A REPORT ON THE

Geology of the Southwestern United States

By

William L. Effinger

U. S. Department of the Interior
NATIONAL PARK SERVICE
FIELD DIVISION OF EDUCATION
Berkeley, California
1935

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FOREWORD

This paper is one of several prepared for the Field Division of Education of the National Park Service during the CWA period of 1933-34. Its purpose was to provide preliminary information for the preparation of geological exhibits at museums in Southwestern National Parks and Monuments and to serve as the first step in the compilation of a general manual for travelers to the region who should be interested in the broad general outlines of Southwestern geology.

Inasmuch as this paper was one of the last to be prepared by the author during the work period, as well as the purposes for which it was intended, it is to be regarded as only the briefest summation of the outstanding features of Southwestern Geology. It is essentially a compilation of published data in convenient form in the preparation of which there was necessarily considerable selection of data. Opinions may easily vary as to what constitute the major features of the geology of a region so varied and extensive as the Southwest.

Despite its limitations this paper may well serve as a simple intorduction to the area in question. Although prepared primarily for use in the museum laboratories and by field officers of the National Park Service, so many requests for copies have been received that it has seemed worthwhile to make the paper more generally available by producing it in this mimeographed form. A special effort was made to compile an extensive and significant bibliography which should be of value.

In order to save time and expense in mimeographing, footnotes have been reduced to a minimum and most citations are included in the text in parentheses. Statements made are documented for the most part but in some cases may represent a synthesis of existing opinions.

Credit is due the Works Progress Administration for providing the workers who have made the mimeographing of this paper possible.

Introduction

This report has been prepared under the direction of the museum staff of the Field Division of Education of the National Park Service at Berkeley. Its immediate purpose is to bring together a more or less generalized body of information on the geology and paleontology of the Southwestern United States. This information has been compiled from the literature as the initial step in the preparation of a proposed guidebook of this region. Since the geology is to constitute only a chapter in this guidebook along with others on the geography, ethnology, biology and anthropology, introductory remarks on the location and general character of the region have purposely been omitted. The material herein contained is mainly in the form of extracts from various publications dealing with the geology and paleontology of this region. The original intention was to present the results in two parts; the first, consisting of a resume of the geological history of the Southwest as a whole; and, second, a discussion of selected local areas, especially the national parks and monuments within the region, which illustrate particularly well the various phases of the history and the geological processes at work here. However, due to the brief time available, it has been impossible to complete even the first portion of that which was originally intended. Many important events have not been touched upon and many of those only mentioned need further elaboration.

DESCRIPTIVE GEOLOGY

Introduction

The geologic formations so well displayed in the labyrinths of deep canyons, the cliffed and terraced mesas, and in barren rocky jumbles of the mountainous areas of the Southwest, present a record of geologic history remarkable in its completeness and latent with intriguing events. In this region of North America all five of the great eras which have been recognized in geologic time are represented, ranging from the oldest known Archeozoic rocks through to those of the Cenozoic. Although a complete section of the rocks cannot be seen in any one locality, by tracing the rocks across the country five great terranes are recognized. The older representing the first two eras of geologic time, the Archeozic and Proterozoic, are shrouded in mystery, for they are of such great antiquity that it is exceedingly difficult to piece together the fragmentary record. We do know that a tremendous length of time is represented by these formations; it has been estimated that the Archeozoic and Proterozoic represent three-fourths of all of geologic time. When we recall that by the latest method of determining the age of the oldest rocks of the earth, by means of the radioactive minerals, an approximate figure of two billion years has been arrived at, the time allotted to the first two eras is almost beyond comprehension.

Overlying these pre-Cambrian rocks are between 16,000 and 20,000 feet of sandstones, shales, limestones and volcanic rocks which represent the Paleozoic, Mesozoic and Cenozoic eras. These rocks contain a varied record of many invasions of the sea over this region, each transgression bringing with it its characteristic faunas which lived and died, often leaving its shelly or bony material as unmistakable evidence of its existence. In other places we see evidence of the old seashores resulting from the advance and retreat of the waters caused by slow undulating movements of the land up and down. Or again we find evidences of ancient sand dunes, testifying to times of distinct aridity; or of the flood plain deposits of wide rivers and streams which meandered their way across land surfaces that were free from mountains and rough topography which are so familiar a part of the scene today. In these land-laid deposits, usually referred to as red beds because of their frequent red color, due to the complete oxidation of minute amounts of disseminated iron, are occasionally found the skulls and skeletons of queer animals which have long been extinct, or great petrified logs or thick beds of coal which have long been extinct, or great petrified logs or thick beds of coal which present undeniable evidence of the existence of great forests during times when the climate was more equable and moist. At other times, especially in the late Cenozoic era, subterranean fires, eating their way through the superincumbent masses of sediments, burst forth on the surface to build up great heaps of volcanic ash and lava flows, forming volcanic cones or piling up to build thick sheets of lava.

Thus, if we but take time to perceive the secrets contained in these vast piles of rocks, we are rewarded by the revelation of a story of unsurpassed interest, a story which as yet is far from complete, and perhaps for that reason all the more interesting. Many now unknown animals and plants remain to be discovered to give us not only a fuller knowledge of the fauna and flora of these past times, but also to give more indication of the phisical conditions prevailing at the time.

The First Great Era
(Archeozoic Era)

This is the oldest group of rocks that the geologist has been able to recognize. It is a complex of a great many different kinds of rocks which have been metamorphosed by great heat and pressure, being folded and squeezed by not one, but several periods of mountain building, until it is almost impossible to determine the relations of the original units to one another. It is very probable that two or more eras are represented in this complex; however, until a great deal more detailed work has been done on these rocks we can only consider it as a single great group which represents perhaps over half of all of geologic time.

This group of rocks is presumably world wide in its distribution; however, over the greater portion of the continents it is deeply buried beneath younger deposits. The areas where these rocks are exposed are of two sorts, the first over rather large areas of the continents which represent the nuclei of the continents, being areas which have remained essentially land areas throughout the remainder of geologic time and have therefore been undergoing erosion rather than sedimentation. The second sort of exposures are the cores of mountain ranges or areas of great uplift where the erosion has been able to strip off the overlying cover to great depths.

The latter is the type of exposure of these ancient rocks in the Southwest. The most notable outcrop of Archean rocks in the Southwest is that of the inner gorge of the Grand Canyon where they have been called the Vishnu Schists. The exposure of these rocks here is the result of the deep trench made by the Colorado River in its journey across that great uplifted area known as the Colorado Plateau. They are revealed in the bottom of the canyon for much of the distance from the mouth of Marble Canyon to the Grand Wash Cliffs, and their outcrop extends far southward along these cliffs and the Cottonwood and Aquarius cliffs and the Juniper Mountains.

Old puartzites appear also at various points, notably in the Mazatzal Mountains and in the Verde Valley, as well as along the axis of the Defiance Uplift, about 75 miles northeast of Holbrook. A large area of pre-Cambrian crystalline rocks has been mapped in south-central Yavapai County and these rocks have been called the Yavapai schists, while in the Globe-Ray region they have been called the Pinal schists. These rocks are also represented in the Buckskin Mountains of northern Yuma County, Arizona.

In New Mexico these rocks are bared in the southern prologation of the Rocky Mountains, in Sandia, Manzano, Nacimiento, Burro, Mimbres, Cooks, Lamitar, Ladrones, Oscura, San Andres, Magdalena, Fra Cristobal, and Sierra Caballo uplifts, in the region between Ojo Caliente and Brazos Peak, and in small areas in the west front of the Sacramento Mountains, in the Hatchet Mountains, in the hills east of Socorro, in the Klondike Hills, In the ridge northwest of Silver City, in Lone Mountain, and near Hanover, as well as in the Zuni Mountains and the Hills of Pedernal. In southern Nevada, Archeozoic rocks constitute a large part of the Eldorado Range, and in Southern California are known in the Inyo Mountains and in the Bristol Mountains near Cadiz.

Throughout the Southwest the Archeozoic rocks are a crystalline complex which include granites of considerable variety, quartz diorites, gneisses of various kinds, and schists, in large part representing metamorphosed sedimentary rocks but in part derived from intrusive and extrusive igneous rocks of considerable range in character.

The Archeozoic rocks have as yet yielded no definate fossil remains, although it is generally believed that life existed on the earth at that time, being made up of primitive forms mostly microscopic in size. However, if substantial remains had been left these would have been largely destroyed by the entense deformation of the rocks.

The Second Great Era
(Proterozoic)

The second great terrane of rocks recognized by the geologist represents perhaps a quarter of all geologic time. This long interval of earth history has been designated the Proterozoic era, or Algonkian. Although these rocks have a much more limited distribution in the Southwest than the Archeozoic rocks, they constitute a thick series of sandstones, conglomerates, shales and limestones or dolomites, with included igneous rocks. These rocks are excellently exposed in the Grand Canyon region of Northern Arizona and in Southern Nevada where they have been called the Grand Canyon series. In Central Arizona about a thousand feet of sandstone, conglomerate, shale and limestone are known to overlie the Archeozoic rocks of that region, and are in turn overlain by the Cambrian. This group of rocks has been referred to as the Apache group and is believed to have been formed contemporaneously with the Grand Canyon series.

The line of contact between the Archeozoic and Proterozoic rocks is extremely interesting. The Archeozoic beds of both the Grand Canyon region and Central Arizona are generally only slightly disturbed from their normal horizontal position. The line of contact with the Archeozoic rocks is an almost plane surface. During the interval between the formation of the Archeozoic and Proterozoic rocks there must have been time enough for erosion to completely wear down the great mountains which were built during the Archeozoic to form a nearly level peneplained surface at an elevation near sea level. Only the great folds and distortions of the Archeozoic rocks below this plained off surface, representing the roots of these old mountains, remain to testify their one-time majesty.

The Algonkian rocks of the Grand Canyon were studied by Walcott in 1882-3, and he recognized in them two divisions which were termed the Unkar (lower) and Chuar (upper) groups.

These two groups have a total thickness of nearly 12,000 feet, and may be seen in the depths of the Grand Canyon at various points between Tapeats Creek and Nunkoweap Valley, the largest area being in the bend of the canyon near the mouth of the Little Colorado River and in Bright Angel and Shinumo Valleys. Smaller exposures occur in Hindu and Ottoman amphitheater, Vishnu Creek, West Vishnu Creek, Phantom Creek and opposite Havasupai Point.

These rocks consist largely of brilliant red shale and sandstone, with conglomerates formed mostly of pebbles, and gray limestones, believed to have been formed mainly by limesecreting plants. There are also igneous members, especially in the upper part where they attain a thickness of 800 feet, consisting largely of amygdular basalts. These evidently represent the surface flows of lavas. The lower strata are invaded by sills of diabase, and in some of the limestone the action of this hot igneous material on the limestone produced asbestos deposits which have been prospected.

The upper group of the Grand Canyon series which has been named the Chuar, appears only in the Chuar, Kwagunt, and Nunkoweap Valleys and their vicinity. It consists principally of dark brown or gray sandy shale, with beds of brown or reddishbrown sandstone and limestones.

Walcott found fossils in the Chuar rocks which suggested early Cambrian age for the group. However, it was believed that the great break (angular unconformity) between the Chuar succession and the overlying Tonto sandstone (Upper Cambrian was indicative of a much greater age, so the group is classed as Algonkian.

In Central Arizona, the Algonkian is believed to be represented by about 1000 feet of sandstone, conglomerate, shale, and limestone which, as was mentioned before, belongs to the Apache group. Especially the lower portion of this group has been intruded by sills of diabase. This group is exposed in the Globe-Ray district, at the Roosevelt Dam, and in the Sierra Ancha. In most of the area the formations composing the Apache group lie nearly horizontal, but locally they are tilted by flextures which also involve later deposits. The Apache Group has been classed as Cambrian by Ransome on the basis of lithology. Walcott, Lee, and Darton, however, regard this series to be the same as the Grand Canyon series with the exception of the uppermost member, the Troy Quartzite, which seems to be Middle or Upper Cambrian. The group as thus restricted comprises the Mescal limestone, Dripping spring quartzite, Barnes conglomerate, Pioneer shale, and the Scanlan conglomerate. During recent years there is an increasing tendency to consider the group thus restricted as equivalent to the Unkar group. Both the Apache group and the Unkar group are characteristically associated with intrusive diabase, largely in the form of sills, and the principal asbestos deposits of Arizona are found at the contacts this diabase with calsareous members of the groups.

In interpreting the physical conditions of this region during Algonkian time we are somewhat handicapped in not having, except in a few cases, fossil organisms present in the rocks. The limestones, and probably a large part of the shales and quartzites, were deposited in shallow marine water, but part of the sandy shale and sandstone is bright red and its bedding planes are so extensively marked by mud cracks as to imply deposition on a low flood plain or delta surface, where exposures between flood seasons allowed the muds to dry and crack. Some of the sands are cross-bedded and ripple-marked, bearing witness to current action. The region was apparently one of a great delta plain over which subaerial and submarine deposition alternated. The great thicknesses of such sediments obviously formed near sea level, proves that the region subsided slowly during the period of deposition. The beds dip gently, but are no more altered than the Cambrian rocks above; yet they are for most part destitute of fossils or other evidences of life. Some of the limy beds, however, have hemispheric or nodular structures with a fine concentric lamination that closely resemble the deposit made by the modern lime-secreting algae. These algae deposits are among the oldest of all known fossils, and it is significant that they represent one of the lowest types of life. Isolated spicules of silicous sponges, which once lived in the sea, have also been reported from the upper part of the Grand Canyon system.

The line of juncture between the deposits of the second great era, the Algonkian, and the third great era, the Paleozoic, represents a second great unconformity. This is excellently displayed in the Grand Canyon, where below the unconformity lie the older, Algonkian formations, in a series of great fault blocks; above it lie the nearly horizontal Cambrian Beds with significant fossils. If the eroded parts of these great fault blocks could be restored they would form a range of mountains exceeding two miles in height. In its lower course the Grand Canyon cuts across a half-dozen of these great wedges that bear witness to a syatem of block mountains of impressive magnitude formed here after the deposition of the Grand Canyon system and before that of the Cambrian. The lost interval represented by the unconformity was sufficient to allow for the complete destruction of the ranges by the tedious process of erosion, an interval whose duration was undoubtedly some tens of millions of years long.

The Third Great Era of Geologic Time
(Paleozoic Era)

In general, it may be said that the Third great era is marked in the Southwest by the gradual submergence of an extensive land area and the gradual encroachment of a great sea from the south. This submergence was not uniformly developed through the entire area, and it was marked by many fluctuations, at times the sea being almost completely withdrawn. However, with each new incursion the sea seems to have extended farther and farther over the remaining portions of the old pre-Cambrian lands until finally, before the close of the Paleozoic, the entire southwest was inundated. This progressive overlap is especially well shown in New Mexico, where, in the southern part of the state, the older Paleozoic rocks are represented. However, as these are traced northward, they thin and gradually disappear, in general the formations of each successively younger period extending farther and farther to the north. In the northern part of the state the younger Paleozoic rocks rest directly upon the old Pre-Cambrian rocks, the intervening formations being lacking.

The floor of old pre-Cambrian rocks upon which the sea encroached was not worn down by erosion to a plain. It was an undulating surface, containing a number of rather persistent ridges. One of these old ridges of crystalline rocks is known in the Zuni Mountains region and is believed to have extended into Northeastern Arizona and accounts for the only outcrop of pre-Cambrian rocks in that general region. Here the Supai red beds of Permian age rest directly upon the pre-Cambrian crystalline rocks.

Paleozoic time was extremely long, enduring something like 340,000,000 years. A study of this great terrane the world over has revealed at least seven usually distinct divisions which are called periods. The events of this era are so varied that it seems best to take them up by periods.

Cambrian Period

A large part of Arizona is occupied by rocks of Cambrian age, mostly belonging to the late Cambrian. It is well represented in the Tonto group exposed in the lower part of the Grand Canyon by about a thousand feet of beds. The formations constituting this group are well exposed from Marble Canyon to the lower end of the Grand Canyon and in a wide area of plateau country to the west and south. The upper formations of this group thin out in the Juniper Mountains south of Seligman, but the lower sandstone is conspicuous in the Jerome region and is believed to be represented in the Tonto Basin.

In the Grand Canyon region and along the western and southern margin of the Arizona Plateau, the lower sandstone lies on the smooth surface of the pre-Cambrian granite and schist. From Tapeats Creek, at intervals, to Marble Canyon, it lies across the planed-off edges of the tilted Grand Canyon series; however, in places, ridges of the older rocks, several hundred feet high, project through the sandstone into the shale which overlies it. In the Grand Canyon region these overlying shales are of a greenish color and contain thinbedded sandstones and snuff-colored dolomite. They are in turn overlain by thin-bedded limestone and massive dolomite.

In the Clifton-Morenci district the basal Paleozoic strata have been called the Coronado quartzite, consisting chiefly of brown, pink, and maroon-colored quartzite which is conglomeritec at the base and varying in thickness from 100 to 250 feet. This formation caps Coronado Mountain and other summits of Coronado Ridge. Rather scarce fossils are indicative of Cambrian age.

In Southern Arizona in the Tombstone and Bishee regions, the Cambrian is believed to be represented by the Bolsa quartzite, which consists of about 430 feet of pebbly conglomerate and quartzite. No fossils have been found, but from its character and stratigraphic position it is believed to represent a portion of the Upper Cambrian. Overlying the Bolsa quartzite in this region is a limestone succession called the Abrigo limestone which contains fossils of Upper Cambrian age.

The Cambrian of New Mexico is represented by the Bliss sandstone of Upper Cambrian age. It is a prominent feature of the Franklin Mountains of Texas and New Mexico and other ranges of south-central and Southwestern New Mexico.

New Mexico. It thins out just north of the San Andres Mountains and is believed not to extend north of latitude 33 degrees 30 minutes in the western part of the state. It is exposed in the Hatchet Mountains, Florida Mountains, Cooks Range, Mimbres Mountains, and Silver City region.

The formation consists most generally of a brownish or grayish sandstone, often with beds of conglomerate at the base. In some places work borings are abundant and the beds frequently contain Brachiopod shells.

Cambrian rocks are also known from Southern Colorado, in the San Juan Mountains, in Southwestern Utah, Southern and Western Nevada and from the Inyo Range of Southern California. Southern California, Eastern California, Nevada and Western Utah are located along an ancient seaway which extended from Southern California northward through Eastern Alaska where it connected with the Artic. This lowland trough which now constitutes the Rocky Mountain region, and into which the seas often spread during the Paleozoic and Mesozoic eras, is generally referred to as the Cordilleran geosyncline. In the center and deepest portion of this trough, where the seas first entered the trough it was gradually submerged below sea level, the most complete record of sedimentation being represented. A branch from this western seaway seems to have extended eastward across Northern Mexico and Southern Arizona and New Mexico into Texas and Oklahoma. The lower Cambrian seas seem to have been largely restricted to the southern portion of the Cordilleran geosyncline and lying between, but not extending beyond, the 111th and 118th meridians. The extent of the passage connecting with the Pacific is unknown, but it was probably an unobstructed wide channel affording free ingress for the ocean waters and fauna. The broadest known portion of the sea was across Western Utah and Nevada into California, where the lower Cambrian beds have been found in localities 300 to 350 miles apart.

In early middle Cambrian time the sea widened somewhat and in upper Cambrian it spread to the eastward into the Colorado region to connect with the Mississippian sea on the North and across Arizona, New Mexico and Texas to join it on the south.

In the absence of all traces of land plants and terrestrial animal life in Cambrian rocks, the criteria for the determination of climatic conditions are limited to the terrigenous sediments and the character of marine life.

With the incursion of the marine lower Cambrian sea, warm conditions are indicated by the presence of calcareous beds containing brachiopods and trilobites associated with the coral-like Archaeocyathinae of world-wide distribution, a type which, like modern corals, probably requires a temperature above 68 degrees. There is also an almost total absence of red sandstones and shales throughout the Cambrian series of strata. In the Cordilleran region a cold period appears to be indicated in the barren arenaceous limestone between the highly fossiliferous upper Olenellus beds of the lower Cambrian and the fossiliferous limestones near the base of the middle Cambrian. The great change of the faunas at this horizon is very marked. The abundant and varied marine faunas during middle Cambrian time point to temperate waters and climate throughout the Cordilleran province from Nevada to the Arctic Ocean, and the same is true of the late upper Cambrian, although the latter epoch was one of shifting strandlines and changing conditions of sedimentation.

The Cambrian seas swarmed with a great variety of invertebrate animals, representing nearly all of the great phyla of the animal kingdom, except the vertebrates. The dominant forms were Trilobites, swimming and groveling crustaceans of predaceous and scavenging habits, which became so numerous and varied as to make up fully 60% of the known fauna. They were the most highly developed forms of their day, however small, generally ranging between 1 and 3 or 4 inches in length. Next in importance to the trilobites came the brachiopoda. During the early and middle epochs of the Cambrian these were mostly very small, primitive types but in places very numerous. In late Cambrian more progressive types are found with thicker, more calcareous shells. The Archaeocyathidae played the role of reef-forming corals in early Cambrian seas and were almost confined to that epoch. Their biologic relationships are problematical. The cone or cupshaped hard parts ranged up to eleven inches in length. The calcareous algae were small but abundant during Cambrian time, sometimes building small reefs.

Even though it is now established that a great variety of animals must have existed in the Proterozoic, the sudden appearance of abundant fossils in the Cambrian is remarkable. The Proterozoic fossils are chiefly those of lowly, lime-secreting algae, with only very rare representatives of three animal phyla, the proterozoa; the sponges, and worms; but the Cambrian strata of North America alone have yielded at least 1200 different kinds of animals including representatives of foraminifers, sponges, coelenterates, worms, brachiopods, gastropods, echinoderms, and arthropods. The difference implies that some great change had taken place in the organization of animals during the interval between the Proterozoic and Cambrian. This undoubtedly involved the use of external armor in the form of shells of chitin or calcium carbonate. The presence of such specialized forms as the trilobites, and representatives of the molluscan phylum would surely indicate that life had existed on the earth long before the Cambrian and that probably far more than half the drama of evolution had been enacted before Cambrian time.

Ordovician Period

In New Mexico, strata of Ordovician age appear rather extensively in the mountains and ridges in the southeastern part of the state. These strata comprise the lower Ordovician El Paso limestone and the upper Ordovician Montoya limestone. As traced to the north, these formations thin out near latitude 34 degrees. The El Paso limestone appears to grade down into the bliss sandstone (Cambrian), but it is seperated from the Montoya limestone by a break in sedimentation, representing part of Ordovician time, and the Montoya limestone is limited above by a break representing an interval of unknown duration.

In the Franklin Mountains, the El Paso limestone consists of about 1000 feet of magnesian gray limestone. The surface of many layers is covered by thin reticullating brown deposits of silica, and most of the rocks weather to a pale gray tint--two features which are distinctive of this formation throughout Southwestern New Mexico. This formation may also be seen along the east front of the San Andres Mountains (300 feet), in the west face of the Sacramento Mountains, southeast of Alamogordo (250 feet), in the west face of the Sierra Caballo (300-400 feet), in the Cooks Range (600 feet), about Silver City and Hanover in the Hatchet Mountains (500 feet), in the Snake Hills, and in a small outcrop in the Peloncillo Mountains, north of Granite Gap.

Fossils are not numerous in the El Paso limestone, and most of those obtained came from the medial and upper beds. A small coiled shell, Ophileta is the most common. The fossils from this formation were regarded by Ulrich and Kirk as correlative of the late Beckmantown time and at some localities as perhaps also Chazy time.

The Montoya limestone, of latest Ordovician (Richmond) age, underlies the portion of New Mexico south of latitude 33 degrees, and may extend farther north beneath overlapping formations. The thickness ranges from 200 to 300 feet, consisting of two parts, a lower member of dark-colored massive limestone, in places sandy, and an upper member of slabby beds, with many thin layers of chert. The usual outcrop is a dark cliff in the mountainside. The formation is exposed along the east slope of the Franklin Mountains, the Cooks Range in the Snake Hills, in the Klondike Hills, in the Silver City region, in the Sierra Caballo and Mimbres Mountains, at Lake Valley, prominent along the eastward facing escarpment of San Andres Mountains, the southern Oscura Mountains, in the Sacramento Mountains and the Hatchet Mountains. Fossils occur throughout the Montoya limestone at nearly all exposures, consisting largely of Brachiopods with some corals.

It is generally believed that the Ordovician beds of New Mexico extend westward and underlie a large part of Eastern New Mexico. In the Morenci district Ordovician strata have been identified and referred to as the Longfellow limestone. It consists of about 400 feet of limestone, more or less dolomitic, being more siliceous in the lower than in the upper beds. It forms bluffs along the San Francisco River above Clifton and occurs in faulted blocks at the foot of Copper King Mountains, east and south of Morenci, and north of Gold Creek, on the slope toward Eagle Creek. The lower portion of the Longfellow limestone contains fossils of Cambrian age while the upper portion contains a number of lower Ordovician (Beckmantown) forms. The formation probably represents sedimentation, extending from late Cambrian into early Ordovician time, although there may be an unrecognized break in this sequence.

Ordovician Rocks are believed to be represented in the Goodsprings dolomite of Southern Nevada. Fossil evidence, obtained about 10,000 to 12,000 feet below the top of this formation, is believed to indicate Early Ordovician Age. The lower portion of this formation is believed to be Cambrian, and the upper portion Silurian and Devonian.

Ordovician strata have also been recognized in the Inyo Mountains north of Owens Lake, California.

From the distribution of the Ordovician rocks in the southwest, it is inferred that during early Ordovician time the waters it is inferred that during early Ordovician time the waters from the Pacific Ocean spread into the Cordilleran geosyncline across Southern California, most of Nevada, Western Utah, and northward. Also an eastwardly extending embayment allowed the seas to transgress across Northern Mexico and extend into Southeastern Arizona and Southern New Mexico. The seas were somewhat restricted in this this region during the middle Ordovician, but during the upper Ordovician they had almost the same distribution in the southwest as during lower Ordovician time.

From the distribution and character of the faunas of Ordovician time, and from the wide distribution of limestones and dolomites it seemes quite clear that this was a time of warm climate, lacking marked climatic zones. Limestones and dolomites containing forms believed restricted to warm seas are known far to the north within the Arctic Circle.

Silurian Period

The rocks representing the Silurian period are extremely restricted in their distribution in the southwest. A small portion of Silurian time is represented by the Fusselman, which is confined to the part of New Mexico south of Latitude 33 degrees. It is represented in the Frankline Mountains by 1000 feet of strata, and is of considerable topographic prominence. In the Cooks Range, near Lake Valley, it is about 200 feet thick, in the Sacramento Mountains 100 to 130 feet, near Silver City 40 feet, in the Hatchet and Victorio Mountains 100 feet or more, and in the San Andres Mountains it ranges from 220 to 120 feet, but thins out rapidly a short distance north of lattitude 33 degrees.

The formation overlies the Montoya limestone (Ordovician) uncomformably showing that this region was subject to erosion following the Upper Ordovician.

Fossils are rare in the Fusselman limestone, the most common form being a brachiopod, Pentamerus; but many corals occur in places, notably in the knoll on the south side of Mine Hill, in the Victorio Mountains.

No strata of Silurian age have been found in Arizona and this period appears to be represented here mainly by erosion, this region at that time constituting a land area. It is not likely that the Fusselman limestone may extend into the extreme eastern part of Arizona, but it covered by desert fill and volcanic rocks.

Devonian Period

The Devonian system is represented in Southern New Mexico by a widespread deposit of black shale named the Percha shale, from Percha Creek near Kingston. It represents a portion of later Devonian time, and, although accordant in attitude with the overlying and underlying formations, it is seperated from them by breaks of sedimentation. It is absent in the Franklin Mountains and apparently also in the Permian overlap in the Florida and Victorio Mountains. It attains a thickness of nearly 500 feet in part of the Silver City region, but is less than half as thick in the Cooks Range and Sierra Caballo, and the Mimbres and Hatchet Mountains, 160 feet at Lake Valley, and about 100 feet in the San Andres and Sacramento Mountains. It thins out in the northern part of the San Andres Mountains, but probably is represented by some red shale overlying Montoya strata in the southern part of the Ascura Mountains. It is absent in the Magdalena Mountains and other ranges in central and northern New Mexico. In most places the lower beds are fissle shales, and the upper beds of gray shale contain layers of slabby and nodular limestone.

Limestones of later Devonian age have been found at many places in Arizona. They have not been recognized in the southwestern corner of the state west of longitude 112 degrees, but may be present in the succession of more or less metamorphosed limestones in that region. They have been found on Canyon Creek, Gila County. Beds of this age are absent in the northeastern part of Arizona, where in the Defiance uplift region, at least, the Permian rocks lie directly against the Pre-Cambrian, but their absence here may be due to removal by erosion in early or middle Carboniferous time.

Remnants of Devonian strata have been found at several places in the Grand Canyon, where the formation is known as Temple Butte limestone from its occurrence in Temple Butte, a plateau remnant lying between Chuar Valley and the Colorado River, a short distance below the mouth of the Little Colorado River. At Kanab Creek they consist of purple and cream limestone and sandstone, passing upward into gray calciferous sandstone, lying on a very irregular surface of the Mauv limestone (Cambrian). In the Grand Canyon, east of the Kiabab plateau, the Temple Butte limestone is in places entirely absent, either through erosion or non-deposition, so that the Redwall limestone (Mississippian) rests directly on the massive calciferous strata of the upper Tonto (Cambrian.) It rarely has a thickness of more than 100 feet. Noble recognized many occurrences of remnants of Devonian strata, mostly occupying channels in the eroded upper surface of the Mauv limestone. There is a good deal of variation in the character of the beds from place to place, the beds being in lenticular layers, commonly wedging out in less than 100 feet with many local unconformities. The prevailing color of the Temple Butte limestone is purplish or purplish-gray, while some beds are yellowish or green, and others are white or cream. Cross bedding and a peculiar gnarled structure are common.

In the vicinity of Clifton and Morenci the Devonian is represented by shale and limestone which has been called the Morenci formation. These formations are believed to represent the westward continuation of the Percha shale of New Mexico. The Morenci formation consists of about 100 feet of dark fissile shale underlain in most places by 75 feet of fine-grained impure limestone. The best exposures are about Morenci, on the San Francisco River, above Clifton, near Garfield Gulch, in slopes north of Coronado Mountain, and at the head of the south fork of Sardine Creek. The formation is accordant in attitude with the inclosing limestones of Ordovician age below and Mississippian age above, although seperated by unconformities representing long periods of time.

In central and southern Arizona the Devonian rocks are known as the Martin limestone, named from Mount Martin near Bisbee. The formation is expised in the Escabrosa ridge in the Bisbee region, and in the line of ridges extending from Mt. Rielly to Gold Hill. They consist largely of dark gray, compact limestone in moderately massive beds, with some slabby and shaly members particularly in the lower part. The thickness is 300 to 350 feet. In the Jerome area these rocks rest upon the Cambrian Tapeats sandstone and consist of thin-bedded, light yellow and gray limestones, some of which are quite sandy. The total thickness here is about 500 feet. Limestones of Devonian age occur at various places in the Empire Mountains, in the Santa Rita Mountains near Helvetia and southwest of Greaterville, and on the eastern slopes of the Patagonian Mountains. They also appear to extend along the northeast slopes of Canelo Hills. They have been identified by Darton in the Salt River basin, Black River Valley, Nantes and Mogollon plateaus, Galiuro, eastern Mescal, Whetstone, Dragoon, Santa Catalina, Tucson, Slate Mountains, and possibly also the Sieretta Mountains. They may yet be discovered in the Vekol Range. It is believed that the Martin limestone is the Westward continuation of the Percha shales of New Mexico, pollibly having been formed in the clearer waters of the embayment.

Fossils are quite numerous in most of the Devonian formations of the Southwest. In the formations of southern New Mexico, and south and central Arizona they consist of marine invertebrates, especially brachiopods and corals with remains of gastropods, crinoid stems, and sponges. In the Grand Canyon region, fossils have been obtained at verious places. In the Kanab Creek section Walcott reported "Placoganoid fishes of Devonian type", while the beds east of Kaibab plateau yielded Cyathopylloid corals, casts of brachiopods and plates of placoganoid fishes. In Sapphire Canyon, about 12 miles west of El Tovar, fragmentary material of Bothriolepis occurs. It seems from the cross-bedded and lenticular nature that much of the Devonian of the Grand Canyon region represents rather near-shore delta deposits. This is also borne out by the occurrence here of the remains of what are supposed to be fresh-water fishes.

In the deeper portions of the Cordilleran heosyncline, extensive thicknesses of Devonian sediments were laid down. Thus, in the Eureka, Nevada section, the Devonian is represented by 4000-6000 feet of limestones and calcareous shales. In the Inyo Mountians, California, the Devonian includes avout 1500 feet of dark gray to black shales and argillaceous limestones, with several beds of hard sandstone. Bands of black chert are common in the limestone, and often carry numerous fossils of corals, brachiopeds, crinoid stems, etc.

Mississippian Period

Mississippian formations occupy most of the soutwestern part of the state of New Mexico, and probably are present under some of the southeastern part, but they appear to be absent in the Franklin, Florida, and Victoric Mountains. They are known generally under the name of the Lake Valley limestones and are conspicuous in the Sacramento, San Andres, Robledo, Caballo, Cooks, and Mimbres Mountains, where they consist generally of 100-200 feet of massive to slabby, mostly coarse-grained, light-colored limestone. In the Magdalena Mountains and Sirra Ladrones the limestones lie on per-Cambrian granite, but elswhere they overlie the Percha shals without discordance in attitude. They are overlain by limestone of Pennsylvanian age without notable difference in attitude, but separated by a break in deposition, representing a long interval of time.

Fossils have been collected from this limestone at Lake Valley, and in the Mimbres Mountains, near Kingston, and in other regions; and they consist mainly of crinoids, corals and brachiopods.

The Mississippian series has a wide distribution in Arizona. It is represented in the Grand Canyon by Redwall limestone, where it forms the most extensive cliffs in the Grand Canyon. It appears impressively in the canyon of the Virgin River, in the Virgin Mountains, and in the Grand Wash Cliffs, in the northwestern part of the state, where its thickness approaches 2000 feet. South of the Grand Canyon it makes a broad bench which extends from Grand Wash Cliffs to Juniper Mountains and Black Mesa, and along the valley of the Verde through the northeastern part of Yavapai county. It skirts the base of the Mogollon Cliffs through northern Gila County and extends up the Valleys of the Salt, White, and Balck rivers, and under the Natanes Plateau, nearly to longitude 110 degrees. It is very thin or absent in the upper part of Canyon Creek. In its southern and southeastern extension it thins greatly, being about 300 feet thich in Yavapai and Gila counties, where it becomes less massive. Characteristic Mississippian invertebrates have been found at a number of places.

In the southern part of Arizona, in the Bisbee region, the limestones overlying the Devonian (Martin limestone) have been called the Escabrosa limestone. The formation consists of rather thick-bedded, nearly white to dark-gray, granular limestones, mostly of great purity, the total thickness being between 600 and 800 feet. Fragments of crinoid stems are very abundant, and remains of corals and shells occur at various horizons. This formation has also been recognized at Tombstone, and in most of the mountains of southeastern Arizona as far west as the Vekol Range, and north through the Santa Catalina and Turnbull Mountains. It is also present in the Globe-Ray and Roosevelt Dam regions, where it is included with Pennsylvanian limestones in the Tornado formation. The Escabrosa limestone represents, according to its contained fossils, the earlier half of Mississippian time.

The Mississippian is represented in southwestern and Central Colorado by the Leadville limestone. Although conformable with the underlying Devonian rocks, it is separated from the overlying Pennsylvanian formations in most places by an unconformity. The

Leadville limestone is the chief host rock for replacement ore deposits in Colorado.

The Mississippian is also represented in Utah, Nevada and southeastern California, principally by deposits of limestone.

Pennsylvanian Period

In New Mexico the Pennsylvanian period is represented by the Magdalena group, a thick succession of limestone which is a prominent feature in the Sacramento, San Andres, Oscura, Franklin, Caballo, Los Pinos, Sandia, and Manzano Mountains and constitutes a large part of the Sangre de Cristo Mountains. It also appears in the Magdalena, Ladron, Robledo, Lemitar, Lone, Hatchet, Cooks, Peloncille, and Mimbres Mountains, and the ridges east and west of Socorro, south and west of Hatchet, and west and north of Silver City, and in the uplift of Santa Rita and Hanover. It underlies a part of the western third of the state, where its limits are not known. It is absent in the Zuni Mountains, in part of Grant County, in the Pedernal region and in most of northeastern New Mexico.

Limestone is the predominant rock of the Magdalena group, but interbedded sandstone and shale occur in all sections, and along the east side of the Sangre de Cristo Mountains gray and red sandstone predominates. Thicknesses range from 900 to 2500 feet, attaining a maximum in parts of the Rocky Mountains.

Fossils occur abundantly in most parts of the Magdalena group at nearly all localities.

In Arizona the Naco limestone at Bisbee, at least 1500 feet and possibly as much as 3000 feet thick, was referred originally to the Pennsylvanian; however, it is now known to contain also beds of Permian and possible Lower Cretaceous age. Pennsylvanian limestones are found in the Santa Rita region, and have considerable development in Central Arizona. Farther to the north, in the plateau and Grand Canyon region, the Calcareous Pennsylvanian strata are succeeded by more arenaceous beds which have not everywhere been definitely separated from the Permian portion of the Supai formation, consisting mainly of red sandstones and shales.

In Colorado the highlands bordering the Central Colorado basin and the southwestern Colorado basin were uplifted at the end of Mississippian time. Along the margins of these basins, Pennsylvanian rocks overlap all of the older formations with marked unconformity. In the central part of the basins the lowest Pennsylvanian rocks are marine shales and limestones interbedded with coaly shales containing abundant plant remains. Grit and conglomerate overlie the lower member. In the lower part of the grit series, beds containing a marine Pennsylvanian fauna are interstratified with beds containing lower Pennsylvanian floras. Beds containing a Permian flora appear about 1500 feet from the base of the Pennsylvanian and overlie a limy member characterized by Fusulina and threadlike algae. The Permian plant beds are interlayered with marine beds containing a fauna which have been considered of Pennsylvanian aspect. In the northwestern part of the central Colorado basin the lower Pennsylvanian beds are overlain by the Weber(?) quartzite of Middle(?) Pennsylvanian age, which is succeeded by the Pary City formation, of upper Pennsylvanian and Permian age. These formations disappear toward the southeast and are overlapped by Permian grits that apparently rest on the Weber(?) formation, of Lower Pennsylvanian age throughout central Colorado. Throughout Colorado the Pennsylvanian grits are characterized by abundant clastic mica and by pre-Cambrian debris. Gypsum beds are common in the Pennsylvanian strata of central and southwestern Colorado and several salt domes have been found in the Paradox Valley region in the southwestern part of the state.

Permian Period

The Permian in New Mexico is represented by the Manzano group, comprising the Abo sandstone below and the Chupadera formation above. The Gym limestone of southwestern New Mexico and the Castile gypsum of southeastern New Mexico may be equivalent to the Chupadera in whole or in part. The Permian beds of New Mexico are both thick and extensive, the maximum total thickness being probably in excess of 4000 feet. In the eastern part of the state, in the Pecos valley, the Permian contains much salt, gypsum, and anhydrite. The great caverns near Carlsbad are in Permian limestone. In southeastern Arizona, beds of Permian age are definitely recognized only in the upper part of the Naco group, but in southeastern New Mexico they have been noted near Santa Rita by Spencer. They constitute, however, an important part of the stratigraphic sequence of the Arizona plateau, where the Supai formation, the Hermit shale, the Coconino sandstone and the Kaibab limestone are all regarded as of Permian age.

Permian rocks are well known in the succession exposed in the walls of the Grand Canyon, being represented by the Supai formation, Hermit shale, Coconino sandstone, and the Kaibab limestone. The Supai formation here consists of a series of massive cross-bedded, fine-grained, red-stained sandstones, interbedded with sandy red shale, and including a few beds of calcareous sand, limestone conglomerate, and cherty limestone. The total thickness exceeds 800 feet. The alternating sandstones and shales give a step-like form to the outcrop. The Supai formation is seperated from the red-wall limestone below and the Hermit shale above by planes of unconformity. Its deposits are those of river flood plains within which impressions of fern-like plants and tracks of land animals have been preserved.

The Hermit shale of the Grand Canyon is a succession of thin layers of red, sandy, friable shale, remarkably alike in color, composition, and bedding. The thickness averages about 300 feet. From the Hermit shale have been collected impressions of ferns, cone-bearing plants, insect wings, and tracks of supposed salamanders.

The Coconino sandstone forms a buff, vertical wall, 300 to 350 feet high, just below the rim of the canyon. It is characterized by uniform fineness and purity of grain; by persistent cross-bedding on a huge scale, and by general massiveness. Most of its beds have the form of interlocking wedges, 10 to 75 feet thick. A few horizontal beds appear at the base. As at present interpreted, the Coconino is largely an eolian deposit. The cross-bedding laminae preserve the tracks of ancestral amphibia.

The Kaibab limestone is the highest stratum in the walls of the Grand Canyon. It is also the basal formation of the plateaus north and south of the Colorado River, being exceptionally widespread. With few interruptions, it forms the surface rock of the Shivwits, Uinkaret, Kanab, and Kaibab plateau, north of the Colorado, and the Coconino plateau south of the river. From the many Echo Cliffs to the Grand Wash Cliffs, a distance of about 130 miles, it constitutes the rim of the Grand Canyon. It is predominantly a gray or buff cherty fossiliferous arenaceous limestone, with some interbedded sandstone and, locally, gypsum at the base. This limestone generally forms ragged, nearly vertical cliffs, with recessed grooves, along the edges of the less resistant beds. The Permian age of the formation is attested by a marine fauna comprising some 80 species. The limestone is

800 to 1000 feet thick in the Virgin River Valley, 500 to 600 feet along the rim of the Grand Canyon, 600 to 700 feet thick in the northern part of the Kaibab Plateau, and 200 to 300 feet about Flagstaff on the Coconino Plateau. The Kaibab is conformable with the underlying Coconino and unconformable with the overlying Moenkopi (Lower Triassic.)

In generalizing the history of the Permian of the Southwest it may be said that western Texas and southern New Mexico present the greatest section of marine Permian known in America and probably the finest in the world, for interior seas from the Gulf of Mexico entered across the region, and in their retreat lingered longest here. As a result, the Permian rocks, which attain a thickness of over 7000 feet, are almost entirely marine and largely dolomites and limestones. Their abundant fossils show resemblances to those of Italy and the Alps. The dolomites that form the higher part of the section in the region of the present Guadalupe and Glass Mountains appear to have been great reefs or banks in the entrance to this entire sea, upon which calcareous deposits formed, while muds and even salts were deposited in the lagoons behind them. The abruptness with which these massive dolomites grade eastward into shales, anhydrite, and salt is remarkable. Westward and northward the Permian is widely distributed in New Mexico, Arizona, Nevada, Colorado, Wyoming, Utah, and Idaho, where it presents largely red-bed facies. At the base, there are locally thin marine limestones, but these are generally followed by red shales and sandstones, into which great tongues of massive, pure quartz sand interfinger. The latest formation to be formed was a widespread middle Permian limestone, the Kaibab, which marks the final Permian inundation of the sea over this region.

Much of the red bed sediment was coming from the Colorado Mountains (Ancestral Rockies of W.T. Lee) which lay to the northeast. In places this sand was water-laid, but in other areas it was blown into dunes.

The Fourth Great

Era

(Mesozoic)

Triassic Period

Triassic rocks are widely distributed throughout Utah, Colorado, Arizona, New Mexico and west Texas. This is the greatest area of continental (land-laid) Triassic deposits in North America. Here continental red beds predominate, although marine members of the older Triassic interfinger from the west. Bright red and maroon shales and cross-bedded red sandstones make colorful landscapes like the Painted Desert of Arizona. The maximum thickness of these red beds is found in southwestern Utah and northwestern Arizona, mounting to 3000 to 4000 feet, and in general the system thins out to several hundred feet toward the east in Colorado and Wyoming. Beds of gypsum occur at various horizons in the red shales, especially in the eastern and northeastern parts of the region. There is also considerable volcanic ash in the red beds of Arizona and Utah. Much of the detrital sediments came from the old crystalline uplifts of the Colorado Mountains in Colorado and northern New Mexico. For the Triassic formations become coarser grained toward regions like the Uncompahgre plateau, where they overlap against the ancient granites.

Throughout the Colorado plateau a three-fold division is generally recognizable, - a lower Moenkopi formation, a middle Shinarump comglomerate member, and an upper Chinle formation. The Moenkopi formation is a series of red-brown, brick-red, gray, white, and yellow gypsiferous sandy shales with inter-bedded layers of earthy yellow limestone in the lower part, and a conglomerate of variable composition at the base. It lies unconformably above the Kaibab limestone, and, like the Kaibab, is present over large areas north and south of the Colorado River. The Moenkopi forms regularly banded cliffs along the Virgin River and at Fredonia. At Virgin City, 1775 feet are represented, in the Little Colorado Valley, 400 feet, at Cedar Mountain, on the south rim of the Grand Canyon, 480 feet. The thickening westward is accompanied by an increase in the amount of limestone and a change in part from arid-climate terrestrial deposits to marine deposits, with which are associated such fossil forms as Meekoceras aff. M. mushbachanum, Bakewellia sp. Myalina n. sp., and Pseudomonotis n. sp.

The Sinarump conglomerate is a stratum of conglomerate and coarse sandstone, containing fragments of fossil wood, and it unconformably overlies the Moenkopi. Its position as a resistant bed between the soft shale of the Moenkopi and Chinle formation gives it particular prominence, though in few places is it more than 100 feet thick. Through the plateau province it is a cliff maker.

The Chinle formation conformably overlies the Shinarump conglomerate and consists of a series of varigated shales, arkosic sandstones, and thin cherty limestone conglomerates. The shales include much volcanic ash. Near the entrance of Zion National Park and at Kanab they constitute brilliantly-colored slopes of shale, broken by cliffs developed on the sandstone members. Within the Plateau province the Chinle ranges in total thickness from 400 feet to about 1000 feet. A distinctive feature of the Chinle is the pressence of fossil wood, which near Rockville, east of Kanab, and at many places in northern Arizona occurs in sufficient abundance to constitute petrified forests. Besides the petrified wood, the Chinle formation contains a wonderful array of fossil reptile and fish remains, and numerous freshwater clams belonging to the genus Unio. Of particular interest are the remains of extinct amphibia, Stegocephalia, and the reptilian Phytosaurs of crocodile-like form and habits which inhabited the stream channels of Chinle time.

The fossils, like the physical features of the rocks, indicate that the red beds were for the most part, at least, deposited above sea level. The Moenkopi was deposited over a vast low flood plain sloping westward from the Colorado Mountains to the margin of a shallow epeiric sea whose shore fluctuated back and forth over the western part of Arizona and Utah. The Chinle was more completely indepentent of the sea and was spread by sluggish streams over a broad basin of almost desert-like character; locally, there were swamps and shallow lakes, while in the higher ground surrounding the basins there were scattered stands of conifers. In the western lands there were explosive volcanoes, shedding ash far about.

Jurassic Period

Over the states of the Colorado plateau the Jurassic system is represented by red beds and dune sands which attain a maximum thickness of 3000 feet or more. The lowest division has been named the Glen Canyon group for its magnificent exposures in the towering walls of Glen Canyon of the Colorado River. The upper part is known as the San Rafael group, for its exposures in the San Rafael swell in Central Utah.

The Glen Canyon group consists essentially of huge piles of sandstone characterized by cross-bedding on an exceptional scale. As expressed in the topography, the group is the outstanding maker of cliffs and canyon walls. It forms the walls of Zion Canyon, of lower Parunuweap Canyon, and in part of Kanab Canyon. The Glen Canyon group is divisable into three formations; at the bottom the Wingate sandstone, lying perhaps unconformably on the Chinle; an intermediate formation, the

Kayenta, consisting of calcareous shale and limestone; and at the top, the Navajo sandstone, from which Rainbow Natural Bridge and El Moro have been carved. In the high plateaus the total thickness of the Glen Canyon group exceeds 2000 feet.

The Carmel formation, the basal formation of the San Rafael group, is a series of hard, gray limestones and calcareous shales 100 feet to 250 feet thick. It conformably overlies the Navajo sandstone. It is well displayed in the Zion-Mt. Carmel highway, in Meadow Brook Canyon, and particularly at Mt. Carmel junction. Fossils from the limestone beds include Pentacrinus stems, Trigonia sp., Camptonectes bellistriatus, and small Ostrea.

Above the Carmel formation is a series of beds with a total thickness of about 250 feet that consists of poorly consolidated pinkish gypsiferous sands overlain in turn by massive gypsum, and thin fossiliferous limestones and sandy shales. The position of these beds in the time scale and their relation to the overlying Cretaceous have not been satisfactorily established. Probably they represent the rest of the San Rafael group and the overlying Morrison formation.

The formations of both the Glen Canyon and the San Rafael groups thin out by overlap on the old pre-Cambrian granite of the Colorado Mountains in western Colorado. The increasing coarseness and the presence of locally derived boulders indicate that much of this detrital material was coming from that region. However, since the sandstones thicken toward the west, it is probable that the Mesocordilleran geanticline lying between the Coloradoan and Californian seaways was supplying a large share of the sediment.

Cretaceous Period

In the plateau province, beds of Cretaceous age attain thicknesses of more than 3000 feet. They constitute long shale slopes, high sandstone cliffs, and vertical canyon walls in the zone between the friable topmost Jurassic strata and the resistant Tertiary Early Colorado, Middle Colorado, Late Colorado, and Montana age. Parunuweap Canyon, and along Coal Creek, has not been subdivided, but probably includes the formations recognized by Gregory and Moore on the east edge of the Paunsaugunt Plateau, namely the Morrison formation of the lower Cretaceous and five recognizable divisions in the upper Cretaceous, the Dakota (?) sandstone, the Tropic shale, the Straight Cliffs sandstone, the Wahweap sandstone, and the Kiaparowits formation.

As described by Richardson, the Cretaceous beds of the Colob Plateau comprise 300 to 400 feet of sandstone, the shale, and coal, resting on basal conglomerate; 1000 feet of drab shale; and 1000 feet of buff sandstone and drab shale. All three are of Colorado age. Buff sandstone of Montana age are resting unconformably on the lower beds.

In northern New Mexico, the somewhat doubtful Cretaceous Morrison formation apparently does not extend south of latitude 33 degrees. In southern New Mexico the chief representatives of later Mesozoic time are sandstones and limestones of Lower Cretaceous age, which rest with marked unconformity on the older rocks. In New Mexico the principal lower Cretaceous formation is what Darton has named the Sarten sandstone, which he regards as identical with Paige's Beartooth quartzite in the Santa Rita region. The age of the Beartooth quartzite is still uncertain; it is possibly the base of the Upper Cretaceous in this region. In the Bisbee region, southeastern Arizona, the Comanche (Lower Cretaceous) attains great thickness and has been divided by Ransome into four formations: the Glance conglomerate below; the Morita formation, chiefly sandstone and shale; the Mural limestones; and the Cintura formation, chiefly shale and sandstone. Fossils collected from the lower part of the Mural limestone were determined as belonging to the upper or Trinity division of the Comanche, perhaps also to the middle or Fredericksburg division. At many other localities in southern Arizona, as at Tombstone and in the Huachuca, Patagonia, Oro Blanco, Baboquivari, Sierrita, Tucson, Santa Rita, Empire, Whetstone, and Dragoon Mountains, occur masses of sediments that rest unconformably on the Paleozoic or older rocks and are probably of Comanche age. They have not however, been correlated definitely with the comanche formations of the Bisbee section.

Estimates of the thickness of Comanche sediments in southern Arizona range from 10,000 to 18,000 feet.

Stratified rocks of Upper Cretaceous age, although abundantly present in northern New Mexico and northeastern Arizona, where they contain valuable beds of coal, have relatively slight areal representation in the southern parts of these states. A considerable outlying area of these upper Cretaceous coal-bearing rocks of the Mesa Verde group occurs in the Sierra Blanca region north of Alamordo. Farther west, a smaller area contains the Carthage coal field about 16 miles southeast of Socorro. About 70 miles farther south, near the south end of the Elephant Butte reservoir, between the Fra Cristobal Range and the Sierra Caballos, is a considerable area of lignitiferous beds, whose position within the upper Cretaceous is not yet definitely determined. In the Silver City region 2000 feet of Colorado shale, underlain by the Beartooth quartzite, have been mapped by Paige. In the Clifton-Morenci district occur 200 feet of shales and sandstone, called the Pinkard formation, and assignable to the upper Cretaceous.

The Morrison formation is widely distributed in Colorado, and extends southward into Arizona and New Mexico. It is represented by continental deposits, which are either of Upper Jurassic or Lower Cretaceous age, or possibly both. The lowest part of the formation is chiefly sandstone, with some interbedded limestone and shale, and in the western part, Colorado gypsum occurs near the bottom of the section. The upper half of the formation is largely variegated shale, but contains interbedded limestones and sandstone. Green, purple, gray and red shales are prominent, and give the formation a characteristic appearance which is easily recognized. This formation contains a wonderful array of fossil dinosaurs.

In northwestern New Mexico and southwestern Colorado, the upper Cretaceous is represented by a series of sandstones and interbedded shales called the Mesa Verde group. Both marine and non-marine sandstones are present in the Mesa Verde rocks, and much of the coal of this region comes from the non-marine sandstones. In southwestern Colorado the coal-bearing Mesa Verde beds are overlain by marine shales (Lewis shales) succeeded by sandstones (Pictured Cliffs sandstone) which in turn underlie brackish-water coal-bearing shales and sandstones (Fruitland and Kirtland formations) that are of approximately the same age as the lower paet of the Vermejo formation of southeastern Colorado. A thick series of Upper Cretaceous(?) andesitic tuffs, sandstones and shales (McDermott formation) rests upon the Kirtland shale unconformably. These beds mark the beginning of a long period of volcanic activity.

Extensive crustal unrest marked the closing stages of the Mesozoic era, especially in western North America where the old Cordilleran geosyncline became the scene of folding and thrusting on a colossal scale resulting in the Rocky Mointain system. This orogenic belt stretched from Alaska to Mexico, and in southern Colorado and northern New Mexico resulted in the great open folds of the Southern Rockies. To the west lay the great resistant place of the Colorado Plateau which remained almost undeformed.

The Fifth and Last Great Era
(Cenozoic Era)

Although the first of Cenozoic time is represented by deposits in local basins, in the Southwest, the principal record of this time lies in the various diastrophic movements followed by erosion cycles and in widespread volcanic activity. Following the closing stages of the Cretaceous, marine waters have been completely excluded from this region, with the possible exception of certain areas of Southern California. During Cenozoic time, the area corresponding to what is now southern New Mexico and southern Arizona was apparently land, partly occupied at times by lakes. The most extensive and noteworthy lacustrine deposit of this period is the Santa Fe formation which occupies large areas in the upper Rio Grande Valley, and has yielded many vertebrate fossils of the late Tertiary age. In southeastern Arizona lacustrine deposits of probable Tertiary age occur in the Patagonia, Santa Rita, and Empire Mountains. In the San Pedro Valley, between Benson and Tombstone, Arizona, are lacustrian deposits carrying vertebrate fossils of Pliocene age.

In the Colorado Plateau region the principal Tertiary sediments are known as the Wasatch formation of Eocene age. They consist of highly-colored beds of limestone, shale, and sandstone, resting on a basal conglomerate that is unconformable with the underlying Cretaceous strata. In most places the thickness of the series as exposed is 400 to 500 feet, but the maximum thickness probably exceeds 1500 feet. On the Markagunt and Paunsaugunt plateaus the most conspicuous part of the formation is the pink limestone that forms the "Pink Cliffs" and gives scenic interest to such places as Red Canyon, Bryce Canyon, and Cedar Breaks.

It has been only within the Cenozoic, and especially the latter part of this era, that the general features of the land, as we know them today, have had their development. At present the Southwest is made up of several distinct physiographic provinces which have come into existence during the Cenozoic. The extreme eastern portions of New Mexico and Colorado are a part of the Great Plains, a great eastwardly sloping surface extending from the Mississippi to the foothills of the Rocky Mountains. Immediately to the west, in central Colorado and extending south through central New Mexico, are the Rocky Mountains, consisting of a mountainous region of folded rocks. Adjoining this, on the west, is the Colorado Plateau, consisting of relatively flat-lying formations, at an elevation ranging from 7,000 to 11,000 feet. The rocks of the Plateau have been thrown into broad swells with local monoclinal flextures, and has in places been broken by a number of normal faults; however, on the whole, it is of contrastingly simple structure. Farther to the west, and extending around to the south of the Colorado Plateau, is the Basin Range province which, on the average lies several thousand feet below the Colorado Plateau. Its ranges are tilted fault blocks of Mesozoic and Paleozoic rocks, flanked and partly buried by late Cenozoic and recent sediments, forming flat basins. Farther to the west lie the Sierra Nevada and Coast Ranges.

In the Cenozoic history of the Great Basin region, it seems probable that the movements of the Laramide revolution continued here into Eocene time and that during the early Cenozoic this region had a high mountainous surface and exterior drainage. For this reason, it is believed, Eocene and Oligocene strata are practically absent. However, Miocene formations are present and are locally of great thickness. In southern Nevada the Miocene deposits began with coarse deposits of conglomerate that range up to 3000 feet in thickness which lie across the beveled edges of early Mesozoic and Paleozoic strata. The Conglomerate varies greatly in thickness within short distances and included angular and subangular fragments of all the older rocks. Overlying the conglomerates are clays and silts, including thick beds of gypsum, Magnesite and borax. The conglomerate is clearly the material of coarse alluvial cones formed in a region of bold relief, and the clays and silts, with their saline deposits, could have formed only in arid basins of interior drainage much like the present basins. In short, normal faulting had begun on a grand scale, and the Great Basis had its inception in the Miocene. As the new ranges were elevated, the intervening basins, all in the rain shadow of the Sierra Nevada, assumed a desert character like that of today. The faulting was only begun at this time, for the Miocene sediments were later steeply tilted and truncated so that they now lie with strong angular unconformity below the Pliocene beds. The latter, ranging up to 1800 feet thick and including gypsum and salt beds as much as 100 feet thick locally, bear witness to continued deepening of the basins. The well defined fault scarps, as well as historically-dated faulting, prove that the movements still continue.

The Colorado plateau is remarkable for tabular plateaus, cliff-bound mesas, and deep canyons, all of the most impressive magnitude. Gently dipping formation of Triassic, Jurassic and Cretaceous ages rise one above another in terraced plateaus abounded by unscalable cliffs many hundreds of feet high. These cliffs are the receding edges of resistant formations, truncated during an early Cenozoic erosion cycle, and their grandeur bears witness to the vast amount of stripping that the region has suffered since the end of the Cretaceous. The region was more or less extensively covered by Eocene sediments like those of the Green River and San Juan basins, and, sinc nc Oligocene formations are present, it appears that by Oligocene time the area had a low relief and well established exterior drainage. At some later date there was regional uplist with more or less profound normal faulting. This started a new cycle of erosion that resulted in extensive degredation, but left no later Cenozoic sediments within the region. It is therefore difficult to date precisely the stages of uplist or to determine how many cycles of erosion are represented. The presence of Eocene beds unconformably overlying truncated folds in the Mesozoic formations indicates that a large amount of the degradation and stripping had been accomplished during the interval between the Laramide uplist and the local beginning of Eocene deposition. On the other hand the Eocene beds manteled an old surface of low relief, hence the present ruggedness of the region has come into being during later Cenozoic time.

The Grand Canyon proper is incised in a part of the area that was most uplifted, though it has since been reduced by erosion to a level 2000 or 3000 feet below the plateaus farther north. The Grand Canyon district is a broad, nearly flat-topped dome about 100 miles across, from which more than 6000 feet of Mesozoic strata have been stripped. Over this dome the strata dip gently, but they are more abruptly bent down at its eastern margin in a pair of great monoclinal flextures. The west side of the dome has broken down along a great normal fault, leaving the Grand Wash Cliffs facing westward toward the Great Basin.

Before the cutting of the Grand Canyon bega, the stripping of this huge dome had reached almost its present stage, and left the high cliffs of the region about as they are now. While these towered above the intervening benches with a relief of a few thousand feet, the region as a whole was much nearer sea level than at present. the final uplift of the region led to a re-organization of the drainage, initiating the present Colorado River system, and starting the Canyon cycle. The date of this uplist can be determined west of the Grand Wash Cliffs where river emerges from its canyon and crosses the Great Basin, flowing over Pliocene beds that are known from their salt and gypsum deposits to have formed in arid basins without exterior drainage. Obviously the Colorado River did not exist, or at least did not have its present course, in Pliocene time. Hence it is believed that the great uplist of the Plateau and the carving of the Canyon are all work of Pleistocene and recent time.

Igneous Record of the Cenozoic

The two major volcanic fields of the plateau region include Mount Trumbull and the San Francisco Mountains. In the Trumbull district, basalt was erupted at two periods. The remnant lavas of the first period now cap mesas of lower Triassic rocks; those of the second, the product of more than 170 vents, rest on Kaibab limestone that forms the surface of the plateau. Associated with them are some 150 low cones that are only slightly affected by erosion. In the San Francisco volcaniz field, evidence of three general periods of eruption have been recognized - basalt flows, eruptions of andesites and rhyolites that built the lofty peaks, and basalt lavas and ash. Here, as at Mount Trumbull, lavas of the first period overlie Triassic beds, and those of the latest period rest on the rock that forms the present surface of the Coconino plateau. Likewise, the San Francisco field included many cinder cones so fresh in appearance as to suggest activity within historic time. Sunset Crater of the Zan Francisco volcanic field is an excellent example of one of these.

In southern New Mexico and southern Arizona there are great seriesof intrusive and extrusive igneous rocks. Although there were some eruptions of lava in late Cretaceous time, it was in the Tertiary that volcanism and intrusion attained the height of their activity. In most parts of the region it isnot possible to assign the supposedly Tertiary igneous rocks to any particular division of Tertiary time, and in some localities there may even be considerable doubt whether certain lavas are Cretaceous or Tertiary. Similar uncertainty exists as regards the age of some of the intrusive masses. Most of those in New Mexico have been regarded by Lingren, Graton, and Gordon as of early Tertiary age, but uncertainty attaches to the age assignment of some of the intrusive masses in Arizona and also in New Mexico.

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