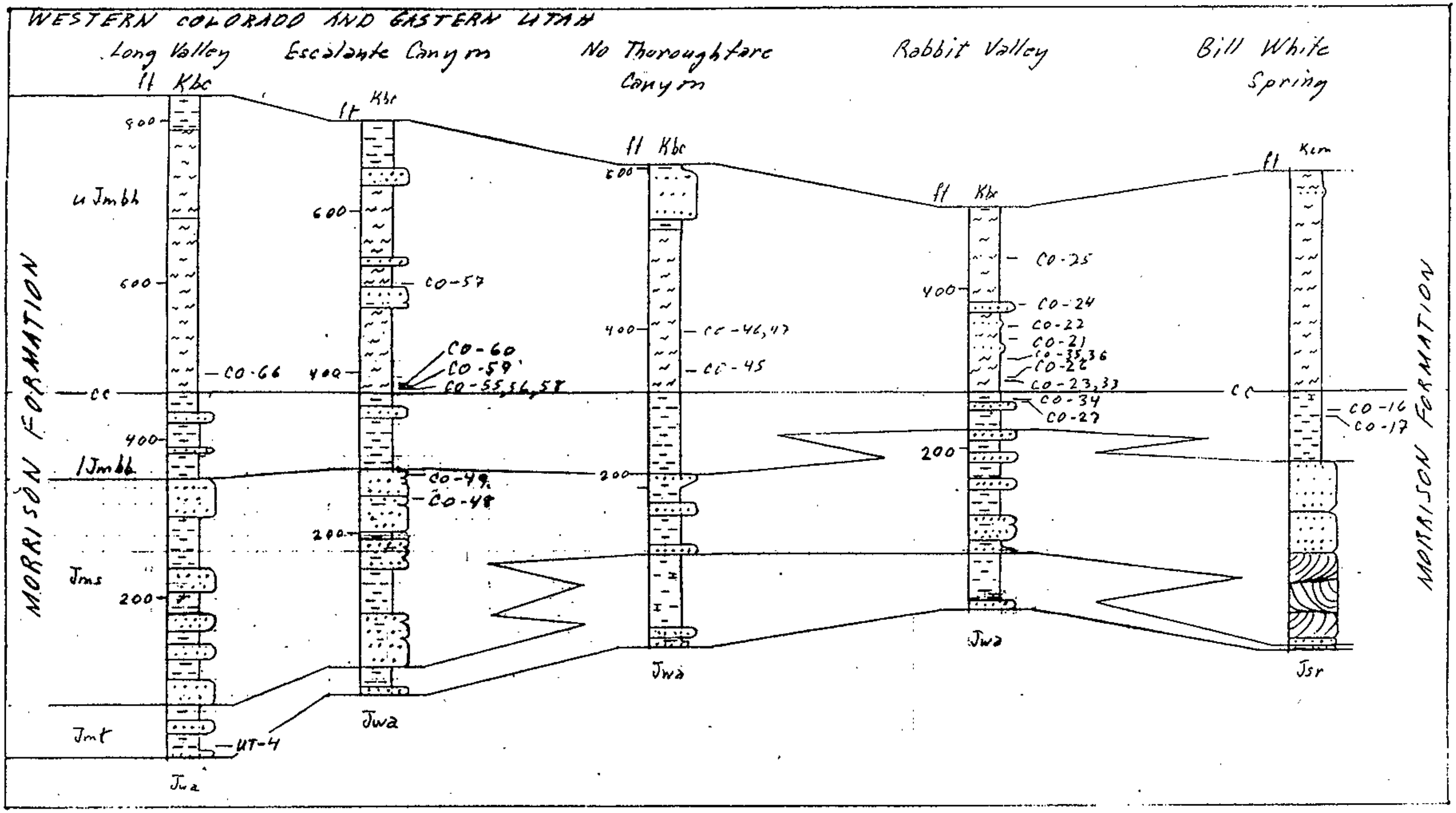

Figure 3.—Stratigraphic section showing stratigraphic position of dinosaur localities in western Colorado and southeastern Utah. Line of section shown on Figure 1.

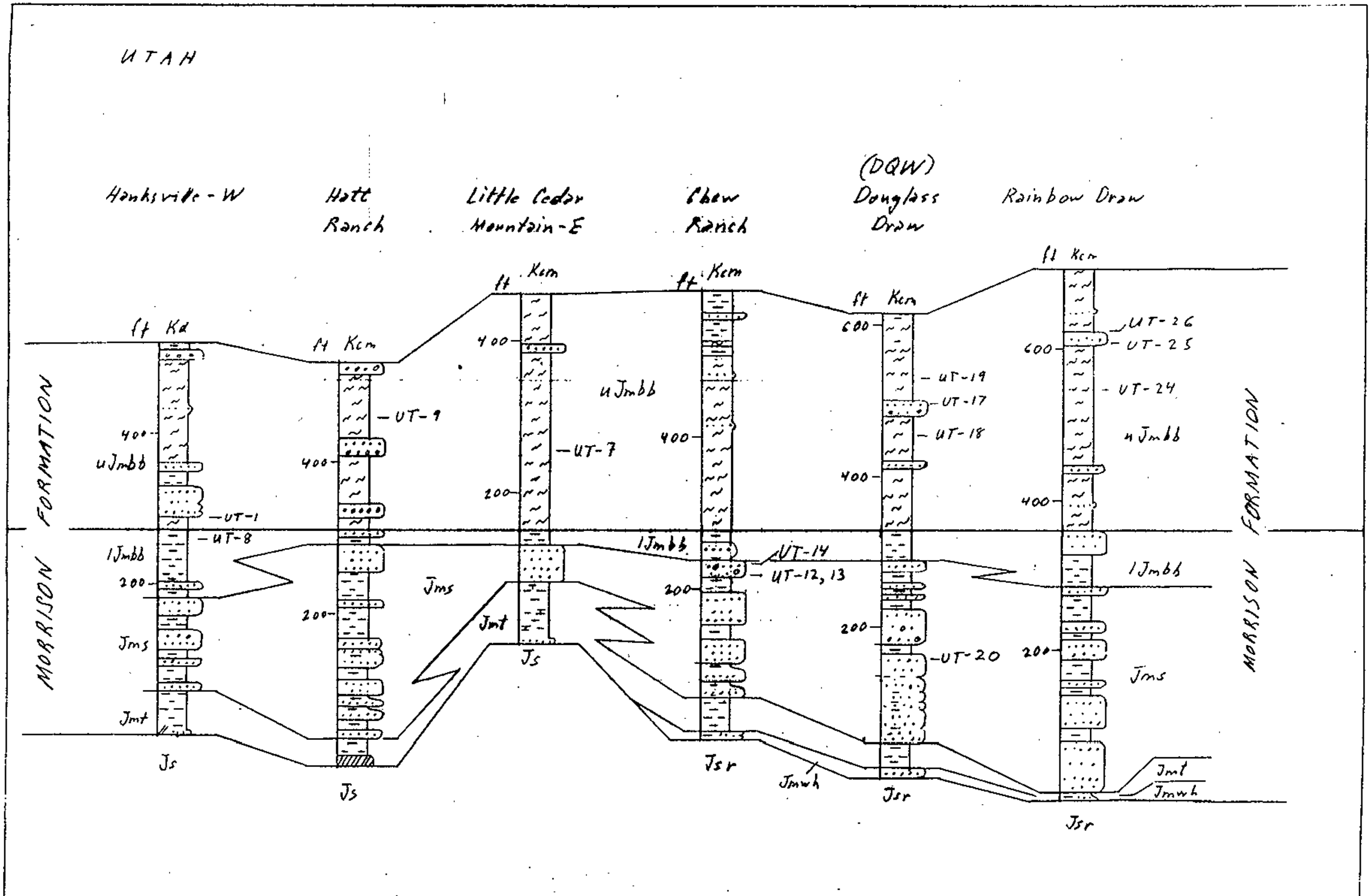

Figure 4.—Stratigraphic section showing stratigraphic position of dinosaur localities in eastern Utah. Line of section shown on Figure 1.

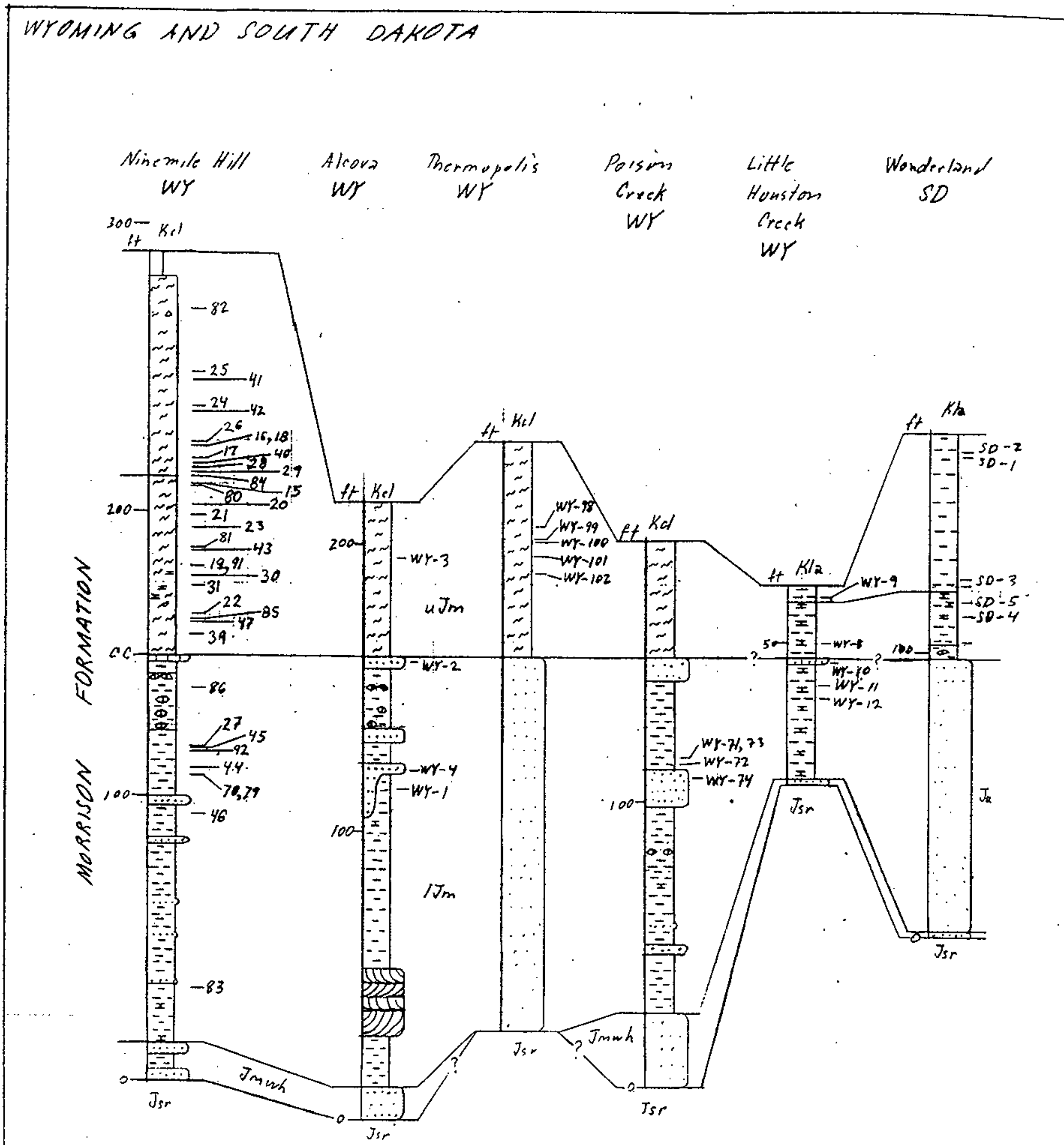

Figure 5.—Stratigraphic section showing stratigraphic position of dinosaur localities in Wyoming and South Dakota. Line of section shown on Figure 1.

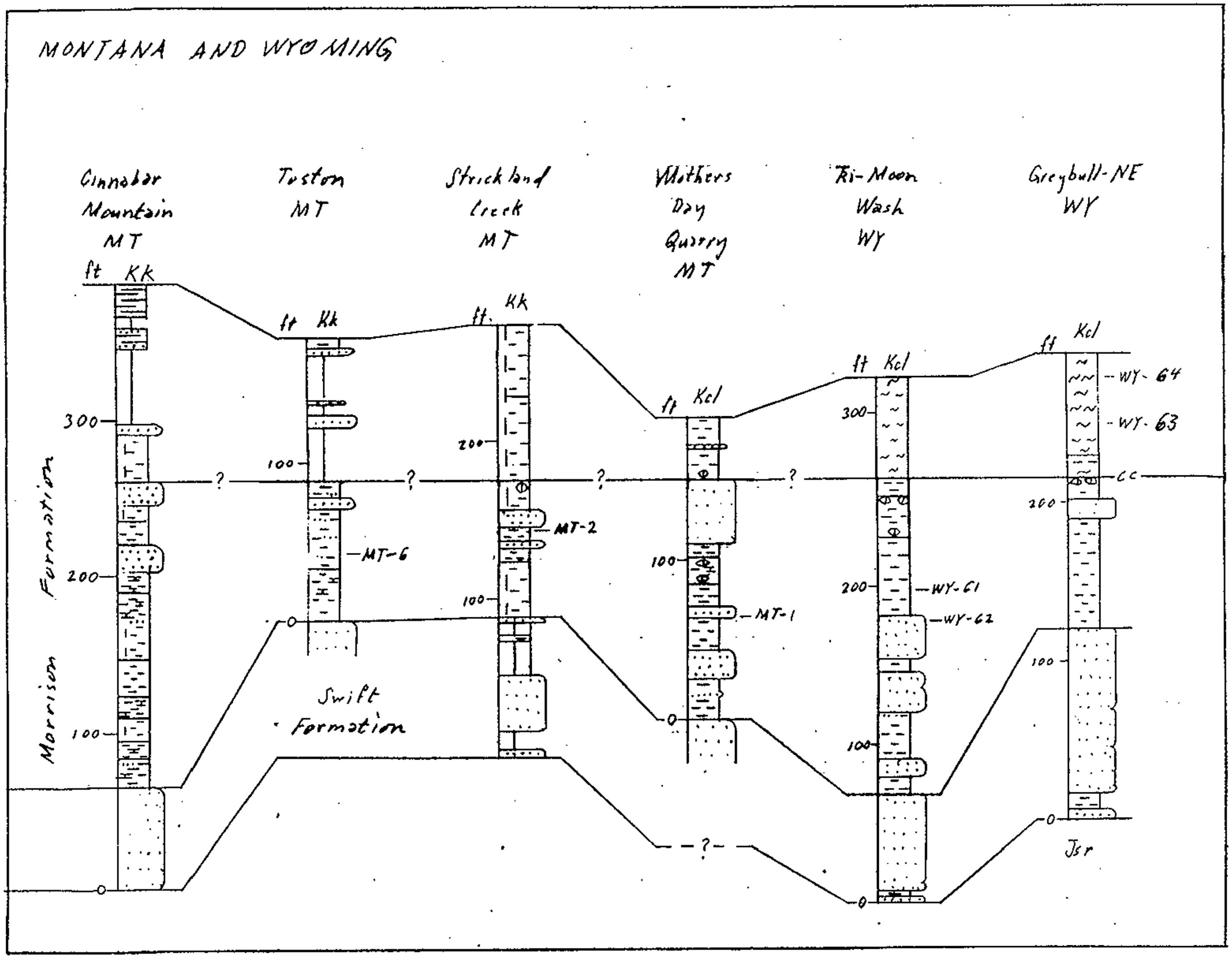

Figure 6.—Stratigraphic section showing stratigraphic position of dinosaur localities in north-central Wyoming and southern Montana. Line of section shown on Figure 1.

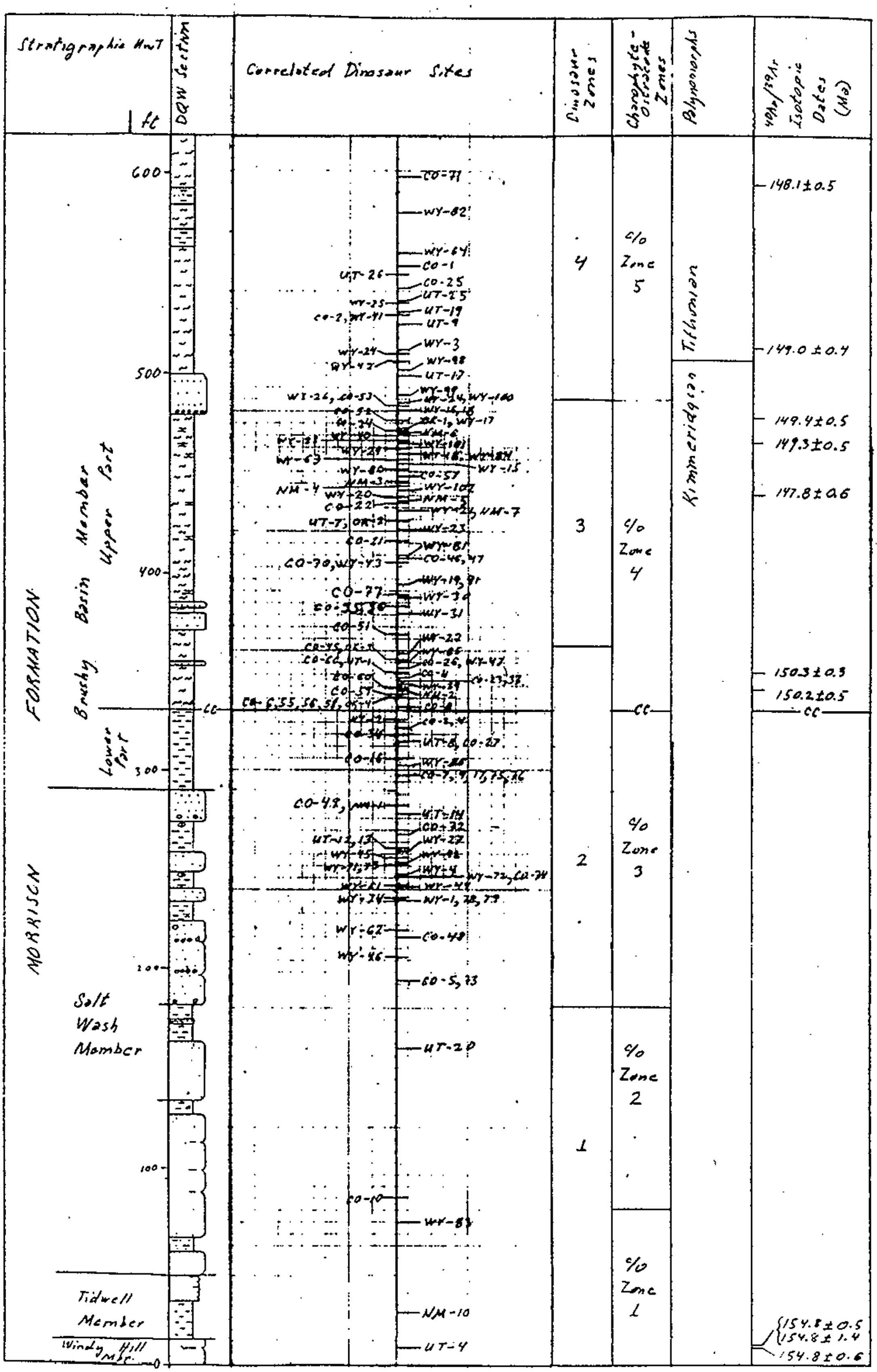

Figure 7.—Primary Reference Section (DQW) in western Dinosaur National Monument, Utah, showing dinosaur zonation of this report and other age-diagnostic criteria. Charophyte-ostracode zonation from Schudack and others (in press), Kimmeridgian-Tithonian boundary from Litwin and others (in press), isotopic dates from Kowallis and others (in press).

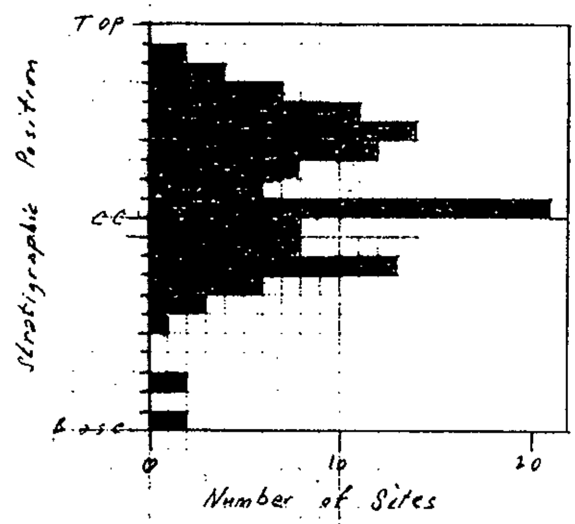

Figure 8.—Number of correlated dinosaur localities in each 30 ft (9.1 m) increment of stratigraphic thickness at the primary reference section (DQW) in western Dinosaur National Monument, Utah. Localities in the Black Hills and Montana not included.
CC = Clay change.

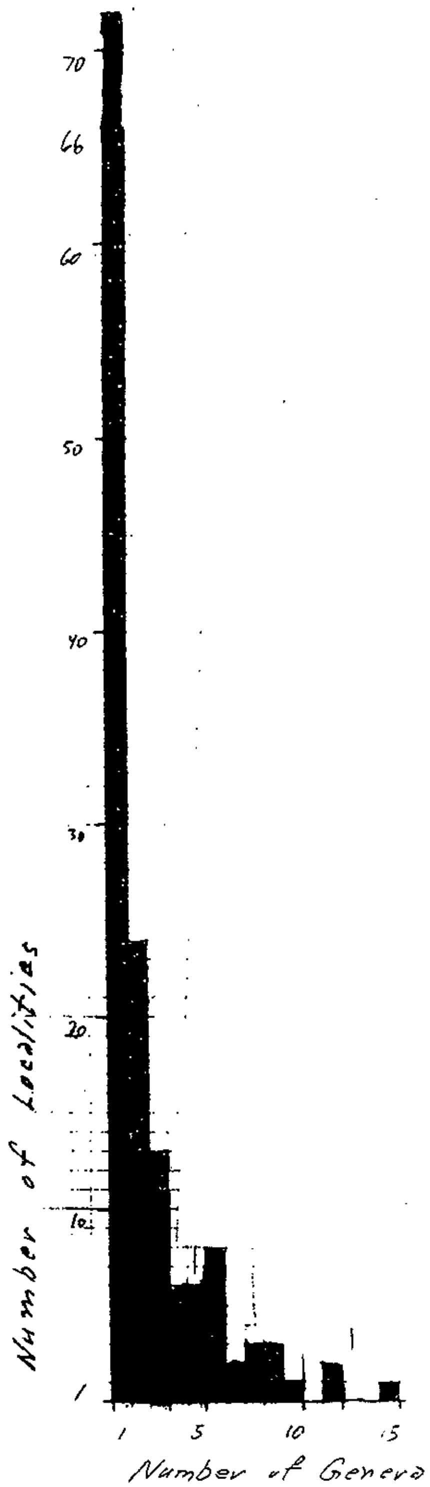

Figure 9.—Number of different dinosaur genera at each of the localities studied. Includes the broader category of ankylosaurs if no ankylosaur genus was identified. 51 percent of the sites have only one genus identified, 67 percent have one or two genera identified.

Figure 10.—Biostratigraphic ranges of dinosaurs in the Morrison Formation from localities that can be correlated to the primary reference section (DQW). The four dinosaur faunal zones are indicated on the right.

Fig. 10

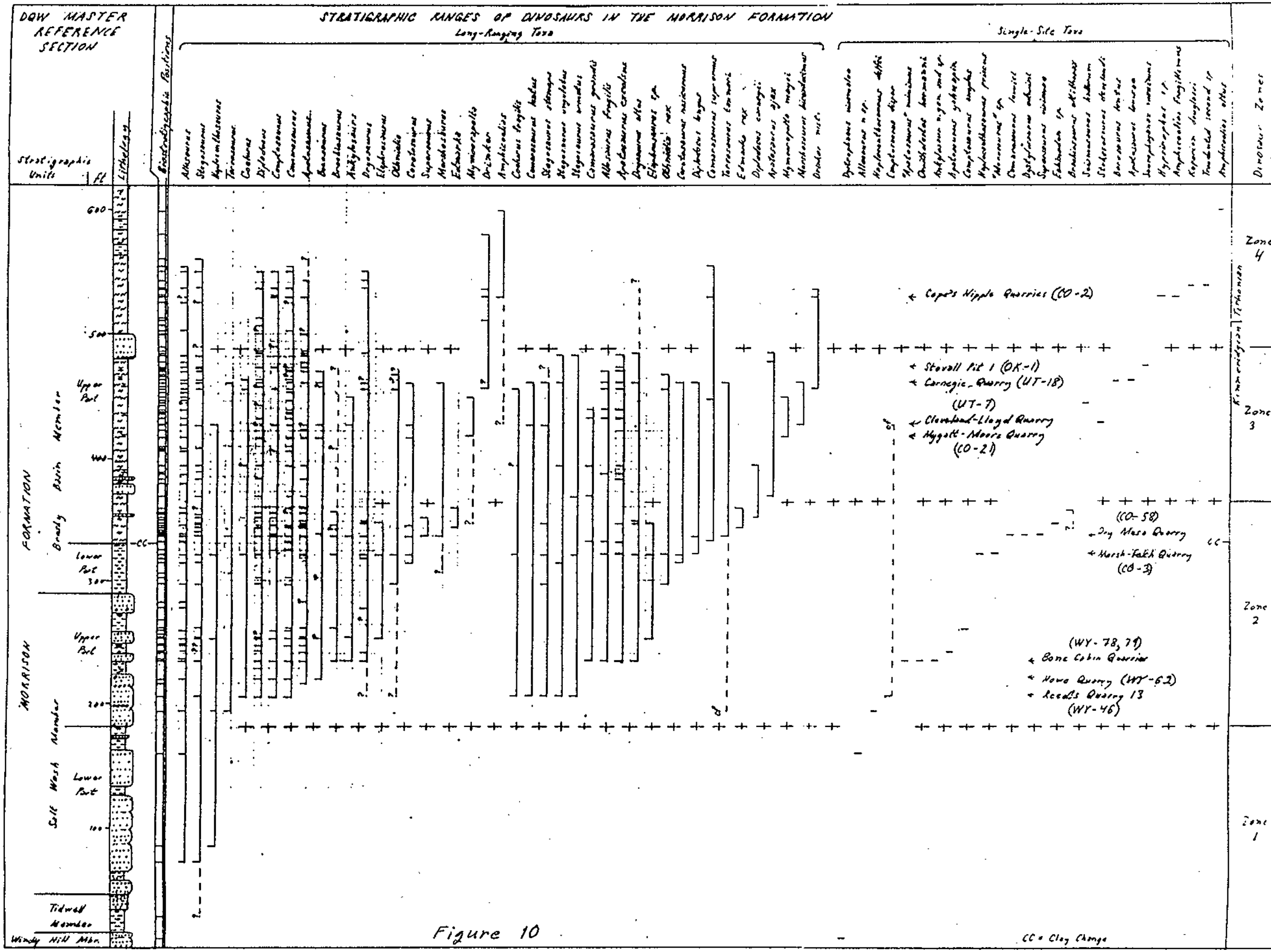

Figure 10

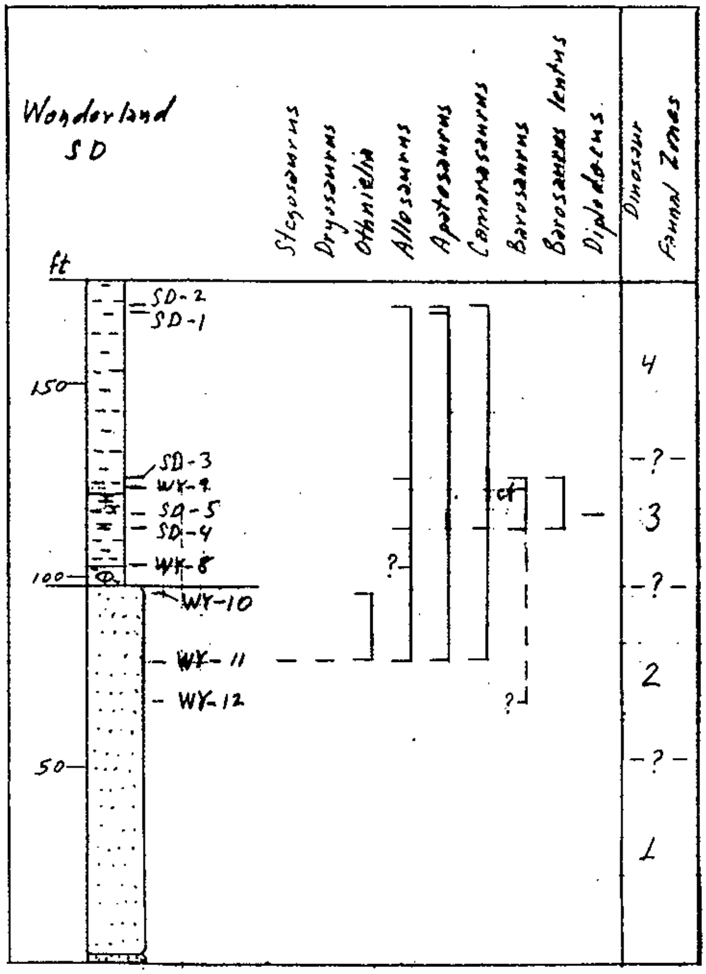

Figure 11.—Biostratigraphic ranges of dinosaurs in the Morrison Formation of the Black Hills of South Dakota and Wyoming.

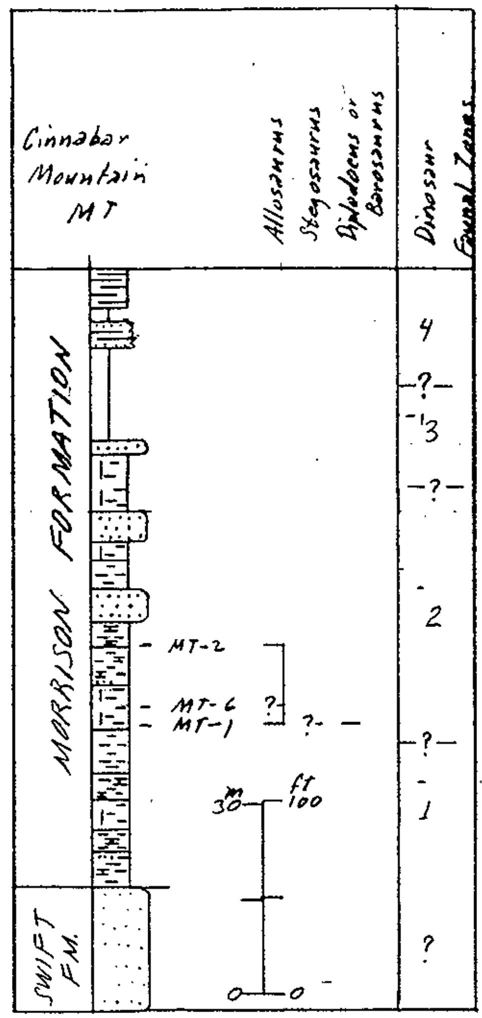

Figure 12.—Biostratigraphic ranges of dinosaurs in the Morrison Formation of southern Montana.

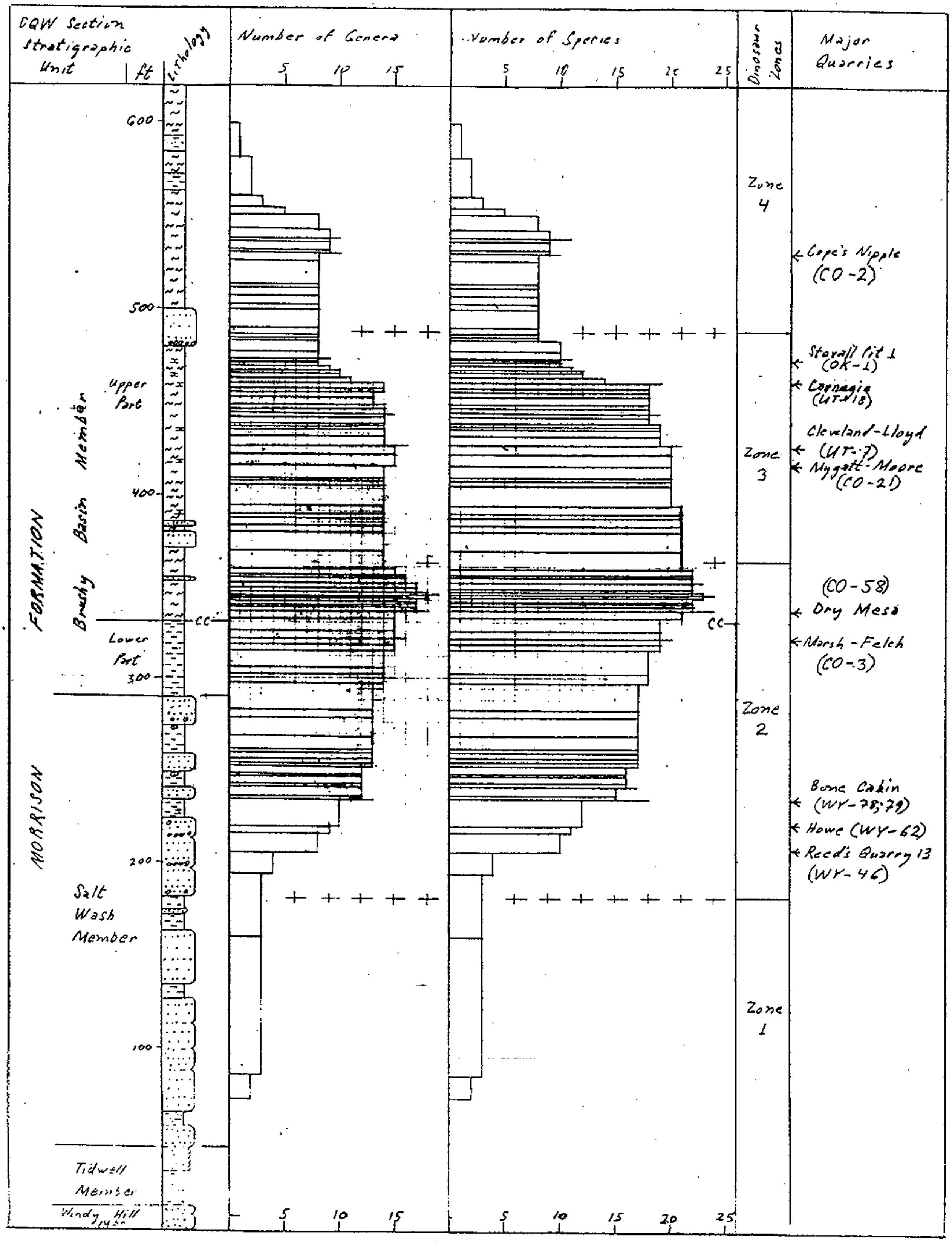

Figure 13.—Taxonomic diversity at the genus and species levels for dinosaurs in the Morrison Formation at localities correlated to the primary reference section (DQW).

TABLE 1.—Biostratigraphy of dinosaur taxa at various localities in the Morrison Formation of the Western Interior excluding the Black Hills and Montana. XX or 3X indicate the number of localities that have the indicated taxon at a stratigraphic level that includes two or three localities, respectively; c represents cf where space is crowded.

TABLE 1

LONG-RANGING TAXA

TAXON / TAXON IDENTITY NO.	Allosaurus 1	Stegosaurus 2	Haplocanthosaurus 3	Torvosaurus 4	Coelurus 5	Diplodocus 6	Camptosaurus 7	Camarasaurus 8	Apatosaurus 9	Barosaurus 10	Brachiosaurus 11	Ankylosaurs 12	Dryosaurus 13	Elaphrosaurus 14	Othnielia 15	Ceratosaurus 16	Supersaurus 17	Marshosaurus 18	Edmarka 19	Mymoorapelta 20	Drinker 21	Amphicoelias 22
CO-71																						X
WY-82																					X	
WY-64		X							?													
CO-1								X														
UT-26	X	X				X	X	X					X									
CO-25									X				X									
UT-25	X	X				X	X	X					X									
WY-25																					X	
UT-19							X															
CO-2, WY-41	?						X	X	X												X	X
UT-9	X	?						?														
WY-3						X																
WY-24																					X	
WY-42						X																
WY-98	X					?		X	?													
UT-17									X													
WY-99		?					?															
UT-24, WY-100						?			X													
WY-26, CO-53						X			X				X									
WY-16, 18	X	X							X													
CO-52	X								X													
OK-1, WY-17	X	X				X	X	?	X?													
CO-24	X	X									?				?							
NM-6								X														
WY-30	X	X						X	X	X												
WY-28															X							
WY-101								?														
WY-29	X	X			X	X		X					?		?							
UT-18, WY-84	X*	X		X		X*		X*	X	X			X			X		X			?	
WY-63						?				?												
WY-15	X	X			X		X	X					X		X						X	
WY-80	X							X														
CO-57	X											X								X		
NM-3	X							X														
NM-4	cf																					
WY-102						?																
WY-20	X							X														
NM-5								X														
CO-22								X														
WY-21, NM-7	X					X*		X														
UT-7, OK-2	X*	X?	X			?	X?	X*	?	X		X				X		X				?
WY-23									X													
CO-21	X					X		X	X	X		X				X				X		
WY-81								X														
CO-46, 47	X	X									?											
CO-70, WY-43	X						?	X														
WY-19, 91	X	X*			?	X*		X*	X													
CO-77		X																				
WY-30	X																					
CO-35, 36		X				X			X													
WY-31	X																					
CO-51		X				X		X	X													
WY-22	X	?						X	X										X			
CO-45, OK-3	X					X	X	?	X		X											
WY-85		X																				
CO-28, WY-47		X				X	X										X					
CO-66, UT-1									X				X									
CO-11		X							X			?	X	X						?		
CO-23, 33	X	X				X	X	X	X		X					X						
WY-39	X	X				X		X	X										X			
CO-60											?											
NM-2		X																				
CO-59	X						X			X												
CO-6,55,56,58, OK-4	X	X*		X	?	X*	X?	3X	X*		X	X	X			X	X	X				
CO-8 . . . . Clay . .	X							X														
WY-2 Charge								X														
CO-3, 4	X*	X	X		X	X			X		X		X	X	X	X						
CO-34													X									
UT-6, CO-27	X	X														X						
CO-16																		?				
WY-86						X		X		?												
CO-7, 9, 17, 75, 76	X*	3X				X		X*							X							
CO-49, NM-1	X*								X													
UT-14	X												X									
CO-72													?									
UT-12, 13		X						X	X		X											
WY-27	X						X	X														
WY-45						?																
WY-92		X				X			X			X										
WY-71, 73	X	X	X			X	X	X*	X	?				X								
WY-4	X																					
WY-72, CO-74	X	?				X*		X	X													
WY-61	X	?				X																
WY-44									X				X									
WY-74	X																					
WY-1, 78, 79	X*	X*				X*	X*	X*	X*		X	X	X*									
WY-62	X					X	X	X		X												
CO-48									X													
WY-46		X			X	X	X	X					?		?							
CO-5, 73	X		X	X																		
UT-20	X																					
CO-10			X																			
WY-83	X	X																				
NM-10		?																				
UT-4																						

TAXON / TAXON IDENTITY NO.	Coelurus fragilis 31	Camarasaurus lentus 32	Stegosaurus stenops 33	Stegosaurus ungulatus 34	Stegosaurus armatus 35	Camarasaurus grandis 36	Allosaurus fragilis 37	Apatosaurus excelsus 38	Dryosaurus altus 39	Elaphrosaurus sp. 40	Othnielia rex 41	Ceratosaurus nasicornis 42	Diplodocus longus 43	Camarasaurus supremus 44	Torvosaurus tanneri 45	Edmarka rex 46	Diplodocus carnegii 47	Apatosaurus ajax 48	Mymoorapelta maysi 49	Marshosaurus bicentesimus 50	Drinker nisti 51
CO-71																					
WY-82																					
WY-64																					
CO-1														X							
UT-26																					
CO-25									?												
UT-25																					
WY-25																					X
UT-19																					
CO-2, WY-41														X							X
UT-9																					
WY-3																					
WY-24																					X
WY-42																					
WY-98																					
UT-17																					
WY-99																					
UT-24, WY-100																					
WY-26, CO-53									X									X			
WY-16, 18				X				X													
CO-52																		X			
OK-1, WY-17								X													
CO-24			?																		
NM-6																					
WY-30							X														
WY-28											X										
WY-101																					
WY-29				X																	
UT-18, WY-84		X	X	X			X		X			X	X		X					X	
WY-63																					
WY-15	X						X				X										X
WY-80																					
CO-57																			X		
NM-3														X							
NM-4																					
WY-102																					
WY-20						X	X														
NM-5																					
CO-22																					
WY-21, NM-7						X	X														
UT-7, OK-2		X	X				X													X	
WY-23																					
CO-21																			X		
WY-81																					
CO-46, 47																					
CO-70, WY-43																					
WY-19, 91	?			X		X		X									X				
CO-77																					
WY-30							X														
CO-35, 36								X													
WY-31																					
CO-51					X													X			
WY-22																X					
CO-45, OK-3																					
WY-85																					
CO-28, WY-47																	X				
CO-66, UT-1									X												
CO-11			X					X	X												
CO-23, 33																					
WY-39																X					
CO-60																					
NM-2																					
CO-59																					
CO-6,55,56,58, OK-4													X		X						
CO-8 . . . . Clay . .						X	X														
WY-2 Charge																					
CO-3, 4	X		X		X		X		X	X	X	X	X								
CO-34																					
UT-6, CO-27				X								X									
CO-16																					
WY-86																					
CO-7, 9, 17, 75, 76			X								X										
CO-49, NM-1																					
UT-14																					
CO-72																					
UT-12, 13																					
WY-27																					
WY-45																					
WY-92																					
WY-71, 73																					
WY-4																					
WY-72, CO-74																					
WY-61																					
WY-44																					
WY-74																					
WY-1, 78, 79			X*			X	X*	X	X												
WY-62																					
CO-48																					
WY-46	X	X		X	X																
CO-5, 73																cf					
UT-20																					
CO-10																					
WY-83																					
NM-10																					
UT-4																					

Table 1 (Right side)

SINGLE-LOCALITY TAXA																											ZONE	AGE
Dystrophaeus viaemalae	*Allosaurus* n. sp.	*Haplocanthosaurus delfsi*	*Camptosaurus dispar*	*'Apatosaurus' minimus*	*Ornitholestes* sp.	*Ornitholestes hermanni*	Ankylosaur n. gen. & sp.	*Apatosaurus yahnahpin*	*Camptosaurus amplus*	*Haplocanthosaurus priscus*	*'Morosaurus'* sp.	*Camarasaurus lewisi*	*Dystylosaurus edwini*	*Supersaurus vivianae*	*Echinodon* sp.	*Brachiosaurus altithorax*	*Stokesosaurus clevelandi*	*Seismosaurus hallorum*	*Barosaurus lentus*	*Apatosaurus louisae*	*Saurophaganax maximus*	*Hypsirophus* sp.	*Amphicoelias fragillimus*	*Koparion douglassi*	Troodontid second sp.	*Amphicoelias altus*		
61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87		
																										X		Tithonian
																								X	X			
																						X	X				4	
																												Tithonian / Kimmeridgian
																					X							
																			X	X								
																		X										
			cf		?												X										3	
																X												
															X												2	
																?												
					?							X	X	X														
																											Clay Change	
										X	X																	
									X																			
																											2	
								X																				
				X	X	X																						
			X																									
		X																										
	X																											
																											1	
X																												Kimmeridgian

TABLE 2	BLACK HILLS (WY & SD)										MONTANA			
TAXON	*Allosaurus*	*Stegosaurus*	*Diplodocus*	*Camarasaurus*	*Apatosaurus*	*Barosaurus*	*Dryosaurus*	*Othnielia*	*Diplodocus* or *Barosaurus*	*Barosaurus lentus*		*Allosaurus*	*Stegosaurus*	*Diplodocus* or *Barosaurus*
TAXON IDENTITY NO.	1	2	5	7	8	9	13	14	22	84		1	2	22
SD-2	X			X	X									
SD-1 (Tithonian?)					X						(Tithonian?)			
SD-3 (Kimmeridgian?)	X					X				X	(Kimmeridgian?)			
WY-9						cf								
SD-5			X											
SD-4	X			X		X				X				
WY-8	?													
WY-10								X						
WY-11	X	X		X	X		X	X	X					
											MT-2	X		
WY-12						?								
											MT-6	?		
											MT-1	X	?	X

TABLE 2.—Biostratigraphy of dinosaur taxa at various localities in the Morrison Formation in the Black Hills and Montana. The clay change is not present in these areas.

LATE JURASSIC LACUSTRINE DEPOSITS AND IMPLICATIONS FOR PALEOHYDROLOGY—DEPOSITION TO EARLY COMPACTION

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ABSTRACT

Hydrologic models of modern lake basins are difficult to apply directly to ancient lake basins because it is difficult to precisely reconstruct the parameters critical to developing accurate paleohydrologic models. We suggest that geologic information can be used to infer some aspects of paleohydrology associated with lacustrine rocks and that this geologic information, although not sufficient to permit precise reconstructions of paleohydrology, provides significant constraints for paleohydrologic modeling.

Lake T'oo'dichi' was a large saline, alkaline lake that developed in the Four Corners area of the United States, during deposition of the Upper Jurassic Morrison Formation. Paleotectonic, sedimentologic, petrologic, and radiometric dating studies provide a large body of data concerning the nature of the lake basin; the source region; delivery of sediments to the basin; and diagenesis of both the lacustrine and associated fluvial rocks that served as aquifers. Certain early diagenetic alterations in fluvial sandstone aquifers of the Morrison Formation are readily linked to the movement of pore waters from the finer grained deposits of Lake T'oo'dichi' into fluvial sandstone aquifers that underlie, interbed with, and overlie the lacustrine deposits. The link between the alterations and pore waters from the ancient lake beds is based on the nature, timing and patterns of these alterations in the fluvial sandstone aquifers.

Two types of patterns--lateral and vertical--emerge from the alteration recorded in the fluvial sandstone aquifers that interacted with pore waters from Lake T'oo'dichi'. Lateral patterns of alteration in the sandstone aquifers that underlie and are interbedded with the lacustrine deposits are concomitant with inferred changes in pore water composition in the

overlying lacustrine deposits. Similarly, vertical alteration patterns in sandstone aquifers that both underlie and overlie the lacustrine deposits (resulting in a mirror image of alterations) indicate movement of pore waters away from the intervening lacustrine deposits, a flow pattern that is reflected in the decreasing intensity of sandstone alteration away from lacustrine deposits. Timing of the various alterations in the fluvial sandstone aquifers indicates that movement of pore waters from the lacustrine deposits may have begun while the lake was extant but probably continued and was significantly enhanced during early compaction of the lacustrine deposits.

Admittedly, we cannot develop a hydrologic model for one specific time horizon during Morrison deposition, but reasonable conclusions about paleohydrology are possible. Although imprecise, inferences gained in this manner are probably more accurate than inferences that might be made by assuming that precise reconstructions can be made.

INTRODUCTION

Paleohydrologic modeling has become an important approach used to determine fluid flow in ancient rocks for purposes of groundwater quality, reservoir analysis, and modeling mineral deposits. Application of hydrologic concepts to modeling in ancient rocks is challenging because it is difficult to accurately reconstruct the hydrologic parameters required to develop an accurate model (Winter, 1981). Hydrologists working in modern groundwater systems calibrate their hydrologic models by field measurements of hydrostatic head, which is not possible when constructing models for the geologic past. Moreover, minor variations in a single hydrologic parameter can result in major revisions in groundwater models (Winter, 1981). In spite of the challenges, it is frequently desirable to reconstruct the groundwater flow patterns to better understand geologic processes. Fortunately, diagenetic alteration of the original sediments leaves at least a partial record of the passage of groundwater through time. Petrologic analysis can lead to identification of these alterations and development of paragenetic sequences of authigenic minerals and altered framework grains, which, in turn, can constrain the interpretation of timing and direction of paleogroundwater flow. These patterns of alteration can then be used to infer groundwater flow directions that in turn allow us to construct paleohydrologic models.

An opportunity to apply this approach in an ancient lacustrine system was afforded by a number of studies of ancient Lake T'oo'dichi', a saline, alkaline lake that developed during deposition of the Late Jurassic Morrison Formation in the Colorado Plateau region (Figs. 1 and 2; T'oo'dichi' means "Bitter Water" in the Navajo language). Studies began with uranium mineralization in the fluvial sandstones of the Morrison Formation (Westwater Canyon and Jackpile Sandstone Members) as the main focus (Adams, 1986; Adams and Saucier, 1981; Fishman and others, 1985; Turner-Peterson, 1985; Fishman and Reynolds, 1986; Hansley, 1986; Reynolds and others, 1986; Turner-Peterson and Fishman, 1986), but it soon became clear that we needed to also study the adjacent lake system (Brushy Basin Member) in addition to the fluvial sandstones because of the apparent involvement of lacustrine pore waters in the mineralizing process. We came to believe that an understanding of the entire package of rocks, including the depositional and compactional hydrology of the lacustrine interval was critical for building a comprehensive model of uranium mineralization. Subsequent studies of saline, alkaline lake mineralogy (Bell, 1986; Turner and Fishman, 1991), clay mineral diagenesis (Owen and others, 1989; Turner and Fishman, 1991), and origin of authigenic albite (Fishman and others, 1995) in deposits of Lake T'oo'dichi' resulted in development of new concepts in paleohydrology associated with a lacustrine system. Our work integrates the results of studies of Lake T'oo'dichi' and demonstrates the major implications for lacustrine paleohydrology, and can be used to place constraints on paleohydrologic models in future studies.

TECTONIC SETTING OF LAKE T'OO'DICHI'

Lake T'oo'dichi', a large saline, alkaline lake, developed during deposition of the Brushy Basin Member of the Morrison Formation during Late Jurassic time. The ancient lake occupied a region that encompassed the ancestral San Juan and Paradox basins (Fig. 1). The combined San Juan/Paradox basin was a smaller depocenter that was part of a larger foreland basin that accumulated Morrison sediments in the Western Interior (Fig. 3). Only the back-bulge deposits remain of the original foreland basin: foredeep and forebulge deposits are thought to have been cannibalized as thrusting progressed eastward from Late Jurassic to Early Cretaceous time, leaving only the back-bulge deposits of the Morrison Formation (Currie, 1997; Horton, 1997). Within the back-bulge basin were smaller subbasins, largely defined by intrabasinal tectonic folding and uplift along preexisting structures (Peterson, 1984). One of the large subbasins was the combined ancestral San Juan and Paradox basins, which developed west of the axis of the ancestral Uncompaghre Uplift (Fig. 3). Lake T'oo'dichi' developed in this subbasin within the back-bulge basin.

Thrust sheets west of the foreland basin (Fig. 3) contributed detritus to eastward flowing streams during deposition of the Morrison Formation (Martinez, 1979; Turner-Peterson, 1986). These streams deposited the fluvial sandstones of the Morrison Formation (Fig. 2). Reconstruction of Late Jurassic paleogeography (Fig. 3) indicates that a large continental-margin magmatic arc existed in the vicinity of the postulated source area of Morrison detritus (Burchfiel and Davis, 1975; Hamilton, 1978; Peterson, 1994). Volcanism associated with emplacement of granitic batholiths probably provided the large amount of silicic volcanic ash that was incorporated into Morrison sediments. Prevailing winds blew predominantly toward the northeast (Poole, 1962; Peterson, 1988), carrying the airborne volcanic ash to the depositional basin. Lake T'oo'dichi' was filled by a mix of airborn and reworked volcanic ash as well as coarser detrital sediment derived from western source areas (Turner and Fishman, 1991).

DEVELOPMENT OF LAKE T'OO'DICHI'

As a saline, alkaline lake, the formation of Lake T'oo'dichi' required a hydrologically closed basin, with no surface outlets, in which evaporation exceeded precipitation and runoff (e.g., Jones, 1966; Garrels and MacKenzie, 1967; Hardie and Eugster, 1970; Surdam and Sheppard, 1978), a combination that is favored by a semi-arid to arid climate. An arid to semi-arid climate has been inferred for the Morrison Formation, based on the presence of evaporite and eolian deposits in the lower Morrison Formation, and oxygen isotopic data throughout the Morrison that reflect a strong rain shadow effect for the Morrison depositional basin (Ekart and Cerling, 1996). Eastward flowing streams provided sediment to the basin and were ponded by the ancestral Uncompaghre uplift, forming the hydrologically closed basin of Lake T'oo'dichi' (Fig. 3). The lake was shallow and frequently evaporated to dryness (Turner and Fishman, 1991). The maximum extent during high stands was 150,000 km^2 (Fig. 3). Fluctuations in lake level resulted in changes in lake chemistry that affected early diagenetic mineral formation in the tuffaceous lake sediments. These fluctuations resulted in a concentric zonation of diagenetic minerals in the tuffaceous lacustrine sediments (Fig. 4). The concentric zonation is a basinward progression of diagenetic mineral zones that reflects the combined effects of the lateral hydrogeochemical gradients that existed in the lake at any specific time and of changes in these gradients related to changes in lake level through time (Turner and Fishman, 1991). The lateral progression of authigenic mineral zones in the tuffs, from the margin to the center of the lake, is smectite $\rightarrow$ clinoptilolite $\rightarrow$ analcime$\pm$potassium feldspar $\rightarrow$ albite (Turner and Fishman, 1991; Fig. 4). The hydrogeochemical processes that led to this mineralogic zonation are outlined below.

Crucial to establishing a saline, alkaline lake is development of saline, alkaline waters, which are characterized by high concentrations of Na^+, Mg^+, K^+, Cl^-, and a high pH (Surdam and Sheppard, 1978). Two processes can contribute to formation of saline, alkaline pore waters and conditions in the Late Jurassic were favorable for both processes to occur in sediments of Lake T'oo'dichi'. One process is the reaction of CO_2-charged meteoric water with igneous and metamorphic rocks, if the water is evaporated and if calcite is precipitated (Surdam and Sheppard, 1978). This process is promoted in a hydrologically closed basin where evaporation exceeds precipitation and runoff. Another process that contributes to development of saline, alkaline lakes is the hydrolysis of silicic volcanic ash (Sheppard and Gude, 1987). Alteration of silicic volcanic ash added to the sediments of Lake T'oo'dichi' would have enhanced the already alkaline and saline pore waters in the closed basin. The silicic ash would have altered readily in the saline, alkaline pore waters because of it unstable nature (Hay, 1966), a process that could have contributed to a further increase in salinity and alkalinity.

A basinward modification of pore waters, from fresher at the margins to more alkaline and saline toward the center, characterizes modern alkaline, saline lake basins (Hay, 1966; Sheppard and Gude, 1968). The chemical activities of silica, cations, and water, as well as changes in pH are all variables affecting the reaction of ash (the alteration of the ash further contributing to pore water modification) to form various authigenic minerals and subsequent replacement of earlier-formed minerals by more stable phases. Around the margins of these lakes, pore waters are freshened by recharge. In deposits of Lake T'oo'dichi', the marginal zone (smectite diagenetic mineral zone), where recharge freshened the pore waters, consists predominantly of mixed-layer illite/smectite that contains 70%-100% smectite layers (Fig. 5; Turner and Fishman, 1991). The alteration of volcanic ash to smectitic clays in sediments near the margins of a saline, alkaline lake increases the pH and the activity of silica in the residual pore waters, both of which create conditions favorable for the formation of zeolites (Surdam and Sheppard, 1978). The initial reaction between the volcanic ash and pore water exchanges H^+ ions from the water for Na^+ and K^+ ions from the surface of volcanic glass shards, which results in an increase in pH and an increase in activities of Na^+ and K^+. As this process continues the activity of silica also increases, which together with an elevated pH and a high $(Na^+ + K^+)/H^+$ ratio favors the formation of zeolites such as clinoptilolite directly from volcanic glass (Hay, 1966; Surdam and Sheppard, 1978). Zeolites will not precipitate in sediments along the lake margin where the waters are freshened by recharge, but will begin to precipitate slightly basinward. In the clinoptilolite diagenetic mineral zone of Lake T'oo'dichi' (Fig. 4), excess silica also precipitated as quartz and chalcedonic cements. Authigenic clays in this zone are predominantly randomly interstratified mixed-layer illite/smectite (70%-100% smectite layers) (Fig. 5).

Farther basinward, increasing alkalinity and salinity appear to favor replacement of earlier-formed zeolites by analcime (Fig. 4). Analcime is thought to form from a zeolitic precursor rather than directly from volcanic glass (Hay, 1966; Sheppard and Gude, 1973). A higher pH increases both the activity of SiO_2 in solution and the Na^+/H^+ ratio, favoring replacement of clinoptilolite by analcime (Hay, 1966; Surdam and Sheppard, 1978). The concomitant basinward increase in salinity decreases the activity of water, which also favors the formation of analcime, a less hydrous mineral than clinoptilolite (Hay, 1966).

With increasing salinity, alkalinity, and silica concentration in the pore waters, analcime may be replaced by authigenic potassium feldspar. Higher water salinity also lowers the activity of water, which, with a favorable Na^+/K^+ ratio, favors formation of the anhydrous potassium feldspar from the hydrous zeolites and/or analcime precursors (Hay, 1966; Surdam and Sheppard, 1978). In Cenozoic saline, alkaline lake-deposits, potassium feldspar forms a discrete diagenetic zone in the center of the lake deposits (Sheppard and Gude, 1968). In Lake T'oo'dichi', however, authigenic potassium feldspar occurs in the same zone as analcime (Figs. 4 and 5); individual tuffs in this zone may contain either or both minerals (Turner and Fishman, 1991). Mixed-layer illite/smectite of variable composition (0%-100% smectite layers) also occurs in this zone. Excess silica in the analcime±potassium feldspar diagenetic mineral zone precipitated as quartz and chalcedonic cements (Fig. 5).

In the innermost diagenetic mineral zone (Fig. 4), tuffs of ancient Lake T'oo'dichi' are characterized by authigenic albite and highly illitic (0%-30% smectite layers) mixed-layer illite/smectite (Turner and Fishman, 1991). Precipitation of illitic clays in this zone apparently depleted pore waters of K^+ ions with respect to Na^+ ions, increasing the Na^+/K^+ ratio, which favored the precipitation of authigenic albite (Fishman and others, 1995) rather than authigenic potassium feldspar (Fig. 5).

The basinward progression of diagenetic mineral zones observed in the tuffs of Lake T'oo'dichi' (Figs. 4 and 5) probably reflects the summation through time of lake level changes and, thus, pore water composition in the underlying lake sediments. During high stands of the lake, when relatively fresh, dilute pore waters existed in sediments across the lake basin, volcanic ash altered to smectite or zeolites. During low stands of the lake, pore waters were more concentrated, and ash-rich sediments in the center of the lake basin were bathed in highly alkaline and saline fluids; here, the lower activity of water drove reactions toward more anhydrous phases, causing replacement of hydrous phases (zeolites) by anhydrous phases (feldspars). During these lake low stands, conditions in the albite diagenetic mineral zone favored precipitation of illitic mixed-layer clays. Return to high lake levels did not reverse the reactions that occurred in the central zones during low stands, so the more anhydrous minerals (feldspars, chlorite, and illitic clays) were preserved (Fig. 5). In contrast, marginal lake sediments were never exposed to the highly alkaline, saline pore waters and thus the more hydrous minerals (smectite and clinoptilolite) remained the dominant phases (Fig. 5). The pattern of concentrically arranged diagenetic mineral zones exhibited by the tuff beds of Lake T'oo'dichi' (Fig. 4) is the result of fluctuating lake levels through time, with the anhydrous phases restricted to the more central parts of the lake sediments. In modern saline, alkaline lakes, the basinward trend in pore-water composition is far more apparent in the resultant deposits than in the pore-fluid profiles at any given instant because of short-term hydrologic variability (Jones and others, 1969). Similarly, the concentric zonation of diagenetic mineral zones observed in the deposits of Lake T'oo'dichi' (Fig. 4) reflects basinward trends in average pore-water composition that developed in response to changes in lake hydrology through time.

Lake T'oo'dichi' was a silica-rich system, the result of the alteration of abundant silicic volcanic glass in the lake sediments. As a consequence, the authigenic minerals that formed in the altered tuffs are principally aluminosilicate minerals (smectite, mixed-layer illite/smectite, chlorite, clinoptilolite, analcime, potassium feldspar, and albite) or silica (in the form of quartz or chalcedony) rather than carbonates, chlorides, and sulfates. Nevertheless, subordinate carbonate and sulfate minerals, such as calcite, dolomite, and barite, occur in deposits of Lake T'oo'dichi' and indicate that some carbonate and sulfate anions were present in the pore waters. The lateral distribution of authigenic minerals in tuffs deposited in Lake T'oo'dichi' is shown in Figure 5. Lack of evaporite minerals, however, confirms that silica dominated the reactions. Analogies with altered ash in Cenozoic alkaline, saline-lake deposits suggest that the smectite, clinoptilolite, analcime, and potassium feldspar in the deposits of Lake T'oo'dichi' could have formed within 500,000 years of deposition. Albite and illitic mixed-layer clays in the deposits of Lake T'oo'dichi' may have also formed over a similar time span, based on petrographic constraints and geologic reasoning (Turner and Fishman, 1991).

MORRISON FLUVIAL AQUIFERS IN COMMUNICATION WITH LAKE T'OO'DICHI'

Several fluvial sandstone aquifers in the Morrison Formation were in hydrologic communication with the early diagenetic pore waters of Lake T'oo'dichi' deposits (Brushy Basin Member), based on patterns and timing of alteration in the fluvial sandstones (Turner and Fishman, 1991; Reynolds and others, 1986; Fishman and others, 1995; Hansley, 1986; Adams, 1986; Adams and Saucier, 1981; Adams and others, 1978). These sandstone aquifers include the fluvial complexes of the Westwater Canyon and Jackpile Sandstone Members, and also more isolated fluvial channel sandstones in the Brushy Basin Member (Fig. 6). From the patterns of alteration in these sandstone aquifers, it has been possible to interpret the direction of paleogroundwater flow during deposition and/or early compaction of the Lake T'oo'dichi' deposits. The alteration patterns observed in major fluvial complexes of the Westwater Canyon and Jackpile Sandstone Members are of chief interest because they were in direct hydrologic communication with lacustrine deposits of

Lake T'oo'dichi' (Fig. 2). The Salt Wash Member, although a major fluvial unit in the Morrison Formation, is not discussed because it is not in direct hydrologic communication with lacustrine deposits of Lake T'oo'dichi' (Fig. 2).

Westwater Canyon Member

The Westwater Canyon Member (Fig. 2), which ranges from 24 to 134 m in thickness (Kirk and Condon, 1986; Turner-Peterson, 1986), represents a major fluvial complex in the Morrison Formation (Craig and others, 1955). It immediately underlies the deposits of Lake T'oo'dichi' (Brushy Basin Member) in northwestern New Mexico (Figs. 2 and 6). The fine- to medium-grained, locally pebbly, cross-bedded sandstones of the Westwater Canyon Member form vertically stacked, laterally continuous braided stream deposits that flowed predominantly in an easterly direction (Turner-Peterson, 1986). The stacked, coalesced nature of the Westwater Canyon Member sandstones, with little overbank material preserved within sandstone sheets, represent broad braided channels that reworked intervening overbank sediments and resulted in a major fluvial complex with significant hydrologic continuity. The Westwater Canyon Member, by virtue of its thick, continuous nature and resulting hydrologic continuity, was a major aquifer during Morrison deposition and remains so today.

Jackpile Sandstone Member

The Jackpile Sandstone Member is a fluvial complex similar to the Westwater Canyon Member, but overlies the deposits of Lake T'oo'dichi' (Brushy Basin Member) and is restricted to the southeastern part of the San Juan basin near Laguna, New Mexico (Fig. 6).

Limited paleocurrent measurements suggest that the streams flowed in a northerly direction. Similar to the Westwater Canyon Member, the Jackpile Sandstone Member is characterized by vertically stacked, laterally coalescing braided stream deposits, with little overbank material preserved. As a result, the Jackpile also has high hydrologic continuity, which suggests that it served as an aquifer during and subsequent to Morrison deposition.

Brushy Basin Member

The Brushy Basin Member is informally divided into lower and upper parts, with the upper part defined largely by deposits of Lake T'oo'dichi' (Fig. 2). Fluvial sandstones in both the lower and upper Brushy Basin Member tend to be isolated ribbon channel sandstones. These isolated sandstones probably represent streams that traversed a dry lake basin and formed during flooding events when sediments were carried well into the basin because of the low depositional gradient across the basin (Turner and Fishman, 1991). Stacked fluvial sandstones occur locally in the upper Brushy Basin Member and are restricted to the southern margin of the Lake T'oo'dichi' depositional basin in northwestern New Mexico (Fig. 2). Sandstones in the Brushy Basin Member are chiefly fine- to medium-grained and locally conglomeratic. Paleocurrent directions are predominantly easterly. The laterally discontinuous nature of most of the fluvial sandstones in the Brushy Basin Member suggest that they have limited hydrologic continuity and thus were not major regional aquifers during or after Morrison deposition. They are of interest, however, because diagenetic alterations within them record the movement of pore waters from the lake sediments into adjacent sandstones.

PALEOGROUNDWATER FLOW IN MORRISON FLUVIAL AQUIFERS RELATED TO LAKE T'OO'DICHI'

In order to discuss groundwater flow in aquifers associated with ancient Lake T'oo'dichi', it is important to establish the scale of hydrologic flow patterns for which inferences can be made. For example, the very existence of ancient Lake T'oo'dichi' on the upstream side of the ancestral Uncompaghre Uplift (Fig. 3) allows us to infer at least a gross regional hydrologic setting--that of a hydrologically closed basin. As discussed earlier, paleotectonic reconstructions of the source regions combined with the ponding of easterly flowing streams by the ancestral Uncompaghre uplift in a semi-arid to arid climate, as well as the contribution of airfall silicic volcanic ash, created conditions favorable for development of a saline, alkaline lake. We can infer regional groundwater flow from mountainous source regions in the west toward the depositional basin to the east (Fig. 3), but without more precise constraints (hydrologic gradients, geochemistry of groundwaters) it is difficult to constrain regional hydrologic models beyond these general inferences.

At the other end of the hydrologic spectrum, the zonation of authigenic minerals in Lake T'oo'dichi' deposits (Figs. 4 and 5) allows us to infer hydrogeochemical gradients that occurred within the lake sediments themselves, at a much finer scale than the regional basinward groundwater flow. Between the larger scale basinward groundwater flow and smaller scale hydrogeochemical interactions in the lake sediments, however, it is possible to infer some local hydrologic flow paths that affected surrounding aquifers. The flow paths are derived from constraints provided by alteration patterns in the fluvial sandstone aquifers that were in hydrologic communication with the lacustrine deposits of Lake T'oo'dichi'.

Alteration Patterns In Sandstone Aquifers

Certain early diagenetic alterations in fluvial sandstone aquifers of the Morrison Formation are readily linked to the movement of pore waters from the finer-grained lacustrine deposits of Lake T'oo'dichi' into these sandstones (Adams, 1986; Hansley, 1986; Turner and Fishman, 1991; Fishman and others, 1995). This link can be discerned from the timing, nature, and pattern of the alterations based on petrographic studies of sandstones that underlie and overlie the Brushy Basin Member (Westwater Canyon and Jackpile Sandstone Members) and sandstones within the Brushy Basin Member that are interbedded with deposits of Lake T'oo'dichi' (Fig. 6). The timing of these early alteration events is constrained by petrographic observations and radiometric dates on authigenic minerals (Ludwig and others, 1984; Fishman and others, 1985). Lateral changes in types of alteration in the sandstones (Fig. 7) reflect lateral changes in the composition of pore waters that entered these sandstones, which in turn reflect the geochemistry of pore waters in beds deposited in Lake T'oo'dichi'. Vertical patterns of alteration reflect communication between saline, alkaline-lacustrine pore waters and associated sandstone aquifers, as discussed below.

Alteration In Sandstones Spatially Associated With The Smectite Diagenetic Mineral Zone

Several types of alteration occur in fluvial sandstone aquifers that are spatially associated with the smectite diagenetic mineral zone in lacustrine beds of ancient Lake T'oo'dichi'. Alteration of these sandstones involved both leaching of framework grains and precipitation of authigenic cements. One of these alterations was extensive leaching of iron from detrital magnetite and ilmenite (FeTi-oxide) grains, which left only concentrations of leucoxene (TiO_2) in place of the former detrital grains (Fig. 8) (Adams and others, 1974; Adams, 1986; Fishman and Reynolds, 1986; Reynolds and others, 1986). These leucoxene relicts of FeTi-oxide grains occur in sandstones that are interbedded with, underlie, and overlie the smectite diagenetic mineral zone of Lake T'oo'dichi'.

The skeletalization of FeTi-oxide grains by leaching of iron is attributed to the movement of humic acid-rich pore waters from the smectite diagenetic mineral zone in the lacustrine deposits into sandstones of the Westwater Canyon, Brushy Basin, and Jackpile Sandstone Members of the Morrison Formation (Adams and others, 1978; Adams and Saucier, 1981; Fishman and others, 1984; Turner-Peterson, 1985; Fishman and Reynolds, 1986; Reynolds and others, 1986; Turner-Peterson and Fishman, 1986). These humic acids precipitated as lenses of humate in sandstone (Fig. 6) that subsequently concentrated uranium from groundwater, forming uranium orebodies (Turner-Peterson, 1985; Turner-

Peterson and Fishman, 1986; Turner and others, 1993). The zone of leached Fe-Ti oxide grains forms an alteration envelop that encloses all sandstone that contains uranium-enriched humate lenses and is thus a guide to the location of uranium ore (Fig. 9).

Within the Westwater Canyon Member in the southern San Juan Basin area, an inferred downward movement of humic acid-rich pore waters from the smectite diagenetic mineral zone of the Brushy Basin Member is supported by the downward decrease in intensity of the alteration of FeTi-oxide grains in sandstone of the Westwater Canyon Member (Fig. 9; Hafen and others, 1976; Adams and Saucier, 1981; Adams, 1986; Reynolds and others, 1986). Completely skeletalized FeTi-oxide grains occur in a zone in the upper part of the Westwater Canyon Member, pristine detrital FeTi-oxide grains occur below this zone, and in between is a zone of partially leached FeTi-oxide grains (Figs. 8 and 9).

Another type of alteration that is abundant in fluvial sandstone aquifers associated with the smectite diagenetic mineral zone (Westwater Canyon and Jackpile Sandstone Members) is the skeletalization of detrital feldspars. The skeletalized nature of these detrital plagioclase grains results from partial to extensive dissolution of the calcium-rich centers of these grains (Austin, 1963; Adams and others, 1978; Hansley, 1986). In turn, the skeletalized grains have been partly albitized (Hansley, 1986). In the Westwater Canyon Member, the skeletalization of plagioclase grains is most pronounced near the top of the member and decreases in intensity downward and basinward (Fig. 10). This skeletalization resulted in abundant moldic porosity in these sandstones (Hansley, 1986). A mirror image of this alteration pattern has been documented in the Jackpile Sandstone Member, in which skeletalization of detrital plagioclase grains decreases in intensity upward, away from the lacustrine deposits (Fig. 11; Adams and others, 1978; Adams, 1986). In both cases the intensity of alteration increases toward the intervening lacustrine deposits of Lake T'oo'dichi' (Brushy Basin Member).

Precipitation of authigenic potassium feldspar cements, an additional feldspar alteration, occurs in sandstone aquifers associated with the smectite diagenetic mineral zone (Hansley, 1986). Potassium feldspar cements (including rhombs of adularia) become abundant in sandstones associated with the central to basinward parts of the smectite zone (Fishman and Reynolds, 1986; Hansley, 1986), and persist in sandstone aquifers associated with the next basinward diagenetic mineral zone--the clinoptilolite zone (Hansley, 1986).

Alteration In Sandstones Spatially Associated With The Clinoptilolite Diagenetic Mineral Zone

Progressing basinward, pore waters associated with Lake T'oo'dichi' changed in composition and these changes are reflected in alteration patterns in associated fluvial sandstone aquifers. A basinward increase in potassium feldspar alteration in sandstone aquifers is associated with the clinoptilolite diagenetic mineral zone and is accompanied by the appearance of clinoptilolite and silica (quartz and chalcedony) as cements (Fig. 12), as well as the persistence of albitization of detrital plagioclase grains (Fig. 7). Potassium feldspar alteration includes skeletalized detrital sanidine grains, overgrowths on detrital feldspar grains, replacements of plagioclase grains (Hansley, 1986), and authigenic submicroscopic (<10 μm across) rhombic crystals of adularia in pore spaces within the sandstones (Hansley, 1986; Fishman and Reynolds, 1986). Some of the potassium feldspar overgrowths in sandstones associated with the clinoptilolite diagenetic mineral zone in the eastern San Juan Basin, New Mexico, are as large as 100 μm (Fishman and Turner, unpublished data). A downward decrease in the intensity of the potassium feldspar cementation occurs in sandstones of the Westwater Canyon Member (Hansley, 1986).

This downward decrease in intensity of alteration is a pattern of alteration similar to that observed for the dissolution of both FeTi-oxide and plagioclase grains associated with the smectite diagenetic mineral zone. The clinoptilolite in sandstone aquifers associated with this diagenetic mineral zone occurs locally as small, euhedral crystals in the pores of the sandstones. Silica begins to occur locally as a cement in the form of quartz and chalcedony; quartz forms small overgrowths and interstitial cements. Where chalcedony is abundant as a cement, the sandstones are well-indurated and contrast with the more friable sandstones characteristically associated with the smectite diagenetic mineral zone. Albitization of skeletalized, detrital plagioclase grains also becomes more common in sandstones associated with the clinoptilolite diagenetic mineral zone (Adams and others, 1978; Austin, 1980; Hicks, 1981; Hansley, 1986).

Alteration In Sandstones Spatially Associated With The Analcime±Potassium Feldspar Diagenetic Mineral Zone

In sandstone aquifers associated with the analcime±potassium feldspar diagenetic mineral zone, detrital feldspar grains are altered in two distinct ways (Fishman and Turner, unpublished data). Some of these grains are albitized, skeletalized detrital plagioclase grains, similar to those observed in the smectite and clinoptilolite diagenetic mineral zones, whereas others are albitized detrital feldspar grains (both plagioclase and potassium feldspars). The presence of these altered feldspars is accompanied by local silica cement and the appearance of analcime as a poikilotopic cement (Fig. 7). Completely albitized grains and albitized skeletalized feldspar grains are more common in sandstone aquifers associated with this more basinward diagenetic mineral zone than the more marginal zones. Quartz cements in sandstones associated with the analcime±potassium feldspar diagenetic mineral zone occur as thin overgrowths and as submicroscopic (~10 μm in length) euhedral crystals. Where chalcedony is abundant as a cement, the sandstones are well indurated.

Alteration In Sandstones Spatially Associated With The Albite Diagenetic Mineral Zone

In the central diagenetic mineral zone--the albite zone--fluvial sandstones that interbed with and underlie the albitic tuffs contain abundant authigenic albite as large overgrowths (as much as 50 μm long), pore-filling cements, and as complete replacement (albitization) of detrital feldspar grains (Fishman and others, 1995). The pore-filling albite is present as euhedral, tabular crystals (>5 μm in length). Albitization (without skeletalization) of detrital plagioclase grains is widespread, whereas albitization of detrital potassium feldspar grains is observed but varies in abundance. Authigenic silica is also abundant in these sandstones and occurs as large overgrowths, microcrystalline euhedra, and chalcedony cements. High intergranular volume (as high as 33%) is characteristic of these albite- and silica-cemented sandstones (Fishman and others, 1995). The abundant albite and silica cements (Fig. 7) in sandstone aquifers associated with the albite diagenetic mineral zone result in sandstones that are typically well indurated.

Summary of alteration patterns. Two types of patterns--lateral and vertical--emerge from the alterations recorded in the fluvial sandstone aquifers spatially associated with the deposits of Lake T'oo'dichi'. A lateral pattern emerges from the observed basinward changes in alteration associated with successive diagenetic mineral zones (Fig. 7). In addition, vertical patterns of downward or upward decreasing intensity of alteration are observed for several of the types of alteration. The types of alteration that exhibit a downward decrease in intensity include the alteration of FeTi oxides (Fig. 9) and skeletalization of feldspars (Fig. 10) in the Westwater Canyon Member. A mirror image of feldspar alteration, with an upward decrease in intensity, occurs within the Jackpile Sandstone Member as well (Fig. 11).

Timing Of Alteration In Fluvial Sandstone Aquifers

The lateral and vertical alteration patterns in the fluvial sandstone aquifers of the Morrison Formation led various workers to infer movement of pore waters from the lacustrine sediments of Lake T'oo'dichi' into these aquifers (Adams, 1986; Adams and Saucier, 1981; Turner-Peterson, 1985; Hansley, 1986; Reynolds and others, 1986; Turner-Peterson and Fishman, 1986; Fishman and others, 1995). The inferred movement of pore waters from lacustrine deposits of Lake T'oo'dichi' into surrounding sandstone aquifers suggests that migration of these pore waters occurred either during or shortly after deposition. Hydrogeochemical gradients associated with the saline, alkaline lake would not persist subsequent to the demise of the lake. Presumably, migration of the saline, alkaline pore waters would be favored when the lake was extant and also soon thereafter, up until and including early compaction of the lacustrine sediments. Petrographic evidence from the fluvial sandstone aquifers of the Morrison Formation supports this inference. Datable alteration events in the sandstone aquifers as well as radiometric dates of Morrison deposition permit us to infer an early timing for several alteration events.

The lateral alteration patterns in sandstones of the Westwater Canyon Member coincide with the lateral distribution of the diagenetic mineral zones in the overlying deposits of Lake T'oo'dichi' (Brushy Basin Member) (Fig. 7). This spatial coincidence strongly implicates migration of pore fluids downward from the lacustrine deposits into underlying sandstone aquifers. Isolated sandstone aquifers in the lower Brushy Basin Member that underlie the albite diagenetic mineral zone shed light on the early migration of pore fluids inferred for aquifers in the Westwater Canyon Member. Early introduction of the pore waters is supported by petrographic studies, which show that albite- and silica-cemented sandstones were cemented early in their diagenetic history, before significant compaction. These well-cemented sandstones exhibit intergranular volumes as high as 33% (Fishman and others, 1995), close to the expected original porosity for sandstones of this grain size and sorting (Beard and Weyl, 1973). Similar early cementation of isolated sandstones in the Brushy Basin Member records early introduction of lacustrine pore waters in the clinoptilolite diagenetic mineral zone (Fig. 12). The high intergranular volumes and low degree of compaction in the sandstones that underlie and are interbedded with lacustrine deposits of Lake T'oo'dichi' suggest that these cements probably were introduced before significant compaction, possibly while the lake was extant.

Vertical alteration patterns in Morrison sandstone aquifers also are attributed to pore waters that originated in lacustrine deposits of Lake T'oo'dichi', although early post-depositional compaction may have been a more dominant factor than the migration of lacustrine pore waters into aquifers while the lake was extant. The development of these vertical alteration patterns can be viewed in the context of depositional and diagenetic time constraints. Deposition of the Morrison Formation began about 155 Ma and ended about 147 Ma based on radiometric dates from tuffs in the lowermost and upper parts of the Morrison Formation (Kowallis and others, 1998). Radiometric dating of uranium mineralization in the Westwater Canyon Member indicates that the ore was emplaced during the time interval from about the end of Morrison Formation deposition to about 130 Ma: the date of 130 Ma represents completion of mineralization (Ludwig and others, 1984). The uranium ore fills voids in dissolved FeTi-oxide and feldspar grains in the Westwater Canyon Member, which places the dissolution of these detrital grains prior to and/or during mineralization (Fishman and Reynolds, 1986). The downward decrease in intensity of the dissolution of detrital grains in the Westwater Canyon Member points to a source for the altering fluids in the lacustrine deposits of the overlying Brushy Basin Member (Lake T'oo'dichi') (Adams and Saucier, 1981; Adams and others, 1978; Adams, 1986; Hansley, 1986; Reynolds and others, 1986). The dates of uranium mineralization indicate that pore water moved out of the deposits of Lake T'oo'dichi' (Brushy Basin Member) and into surrounding fluvial sandstone aquifers soon after deposition.

The vertical pattern of dissolution of detrital feldspar grains in the Jackpile Sandstone Member (Fig. 11; Adams and others, 1978; Adams, 1986)--a mirror image of that in the Westwater Canyon Member (Fig. 10; Hansley, 1986; Adams and others, 1978)--requires that pore fluid movement occurred at least after deposition of the Jackpile Sandstone Member. This suggests that compaction was a major factor in expulsion of pore waters from the Brushy Basin Member, which moved saline, alkaline pore waters into sandstone aquifers above and below the Brushy Basin Member. It is important to note, however, that in the case of the Westwater Canyon Member and isolated sandstones that interbed with the Brushy Basin Member, movement of fluids may have begun while the lake was extant but probably continued and was significantly enhanced during early compaction.

Implications Of Alteration Patterns For Paleohydrology

We can conclude that pore waters from lacustrine deposits of Lake T'oo'dichi' affected surrounding aquifers while the lake was extant and continued thereafter at least through early compaction, based on the nature, patterns, and timing of alteration of framework grains in the sandstone aquifers of the Morrison Formation. To reconstruct the paleohydrology in a manner that accommodates the inferred pore-water movement responsible for the alteration patterns, we need to evaluate the hydrologic models for both saline, alkaline lakes and compaction.

Hydrology Of Saline, Alkaline Lakes

Communication between saline, alkaline lake pore waters and underlying and interbedded sediments, similar to that inferred for the Morrison Formation, has been documented in modern-day settings. Downward movement of pore waters is indicated by mineralogic and isotopic studies of sediments in and beneath Searles Lake, California (Friedman and others, 1982). At Searles Lake, the piezometric surface in the center of the lake is about 9 m higher than that near the edge of the lake, indicating that the natural flow of groundwater in this system is downward and away from the lake (Hardt and others, 1972). Increasingly higher salinity of pore water toward the center of the lake results in higher pore-water density than at the margin of the lake, where the water is fresher (Hardt and others, 1972). The resulting density differences between water in the center and water at the margin of the lake affect the position of the piezometric surface, because density, in addition to elevation, controls the position of the piezometric surface in groundwater systems. A similar density-driven movement of fluids has been established in studies of a hydrologically closed basin (Pilot Valley, Utah) in a desert environment (Duffy and Al-Hassan, 1988). Numerical simulations coupled with field observations indicate that intense evaporation on the playa produce concentrated brine solutions, which lead to large vertical and horizontal density gradients in underlying groundwater. These gradients set in motion a free convection cell that move solutes into sediments underlying the playa (Duffy and Al-Hassan, 1988). The result is a "leaky" lake that loses water and solutes downward into underlying sediments.

In the Morrison Formation, early cementation of local sandstone aquifers within the Brushy Basin Member by pore-filling albite and silica probably was related to a "leaky" Lake T'oo'dichi', in which lacustrine pore waters moved into underlying aquifers. This is a particularly compelling explanation for the albite and silica cemented sandstones that underlie the albite diagenetic mineral zone in the center of Lake T'oo'dichi'. The albite diagenetic mineral zone formed during low stands of the lake when pore waters were the most concentrated, increasing the likelihood that density-driven pore waters escaped downward.

Compaction Hydrology

Compaction of fine-grained sediments in response to increased overburden during early burial can also result in movement of pore waters into surrounding aquifers (Magara, 1978, 1980). This process is essentially a physical expulsion of unbound interstitial formation waters. Clayey sediments, for example, lose about 70% of their interstitial water during the first stage of dewatering (Burst, 1969), which begins while the sediments are still being deposited. Movement of pore waters in any direction--downward, upward, or lateral--is possible during compaction of sediments because pore fluids typically move in the direction of lower hydrostatic pressure, whatever that may be (Magara, 1978).

In ancient systems such as the Morrison Formation, pore-water movement associated with depositional hydrology may be difficult to distinguish from pore-water movement associated with waters expelled during early stages of compaction. In fact, there is probably some overlap and possibly a continuum. Only in the case where lacustrine pore waters moved upward into overlying sandstone aquifers (such as the Jackpile Sandstone Member) can the case for compaction be clearly made, because depositional hydrology could not have been a factor. The mirror image patterns of alteration recorded in the Westwater Canyon and Jackpile Sandstone aquifers, which exhibit a decrease in intensity away from the intervening lacustrine deposits of the Brushy Basin Member (Lake T'oo'dichi'), suggest that a similar mechanism was involved for both aquifers. Although the upward movement of pore waters into the Jackpile Sandstone Member was necessarily driven by compaction, downward movement of pore waters into the Westwater Canyon Member may have begun during deposition of lake sediments of Lake T'oo'dichi' and continued through early compaction of the lacustrine deposits.

SUMMARY OF MORRISON PALEOHYDROLOGY

Documentation of movement of lacustrine pore waters into adjacent fluvial sandstone aquifers provides constraints for the timing and direction of local groundwater flow. It is important now to place these constraints in a larger framework to see what can be inferred for regional hydrologic models from these more local observations. Lake T'oo'dichi' was only part of a larger depositional basin that experienced larger scale hydrologic flow patterns. Eastward flowing streams and groundwaters were ponded by the ancestral Uncompaghre Uplift, creating the hydrologically closed basin in which Lake T'oo'dichi' developed. Alteration of airfall silicic volcanic ash modified pore waters in the sediments of Lake T'oo'dichi' and this, combined with high evapotranspiration in an arid to semi-arid climate, resulted in development of dense saline, alkaline pore waters. Major aquifers delivered groundwater from precipitation that fell in the upland regions to the evaporative basin, which probably received lesser amounts of surface water because of the rainshadow effect created by the same uplands.

Development of high density pore waters resulted in downward movement of lacustrine pore waters in certain parts of the lake, especially the central part of the lake during low stands, when evaporative concentration of pore waters resulted in large vertical density gradients. Sandstones deposited by easterly flowing streams served as aquifers that both delivered water from mountainous source regions to the lake basin and also received pore waters expelled by lacustrine sediments during and subsequent to deposition.

Fluvial sandstone aquifers that underlie deposits of Lake T'oo'dichi' exhibit lateral alteration patterns that reflect hydrogeochemical gradients that existed in the overlying lacustrine sediments. The nature, timing, and patterns of this alteration demonstrate that lacustrine pore waters moved downward during deposition and also probably were expelled downward during compaction into the underlying sandstone aquifers. Mirror images of vertical alteration patterns in sandstone aquifers that both underlie and overlie deposits of Lake T'oo'dichi' similarly indicate that pore waters moved away from the lacustrine deposits and into adjoining aquifers. Although compaction is required to explain upward movement of pore waters into overlying aquifers, expelled waters probably entered the underlying sandstone aquifers and enhanced alteration that began when the lake was extant.

Understanding the regional geologic framework of the Morrison depositional basin, as well as the local alteration patterns in sandstone aquifers, helps constrain both large-scale and local hydrologic flow. It also permits reasonable inferences about the interaction between lacustrine deposits and their surrounding aquifers. Admittedly, hydrologic models cannot be developed for any instant in time using this approach, but reasonable approximations about paleohydrology are possible. Modeling with the constraints provided by the geology is an approach to paleohydrology that can be used in the absence of precise hydrologic data which is needed to generate accurate hydrologic models. Often precise hydrologic data is difficult to obtain. For example, Reilly (1993) points out that modeling in mixed freshwater-saltwater environments is difficult because what is important is the three-dimensional density distribution for the entire system and yet these data are rarely known to the extent necessary. This emphasizes the usefulness of geologic constraints, which although imprecise, probably permit more accurate inferences than might be drawn from paleohydrologic modeling in the absence of precise data.

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REFERENCES CITED

Adams, S.S., 1986, Organic-related alteration and authigenesis associated with epigenetic-humate sandstone uranium deposits, San Juan Basin, New Mexico; in, Dean, W.E., (ed.), Organics and Ore Deposits, Proceeding of the Symposium, Denver Region Exploration Geologists Society, p. 205-212.

Adams, S.S., and Saucier, A.E., 1981, Geology and recognition criteria for uraniferous humate deposits, Grants uranium region, New Mexico: U.S. Department of Energy Report GJBX-2(81), 225 p.

Adams, S.S., Curtis, H.S., and Hafen, P.L., 1974, Alteration of detrital magnetite-ilmenite in continental sandstones of the Morrison Formation, New Mexico; in, Formation of Uranium Ore Deposits: Vienna, International Atomic Energy Agency (Proceedings), p. 219-253.

Adams, S.S., Curtis, H.S., Hafen, P.L., and Salek-Nejad, H., 1978, Interpretation of postdepositional processes related to the formation and destruction of the Jackpile-Paguate uranium deposit, northwest New Mexico: Economic Geology, v. 73, p. 1635-1654.

Austin, S.R., 1963, Alteration of Morrison sandstone, in Kelley, V.C. ed., Geology and Technology of the Grants Uranium Region: New Mexico Bureau of Mines and Mineral Resources Memoir 15, p. 38-44.

Austin, S.R.,, 1980, Dissolution and authigenesis of feldspars; in, Rautman, C.A., (compiler), Geology and Mineral Technology of the Grants Uranium Region, 1979: New Mexico Bureau of Mines and Mineral Resources Memoir 38, p. 107-115.

Beard, D., and Weyl, P., 1973, Influence of texture on porosity and permeability of unconsolidated sand: American Association of Petroleum Geologists Bulletin, v. 57, p. 349-369.

Bell, T.E., 1986, Deposition and diagenesis of the Brushy Basin Member and upper part of the Westwater Canyon Member of the Morrison Formation, San Juan Basin, New Mexico; in, Turner-Peterson, C.E., Santos, E.S., and Fishman, N.S., (eds.), A Basin Analysis Case Study—The Morrison Formation, Grants Uranium Region, New Mexico: American Association of Petroleum Geologists Studies in Geology no. 22, p. 77-91.

Burchfiel, B.C., and Davis, G.A., 1975, Nature and controls of Cordilleran orogenesis, western United States—Extensions of an earlier synthesis: American Journal of Science, v. 275-A, p. 516-528.

Burst, J.F., 1969, Diagenesis of Gulf Coast clayey sediments and its possible relation to petroleum migration: American Association of Petroleum Geologists Bulletin, v. 53, p. 73-93.

Craig, L.C., Holmes, C.N., Cadigan, R.A., Freeman, V.L., and Mullens, T.E., 1955, Stratigraphy of the Morrison and related formations, Colorado Plateau region—A preliminary report: U.S. Geological Survey Bulletin 1009-E, p. 125-168.

Currie, B.S., 1997, Sequence stratigraphy of nonmarine Jurassic-Cretaceous rocks, Central Cordilleran foreland basin system: Geological Society of America Bulletin, v. 109, p. 1206-1222.

Duffy, C.J. and Al-Hassan, Sumani, 1988, Groundwater circulation in a closed desert basin—Topographic and scaling and climatic forcing: Water Resources Research, v. 24, no. 10, p. 1675-1688.
Ekart, D.D., and Cerling, T.E., 1996, PCO_2 during deposition of the Late Jurassic Morrison Formation and other paleoclimatic/ecologic data as inferred from stable carbon and oxygen isotope analyses: Geological Society of America, Abstracts with Programs, v. 28, no. 7, p. A252.
Fishman, N.S., Reynolds, R.L., and Robertson, J.F., 1985, Uranium mineralization in the Smith Lake district of the Grants uranium region, New Mexico: Economic Geology, v. 80, p. 1348-1364.
Fishman, N.S., and Reynolds, R.L., 1986, Origin of the Mariano Lake uranium deposit, McKinley County, New Mexico; in, Turner-Peterson, C.E., Santos, E.S., and Fishman, N.S., (eds.), A Basin Analysis Case Study—The Morrison Formation, Grants Uranium Region, New Mexico: American Association of Petroleum Geologists Studies in Geology No. 22, p. 211-226.
Fishman, N.S., Turner, C.E., and Brownfield, I.K., 1995, Authigenic albite in a Jurassic alkaline, saline lake deposit, Colorado Plateau--Evidence for early diagenetic origin: U.S. Geological Survey Bulletin 1808-P, 14 p.
Fishman, N. S., Turner-Peterson, C.E., and Reynolds, R.L., 1984, Alteration of magnetite and ilmenite in Upper Jurassic Morrison Formation, San Juan basin, New Mexico—Relationship to facies and primary uranium mineralization: American Association of Petroleum Geologists Bulletin, v. 68, p. 936.
Friedman, I., Smith, G.I., and Matsuo, S., 1982, Economic implications of the deuterium anomaly in the brine and salts in Searles Lake, California: Economic Geology, v. 77, p. 694-702.
Garrels, R.M., and MacKenzie, F.T., 1967, Origin of the chemical composition of some springs and lakes; in, Stumm, W., (ed.), Equilibrium Concepts in Natural Water Systems: American Chemical Society Advances in Chemistry, v. 67, p. 222-242.
Hafen, P.L., Adams, S.S., and Secor, G.B., 1976, Application of magnetic susceptibility measurements to uranium exploration in sandstones; in, Exploration for Uranium Ore Deposits: Vienna, International Atomic Energy Agency (Proceedings), p. 367-378.
Hamilton, W., 1978, Mesozoic tectonics of the western United States; in, Howell, D.E., and McDougall, K.A., (eds.), Mesozoic Paleogeography of the Western United States: Society of Economic Paleontologists and Mineralogists, Pacific Section, p. 33-70.
Hansley, P.L., 1986, Relationship of detrital, nonopaque heavy minerals to diagenesis and provenance of the Morrison Formation, southwestern San Juan Basin, New Mexico; in, Turner-Peterson, C.E., Santos, E.S., and Fishman, N.S., (eds.), A Basin Analysis Case Study—The Morrison Formation, Grants Uranium Region, New Mexico: American Association of Petroleum Geologists Studies in Geology no. 22, p. 257-276.
Hardie, I.A., and Eugster, H.P., 1970, The evolution of closed basin brines: Mineralogical Society of America Special Paper 3, p. 273-290.
Hardt, W.F., Moyle, W.R., Jr., and Dutcher, L.C., 1972, Proposed water-resources study of Searles Valley, California: U.S. Geological Survey Open-File Report, 69 p.
Hay, R.L., 1966, Zeolites and zeolitic reactions in sedimentary rocks: Geological Society of America Special Paper 85, 130 p.
Hicks, R.T., 1981, Diagenesis of the Westwater Canyon Member, Morrison Formation, East Chaco Canyon drilling project, New Mexico: Unpublished M.S. thesis, University of New Mexico, Albuquerque, 131 p.
Hilpert, L.S., 1969, Uranium resources of northwestern New Mexico: U.S. Geological Survey Professional Paper 603, 166 p.
Horton, B.K., 1997, Comparison of the North American Cordilleran retroarc foreland with the modern Central Andean foreland basin system: Geological Society of American Abstracts With Programs, Annual Meeting, Salt Lake City, p. A-203.

Jones, B.F., 1966, Geochemical evolution of closed basin waters in the western Great Basin: Ohio Geological Society, Second Symposium on Salt, Cleveland, Ohio, v. 1, p. 181-200.

Jones, B.F., VanDenburgh, A.S., Truesdell, A.H., and Rettig, S.L., 1969, Interstitial brines in playa sediments: Chemical Geology, v. 4, p. 253-262.

Kirk, A.R., and Condon, S.M., 1986, Structural control of sedimentation patterns and the distribution of uranium deposits in the Westwater Canyon Member of the Morrison Formation, Northwestern New Mexico—A subsurface study; in, Turner-Peterson, C.E., Santos, E.S., and Fishman, N.S., (eds.), A Basin Analysis Case Study—The Morrison Formation, Grants Uranium Region, New Mexico: American Association of Petroleum Geologists Studies in Geology no. 22, p. 105-143.

Kowallis, B.J., Christiansen, C.H., Deino, A.L., Peterson, Fred, Turner, C.E., Kunk, M.J., and Obradovich, J.D., 1998, The age of the Morrison Formation; in, Carpenter, K., Chure, D.J., and Kirkland, J.I., (eds.), The Upper Jurassic Morrison Formation—An interdisciplinary study: Modern Geology, v. 22, nos. 1-4, p. 235-260. .

Ludwig, K.L., Simmons, K.R., and Webster, J.D., 1984, U-Pb isotope systematics and apparent ages of uranium ores, Ambrosia Lake and Smith Lake districts, Grants mineral belt, New Mexico: Economic Geology, v. 79, p. 322-337.

Magara, K., 1978, Compaction and fluid migration: Amsterdam, Elsevier, 320 p.

Magara, K.,, 1980, Comparison of porosity-depth relationships of shale and sandstone: Journal of Petroleum Geology, v. 3, p. 175-185.

Martinez, R. 1979, Provenance study of the Westwater Canyon and Brushy Basin Members of the Morrison Formation between Gallup and Laguna, New Mexico: Unpublished Ph.D. dissertation, University of New Mexico, Albuquerque, 79 p.

Owen, D.E., Turner-Peterson, C.E., and Fishman, N.S., 1989, X-ray diffraction studies of the <0.5 µm fraction from the Brushy Basin Member of the Upper Jurassic Morrison Formation, Colorado Plateau: U.S. Geological Survey Bulletin 1808-G, 25 p.

Peterson, Fred, 1984, Fluvial sedimentation on a quivering craton—Influence of slight crustal movements on fluvial processes, Upper Jurassic Morrison Formation, western Colorado Plateau: Sedimentary Geology, v. 38, no. 1-4, p. 21-49.

Peterson, Fred, 1988, Pennsylvanian to Jurassic eolian transportation systems in the western United States: Sedimentary Geology, v. 56, p. 207-260.

Peterson, Fred, 1994, Sand dunes, sabkhas, streams, and shallow seas—Jurassic paleogeography in the southern part of the Western Interior Basin; in, Caputo, M.V., Peterson, J.A., and Franczyk, K.J., (eds.), Mesozoic Systems of the Rocky Mountain Region, USA: Rocky Mountain Section Society of Sedimentary Geology, p. 233-272.

Poole, F.G., 1962, Wind directions in late Paleozoic to middle Mesozoic time on the Colorado Plateau; in, Short papers in geology, hydrology, and topography: U.S. Geological Survey Professional Paper 450-D, p. D147-D151.

Reilly, T.E., 1993, Analysis of ground-water systems in fresh water-salt water environments; in, Alley, W.M., (ed.), Regional Ground-Water Quality: Van Nostrand Reinhold, New York, p. 443-469.

Reynolds, R.L., Fishman, N.S., Scott, J.H., and Hudson, M.R., 1986, Iron-titanium oxide minerals and magnetic susceptibility anomalies in the Mariano Lake-Lake Valley cores—Constraints on conditions of uranium mineralization in the Morrison Formation, San Juan Basin, New Mexico; in, Turner-Peterson, C.E., Santos, E.S., and Fishman, N.S., (eds.), A Basin Analysis Case Study—The Morrison Formation, Grants Uranium Region, New Mexico: American Association of Petroleum Geologists Studies in Geology no. 22, p. 303-329.

Sheppard, R.A., and Gude, A.J., 3rd, 1968, Distribution and genesis of authigenic silicate minerals in tuffs of Pleistocene Lake Tecopa, Inyo County, California: U.S. Geological Survey Professional Paper 597, 38 p.
Sheppard, R.A., and Gude, A.J., 3rd,, 1973, Zeolites and associated authigenic silicate minerals in tuffaceous rocks of the Big Sandy Formation, Mohave County, Arizona: U.S. Geological Survey Professional Paper 830, 36 p.
Sheppard, R.A., and Gude, A.J., 3rd,, 1987, Field trip guide to the Sheaville and Rome zeolite deposits, southeastern Oregon: Oregon Geology, v. 49, p. 3-10.
Surdam, R.C., and Sheppard, R.A., 1978, Zeolites in saline, alkaline-lake deposits; in, Sand, L.B., and Mumpton, F.A., (eds.), Natural zeolites—Occurrence, properties, use: Elmsford, New York, Pergamon Press, p. 145-174.
Turner, C.E., and Fishman, N.S., 1991, Jurassic Lake T'oo'dichi'—A large, alkaline, saline lake, Morrison Formation, eastern Colorado Plateau: Geological Society of America Bulletin, v. 103, p. 538-558.
Turner, C.E., Fishman, N.S., Hatcher, P.G., and Spiker, E.S., 1993, Nature and role of organic matter in sandstone uranium deposits, Grants uranium region, New Mexico, USA; in, Parnell, J., Kucha, H., and Landais, P., (eds.), Bitumens in ore deposits: Special Publication No. 9 of the Society for Geology Applied to Mineral Deposits, Springer Verlag, Berlin, p. 239-275.
Turner-Peterson, C.E., 1985, Lacustrine-humate model for primary uranium ore deposits, Grants uranium region, New Mexico: American Association of Petroleum Geologists Bulletin, v. 69, p. 1999-2020.
Turner-Peterson, C.E., 1986, Fluvial sedimentology of a major uranium-bearing sandstone—A study of the Westwater Canyon Member of the Morrison Formation, San Juan Basin, New Mexico; in, Turner-Peterson, C.E., Santos, E.S., and Fishman, N.S., (eds.), A Basin Analysis Case Study—The Morrison Formation, Grants Uranium Region, New Mexico: American Association of Petroleum Geologists Studies in Geology no. 22, p. 47-75.
Turner-Peterson, C.E., 1987, Sedimentology of the Westwater Canyon and Brushy Basin Members of the Morrison Formation, Colorado Plateau, and relationship to uranium mineralization: Unpublished Ph.D. dissertation, University of Colorado, Boulder, 169 p.
Turner-Peterson, C.E., and Fishman, N.S., 1986, Geologic synthesis and genetic models for uranium mineralization in the Morrison Formation, Grants uranium region, New Mexico; in, Turner-Peterson, C.E., Santos, E.S., and Fishman, N.S., (eds.), A Basin Analysis Case Study—The Morrison Formation, Grants Uranium Region, New Mexico: American Association of Petroleum Geologists Studies in Geology no. 22, p. 357-388.
Winter, T.C., 1981, Uncertainties in estimating the water balance of lakes: Water Resources Bulletin, v. 17, no. 1, p. 82-115.

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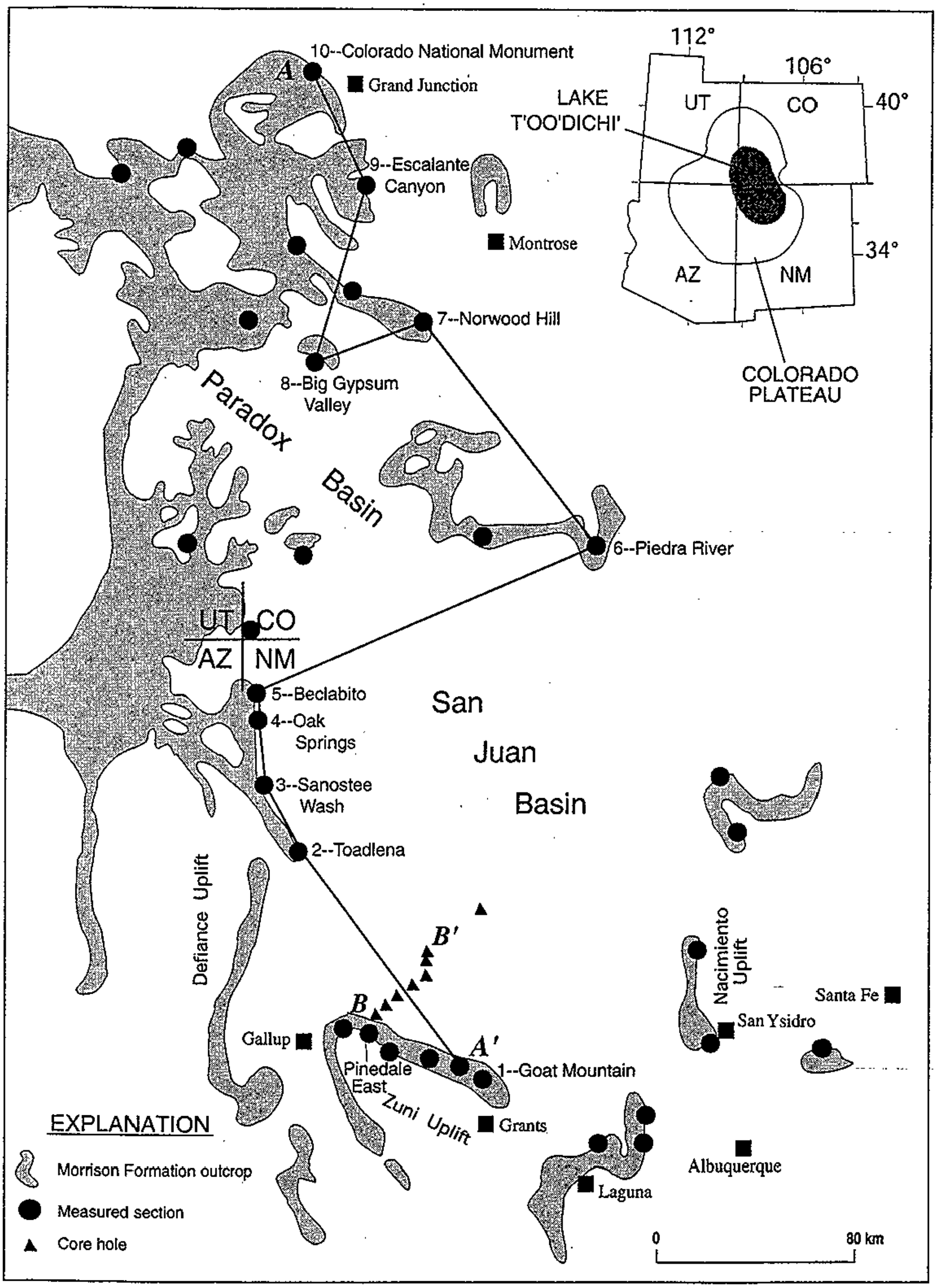
Figure 1.—Map showing the extent of Lake T'oo'dichi' within combined Paradox-San Juan Basins of the Colorado Plateau physiographic province. Outcrops of the Upper Jurassic Morrison Formation outlined in gray. Stratigraphic section A-A' (with localities 1-10) shown in Figure 2. Section B-B' in southern San Juan Basin is a core fence through the Brushy Basin and Westwater Canyon Members of the Morrison Formation.



10--Colorado National Monument
A
Grand Junction
9--Escalante Canyon
Montrose
7--Norwood Hill
8--Big Gypsum Valley
Paradox Basin
6--Piedra River
UT
CO
AZ
NM
5--Beclabito
4--Oak Springs
3--Sanostee Wash
2--Toadlena
San Juan Basin
Defiance Uplift
Nacimiento Uplift
B'
B
A'
Gallup
Pinedale East
1--Goat Mountain
Zuni Uplift
Grants
San Ysidro
Santa Fe
Laguna
Albuquerque
112°
106°
40°
34°
LAKE T'OO'DICHI'
COLORADO PLATEAU
EXPLANATION
Morrison Formation outcrop
Measured section
Core hole
0
80 km

Figure 1.

Figure 2.—North-south stratigraphic section of the Morrison Formation across the study area. Diagenetic mineral zones in the Brushy Basin Member in New Mexico and equivalent beds to the north (upper part of the Brushy Basin Member) are determined from authigenic minerals in tuff beds (from Turner-Peterson, 1987). See Figure 1 for location of A-A' (with localities 1-10). J-5, a regional unconformity between the Morrison Formation and underlying rocks of the San Rafael Group.

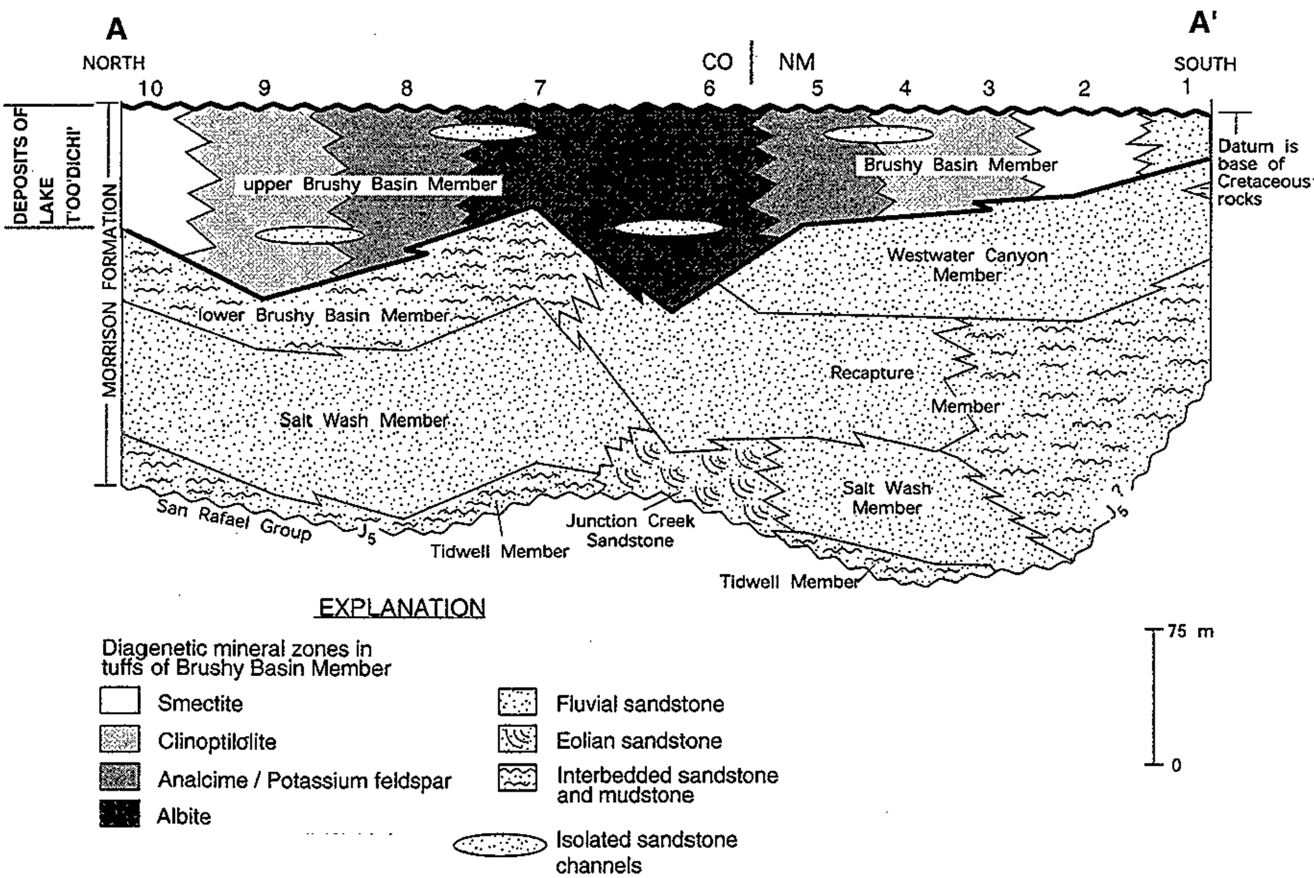
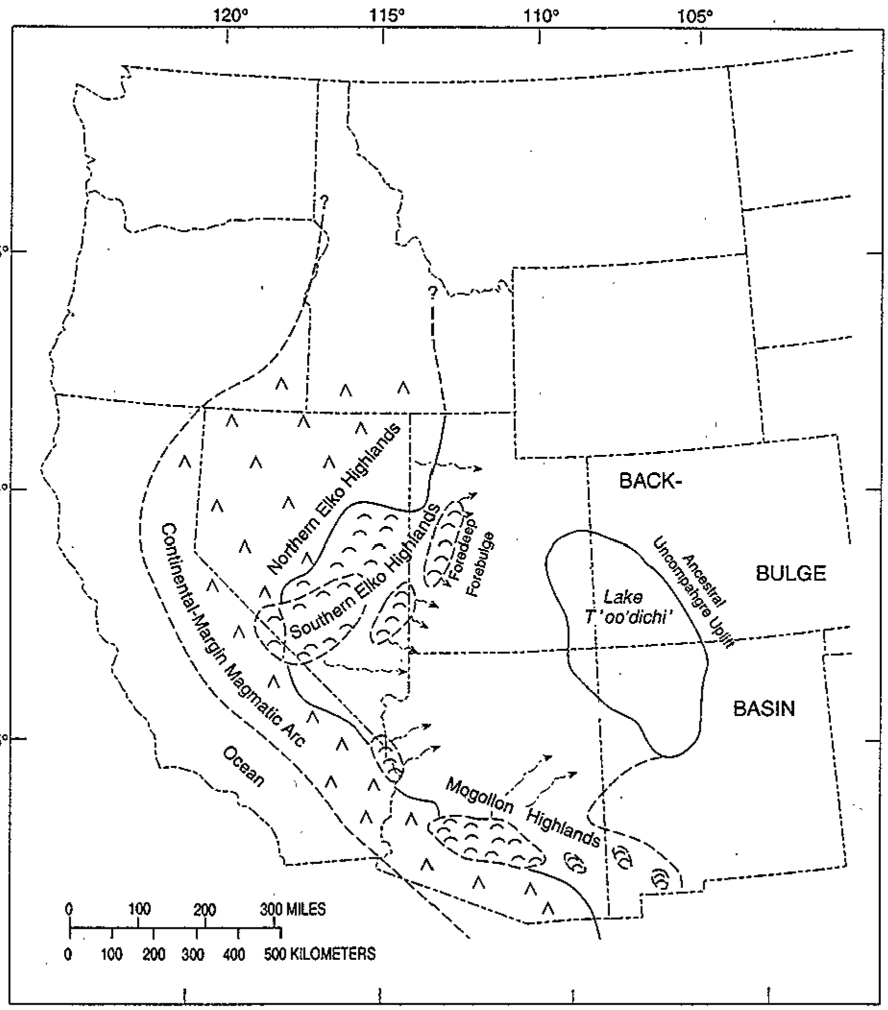

A
A'
NORTH
SOUTH
CO
NM
10
9
8
7
6
5
4
3
2
1
DEPOSITS OF LAKE T'OO'DICHI'
MORRISON FORMATION
upper Brushy Basin Member
Brushy Basin Member
Datum is base of Cretaceous rocks
Westwater Canyon Member
lower Brushy Basin Member
Recapture Member
Salt Wash Member
Salt Wash Member
San Rafael Group
J5
Tidwell Member
Junction Creek Sandstone
Tidwell Member
EXPLANATION
Diagenetic mineral zones in tuffs of Brushy Basin Member
Smectite
Clinoptilolite
Analcime / Potassium feldspar
Albite
Fluvial sandstone
Eolian sandstone
Interbedded sandstone and mudstone
Isolated sandstone channels
75 m
0

Figure 2.

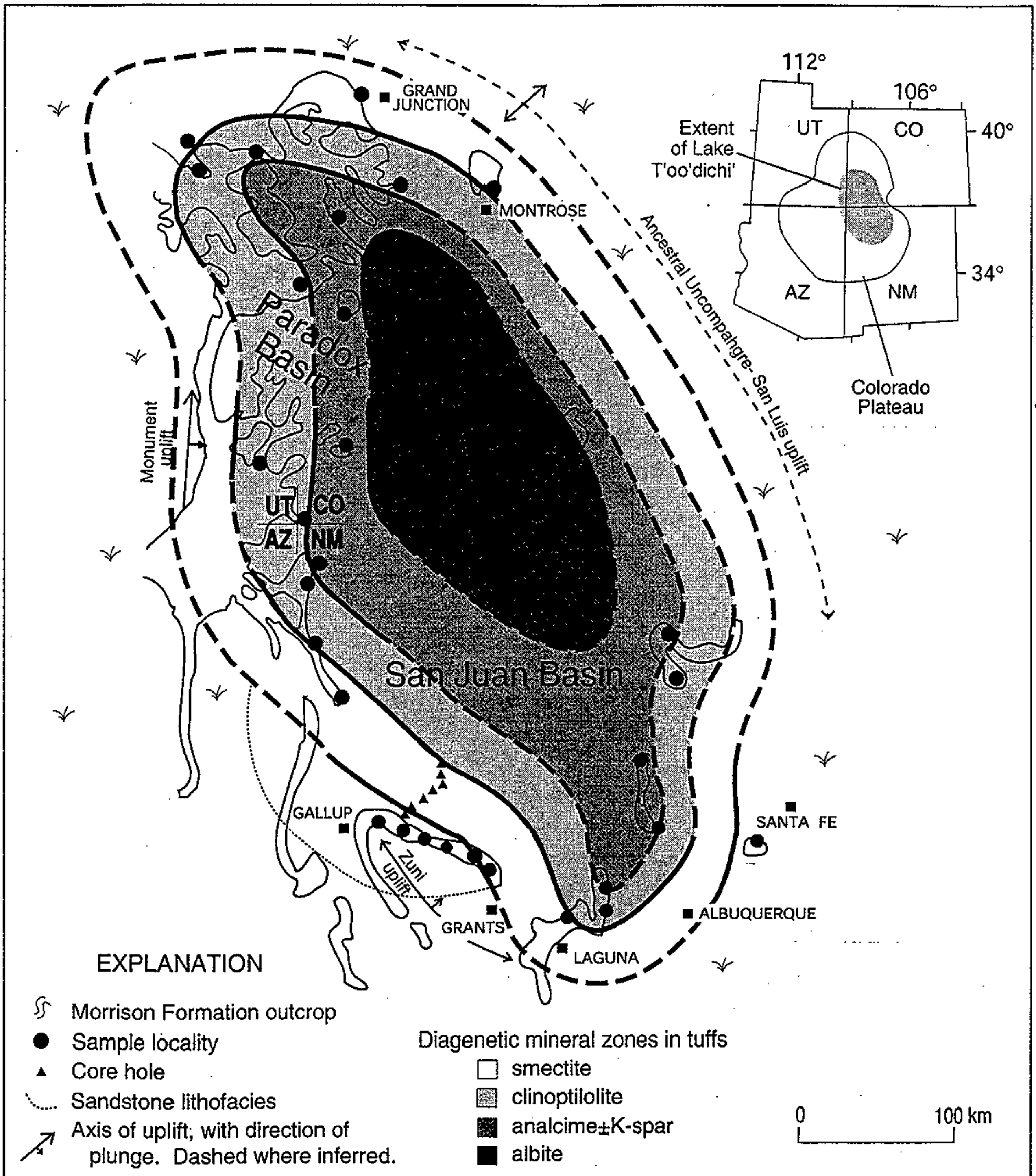
Figure 3.—Paleogeography of southwestern U.S. in Late Jurassic time (early Tithonian). Location of magmatic arc and uplands from Peterson (1994). Location of foredeep, forebulge, and back arc parts of foreland basin inferred from Currie (1997).



120°
115°
110°
105°
45°
40°
35°
?
BACK-
BULGE
BASIN
Northern Elko Highlands
Southern Elko Highlands
Foredeep
Forebulge
Ancestral Uncompahgre Uplift
Lake T'oo'dichi'
Continental-Margin Magmatic Arc
Ocean
Mogollon Highlands
0 100 200 300 MILES
0 100 200 300 400 500 KILOMETERS

Figure 3.

Figure 4.—Map showing the basinward progression of concentric diagenetic mineral zones in tuff beds of the Brushy Basin Member that outline ancient Lake T'oo'dichi'. The ancient lake occupied the combined San Juan-Paradox basin area. Note how bounding structural elements that were active during deposition controlled details of lake geometry. Fluvial sandstones of the sandstone lithofacies also shown. From Turner and Fishman (1991).



GRAND JUNCTION
MONTROSE
Ancestral Uncompahgre- San Luis uplift
Paradox Basin
Monument uplift
UT
CO
AZ
NM
San Juan Basin
GALLUP
Zuni uplift
GRANTS
LAGUNA
ALBUQUERQUE
SANTA FE
112°
106°
40°
34°
Extent of Lake T'oo'dichi'
UT
CO
AZ
NM
Colorado Plateau
EXPLANATION
Morrison Formation outcrop
Sample locality
Core hole
Sandstone lithofacies
Axis of uplift; with direction of plunge. Dashed where inferred.
Diagenetic mineral zones in tuffs
smectite
clinoptilolite
analcime±K-spar
albite
0
100 km

Figure 4.

Figure 5.—Diagram showing the basinward progression of authigenic minerals in tuffs across diagenetic mineral zones of Lake T'oo'dichi' deposits of the Brushy Basin Member. Dashed where present but not abundant.

*Smectitic mixed-layer illite/smectite (70%-100% smectite layers);

**Illitic mixed-layer illite/smectite (0%-30% smectite layers).

Mixed-layer illite/smectite is highly variable in composition (0%-100% smectite layers) in the analcime±potassium feldspar diagenetic mineral zone. Qtz/chal, silica in the form of quartz and chalcedony. From Turner and Fishman (1991).

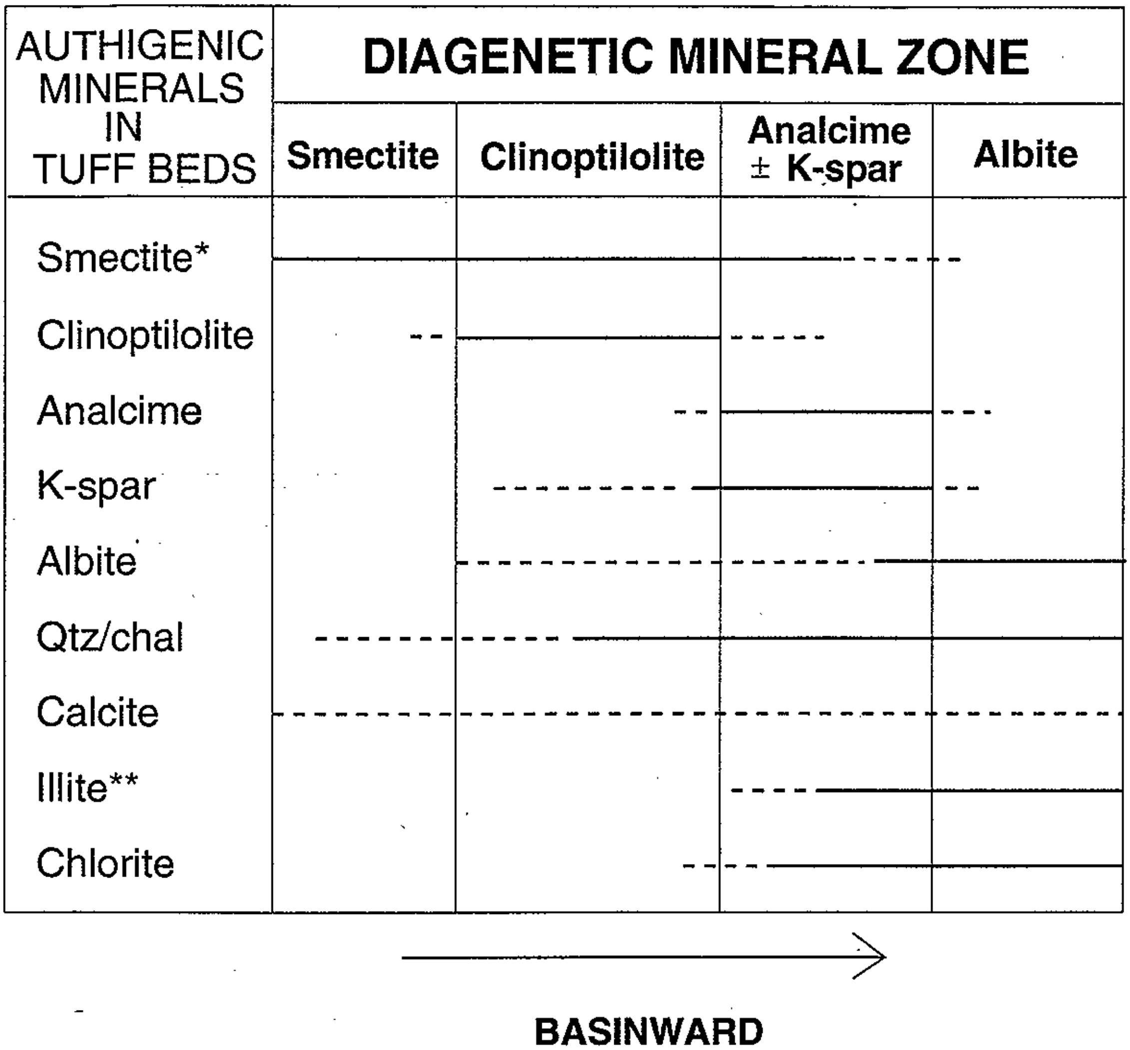

AUTHIGENIC MINERALS IN TUFF BEDS
DIAGENETIC MINERAL ZONE
Smectite
Clinoptilolite
Analcime ± K-spar
Albite
Smectite*
Clinoptilolite
Analcime
K-spar
Albite
Qtz/chal
Calcite
Illite**
Chlorite
BASINWARD

Figure 5.

Figure 6.—Schematic cross-section of the Morrison Formation along the southern edge of the San Juan Basin, New Mexico, showing deposits of Lake T'oo'dichi' and surrounding fluvial sandstone aquifers (after Hilpert, 1969). Location of Gallup, Grants, and Laguna shown in Figure 1.

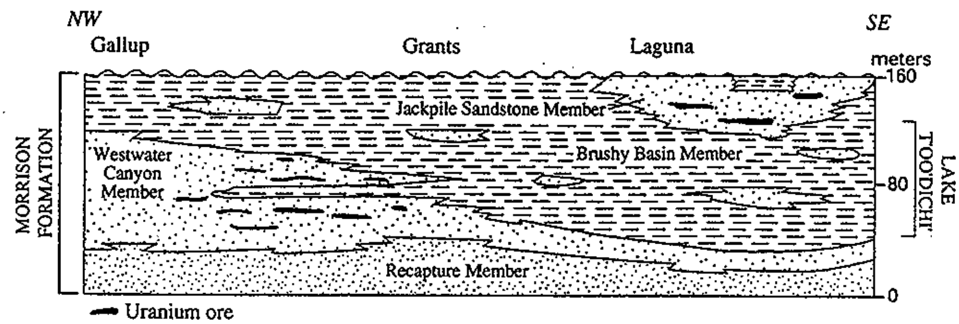

NW
SE
Gallup
Grants
Laguna
meters
160
80
0
MORRISON FORMATION
Jackpile Sandstone Member
Westwater Canyon Member
Brushy Basin Member
Recapture Member
LAKE T'OO'DICHI'
Uranium ore

Figure 6.

Figure 7.—Diagram showing the basinward progression of diagenetic alterations in fluvial sandstone aquifers associated with diagenetic mineral zones of deposits of Lake T'oo'dichi' in the Brushy Basin Member. Dashed where present but not abundant. *Smectitic mixed-layer illite/smectite (70%-100% smectite layers); **Illitic mixed-layer illite/smectite (0%-30% smectite layers). Mixed-layer illite/smectite is highly variable in composition (0%-100% smectite layers) in sandstones associated with the analcime±potassium feldspar diagenetic mineral zone. Qtz/chal, silica in the form of quartz and chalcedony; Dissol., dissolution; Ppt., precipitation; Skel., skeletalization.

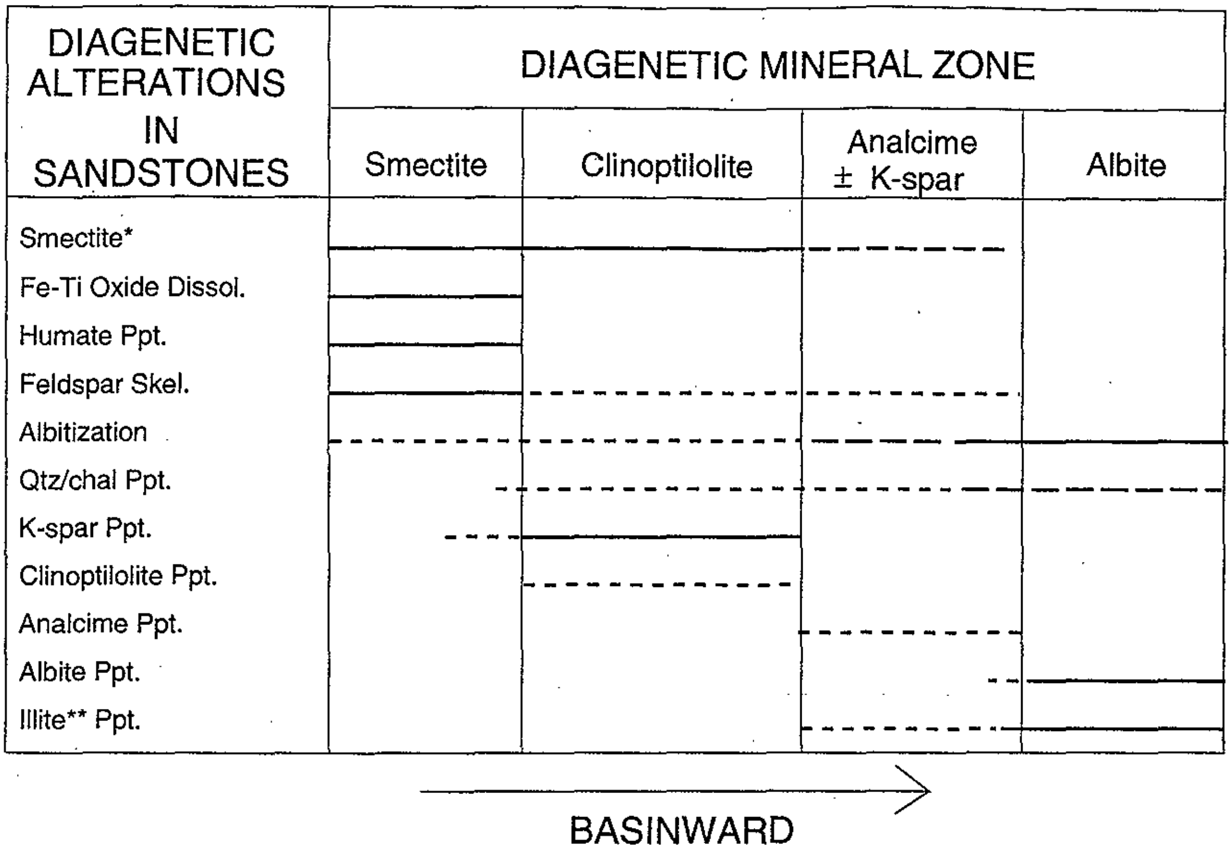

DIAGENETIC ALTERATIONS IN SANDSTONES
DIAGENETIC MINERAL ZONE
Smectite
Clinoptilolite
Analcime ± K-spar
Albite
Smectite*
Fe-Ti Oxide Dissol.
Humate Ppt.
Feldspar Skel.
Albitization
Qtz/chal Ppt.
K-spar Ppt.
Clinoptilolite Ppt.
Analcime Ppt.
Albite Ppt.
Illite** Ppt.
BASINWARD

Figure 7.

Figure 8.—Detrital FeTi-oxide grains from the Westwater Canyon Member of the Morrison Formation showing varying amounts of alteration downsection, Toadlena locality (see Fig. 1).

A) Altered FeTi-oxide grain from upper part of section, in which iron is completely leached from original titanomagnetite grain. Relict TiO_2 lamellae (white) indicate positions of former ilmenite exsolution lamellae.

B) Partly altered FeTi-oxide grain from middle part of section, in which iron is partly leached from an ilmeno-hematite grain.

C) Fresh, unaltered titanomagnetite grain from lower part of section. Photomicrographs taken with vertically reflected light in oil.

Figure 8.

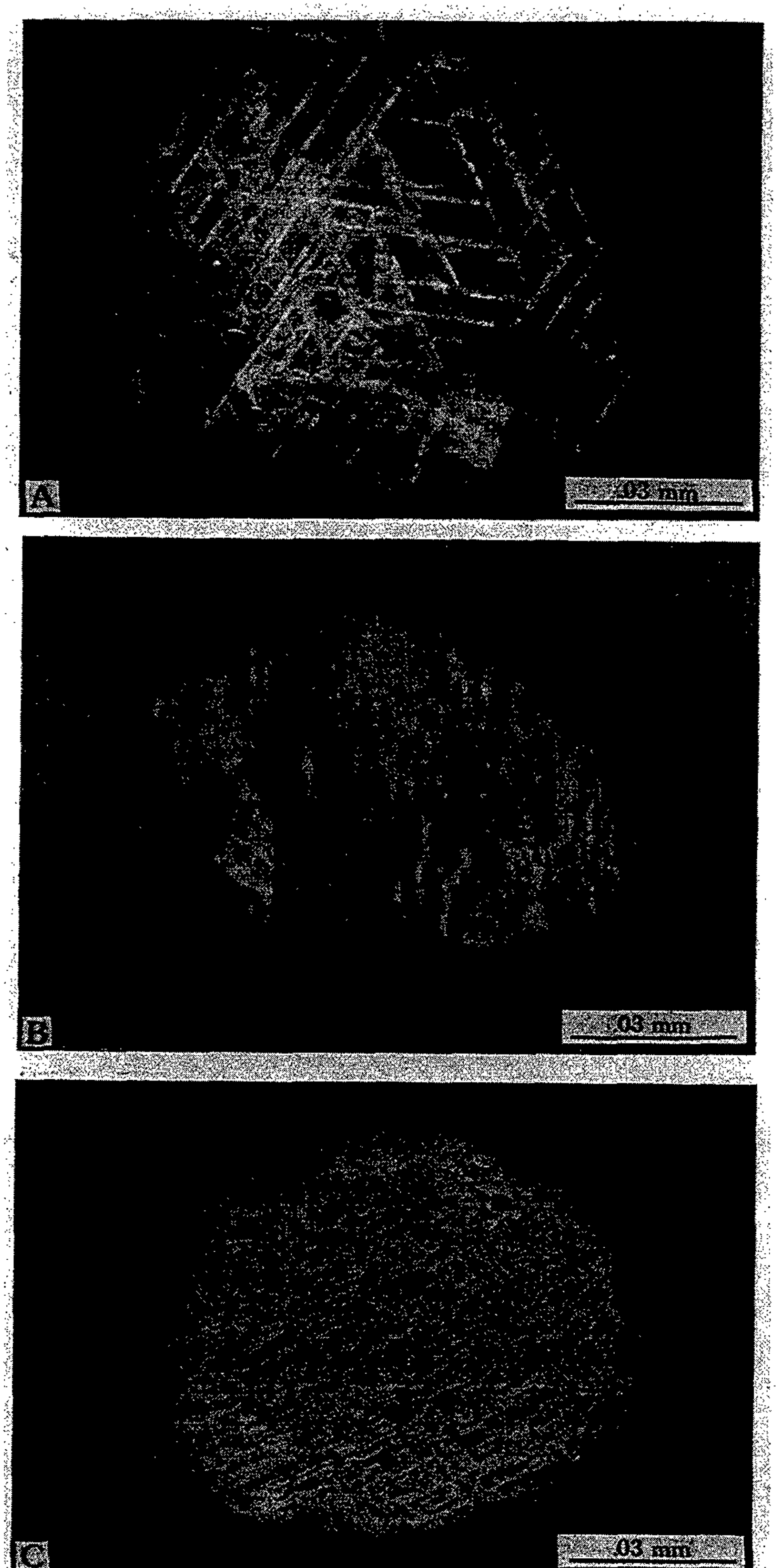


Figure 9.—Stratigraphic section from core fence B-B' (see Figure 1), showing alteration zones of detrital FeTi-oxide grains in fluvial sandstones of the Westwater Canyon Member based on petrography of core samples and borehole magnetic susceptibility data. The dashed line separates a zone of nearly complete destruction of FeTi-oxide grains in the uppermost sandstones from a zone of preservation of these minerals in the lowermost sandstones (from Reynolds and others, 1986).

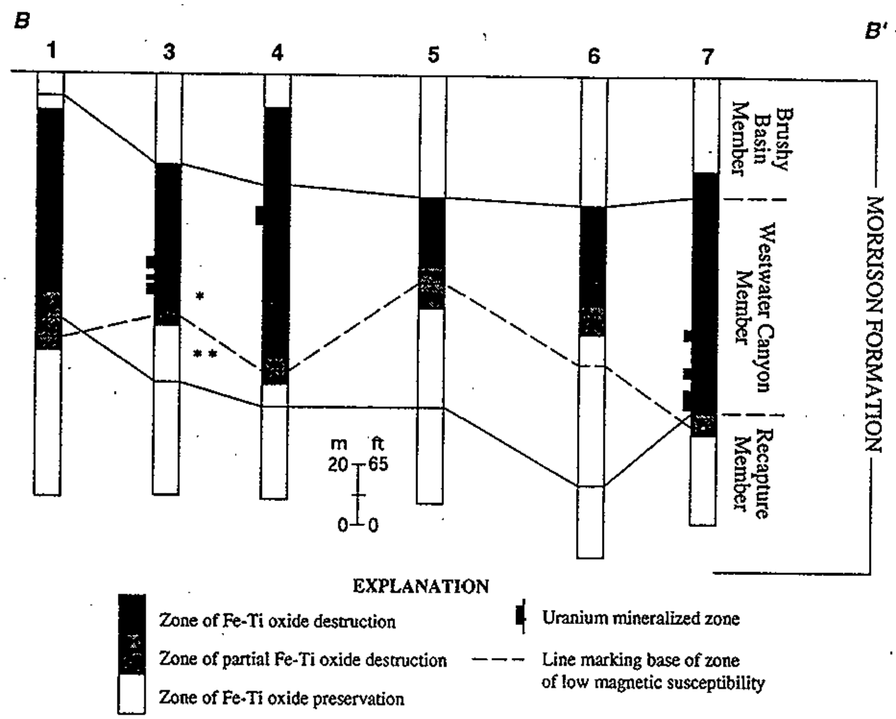
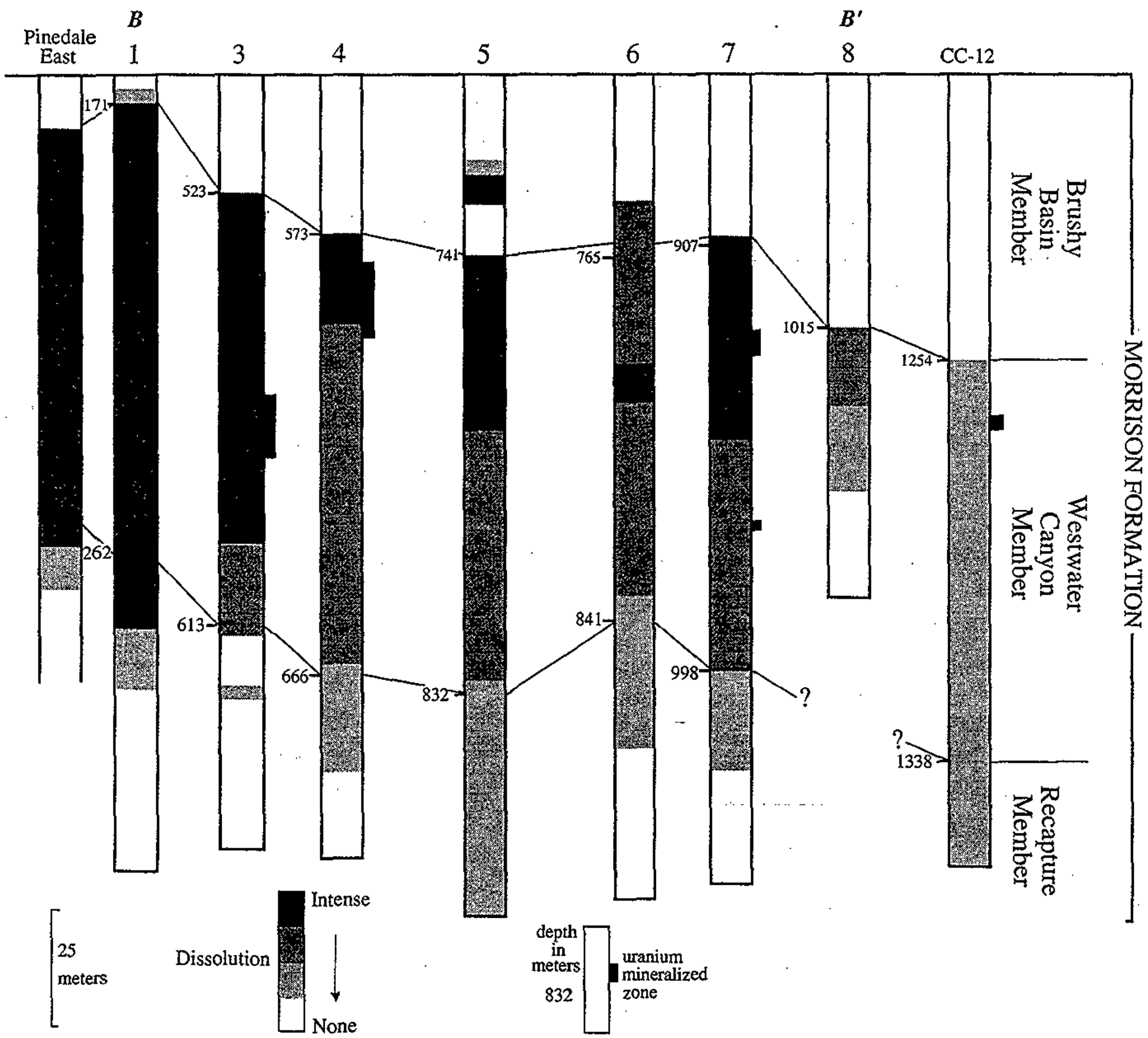

B
B'
1
3
4
5
6
7
Brushy Basin Member
Westwater Canyon Member
Recapture Member
MORRISON FORMATION
m ft
20 65
0 0
*
* *
EXPLANATION
Zone of Fe-Ti oxide destruction
Zone of partial Fe-Ti oxide destruction
Zone of Fe-Ti oxide preservation
Uranium mineralized zone
Line marking base of zone of low magnetic susceptibility

Figure 9.

Figure 10.—Stratigraphic section from core fence B-B' (see Figure 1), showing alteration zones of detrital plagioclase feldspar grains in fluvial sandstones of the Westwater Canyon Member based on petrography of core samples.



Pinedale East
B
1
3
4
5
6
7
B'
8
CC-12
171
262
523
613
573
666
741
832
765
841
907
998
?
1015
1254
?
1338
Brushy Basin Member
Westwater Canyon Member
Recapture Member
MORRISON FORMATION
25 meters
Dissolution
Intense
None
depth in meters
832
uranium mineralized zone

Figure 10.

Figure 11.—Schematic diagram showing mirror image of feldspar alteration in fluvial sandstone aquifers above (Jackpile Sandstone) and below (Westwater Canyon Member) deposits of Lake T'oo'dichi' in Brushy Basin Member (from Adams, 1986).

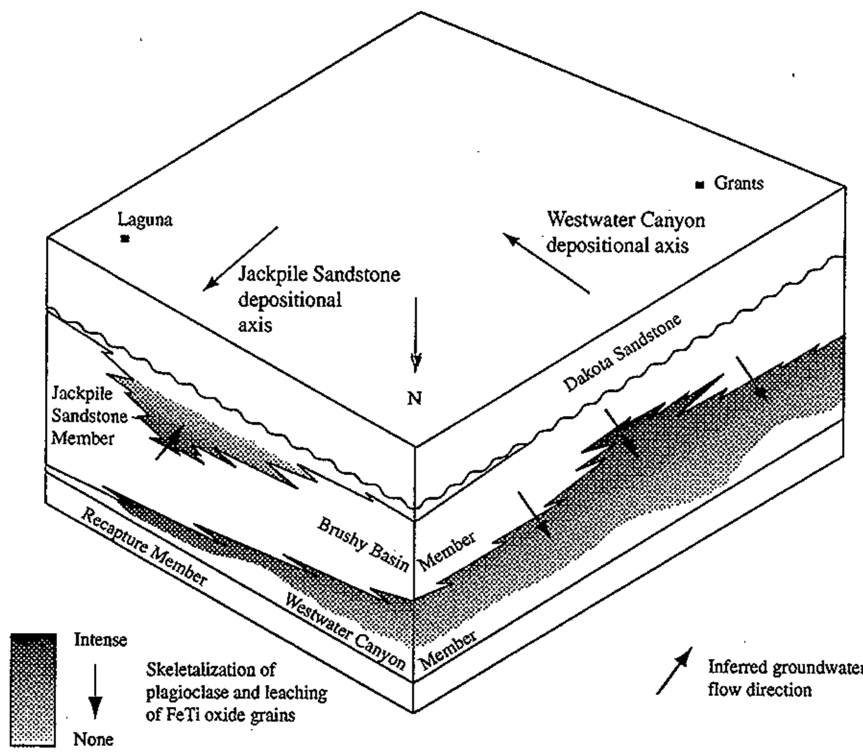

Grants
Laguna
Westwater Canyon depositional axis
Jackpile Sandstone depositional axis
N
Dakota Sandstone
Jackpile Sandstone Member
Brushy Basin Member
Recapture Member
Westwater Canyon Member
Intense
None
Skeletalization of plagioclase and leaching of FeTi oxide grains
Inferred groundwater flow direction

Figure 11.

Figure 12.—Photomicrograph showing chalcedonic cement in isolated fluvial sandstone in the Brushy Basin Member, with high intergranular volume and low degree of compaction.
Q, detrital quartz grain. Sample from Sanostee Wash locality (see Figure 1). Photomicrograph is 1.3 mm across.

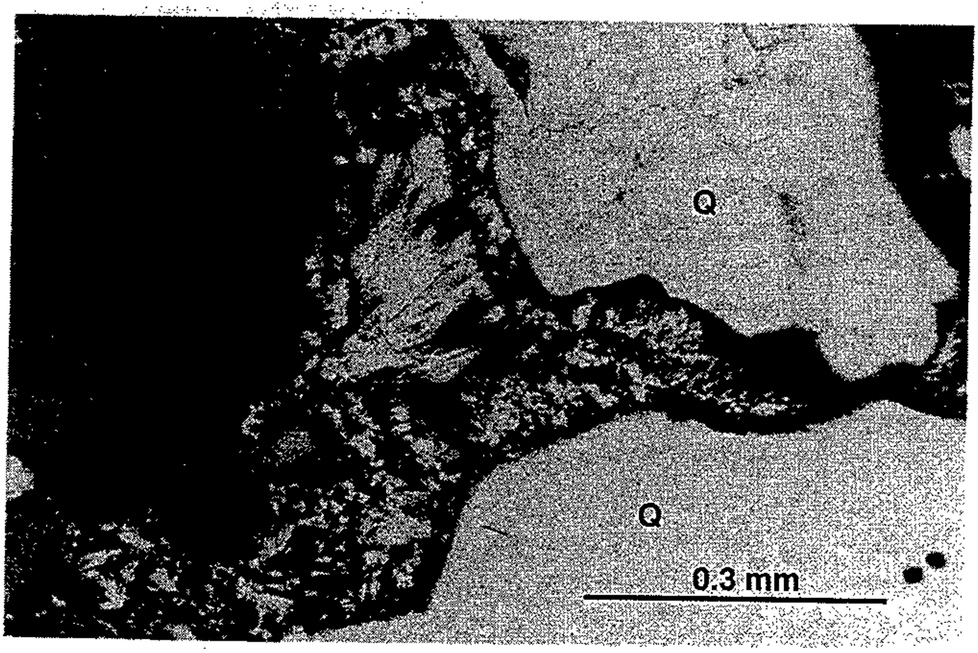


Figure 12

CONCLUSIONS

The Morrison Extinct Ecosystems Project was a multidisciplinary effort designed to investigate the nature and evolution of environments, habitats, communities, and climate in and near many National Park Service units in the Western Interior of the United States through some 7 million years of Earth history when the Upper Jurassic Morrison Formation was deposited. Scientific interpretations concerning the ancient Morrison ecosystem are somewhat tentative in this report because of the recency of the research. The Morrison Formation was studied mostly in Utah, Colorado, Wyoming, and Montana but also to some extent in Arizona, New Mexico Oklahoma and South Dakota to provide a more accurate regional framework and to collect samples for laboratory analyses. Included in the following pages are brief discussions of interpretations according to major subspecialty categories. The last names of the researchers most involved in the specific topics are enclosed in brackets [thus].

Stratigraphy and Sedimentology

Regional stratigraphic and sedimentologic studies [Turner and Peterson] demonstrate that strata deposited in relatively dry environments are fairly common in the Morrison Formation in the southern and central parts of the Western Interior. These include extensive evaporite deposits (chiefly gypsum) in the lowermost part of the formation in Utah and Colorado and locally in eastern Wyoming; large eolian dune field deposits (erg deposits) at or near the Four Corners area; small eolian sandstone beds scattered through Arizona, Utah, Colorado, and extending as far north as northern Wyoming; and the rather extensive alkaline, saline lake deposits of ancient Lake T'oo'dichi' in the eastern part of the Colorado Plateau. Farther north in Montana, widely distributed coal beds in the upper part of the Morrison suggest deposition late in Morrison deposition was in a more humid climate.

Fluvial and overbank architectural styles [Demko] are suggestive of seasonally wet-dry precipitation-discharge regimes. Floodplain paleosols in the Morrison Formation are associated with each of the fluvial deposits. Thin floodplain paleosols in the Morrison Formation, like the channel and overbank architectural styles, are indicative of at least periodic dryness.

Two sequence-bounding paleosols (or paleosol complexes) have been identified in the Morrison Formation and represent significant diastems in the part of the formation where they occur. The first is immediately above the Salt Wash Member (within the lower part of the Brushy Basin Member). This paleosol complex marks a change in fluvial style from low- to high-sinuosity planform patterns. Some contemporaneous erosion is associated with this horizon in the Dinosaur National Monument area. The climatic implication of this paleosol is no different from those of the other calcic paleosols in the Salt Wash and Brushy Basin Members and is only differentiated by its greater development and regional extent. The second sequence-bounding paleosol complex is at the top of the Brushy Basin Member, at its boundary with overlying Lower Cretaceous deposits. This paleosol represents a long period of exposure and pedogenesis (>5 my) and possibly the overprinting of different climatic regimes (wetter upon drier). This interval is also typically overprinted by later calcretization associated with early diagenesis during deposition of overlying Lower Cretaceous deposits. These two paleosols are interpreted to mark the tops of two aggradational sequences that comprise Morrison deposition.

The calcretes of the Upper Morrison Formation-Lower Burro Canyon Formation are being studied petrographically and can be classified as mostly alpha type calcretes [Skipp]. That is, they consist largely of a dense micrite to microcrystalline groundmass that contains peloids, nodules, circumgranular cracks, floating grains (both detrital and authigenic), coated grains, coated fractures, and complex arrays of micro- to macro-fractures. In addition to the microcrystalline textures, some coarse recrystallized textures were observed in samples collected in Salt Valley anticline near Arches National Park, Utah. Very few biogenic textures were observed.

Paleontology

The terrestrial facies of the Morrison is fossiliferous in all areas where the formation is sufficiently exposed to allow a reasonable chance of encountering the fossils [Engelmann]. However, there is a variation in the geographic and stratigraphic distribution of some types of fossils. Both of these observations have important implications for resource management in the Park Service units that contain outcrops of the Morrison Formation. In addition, Morrison faunas are diverse, including fossils of vertebrates, invertebrates, and traces of both, as well as plant fossils of various types. In some of the study areas, invertebrate trace fossils, including the burrows of crayfish, termites, ants, beetles, and other insects, were found to be abundant, particularly within the upper Salt Wash and lower Brushy Basin Members. This horizon may be explained by modeling Morrison sedimentation in that area as accumulation in a tectonically-controlled depositional basin with climatic and ecological controls.

Based on comparative studies of the mammalian faunas of the Morrison [Englemann], there is some geographic variation. Mammal faunas from the Fruita Paleontological Area near Colorado National Monument and from Dinosaur National Monument lack docodonts, which is typical for Morrison faunas west of the Rocky Mountains. This lack of docodonts contrasts with the presence of them from even small samples of Morrison mammalian fossils east of the Rockies. This may be explained by the presence of a divide separating the Morrison into eastern and western geographic subareas, an interpretation that may be suggested by other stratigraphic evidence.

Illegal collecting of fossils within the Park Service units studied does not appear to have been intensive, in contrast to the evidence of extensive collecting on State and Federal lands adjacent to the Park Service lands [Engelmann]. This makes the interpretation of observations on fossil occurrences somewhat problematic. In particular, the apparent scarcity of silicified wood in the vicinity of Arches National Park and Colorado National Monument relative to occurrences at Dinosaur National Monument may be the result of intensive collecting by rock hounds.

Preliminary work indicates that the dominant group of theropod dinosaurs from the Morrison Formation belong to the Family Allosauridae [Chure]. A new and relatively primitive allosaurid from the Salt Wash Member that was recently excavated at Dinosaur National Monument is currently being studied. Reexamination of the original material of Saurophaginax (originally Saurophagus) from the uppermost Morrison of western Oklahoma has established that it is genetically separate from Allosaurus. Thus, at least three genera from Family Allosauridae (the new Salt Wash primitive allosaurid, Allosaurus, and Saurophaginax) existed during the Late Jurassic in the Western Interior of the United States.

Taphonomic analysis on the bivalve assemblage preserved in the Quarry Sandstone Bed at Dinosaur National Monument demonstrates that the shells occur in current-stable orientations, locally with imbricated stacking, in troughs of mid-channel bars within the ancient stream bed [Good]. The shells are well sorted by size; however, fragmentation and abrasion are minimal. These features indicate a transported assemblage that has not been moved very far from the original life habitat (probably less than a few kilometers, at most). The shell form of the bivalves indicate they inhabited a fast velocity, small fluvial system. The abundance of the specimens suggests that a nearby upstream optimum habitat for unionid bivalves provided shells from the dead and decayed members of the population. Only a few articulated specimens have been found and they are generally not in life position, suggesting they were transported, buried, and unable to reestablish life functions. The disarticulated valves, which dominate the bivalve assemblages, require days to weeks of postmortem decay of the ligament to disjoin the valves, suggesting that the fauna represents a transported death assemblage. The unique dispersal mechanism employed by unionacean bivalves permits documentation of paleodrainage confluence patterns, which enhances our understanding the paleogeography of the Morrison basin.

Paleoecological interpretations comparing the ostracode and charophyte genera with their modern counterparts suggest mostly nonmarine environments, although the salinity could have been slightly higher in several beds, perhaps to about 16 parts per thousand in some cases [Schudack]. An analysis of the spatial distribution of both ostracodes and charophytes suggests close but complex biogeographic relationships between North America and Europe during the Late Jurassic.

The wide variety of palynomorphs suggests that much of the Morrison depositional basin contained a highly diverse flora during much or most of Morrison time [Litwin].

The integration of ichnological (i.e., trace fossil) information [Hasiotis] combined with paleontological, sedimentological, paleopedological, and geochemical data, produces a more holistic reconstruction of the paleoecological settings during Morrison times. Though some contradictions do exist between different sources of data, the results are still meaningful. In general, the traces reflect the sedimentological pattern of a drier climatic setting in the lower Morrison to a slightly more seasonally wet climatic setting at the end of Morrison deposition. The interpretations deduced from the trace fossils corroborate many of the interpretations from the molluscs, pollen, and plants that suggest there were periods of seasonally ample rainfall during deposition of portions of the Morrison Formation. The trace fossils, along with the carbonate paleosols and geochemical analysis, support a seasonally wet-dry climatic setting for most of the Morrison, but differs in that the traces (especially the rhizoliths and crayfish) show slightly higher precipitation than what might be expected. The diversity of invertebrate and vertebrate body fossils and trace fossils (e.g. invertebrates) suggests that the overall sedimentologic and paleoenvironmental landscapes had to sustain climates analogous or roughly analogous to today's savannah of the southern African continent. The larger vertebrates probably migrated latitudinally between conterminous landscapes shaped by different depositional systems.

Stable Isotope Geochemistry

Many fossil materials retain their carbon and oxygen stable isotopic compositions through geologic time. A suite of materials from the Morrison Formation (fossil soil nodules, plant materials, eggshells, teeth, lake sediments) have been analyzedto determine patterns in the distribution of isotopes [Ekart and Cerling]. The focus was on carbonate nodules from paleosols (fossil soils) in the Brushy Basin Member of the Morrison Formation. The isotopic data show that much of the Western Interior was in a rain shadow during the Late Jurassic, which is consistent with paleogeographic reconstructions that place the Morrison landscape east of a Mesocordilleran mountain range that extended along the western side of the paleo-North American continent.

Age Determinations

Research on the relative age of the Morrison Formation based on studies of palynomorphs (spores, pollen, and dinoflagellates) [Litwin] and calcareous microfossils (charophytes and ostracodes) [Schudack] has established a much more refined relative age for the formation. It is now clear that all of the Morrison Formation and related beds are entirely Late Jurassic in age and were deposited during the Kimmeridgian and early Tithonian Ages. None of the microfossil evidence corroborates previously published accounts proposing an Early Cretaceous age for some of these beds.

Isotopic dating of altered volcanic ash beds in the The Morrison Formation in Utah and Colorado [Kowallis] yielded numerical ages in terms of millions of years before the present (Ma). The Brushy Basin Member at the top of the formation gives single-crystal, laser-fusion and step-heating, plateau $^{40}Ar/^{39}Ar$ ages on sanidine that range between 148.1 Ma at the top of the member and 150.3 Ma at the base of the member. The Tidwell Member at the base of the formation contains one datable ash bed about 3 m (10 ft) above the J-5 unconformity that has been found in at least two widely separated localities. This bed has been dated using $^{40}Ar/^{39}Ar$ dating of sanidine and gives ages ranging between 154.75 and

154.87 Ma. The Morrison Formation, therefore, ranges in age from about 148 to 155 Ma. By comparison with recent standard geologic time scales that attempt to calibrate the relative time scale based upon fossils with isotopic dates, the Morrison Formation and related beds are entirely Late Jurassic in age.

Summary

In summary, the habitat for the Late Jurassic dinosaurs was a broad alluvial plain in the rainshadow of highlands that bordered the plain to the west. The presence of large dunefields, evaporites, intermittent streams, and development of a large alkaline, saline lake at various times during Morrison deposition all indicate that the Morrison experienced times of considerable aridity. In spite of the semi-arid to arid climate, life-giving water was delivered to the plain by several means. These included seasonal or intermittent precipitation, perennial and intermittent streams that drained the western highlands, and shallow groundwater that was delivered by aquifers recharged by infiltration in the highlands.

Riparian vegetation was largely supported by water from perennial streams and substream flow within intermittent streambeds. Vegetation on the floodplain had to depend primarily on direct precipitation onto the floodplain (which may have been largely seasonal) and the ability to tap shallow aquifers. The large herbivorous dinosaurs could range across the plain in search of water and vegetation, whereas many of the smaller animals would have found water and shelter in riparian habitats. Scattered lakes and ponds across the alluvial plain supported a variety of aquatic life. Thus, although the Morrison climate was much drier than originally interpreted, the Morrison ecosystem supported a considerable diversity of life, including the largest herbivores that ever lived.

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PUBLICATIONS OF THE MORRISON RESEARCH TEAM

The following list of publications includes all 109 reports that have been published thus far by one or more members of the Morrison Research Team. Only those reports that have been published or are in "in press" status are cited; not included are any reports that have not yet been through peer review, that are being written, or that are planned.

Ash, S.R. , 1994, First occurrence of Czekanowskia (Gymnospermae, Czekanowskiales) in the United States. Review of Palaeobotany and Palynology, v. 81, p. 129-140.

Ash, S.R., and Tidwell, W.D., 1998, Plant megafossils from the Brushy Basin Member of the Morrison Formation near Montezuma Creek Trading Post, southeastern Utah: Modern Geology, v. 22, nos. 1-4, p. 321-340.

Aubrey, W.M., 1992, New interpretations of the stratigraphy and sedimentology of the uppermost Jurassic to lowermost Upper Cretaceous strata in the San Juan Basin of Northwestern New Mexico: U.S. Geological Survey Bulletin 1808-J, 17 p.

Aubrey, W.M., 1998, A newly discovered, widespread fluvial facies and unconformity marking the Upper Jurassic/Lower Cretaceous boundary, Colorado Plateau: Modern Geology, v. 22, nos. 1-4, p. 209-234.

Bradley, L. W., Callison, G., and Engelmann, G.F., 1997, Jaw musculature of a Late Jurassic multituberculate from North America: Journal of Vertebrate Paleontology, v. 17, Supplement to no. 3, p. 33A.

Christiansen, E.H., Kowallis, B.J., and Barton, M.D., 1994a, Temporal and spatial distribution of volcanic ash in Mesozoic sedimentary rocks of the Western Interior: An alternative record of Mesozoic magmatism; in, Caputo, M.V., Peterson, J.A., and Franczyk, K.J., (eds.), Mesozoic Systems of the Rocky Mountain region, USA: Rocky Mountain Section SEPM, Denver, Colorado, p. 73-94.

Chure, D.J., 1992, The flora and non-dinosaurian fauna of the Morrison Formation: How rare is it?: Geological Society America, Abstracts With Programs, v. 24, no. 6, p. 5.

Chure, D.J., 1995, The teeth of small theropods from the Morrison Formation (Upper Jurassic, Kimmeridgian) of Utah: Journal of Vertebrate Paleontology, v. 15, Supplement to no. 3, p. 23A.

Chure, D.J., 1995, A reassessment of the gigantic theropod Saurophaganus maximus from the Morrison Formation (Upper Jurassic) of Oklahoma, USA; in, Sun, A.L., and Wang, Y.Q., (eds.), Proceedings of the Sixth International Symposium on Mesozoic Ecosystems and biota: Short Papers, China Ocean Press, Beijing, p. 103-106.

Chure, D.J., in press, Earl Douglass and the discovery of Dinosaur National Monument; in, Gillette, D.D., (ed.), Vertebrate fossils of Utah: Utah Geological Survey publication.

Chure, D.J., in press, Dinosaur National Monument: Science and education in northeastern Utah; in, Gillette, D.D., (ed.), Vertebrate fossils of Utah: Utah Geological Survey publication.

Chure, D.J., in press, Let them eat meat: Carnivorous dinosaurs of the Late Jurassic Morrison Formation, Utah; in, Gillette, D.D., (ed.), Vertebrate fossils of Utah: Utah Geological Survey publication.

Chure, D.J., and Madsen, J.H., Jr., 1996, Variation in aspects of the tympanic pneumatic system in a population of Allosaurus fragilis from the Morrison Formation (Upper Jurassic): Journal of Vertebrate Paleontology, v. 16, p. 63-66.
Chure, D.J., and Fiorillo, A.R., 1997, "One Big Al to go and hold the mayo": Evidence of scavenging of a specimen of Allosaurus from the Morrison Formation (Late Jurassic) of Wyoming: : Journal of Vertebrate Paleontology, v. 17, Supplement to no. 3, p. 38A.
Chure, D.J., Britt, B.B., and Madsen, J.H., 1997, A new specimen of Marshosaurus bicentesimus (Theropoda) from the Morrison Formation (Late Jurassic) of Dinosaur National Monument: Journal of Vertebrate Paleontology, v. 17, Supplement to no. 3, p. 38A.
Chure, D.J., Carpenter, K., Litwin, R., Hasiotis, S., and Evanoff, E., 1998, The fauna and flora of the Morrison Formation: Modern Geology, v. 23, nos. 1-4, p. 507-537.
Chure, D.J., and Evans, S.E., 1998, A new occurrence of Cteniogenys, with comments on its distribution and abundance: Modern Geology, v. 23, nos. 1-4, p. 49-56.
Chure, D.J., and Madsen, J.H., 1998, An unusual braincase (?Stokesosaurus clevelandi) from the Cleveland-Lloyd Dinosaur Quarry, Utah (Morrison Formation: Late Jurassic): Journal of Vertebrate Paleontology, v. 18, no. 1, p. 115-125.
Chure, D.J., Fiorillo, A.R., and McIntosh, J.S., in press, The Dinosaur National Monument Mapping Project: An educational and scientific resource; in, Gillette, D.D., (ed.), Vertebrate fossils of Utah: Utah Geological Survey publication.
Chure, D.J., and Madsen, J.H., Jr., in press, Allosaurus: The making of Utah's state fossil; in, Gillette, D.D., (ed.), Vertebrate fossils of Utah: Utah Geological Survey publication.
Chure, D.J., and Madsen, J.H., Jr., in press, On the furcula of Allosaurus: Journal of Vertebrate Paleontology.
Currie, B.S., 1993, Sequence Stratigraphy of the Jurassic-Cretaceous Morrison and Cedar Mountain Formations, NE Utah-NW Colorado: Geological Society of America, Abstracts With Programs, v. 25, no. 5, p. 26-27.
Currie, B.S., 1994, "Back-bulge" to foredeep evolution of the Late Jurassic-Early Cretaceous Cordilleran foreland basin: Evidence from the Morrison and Cedar Mountain Formations, central-eastern Utah: Geological Society of America, Abstracts With Programs, v. 26, no. 6, p. 9.
Currie, B.S., 1997a, Sequence stratigraphy of nonmarine Jurassic-Cretaceous rocks, central Cordilleran foreland-basin system: Geological Society of America Bulletin, v. 109, no. 9, p. 1206-1222.
Currie, B.S., 1997b, Jurassic-Cretaceous evolution of the central Cordilleran foreland-basin system : Unpublished Ph.D. dissertation, University of Arizona, Tucson, 239 p.
Currie, B.S., 1997, Jurassic-Cretaceous accommodation development in the Western Interior United States: Linking basin subsidence with oceanic plate subduction. Geological Society of America Abstracts With Programs, v. 29, no. 6, p. A-202.
Currie, B.S., 1998, Upper Jurassic-Lower Cretaceous Morrison and Cedar Mountain Formations, NE Utah-NW Colorado: Relationships between nonmarine deposition and early Cordilleran foreland-basin development: Journal of Sedimentary Research, v. 68, no. 4., p. 632-652.
Currie, B.S., and DeCelles, P.G., 1996, Middle Jurassic-Eocene sediment accumulation in the Cordilleran foreland basin system: Reconciling stratigraphic and tectonic records of mountain building: Geological Society of America, Abstracts With Programs, v. 28, no. 7, p. A-251
Demko, T.M., and Hasiotis, S.T., 1995, Jurassic continental alluvial trace fossils in Felch Quarry sandstone, Garden Park Paleontological Area, Cañon City, Colorado: Society of Sedimentary Geologists First Congress on Sedimentary Geology, St. Pete Beach, Florida, (Ichnofossils; Linkages to Life Habitats and Environments), v. 1, p. 44.

DeCelles, P.G., and Currie, B.S., 1996, Long-term sediment accumulation in the Middle Jurassic-Early Eocene Cordilleran retroarc foreland-basin system: Geology, v. 24, p. 591-594.
DeCelles, P.G., Pile, H.T., and Currie, B.S., 1992, Regional stratigraphic analysis of Jurassic-Cretaceous nonmarine rocks, central Western Interior Basin: SEPM (Society for Sedimentary Geology) 1992 Theme Meeting (Mesozoic of the Western Interior), Fort Collins, Colorado, p. 23.
Demko, T.M., Currie, B.S., and Nicoll, K.A., 1996, Paleosols at sequence boundaries in the Upper Jurassic Morrison Formation, Colorado Plateau and Rocky Mountain Regions, USA: Geological Society of America, Abstracts With Programs, v. 28, no. 7, p. A-185.
Demko, T.M., and Parrish, J.T., 1998, Paleoclimatic setting of the Upper Jurassic Morrison Formation: Modern Geology, v. 22, nos. 1-4, p. 283-296.
Dunagan, S.P., 1997, Jurassic freshwater sponges from the Morrison Formation, U.S.A.: Southeastern Section, Geological Society of America, Abstracts With Program, v. 29, no. 3, p. 14-15.
Dunagan, S.P., 1998, Insights into Late Jurassic paleohydrology and paleoclimatology from palustrine and lacustrine carbonates of the Morrison Formation, Colorado, USA: Fifth International Symposium on the Jurassic System, Vancouver, British Columbia, Canada, p. ?
Dunagan, S.P., 1998, Lacustrine and palustrine carbonates from the Morrison Formation (Upper Jurassic), east-central Colorado, USA: Implications for depositional patterns, paleoecology, paleohydrology, and paleoclimatology: Unpublished Ph.D. dissertation, University of Tennessee, Knoxville, 276 p.
Dunagan, S.P., Demko, T.M., Driese, S.G., and Walker, K.R., 1996, Lacustrine and palustrine carbonate facies of the Morrison Formation (Upper Jurassic): Implications for paleoenvironmental reconstructions: Geological Society of America, Abstracts With Programs, v. 28, no. 7, p. A-336.
Dunagan, S.P., Driese, S.G., and Walker, K.R., 1997, Paleolimnological implications of Magadi-type cherts from lacustrine carbonate in the Morrison Formation (Upper Jurassic), Colorado, U.S.A.: Geological Society of America, Abstracts With Program, v. 29, no. 6, p. 270.
Ekart, D.D., and Cerling, T.E., 1996, PCO_2 during deposition of the Late Jurassic Morrison Formation and other paleoclimatic/ecologic data as inferred by stable carbonate and oxygen isotope analyses: Geological Society of America, Abstracts With Programs, v. 28, no. 7, p. A-252.
Engelmann, G.F., 1990, Paleontological survey of the Jurassic Morrison Formation in Dinosaur National Monument; in, Boyce, M.S., and Plumb, G.E., (eds.), 14th Annual Report—1990: University of Wyoming-National Park Service Research Center, p. 37-38.
Engelmann, G.F., 1991, Paleontological survey of the Jurassic Morrison Formation in Dinosaur National Monument; in, Plumb, G.E., (ed.), 15th Annual Report—1991: University of Wyoming-National Park Service Research Center, p. 83-84. .
Engelmann, G.F., 1992, Paleontological Survey of the Jurassic Morrison Formation in Dinosaur National Park: Park Science, v. 12, no. 3, p. 8-9.
Engelmann, G.F., in press, Stratigraphic and geographic distribution of fossils in the upper part of the Upper Jurassic Morrison Formation of the Rocky Mountain region; in, Gillette, D.D., (ed.),Vertebrate Fossils of Utah: Utah Geological Survey.
Engelmann, G.F., in press, Distribution of fossils in the Morrison Formation of the Rocky Mountain Region; in, Gillette, D.D., (ed.), Vertebrate fossils of Utah: Utah Geological Survey publication.
Engelmann, G.F. and Callison, G., 1998, Mammalian Faunas of the Morrison Formation: Modern Geology, v. 23, nos. 1-4, p. 343-380.

Engelmann, G.F. and Callison, G., in press, Glirodon grandis, a new multituberculate mammal from the Jurassic Morrison Formation; in, Gillette, D.D., (ed.), Vertebrate Fossils of Utah: Utah Geological Survey.

Engelmann, G.F. and Hasiotis, S.T., in press, Deep dinosaur tracks in the Morrison: Sole marks that are really sole marks; in, Gillette, D.D., (ed.), Vertebrate Fossils of Utah: Utah Geological Survey.

Evanoff, E., 1998, Paleoenvironmental implications of freshwater gastropod faunas in the Upper Jurassic Morrison Formation: An enigma between geologic and biologic evidence: Fifth International Symposium on the Jurassic System, Vancouver, British Columbia, Canada, p. ?

Evanoff, E., and Carpenter, K., 1998, History, sedimentology, and taphonomy of Felch Quarry 1 and associated sandbodies, Morrison Formation, Garden Park, Colorado: Modern Geology, v. 22, nos. 1-4, p. 145-170.

Evanoff, E., Good, S.C., and Hanley, J.H., 1998, An overview of the freshwater mollusks from the Morrison Formation (Upper Jurassic, Western Interior, USA): Modern Geology, v. 22, nos. 1-4, p. 423-450.

Evans, S.E., and Chure, D.J., 1998, Morrison lizards: Structure, relationships, and biogeography: Modern Geology, v. 23, nos. 1-4, p. 35-48.

Evans, S.E., and Chure, D.C., 1998, Paramacellodid lizard skulls from the Jurassic Morrison Formation at Dinosaur National Monument, Utah: Journal of Vertebrate Paleontology, v. 18, no. 1, p. 99-114
[note error in original, second author's name should read D.J. Chure]

Fiorillo, A.R., 1991, Prey bone utilization by predatory dinosaurs: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 88, p. 157-166.

Fiorillo, A.R., 1991, Dental microwear on the teeth of Camarasaurus and Diplodocus: Implications for sauropod paleoecology; in, Kielan-Jaworowska, Z., Heintz, N., and Nakrem, H.A., (eds.), Fifth Symposium on Mesozoic Terrestrial Ecosystems and Biota: Contributions from the Palaeontological Museum, University of Oslo, Norway, p. 23-24.

Fiorillo, A.R., 1994, Time resolution at Carnegie Quarry (Morrison Formation: Dinosaur National Monument, Utah): Contributions to Geology, University of Wyoming, v. 30, p. 149-156.

Fiorillo, A.R., 1995, Enamel microstructure in Diplodocus, Camarasaurus, and Brachiosaurus (Dinosauria: Sauropoda) and its lack of influence on resource partitioning by sauropods in the Late Jurassic; in, Sun, A., and Wang, Y., (eds.), Sixth Symposium on Mesozoic Terrestrial Ecosystems and Biota: China Ocean Press, Beijing, p. 147-149.

Fiorillo, A.R., 1998a, Bone modification features on sauropod remains (Dinosauria) from the Freezeout Hills Quarry N (Morrison Formation) of southeastern Wyoming and their contribution to fine-scale paleoenvironmental interpretation: Modern Geology, v. 23, nos. 1-4, p. 111-126.

Fiorillo, A.R., 1998b, Dental microwear patterns of the sauropod dinosaurs Camarasaurus and Diplodocus: Evidence for resource partitioning in the Late Jurassic of North America: Historical Biology, v. 13, p. 1-16.

Fiorillo, A.R., and Hasiotis, S.T., 1996, Preliminary report on the continental ichnofossils from the Upper Jurassic Morrison Formation of Curecanti National Recreation Area, Colorado: Geological Society of America, Rocky Mountain Section, Abstracts With Programs, v. 24, no. 4, p. 7-8.

Fiorillo, A.R., and May, C.L., 1996, Preliminary report on the taphonomy and depositional setting of a new dinosaur locality in the Morrison Formation (Brushy Basin Member) of Curecanti National Recreation Area, Colorado; in, Morales, M. (ed.), The Continental Jurassic: Museum of Northern Arizona Bulletin 60, p. 555-561.

Fiorillo, A.R., and McCarty, D.K., 1996, Paleopedological evidence for a humid environment in the lower part of the Brushy Basin Member, Morrison Formation, of Curecanti National Recreation Area, Colorado; in, Morales, M. (ed.), The Continental Jurassic: Museum of Northern Arizona Bulletin 60, p. 575-580.

Fiorillo, A.R., May, C.L., and Harris, R, 1997, Comparison of paleontological resource management in the Rocky Mountain Region by the National Park Service and the U.S. Forest Service; in, Harmon, D. (ed.), Making Protection Work: The George Wright Society Biennial Conference, The George Wright Society, Hancock, Michigan, p. 308-311.

Foster, J.R., and Chure, D.J., 1998, Patterns of theropod diversity and distribution in the Late Jurassic Morrison Formation, western USA: Fifth International Symposium on the Jurassic System, Vancouver, British Columbia, Canada, p. ?

Good, S.C., and Kozlowski, A.L., 1995, Taphonomic features of unionacean bivalves of the Upper Jurassic Brushy Basin Member of the Morrison Formation in Dinosaur National Monument, Utah: Geological Society of America, Abstracts With Programs, v. 27, no. 1, p. 48-49.

Hasiotis, S.T., 1995, Terrestrial and freshwater-aquatic trace fossils in the Upper Jurassic Morrison Formation, Colorado Plateau: Invertebrates out-shine the dinosaurs: Third National Biological Service Biannual Conference of Research on the Colorado Plateau, Abstracts With Program, v. 3, p. 33.

Hasiotis, S.T., 1996, Termite (Insecta: Isoptera) nests from the Upper Jurassic Morrison Formation: Evolutionary, paleoecologic, and paleoclimatic implications: Geological Society of America, Abstracts With Programs, v. 28, no. 4, p. 10.

Hasiotis, S.T., 1996, Invertebrate ichnofossils from the Upper Jurassic Morrison Formation, Colorado Plateau: Jurassic biodiversity, ecologic, and climatic implications: Geological Society of America, Abstracts With Programs, v. 28, no. 4, p. 10.

Hasiotis, S.T., 1998, Continental trace fossils as the key to understanding Jurassic terrestrial and freshwater ecosystems: Modern Geology, v. 22, nos. 1-4, p. 451-460.

Hasiotis, S.T., and Demko, T.M., 1996, Ant (Hymenoptera: Formicidae) nest ichnofossils, Upper Jurassic Morrison Formation, Colorado Plateau: Evolutionary and ecologic implications: Geological Society of America, Abstracts With Programs, v. 28, no. 7, p. A-106.

Hasiotis, S.T., and Demko, T.M., 1996, Terrestrial and freshwater trace fossils, Upper Jurassic Morrison Formation, Colorado Plateau; in, Morales, M., (ed.)., The continental Jurassic: Museum of Northern Arizona Bulletin 60, p. 355-370.

Hasiotis, S.T., and Kirkland, J.I., 1996, Crayfish fossils and burrows, Upper Jurassic Morrison Formation, Colorado Plateau, USA: International Association of Astacology, Freshwater Crayfish XI, Abstracts With Program, Thunder Bay, Ontario, p. 37.

Hasiotis, S.T., and Demko, T.M., 1998, Ichnofossils from Garden Park Paleontological Area, Colorado: Implications for paleoecologic and paleoclimatic reconstructions of the Upper Jurassic: Modern Geology, v. 22, nos. 1-4, p. 461-480.

Hasiotis, S.T., Kirkland, J.I., and Callison, G., 1998, Crayfish fossils and burrows from the Upper Jurassic Morrison Formation of western Colorado: Modern Geology, v. 22, nos. 1-4, p. 481-492.

Hasiotis, S.T., Kirkland, J.I., Windscheffer, G.W., and Safris, C., 1998, Fossil caddisfly cases (Insecta: Trichoptera), Upper Jurassic Morrison Formation, Fruita Paleontological Area, Colorado: Modern Geology, v. 22, nos. 1-4, p. 493-502.

Hasiotis, S.T., Peterson, F., Turner, C.E., Englemann, G.F., and Demko, T.M., 1998, Upper Jurassic Morrison Formation continental and marine ichnofossils, Rocky Mountains, USA: New implications to Jurassic biodiversity, paleoecology, and paleoclimate: Fifth International Symposium on the Jurassic System, Vancouver, British Columbia, Canada, p. ?

Hirsch, K.F., Hasiotis, S.T., Bray, E.S., Demko, T.M., Currie, B., Ekart, D., and the Morrison Research Group, 1996, Dinosaur eggshell from the uppermost part of the Upper Jurassic Morrison Formation, southeastern Utah: Geological Society of America, Abstracts With Programs, v. 28, no. 7, p. A-296.

Horton, B.K., DeCelles, P.G., and Currie, B.S., 1997, Comparison of the North American Cordilleran retroarc foreland with the modern central Andean foreland basin system: Geological Society of America, Abstracts With Programs, v. 29, no. 6, p. A-203.

Kowallis, B.J., Christiansen, E.H., and Deino, A.L., 1991, Age of the Brushy Basin Member of the Morrison Formation, Colorado Plateau, western USA: Cretaceous Research, v. 12, p. 483-493.

Kowallis, B.J., Christiansen, E.H., Tingey, D.G., Deino, A.L., Peterson, F., and Turner, C.E., 1993, Volcanic ash layers in the Tidwell Member of the Upper Jurassic Morrison Formation; minimum age of the J-5 unconformity on the Colorado Plateau: Geological Society of America, Abstracts With Programs, v. 25, no. 6, p. 472-473.

Kowallis, B.J., Christiansen, E.H., Deino, A.L., Peterson, F., Turner, C.E., and Blakey, R.C., 1996, Implications of new high precision $^{40}Ar/^{39}Ar$ laser-microprobe ages for the Jurassic time scale; in, Morales, M., (ed.), The Continental Jurassic: Museum of Northern Arizona Bulletin 60, p. 7-8.

Kowallis, B.J., Christiansen, E.H., Deino, A.L., Peterson, F., Turner, C.E., Kunk, M.J., and Obradovich, J.D., 1998, The age of the Morrison Formation: Modern Geology, v. 22, nos. 1-4, p. 235-260.

Laws, G.R., Hasiotis, S.T., Fiorillo, A.R., Chure, D.J., Breithaupt, B.H., and Horner, J., 1996, The demise of a Jurassic dinosaur after death—Three cheers for the dermistid beetle: Geological Society of America, Abstracts With Programs, v. 28, no. 7, p. A-299.

Litwin, R.J., Turner, C.E., and Peterson, Fred, 1998, Palynological evidence on the age of the Morrison Formation, Western Interior, U.S.: Modern Geology, v. 22, nos. 1-4, p. 297-320.

McIntosh, J.S., 1998, New information about the Cope collection of sauropods from Garden Park, Colorado: Modern Geology, v. 23, nos. 1-4, p. 481-506.

McIntosh, J.S., and Carpenter, K., 1998, The holotype of Diplodocus longus, with comments on other specimens of the genus: Modern Geology, v. 23, nos. 1-4, p. 85-110.

Medlyn, D.A., Tidwell, W.D., and Bilbey, S.A., 1994, Coniferous wood associated with dinosaurian Stegosaurus remains from the Salt Wash Member of the Upper Jurassic Morrison Formation near Jensen, Utah: American Journal of Botany, Abstracts Supplement, v. 81, no. 6., p. 98.

Newell, D.L., 1997, Geology of the Brushy Basin Member of the Morrison Formation, Fruita Paleontological Resource Area, Colorado: Unpublished MS thesis, Colorado State University, Fort Collins, 197 p.

Pagnac, D., and Chure, D.J., 1997, Rare sauropod elements from the Carnegie Quarry (Morrison Fm), Dinosaur National Monument, UT: Journal of Vertebrate Paleontology, : Journal of Vertebrate Paleontology, v. 17, Supplement to no. 3, p. 68A.

Peterson, Fred, 1994, Sand dunes, sabkhas, streams, and shallow seas: Jurassic paleogeography in the southern part of the Western Interior Basin; in, Caputo, M.V., Peterson, J.A., and Franczyk, K.J., (eds.), Mesozoic Systems of the Rocky Mountain Region, USA: Rocky Mountain Section SEPM (Society for Sedimentary Geology), p. 233–272.

Peterson, F., and Turner, C.E., 1998, Stratigraphy of the Ralston Creek and Morrison Formations (Upper Jurassic) near Denver, Colorado: Modern Geology, v. 22, nos. 1-4, p. 3-38.

Schudack, M.E., 1994, Die ostracoden und charophyten der Morrison-Formation (Oberjura, Westliche USA)—Systematik, biostratigraphie, ökologie, biogeographie: Abschlussbericht zur Deutsche Forschungsgemeinschaft-Sachbeihilfe Schu 694/4-1, Institut für Paläontologie der Freien Universität Berlin, Berlin, 1994, 139 p.
Schudack, M.E., 1995, Neue mikropaläontologische Beiträge (Ostracoda, Charophyta) zum Morrison-Ökosystem (Oberjura des Western Interior, USA): Berliner Geowissenschaftliche Abhandlungen, (E), v. 16, p. 389–407.
Schudack, M.E., 1996, Ostracode and charophyte biogeography in the continental Upper Jurassic of Europe and North America as influenced by plate tectonics and paleoclimate; in, Morales, M., (ed.), The Continental Jurassic: Museum of Northern Arizona Bulletin 60, p. 333-341.
Schudack, M.E., 1998, The role of ostracods and charophytes to detect Late Jurassic paleoclimates in North America: Fifth International Symposium on the Jurassic System, Vancouver, British Columbia, Canada, p. ?
Schudack, M.E., Turner, C.E., and Peterson, F., 1998, Biostratigraphy, paleoecology, and biogeography of charophytes and ostracodes from the Upper Jurassic Morrison Formation, Western Interior, USA: Modern Geology, v. 22, nos. 1-4, p. 379-414.
Shultz, R.J., Steinhardt, E.I., and Good, S.C., 1997, Ultrastructure of unionid bivalves from the Late Jurassic Morrison Formation: Geological Society of America, Abstracts With Programs, v. 29, no. 1, p. 79.
Skipp, G.L., 1997, Characterization and paleoenvironmental interpretation of pedogenic carbonate at the J-K boundary, east-central Utah and west-central Colorado: Unpublished MS thesis, Colorado School of Mines, Golden, 113 p.
Tidwell, W.D., and Medlyn, D.A., 1992, Short shoots from the Upper Jurassic Morrison Formation, Utah, Wyoming, and Colorado, USA: Review of Palaeobotany and Palynology, v. 71, nos. 1-4, p. 219-238.
Tidwell, W.D., and Medlyn, D.A., 1993, Conifer wood from the Upper Jurassic of Utah, USA—Part II: Araucarioxylon hoodii sp. nov.: The Palaeobotanist, v. 42, no. 1, p. 70-77.
Tidwell, W.D., Britt, B.B., and Ash, S.R., 1998, Preliminary floral analysis of the Mygatt-Moore Quarry in the Jurassic Morrison Formation, west-central Colorado: Modern Geology, v. 22, nos. 1-4, p. 341-378.
Turner, C.E., and Peterson, F., 1990, Sedimentology and stratigraphy of the Morrison Formation in Dinosaur National Monument; in, Boyce, M.S., and Plumb, G.E., (ed.), 14th Annual Report—1990: University of Wyoming-National Park Service Research Center, p. 43-44.
Turner, C.E., and Peterson, F., 1991, Sedimentology and stratigraphy of the Morrison Formation in Dinosaur National Monument; in, Plumb, G.E., (eds.), 15th Annual Report—1991: University of Wyoming-National Park Service Research Center, p. 91-93.
Turner, C.E., and Fishman, N.S., 1991, Jurassic Lake T'oo'dichi': A large alkaline, saline lake, Morrison Formation, eastern Colorado Plateau: Geological Society of America Bulletin, v. 103, p. 538-558.
Turner, C.E., Fishman, N.S., Hatcher, P.G., and Spiker, E.S., 1993, Nature and role of organic matter in sandstone uranium deposits, Grants uranium region, New Mexico, USA; in, Parnell, J., Kucha, H., and Landais, P., (eds.), Bitumens in ore deposits: Special Publication No. 9 of the Society for Geology Applied to Mineral Deposits, Springer Verlag, Berlin, p. 239-275.
Turner, C.E., and Peterson, F., 1996, Morrison Ecosystem Project; in, Harlow, H.J., and Harlow, M. (eds.), 18th Annual Report—1994: University of Wyoming-National Park Service Research Center, p. 152-155.
Turner, C.E., Peterson, F., and the Morrison Research Team, 1998, Reconstruction of the Late Jurassic ecosystem in the Western Interior of the United States: Fifth International Symposium on the Jurassic System, Vancouver, British Columbia, Canada, p. ?

Turner, C.E., and Peterson, F., 1998, Biostratigraphy of dinosaurs in the Upper Jurassic Morrison Formation of the Western Interior, USA: Fifth International Symposium on the Jurassic System, Vancouver, British Columbia, Canada, p. ?

Turner, C.E., and Peterson, F., 1998, Late Jurassic ecosystem reconstruction in the Western Interior of the United States; in, Santucci, V.L., and McClelland, L., (eds.), National Park Service Paleontological Research: National Park Service, Geologic Resources Division Technical Report, NPS/NRGRD/GRDTR-98/01, p. 158-162.

Turner, C.E., and Fishman, N.S., 1998, Late Jurassic lacustrine deposits and implications for paleohydrology; in, Pitman, J.K., and Carroll, A.R., (eds.), Modern and Ancient Lake Systems: Utah Geological Association Guidebook No. 26, p. 31-49.

Turner, C.E., and Peterson, F., in press, Biostratigraphy of dinosaurs in the Upper Jurassic Morrison Formation of the Western Interior, USA; in, Gillette, D.D., (ed.), Vertebrate fossils of Utah: Utah Geological Survey publication.

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