National Park Service
U.S. Department of the Interior

Natural Resource Stewardship and Science

Mojave National Preserve

Paleontological Resource Inventory (Public Version)

Natural Resource Report NPS/MOJA/NRR—2023/2541

ON THE COVER

Colonial coral in the Mississippian Monte Cristo Limestone in Bonanza King Canyon, Mojave National Preserve. Scale bar has 1 cm (0.4 in) squares and 1 mm (0.04 in) tick marks. Photo by Sofia Andeskie (NPS).

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Note: Paleontological resources in National Park Service lands are protected by law. Unauthorized collection of fossils from National Park Service lands is prohibited except under the terms of an approved research and collecting permit. See the text for more information on protecting and preserving these non-renewable resources for the benefit of all.

July 2023

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Natural Resource Stewardship and Science
Fort Collins, Colorado

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Executive Summary

Mojave National Preserve (MOJA) in the Mojave Desert of southern California hosts an extensive geologic record, with units ranging in age from the Paleoproterozoic (2.5 to 1.7 billion years ago) to the Quaternary (present day). MOJA topography is dominated by numerous mountain ranges hosting extensive geological exposures divided by expansive valleys, dunes, and a low elevation dry salt lake. Some geological units are fossil-bearing, both within the preserve and in adjacent lands outside the boundaries of the preserve. The fossils preserved within MOJA span from the Proterozoic Eon (uncertain maximum age of fossiliferous rocks, but at least approximately 550 million years ago) to the Holocene Epoch (beginning 11,700 years ago). Abundant and diverse marine fossils are preserved in units dated from the late Proterozoic through most of the Cambrian, as well as from the Devonian through the early Permian. More recent volcanic tuff and unconsolidated sedimentary deposits in valleys preserve Cenozoic flora and fauna.

Geologic surveys documented paleontological resources within the modern (2023) boundaries of MOJA as early as 1914, but fossils were rarely the focus of detailed study, and no comprehensive inventory was compiled. John Hazzard was the first geologist to devote significant attention to the study of paleontology within MOJA. Throughout the 1930s and 1940s, Hazzard and collaborators identified Paleozoic assemblages within the Kelso and Providence Mountains. Between the 1950s to 1980s, several dissertations and theses described the geology of various areas within MOJA, in which the authors provided limited paleontological descriptions and fossil locality information. Jack Mount conducted extensive paleontological research in the Cambrian sections of the Providence Mountains in the 1970s and 1980s, focusing on olenellid trilobites in the Latham Shale. As early as the 1960s, rockhounds collecting opalite and petrified wood discovered fossilized plant material and vertebrate bones in areas now in south-central MOJA and notified paleontologists at San Bernardino County Museum (SBCM). This resulted in one of the only paleontological excavations in what is now MOJA, with collections of Miocene vertebrate fauna including camelid and early rhino material. More recently, James Hagadorn reported the late-surviving Ediacaran organism *Swartpuntia* in an assemblage from the Wood Canyon Formation of the Kelso Mountains in 2000.

From October 2021 to January 2022, a field inventory was conducted to determine the scope and distribution (both temporal and geospatial) of paleontological resources at MOJA. An additional week of field work was conducted in December 2022. A total of thirteen localities were documented and field-checked throughout the preserve. These localities resulted from field checks of previously reported fossil sites, as well as new discoveries based on literature searches and information provided by MOJA staff. The findings of this report constitute a baseline of paleontology resource data for MOJA, and reflect the current understanding of the scope, significance, and distribution of MOJA’s fossil record. This report provides a foundation for the management and protection of paleontological resources within MOJA and supports future education, interpretation, and research.

Acknowledgments

We would like to thank all the staff and volunteers at Mojave National Preserve who have assisted throughout this inventory, including Nic Anderson, Mike Burchett, Tom Burge, Matt Caire, Sarah De Groot, Danilo Giordano, Wendy Elias, Drew Kaiser, Erin Knight, Dave Nichols, and Sierra Willoughby. We would like to acknowledge Melanie Spoo's assistance as MOJA curator. Past staff at Mojave National Preserve, including Ted Weasma, began Mojave National Preserve collections, which served as the catalyst for this project. Erin Eichenberg and Lauren Parry of Tule Springs Fossil Beds National Monument greatly assisted in providing expertise and materials to begin this inventory. Andrew Fitzgerald at Providence Mountains State Recreation Area provided an invaluable tour of Mitchell Caverns and the belly of the Bird Spring Formation beast. Thank you to Alton Dooley of the Western Science Center for communications and discussions on MOJA paleontological collections. Christine Garcia (California Academy of Sciences), Scott Kottkamp (San Bernardino County Museum), Jeffrey Saunders (University of Arizona Laboratory of Paleontology), Ashley Dineen and Pat Holroyd (University of California Museum of Paleontology), and Lauren English (University of California–Riverside) provided information on their collections. Jack Mount graciously provided information on his investigations. Tim Connors (Intermountain Region) assisted with map preparation. Kathleen Springer (U.S. Geological Survey) provided information on the Jurassic tracksite near MOJA. We also wish to recognize people who shared information with us over the years before this inventory was initiated, including David Burdette (on behalf of MOJA), James Hagadorn (on behalf of the Denver Museum of Nature and Science), Erica Clites and Dave Strauss (on behalf of the University of California Museum of Paleontology), Jessica Miller-Camp (on behalf of the University of California–Riverside), and Robert Reynolds. Thank you also to peer review coordinator Allen Calvert (Mojave Inventory & Monitoring Network), Lauren Parry, Ted Weasma, and Cullen Scheland (Geologic Resources Division) for their insight and reviews on this report.

Dedication

This inventory is dedicated to Dr. Debra Hughson, Chief of Science and Resource Stewardship at Mojave National Preserve. Debra's thoughtful consideration of all natural and cultural resources has set a high standard for resource protection at Mojave National Preserve. Debra's action and choices have provided the opportunity for staff to complete this inventory, enabling the protection of fossil resources in MOJA. Additionally, thanks go out to all the Monera, Protista, Plantae, and Animalia that were fortunate enough to be fossilized and preserved in the rock record present in current-day Mojave National Preserve.

Introduction

Mojave National Preserve (MOJA) in southeastern California protects diverse natural and cultural resources of the Mojave Desert, including wildlife, mountain ranges, and remnants of historic mining activity. This report provides detailed information on the paleontological resources of MOJA, including the history of paleontological work in the lands now within the preserve, geologic units, taxonomic groups, fossil localities, museum collections, research, interpretation, and management and protection. In addition to the main body of text, there are seven appendices: Appendix A, tables of paleontological species arranged by stratigraphy; Appendix B, South Kelso Mountains stratigraphic information; Appendix C, contact information for repositories; Appendix D, glossary; Appendix E, paleontological resource law and policy; Appendix F, paleontological locality data; and Appendix G, a geologic time scale.

Geographic Setting

MOJA was authorized as a unit of the National Park Service (NPS) on October 31, 1994. The national preserve includes the majority of the East Mojave National Scenic Area, a unit previously administered by the Bureau of Land Management (BLM). MOJA encompasses 643,241.91 ha (1,589,485.38 acres), more than 535,400 ha (1,323,000 acres) of which is federally managed. Most of this land is in one large unit, but there is a detached unit encompassing most of Clark Mountain on the north side of Interstate 15.

MOJA is located within a sparsely populated area of southeastern California, in eastern San Bernardino County. The northeastern boundary adjoins the Nevada state boundary. The geography and topography of the preserve are dominated by numerous mountain ranges (Figure 1). MOJA is approximately bisected by the Providence Mountains (south), Mid Hills (center), and New York Mountains (north). East of the New York Mountains are the Castle Mountains, outside of the MOJA boundary within Castle Mountains National Monument (CAMO), established on February 12, 2016. South-southeast of the Castle Mountains is the Piute Range, running north–south on the eastern boundary of MOJA. A series of small ranges are located between the north end of the Providence Mountains and the south end of the Piute Range; from west to east, these are the Woods Mountains, Hackberry Mountain, and Vontrigger Hills. The Blind Hills and Fenner Hills are found along the south border of MOJA. West of the south end of the Providence Mountains are the Granite Mountains. The Kelso Mountains and Marl Mountains are found in west-central MOJA. To their west, but still in MOJA, are the smaller prominences Old Dad Mountain, Cowhole Mountain, and Little Cowhole Mountain. In north-central MOJA, Cima Dome (also part of Cinder Cone Natural Area National Natural Landmark) leads north into the Ivanpah Mountains, which are flanked on the north by the Mineral Hills, on the west by the Striped Mountains, and on the northwest by the Mescal Range. Most of the Mineral Hills and the Mescal Range are outside of MOJA. The northern detached unit of MOJA includes Clark Mountain and the southern half of the Clark Mountain Range. Between the detached unit and the main unit of MOJA is Mohawk Hill. Just south of MOJA from west to east are the Old Dad Mountains (not to be confused with Old Dad Mountain in MOJA), the Marble Mountains, the Clipper Mountains, and the Piute Mountains (not to be confused with the Piute

Range). A segment of Old Spanish National Historic Trail (OLSP) crosses MOJA east–west, and another intersects the far west margin of the preserve.

Several large valleys are present between the mountain ranges. The southern parts of Shadow Valley and Ivanpah Valley are found in north MOJA, west and east of the Ivanpah Mountains respectively. Lanfair Valley occupies much of the northeastern quarter of MOJA, between the New York Mountains, Piute Range, and several smaller mountains on the south. North of the Granite Mountains are the Kelso Dunes, and southwest of the Kelso Mountains is an area called Devils Playground. The only perennial drainage in MOJA is Piute Creek, but a number of periodically wet washes are present, the largest of which is the Mojave River. When it has sufficient flow, this river enters MOJA from the south near its western boundary, flows through the Soda Lake playa, and then exits the preserve into the Silver Lake playa just north of Baker. Bullhead City–Laughlin is about 30 km (20 mi) east of MOJA, and Las Vegas is about 60 km (40 mi) northeast of the nearest part of MOJA. There is a small enclave of land owned by the California Department of Parks of Recreation within MOJA, in the central Providence Mountains. This consists of Providence Mountains State Recreation Area and Mitchell Caverns (which is also a National Natural Landmark). University of California–Riverside also owns land within MOJA, and maintains the Sweeney Granite Mountains Desert Research Center, found on the east slope of the Granite Mountains. In 2016, most of the area bordering MOJA on the south was incorporated into Mojave Trails National Monument, managed by the Bureau of Land Management.

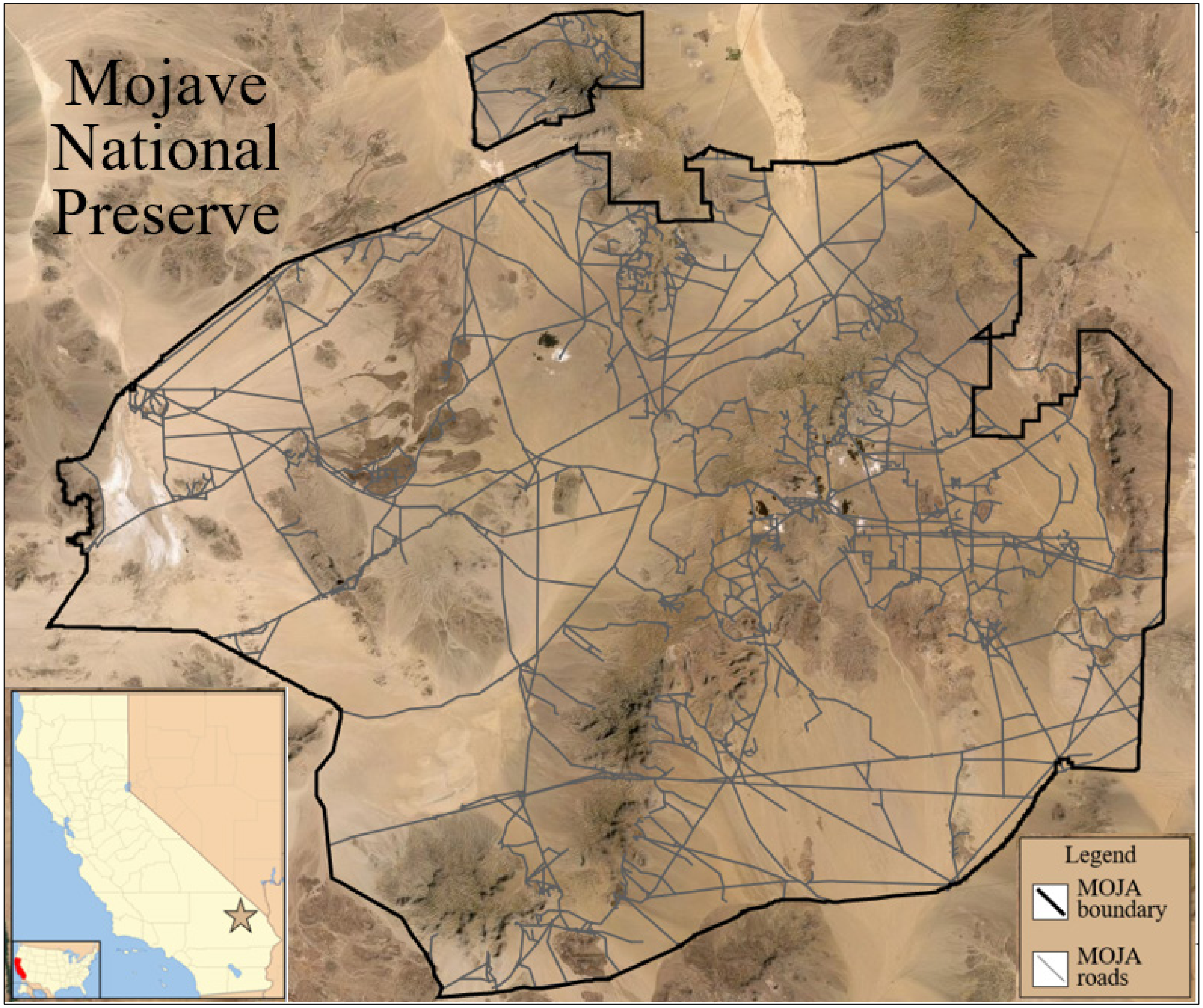

Figure 1. Park map of MOJA (NPS).

Significance of Paleontological Resources at MOJA

Mojave National Preserve has a temporally extensive fossil record, currently known to extend from the late Proterozoic Eon (at least 550 million years ago) to the Holocene Epoch (11,700 years ago to the present). However, there have been few focused studies identifying fossils and fossil-bearing locations within the preserve, resulting in a significant knowledge gap about paleontological resources. It is essential to complete a paleontological inventory to compile baseline paleontological resource information in order to protect, preserve, and inform park management about MOJA fossils.

Purpose and Need

The NPS is required to manage its lands and resources in accordance with federal laws, regulations, management policies, guidelines, and scientific principles. Those authorities and guidance directly applicable to paleontological resources are cited below in Appendix E. Paleontological resource inventories have been developed by the NPS in order to compile information regarding the scope, significance, distribution, and management issues associated with fossil resources present within NPS units. These inventories are intended to increase awareness of fossils on NPS lands and paleontological resource management issues in order to inform management decisions and actions that comply with these laws, directives, and policies. Options for paleontological resource management are locality-specific, and may include surveys, site monitoring, cyclic prospecting, stabilization and reburial, shelter construction, excavation, closure, patrols, and alarm systems or electronic surveillance. Appendix E further details applicable laws and legislation.

Project Objectives

This park-focused paleontological resource inventory project was initiated to provide information to MOJA staff for use in formulating management activities and procedures that would enable compliance with related laws, regulations, policy, and management guidelines. Additionally, this project will facilitate future research, proper curation of specimens, and resource management practices associated with the paleontological resources at MOJA. Methods and tasks addressed in this inventory report include:

- Locating, identifying, and documenting paleontological resource localities through field reconnaissance and perusal of archives, using photography, GPS data, standardized data collection forms, and cave surveyor reports.
- Relocating and assessing historic fossil localities to meet current NPS standards.
- Assessing collections of MOJA fossils maintained within NPS collections and in external repositories.
- Documenting current information on faunal assemblages and paleoecological reconstructions.
- Interviewing preserve staff to gather information on the current status of paleontological resources, aid in formulating plans for management, provide ideas for interpretation, and establish recommendations for future actions and activities involving fossils.
- Conducting a thorough literature review to summarize relevant publications, unpublished geologic records and archives, and outside fossil collections from MOJA.

History of Paleontological Work at MOJA

Fossils have been documented in what is now MOJA since at least the early 20th century but have rarely been the focus of a publication. Instead, they have usually been reported as one facet of a broader investigation. The earliest scientific investigation of fossils from lands of the preserve appears to have been made by USGS geologist Nelson Horatio Darton in the early 1900s. Although some references (e.g., Waggoner and Hagadorn 2005) have erroneously reported that Darton (1907) reported Cambrian fossils in the Providence Mountains (within the MOJA boundary), the fossils in that publication actually came from the Marble Mountains (which he called Iron Mountain), outside the MOJA boundary. As documented in internal USGS communications (T. H. Stanton?, written comm. to N. H. Darton, December 10, 1914), in the fall of 1914, Darton collected two lots from the east slope of the Providence Mountains and ten lots from the west slope. Without more specific provenance, it is not possible to determine whether some or all of the collections actually came from what is now NPS land, but Darton's numerous collections from the west slope suggest that at least some were from MOJA. No geologic context was stated, but the Pennsylvanian or Permian age of the collections indicates that they likely came from the Bird Spring Formation. The fossils included various horn and tabulate corals, brachiopods, crinoids, and fusulinid foraminifera. During the same time frame, Esper Signius Larson of the USGS found Carboniferous-aged fossils (Mississippian or Pennsylvanian) in the Mid Hills–New York Mountains area (Thompson 1920).

Little work was undertaken on MOJA paleontology for much of the next few decades. One notable exception was the work of John Hazzard (Hazzard 1933, 1954; Hazzard and Mason 1936; Thompson and Hazzard 1940, 1946). Hazzard's work first focused on the Cambrian. Hazzard (1933) included three Cambrian assemblages from the Kelso area and Providence Mountains. In 1936, Hazzard and Mason published on the middle Cambrian formations of the Providence Mountains (Hazzard and Mason 1936). This publication provided lithologic observations on middle Cambrian stratigraphy, including the Cadiz Formation, Bonanza King Formation, and Cornfield Springs Formation (referred to in this report as the Nopah Formation). Hazzard and Mason (1936) identified and referenced 25 fossil taxa from the Cadiz Formation and six taxa from the Nopah Formation, but did not specify the exact provenance (for example, the Cadiz Formation fossils incorporate both the Providence and Marble Mountains). Hazzard then collaborated on a study of fusulinid foraminifera from the Bird Spring Formation in the Providence Mountains (Thompson and Hazzard 1940, 1946), which included areas now within MOJA and within the Providence Mountains State Recreation Area. Hazzard (1954) summarized the formations present in the northern Providence Mountains, with paleontological localities and taxonomic lists. It is possible to determine whether his localities are within MOJA or the state land. However, it is not possible to completely reconstruct faunal lists for individual localities from this reference because the faunal lists for each formation are composites. Due to this uncertainty, there is some question about whether specific taxa in certain formations can be attributed to the preserve.

Hewett (1956) published on the geological resources in the Ivanpah Quadrangle. The written report portion discusses Proterozoic to Quaternary geology. Hewett reports Cambrian, Devonian, Mississippian, Pennsylvanian, and Triassic fossils.

Multiple dissertations and theses from the 1950s through the 1980s described the geology of various locations within MOJA (Haskell 1959; Barca 1960; Dobbs 1961; Yelverton 1963; Medall 1964; Balkwill 1965; Law 1969; Dunne 1972; Knaup 1977; Novitsky-Evans 1978; Wilson 1978; Miller 1983). These localities included Devils Playground, the New York Mountains, Lanfair Valley, Old Dad Mountain, the Cowhole Mountains, Clark Mountain, and the Castle Mountains. In these publications, the authors identified fossils but did not provide detailed paleontological descriptions. Few theses focused solely on paleontology, although Law (1969) focused on the Pennsylvanian–Permian conodont succession of the Bird Spring Formation.

As early as the 1960s, rockhounds and amateur fossil collectors would go to areas now in south-central MOJA to collect jasper, opalites, petrified wood, and vertebrate fossils from Miocene deposits (Strong 1966, 1975; Reynolds et al. 1995). In the 1970s and 1980s, researchers from the San Bernardino County Museum established a systematic approach to search for fossil localities. As a result of these studies, a small local fauna of Miocene mammals was found and described (Reynolds et al. 1995; Tedford et al. 2004).

MOJA is paleontologically notable in the NPS for its Cambrian fossils. Unusual Cambrian fossils were first reported from the Providence Mountains in the 1970s. Jack Mount (Mount 1974, 1976, 1980; Briggs and Mount 1982) documented the presence of radiodont arthropods, armored palaeoscolecid worms, and eocrinoids in the Latham Shale. Other researchers have found additional eocrinoids (Wilbur 2005) and the counterpart of Mount's worm specimen (Conway Morris and Peel 2010). Late-surviving soft-bodied organisms have been found in the Wood Canyon Formation in the Kelso area (Hagadorn et al. 2000). Knowledge of the Kelso finds appears to have inspired attempts at unauthorized collecting within MOJA in recent years.

The East Mojave National Scenic Area, managed by the BLM, was created in 1981 by the Desert Plan. Mojave National Preserve, managed by the NPS, was established in 1994 by the California Desert Protection Act from much (but not all) of the scenic area. Another part of the scenic area was protected with the creation of Castle Mountains National Monument (CAMO) in 2016, while other parts are still managed by the BLM, such as the corridor between the main body of MOJA and the Clark Mountain outlier. Beginning in 2001, MOJA geologists have worked on identifying fossil localities, but reports and collections were minimal. Ted Weasma, former geologist at MOJA, completed paleontological surveys and collected seven fossils that are currently stored at MOJA headquarters. These collections contain data on specimen information and localities but are not currently established as part of the permanent museum collections. Additionally, Weasma created archives of publications and field notes of paleontological work throughout MOJA's history.

Paleontological work by external researchers since the establishment of MOJA has primarily relied on older collections, such as Mount's collections (e.g., Gaines and Droser 2002; Webster et al. 2003; Webster 2009). An important exception has been the work published by Stevens and Stone on the Providence Mountains, incorporating new fossil collections. Stevens and Stone (2007) resolving fusulinid biostratigraphy, paleogeographic evolution, and tectonic implications of the Pennsylvanian–early Permian Bird Formation in multiple localities. In the preserve, locations studied include the Cowhole Mountains, Old Dad Mountains, and the Providence Mountains. Stone et al. (2017)

published a geologic map of the Providence Mountains. While some of the land in the map area is owned by the state, the majority is managed by the NPS. Fossils were documented in several of the Cambrian to Triassic sedimentary rock units (Stone et al. 2017).

The NPS Geologic Resources Division coordinated a geologic resources inventory scoping meeting for MOJA in April 2003 (Covington 2003) and produced a digital map of MOJA in 2011 (National Park Service 2011) based largely on Theodore (2007). Santucci et al. (2004) prepared the original paleontological resource inventory and summary for MOJA, and Tweet et al. (2016) prepared a greatly expanded and more detailed version, which has been adapted in part for this inventory report. The NPS has completed a Foundation Document for MOJA (National Park Service 2013).

Summary of 2021–2022 Paleontological Survey

Due to the limited paleontology work at MOJA, little information was available covering the breadth and distribution of paleontological resources with the preserve prior to this survey. No preserve-wide paleontological resource inventory had been established. This inventory involved prospecting and field documentation, compiling data from published sources, reviewing unpublished field notes from past MOJA geologists, reviewing sensitive preserve records and permits, resolving locations of previous collections, and discussions with current and former preserve staff and others to obtain expert first-hand accounts of paleontological resources within the preserve. For this inventory, field inventories were mainly conducted by MOJA Physical Scientist Sofia Andeskie and Scientists in Parks intern Emily Johnson, and other MOJA staff, with guidance from Vincent Santucci, Justin Tweet, and Debra Hughson. Detailed work was focused on the Kelso and Providence Mountains. Johnson conducted an extensive literature search and review as part of this inventory, in addition to a detailed review of all past field notes and scientific permits to identify potential localities. Thirteen localities from the records search were field-checked and documented throughout this survey using GPS, photographs, locality forms, and field notes. MOJA specimens on loan to other institutions and museums were located with the help of Justin Tweet.

A comprehensive taxonomic list of fossil species found within MOJA was developed as part of this project (Appendix A). Contemporary names are subject to changes in taxonomic nomenclature and interpretations over time. Further inventory may add taxa to this list.

It is strongly recommended that future work take place in MOJA to add to the results of this inventory. Due to the extensive size of the preserve, paleontological surveys will take decades to complete. Additionally. further identifications of fossils to genus and species levels are especially needed. Vandalism, theft, and rapid eolian erosion pose risks to MOJA fossil resources. Expanding this inventory in the future will help guard against these risks by better constraining the scarcity of fossil resources and elucidating the need for more site monitoring.

Geology

Geologic History

Like some of the other NPS units in the Mojave Inventory & Monitoring Network (MOJN), such as Death Valley National Park (DEVA), Joshua Tree National Park (JOTR), and Lake Mead National Recreation Area (LAKE), MOJA has an expansive geologic record beginning in the Proterozoic (see Appendix G for a geologic time scale). The oldest rocks in MOJA are more than 1.7 billion years old and represent part of the southwest margin of the North American continent. This area, called the Mojave Province, has metamorphosed sedimentary rocks that may be as old as 2.6 to 2.4 Ga (billion years ago), and recycled minerals as old as 3.42 Ga (Wooden et al. 2012). The oldest rocks at MOJA are igneous and metamorphic rocks that form portions of the ranges. Around 1.71 to 1.69 Ga, a mountain-building event called the Ivanpah Orogeny metamorphosed the existing rocks. More igneous intrusions followed over the next few hundred million years (Miller and Wooden 1993; Strickland et al. 2013). Sedimentary rocks were deposited over the old igneous rocks following a continental rifting event (Corsetti et al. 2002; Kaufman et al. 2007). The oldest sedimentary rocks have proven difficult to interpret due to later deformation.

Sedimentary rocks that are less deformed and easier to interpret begin with the Johnnie Formation, a late Proterozoic unit deposited by approximately 550 Ma (million years ago). The Ediacaran Johnnie Formation is the oldest in a sequence of primarily marine formations that document the latest Proterozoic and most of the Cambrian within MOJA. These shallow marine formations commonly include fossils of invertebrates, illustrating the transition from the earliest multicellular animals to early shelled animals. This area was submerged and exposed multiple times as sea level rose and fell, cyclically shifting from rivers and deltas, and to tidal flats to shallow marine shelves (Foster 2011a; Keller et al. 2012). Ordovician and Silurian strata are not mapped at MOJA, although Ordovician rocks are reported from between the larger unit of MOJA and the Clark Mountain parcel (Cooper and Keller 1995). The next hundred million years of geologic history, spanning the Middle Devonian to early Permian,[1] are well-represented by abundantly fossiliferous marine formations at MOJA. These faunas are more diverse than the Cambrian faunas, and do not include as many enigmatic extinct organisms.

The mass extinction at the Permian–Triassic boundary (252 Ma) greatly altered biological communities worldwide. The marine setting of the Early and Middle Triassic in the MOJA area after this mass extinction contained anoxic and alkaline waters. Reef-like microbial structures spread (Woods 2009). Also, during the Triassic, the tectonics of the southwestern United States changed from a passive margin, where there is little activity, to an active margin, where oceanic crust was subducted beneath continental crust (Dunne 1977; Trent 2004). At this kind of margin, igneous activity is common, and fragments of crust are scraped from the descending oceanic crust and

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[1] Epochs that are formally defined are capitalized (e.g., Late Devonian), where those that aren't are in lower case (e.g., early Permian). "Early" and "Late" relate to age, whereas "Lower" and "Upper" relate to stratigraphic position.

accreted onto the continental margin. The Mesozoic setting for the MOJA region has been compared to the Andes, a modern active margin in South America with ongoing volcanism (Dunne 1977). Compressive events folded and faulted the older rocks of MOJA in several major episodes (Dunne 1977; Brown 1989). Faulting and earthquakes have occurred and occur commonly (Brown 1989); some lake beds appear to have been uplifted 60 m (200 ft) in the past 2.2 million years (Wilshire 1992a). Igneous events occurred during the Triassic (Walker 1987; Brown 1989), Early Jurassic (200–190 Ma), Middle Jurassic (167–162 Ma), Late Jurassic (162–157 Ma and 145 Ma), and much of the Late Cretaceous (about 100–83 Ma; Busby et al. 2002; Theodore 2007).

MOJA is not known to have rocks of Paleogene age (Paleocene–Oligocene). Beginning around the early Miocene, the MOJA area again became volcanically active, evidenced by igneous intrusions and volcanic eruptions. Miocene volcanic activity in MOJA is particularly associated with the Woods Mountain volcanic center, today a caldera 10 km (6 mi) across. This large volcano was active between approximately 18.5 and 17.6 Ma (Mickus and McCurry 1999). Fossils of Miocene mammals have been found in sedimentary rocks deposited between eruptions (Reynolds et al. 1995). In the late Miocene, another volcanic center became active within MOJA. The Cima Volcanic Field of western MOJA includes more than 70 vents. It has been active over two main pulses, 7.6 to 3.0 Ma and 1.0 Ma to approximately the present (Farmer et al. 1995). The most recent eruptions took place between approximately 30,000 and 10,000 years ago (Phillips 2003).

During the Quaternary (2.58 Ma to the present), there was commonly more moisture available in the region than at present, and large pluvial lakes formed. Two lakes formed as termini of the Mojave River: Lake Manix and the more recently formed Lake Mojave. Lake Manix covered 236 km^2 (91 mi^2) at its greatest extent, and its deposits are up to 40 m (130 ft) thick (Jefferson 2003). The lake first appeared approximately 450,000 years ago and expanded and shrank many times until approximately 25,000 years ago, contemporaneous with the Last Glacial Maximum, when it breached at Afton Canyon and the river began flowing farther east, forming Lake Mojave (Reheis et al. 2014). Lake Mojave filled and reached highstands at approximately 18,400 to 16,600 years ago and 13,700 to 11,400 years ago, desiccating between the two highstands (Wells et al. 2003). The plant community surrounding the lakes consisted of juniper, sagebrush, and creosote brush, with woodlands at higher elevations (Seiple 1994; Jefferson 2003). The remnants of Lake Mojave today are the playa lakes Silver Lake, just north of MOJA, and Soda Lake, contained in the westernmost part of MOJA (Reynolds et al. 2003). People have been present in and around MOJA since perhaps the end of the Pleistocene (Knell 2014).

Geologic Formations

The GRI map and its source map (Theodore 2007) only briefly consider the Proterozoic and Paleozoic sedimentary rocks that are of interest for this report, so the descriptions have been supplemented by several other sources. In particular, Hazzard and Mason (1936) published on the Cambrian rocks of the area, Hazzard (1954) and Stone et al. (2017) published on the Providence Mountains, Hewett (1956) mapped the Ivanpah 30′ x 60′ Quadrangle, Stewart (1970) and Bahde et al. (1997) published on the Proterozoic and lower Cambrian rocks, and several theses and dissertations document specific mountain ranges in this region (Evans 1958; Haskell 1959; Barca

1960; Dobbs 1961; Yelverton 1963; Balkwill 1965; Dunne 1972). With some corrections for obsolete terminology (explained below in the relevant sections), the stratigraphy that will be used in this report is as follows: Paleoproterozoic intrusive igneous and metamorphic rocks; Mesoproterozoic intrusive igneous rocks; Neoproterozoic sedimentary rocks of uncertain correlation; Johnnie Formation (Neoproterozoic); Stirling Quartzite (Neoproterozoic); Wood Canyon Formation (Neoproterozoic–lower Cambrian); Zabriskie Quartzite (lower Cambrian); Latham Shale, Chambless Limestone, and Cadiz Formation (lower–middle Cambrian; this interval also known as the Carrara Formation); Bonanza King Formation (middle–upper Cambrian); Nopah Formation (upper Cambrian); Sultan Limestone (Middle–Upper Devonian); Monte Cristo Limestone (Lower–Middle Mississippian); Bird Spring Formation (Pennsylvanian–lower Permian); Moenkopi Formation (Lower Triassic); Mesozoic intrusive, volcanic, and sedimentary rocks, some metamorphosed (Triassic–Middle Jurassic); Aztec Sandstone (Middle Jurassic); Mesozoic post-Aztec volcanic and intrusive rocks (Middle Jurassic–Upper Cretaceous); Neogene–Quaternary sedimentary rocks and deposits, usually units of limited distribution (lower Miocene–Holocene); and Neogene–Quaternary volcanics (lower Miocene–upper Pleistocene). Most of the sedimentary rocks and deposits are fossiliferous within MOJA, and the fossil record of the preserve is temporally and taxonomically diverse (Figure 2; Table 1).

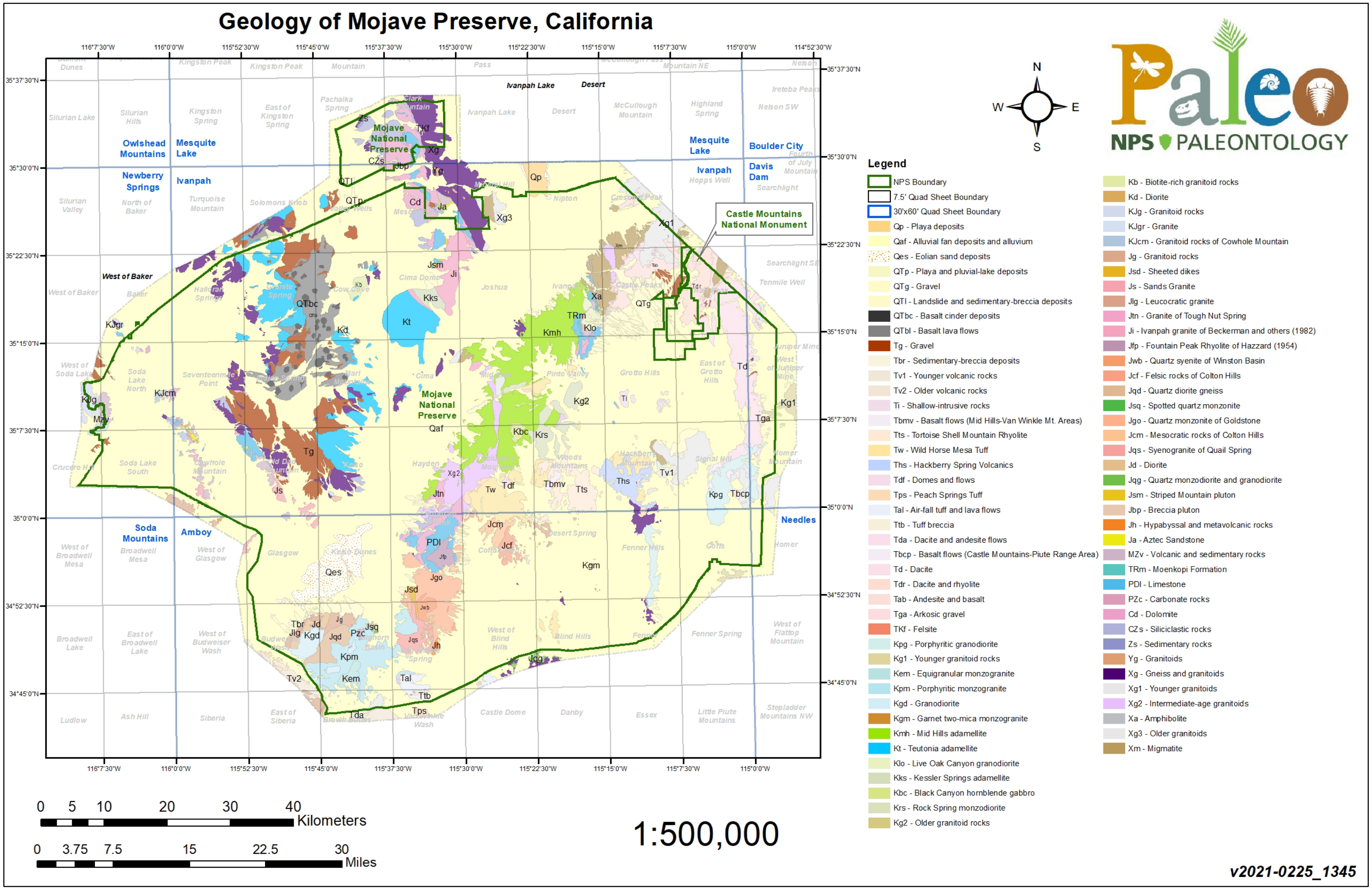

Figure 2. Geologic map of MOJA, derived from digital geologic map data available at the following URL: https://irma.nps.gov/DataStore/Reference/Profile/2174439.

Table 1. Summary of MOJA stratigraphy, fossils, and depositional settings in descending order of age, from youngest to oldest. Details and references can be found in the text and in Tweet et al. (2016).

Formation	**Age**	**Fossils Within MOJA**	**Depositional Environment**
Quaternary sediments	Pleistocene–Holocene	Packrat middens including conifer and angiosperm fossils, faunal remains, and packrat droppings (late Pleistocene–Holocene); freshwater bivalves (middle–late Pleistocene); fishes, rodents, mammoths, horses, and camels (late Pleistocene); bivalves and gastropods (undetermined)	Fluvial, alluvial, eolian, lacustrine, volcanic, and landslides
Late Cenozoic volcanics	late Miocene–Pleistocene	None to date; fossils are unlikely but possible	Terrestrial volcanic eruptions
Pre-Quaternary sedimentary rocks	Miocene–Pliocene (fossils primarily early Miocene, 18.5–17.8 Ma)	Logs and wood of *Sequoia langsdorfii*, other conifer wood and needles, reed- and grass-like fossils, ostracodes, and teeth and bones of rodents, pikas, canids, felids, rhinocerotids, camelids, and small deer-like artiodactyls, and flamingo tracks (early Miocene); petrified wood, unspecified vertebrate fossils, and possibly "algal" filaments	Lacustrine, fluvial, alluvial, and other terrestrial settings
Miocene igneous rocks	Miocene	None to date; the volcanic rocks have a small chance of including fossils	Volcanic eruptions and igneous rocks that solidified at depth
Cretaceous igneous rocks	Late Cretaceous	None to date; the volcanic rocks have a small chance of including fossils	Volcanic eruptions and igneous rocks that solidified at depth
Jurassic intrusive rocks	Early, Middle, and Late Jurassic	Nonfossiliferous (intrusive igneous rocks)	Not applicable (igneous rocks that solidified at depth)
Aztec Sandstone	Middle Jurassic	Burrows, possible fecal pellets, and reworked Paleozoic brachiopods and fusulinid foraminifera	Sand dunes and interdunal areas
Mesozoic volcanic and associated sedimentary rocks	Various ages, Triassic–Cretaceous	None to date; fossils are unlikely but possible	Terrestrial volcanic eruptions
Moenkopi Formation	Early Triassic	Shallow marine fossils such as brachiopods, bivalves, ammonoids, gastropods, microbial structures, and invertebrate trace fossils are likely present	Shallow marine to coastal terrestrial
Bird Spring Formation	Pennsylvanian–early Permian	The sponge *Chaetetes*, tabulate and rugose corals, bryozoans, brachiopods, bivalves, ammonoids, nautiloids, gastropods, annelids, trilobites, ostracodes, crinoids, echinoids, holothurians, conodonts, fishes, and fusulinid foraminifera; probably also rostroconchs, echinoids, and stromatolites	Marine shelf

Table 1 (continued). Summary of MOJA stratigraphy, fossils, and depositional settings in descending order of age, from youngest to oldest. Details and references can be found in the text and in Tweet et al. (2016).

Formation	**Age**	**Fossils Within MOJA**	**Depositional Environment**
Monte Cristo Limestone	Early–Middle Mississippian	Tabulate and rugose corals, bryozoans, brachiopods, bivalves, cephalopods, gastropods, crinoids, and possibly echinoids	Shallow marine
Sultan Limestone	Middle–Late Devonian	Stromatoporoid sponges, tabulate and rugose corals, brachiopods, gastropods, crinoids, and conodonts	Shallow marine shelf, intertidal to subtidal
Nopah Formation	late Cambrian	Sponges, brachiopods, trilobites, echinoderms, and trace fossils	Marine, lagoonal, and microbial bank
Bonanza King Formation	middle–late Cambrian	Trilobites, fossil debris, and possible stromatolites	Shallow marine shelf
Cadiz Formation	early–middle Cambrian	Brachiopods, hyoliths, trilobites, and trace fossils	Marine shelf, subtidal to supratidal
Chambless Limestone	early Cambrian	Brachiopods, hyoliths, gastropods, trilobites, eocrinoids, and microbial structures ("*Girvanella*", oncoids)	Marine shelf, subtidal to supratidal
Latham Shale	early Cambrian	*Sphenothallus*, brachiopods, hyoliths, an undescribed palaeoscolecid worm, radiodonts, trilobites, eocrinoids, invertebrate burrows and fecal trails, cyanobacteria (*Morania*), and an enigmatic wrinkled patch	Marine shelf, subtidal to supratidal
Zabriskie Quartzite	early Cambrian	Invertebrate trace fossils	Shallow marine to fluvial over time
Wood Canyon Formation	Neoproterozoic–early Cambrian	An Ediacaran-type soft-bodied organism, archaeocyathid sponges, trilobites, and vertical (*Skolithos*) and horizontal invertebrate burrows and traces	Fluvial, deltaic, tidal flat, and marine
Stirling Quartzite	Neoproterozoic	None to date; fossils are uncommon in this formation	Fluvial to marine shoreface lower, tidal flat to subtidal upper
Johnnie Formation	Neoproterozoic	Microbial laminations	Marine shelf
Pre-Johnnie Formation sedimentary rocks	Neoproterozoic?	Stromatolite and oncoids	Marine
Intrusive igneous rocks	Mesoproterozoic	Nonfossiliferous (intrusive igneous rocks)	Not applicable (igneous rocks that solidified at depth)

Table 1 (continued). Summary of MOJA stratigraphy, fossils, and depositional settings in descending order of age, from youngest to oldest. Details and references can be found in the text and in Tweet et al. (2016).

Formation	Age	Fossils Within MOJA	Depositional Environment
Intrusive igneous and metamorphic rocks	Paleoproterozoic	Nonfossiliferous (high-grade metamorphic rocks and intrusive igneous rocks)	Not applicable (strongly metamorphosed igneous and sedimentary rocks, and igneous rocks that solidified at depth)

Intrusive igneous and metamorphic rocks (Paleoproterozoic)

Description: Paleoproterozoic rocks include metamorphic and intrusive igneous rocks of diverse compositions (Wooden and Miller 1990).

Fossils found within MOJA: Nonfossiliferous (intrusive igneous and high-grade metamorphic rocks); included for completeness.

Fossils found outside of MOJA: Nonfossiliferous.

Intrusive igneous rocks (Mesoproterozoic)

Description: Intrusive rocks of Mesoproterozoic age found in the preserve include diverse compositions (DeWitt et al. 1987; Wooden and Miller 1990).

Fossils found within MOJA: Nonfossiliferous (intrusive igneous rocks); included for completeness.

Fossils found outside of MOJA: Nonfossiliferous.

Pre-Johnnie Formation sedimentary rocks (Neoproterozoic?)

Description: The stratigraphic nomenclature of the oldest sedimentary rocks of MOJA is not formally settled. Theodore (2007) suggested that some of the Proterozoic sedimentary rocks in the MOJA area were correlative with the Kingston Peak Formation and Noonday Dolomite, the units immediately beneath the Johnnie Formation elsewhere, but Stewart (1970), Bahde et al. (1997), and Fedo and Cooper (2001) did not report any Neoproterozoic sedimentary rocks beneath the Johnnie Formation in MOJA and adjoining areas. Hewett (1956), which documents the geology of the Ivanpah 30′ x 60′ Quadrangle, included both of these formations, but did not map them in MOJA. The Kingston Peak Formation of the MOJA area is between 300 and 600 m (1,000 and 2,000 ft) thick and is broadly divisible into thirds: the lower and upper thirds are composed of shaly sandstone with zones of pebbles, and the middle third is composed of coarse quartzite and dolomite conglomerate. The overlying Noonday Dolomite of the MOJA area can be more than 600 m (2,000 ft) thick but thins over a short distance to the southeast. It is almost entirely composed of pure pale-cream-colored dolomite (Hewett 1956).

Knaup (1977) tentatively correlated some rocks in the Old Dad Mountain 15′ Quadrangle (in MOJA) with the Crystal Spring Formation and introduced an additional informal unit beneath it, the “Willow Wash arkose”. Knaup’s Willow Wash arkose is a 393 m (1,290 ft)-thick sequence of arkose and quartz-rich sandstone, interpreted as turbidite deposits on a deep-sea submarine fan. It has been partly metamorphosed, probably before deposition of the overlying rocks that Knaup correlated to the Crystal Spring Formation. These overlying rocks form a 128 m (420 ft)-thick sequence of arkose, siltstone, and dolomite. The contact between the two is an angular unconformity. The Crystal Spring sequence begins with a basal conglomerate, followed by arkose, then alternating dolomite and siltstone, then interbedded sandstone and siltstone. Some of the dolomite includes stromatolite-bearing intervals. This formation is interpreted as a southern shelf facies (Knaup 1977). A year later, another thesis (Wilson 1978) appears to have renamed Knaup’s “Crystal Spring Formation” interval the “Seventeenmile Point Formation”. Some of Knaup’s and Wilson’s work is summarized in an abstract (Osborne et al. 1978), but otherwise neither of these informal units has attracted comment.

The three formally described pre-Johnnie Formation units attributed to the MOJA area, the Crystal Spring Formation, Kingston Peak Formation, and Noonday Dolomite, represent several hundred million years of deposition. The Crystal Spring Formation was deposited between 1,320 and 1,080 Ma (Mahon et al. 2014). It is intruded by diabase sills, two of which have been dated to 1,087 ± 3 Ma and 1,069 ± 3 Ma using uranium-lead baddeleyite dating (Heaman and Grotzinger 1992). If Knaup (1977) is correct in its correlations, the “Willow Wash arkose” would be older than the Crystal Spring Formation. The Kingston Peak Formation was primarily deposited between about 710 and 635 Ma, although the oldest rocks may be as old as 740 Ma (Mahon et al. 2014). Deposition of the Noonday Dolomite is thought to have occurred approximately 635 to 632 Ma (Petterson et al. 2011). These formations are marine units representing a variety of settings. The Kingston Peak Formation represents marine deposition during two glacial episodes. The older episode, the Sturtian glaciation, occurred approximately 715 to 670 Ma, and the more recent episode, the Marinoan glaciation, occurred about 650 to 635 Ma (Mahon et al. 2014). The Noonday Dolomite is a “cap carbonate”, a type of carbonate rock that forms at the end of a glacial interval (Petterson et al. 2011). It was deposited on a shallow marine platform blanketed by microbial mats (Wright et al. 1978).

Fossils found within MOJA: The rocks correlated to the Crystal Spring Formation by Knaup (1977) and named the Seventeenmile Point Formation by Wilson (1978) include possible microbial laminations in the lower interval, a middle interval composed of stromatolitic dolomite, and oncoids in the upper interval (Wilson 1978).

Fossils found outside of MOJA: In general, stromatolites and similar microbial structures (e.g., oncoids and thrombolites) are the major types of fossils apparent to the naked eye in the formations cited as possibly being present in MOJA. The Crystal Spring Formation outside of MOJA has stromatolites (Pierce and Cloud 1979). The Kingston Peak Formation outside of MOJA has yielded microfossils (Horodyski and Mankiewicz 1990), including vase-shaped microfossils and various filaments and coccoid bodies (Pierce and Awramik 2010), oncoids, and stromatolites (Corsetti et al. 2003). Fossils in the Noonday Dolomite are apparently limited to stromatolites, but the stromatolites of the formation can form enormous mounds (Cloud et al. 1974; Wright et al. 1978; Petterson et al.

2011), with vertical relief up to 200 m (660 ft) (Wright et al. 1978). Vertical tubes on the order of 1 cm (0.4 in) in diameter and 1 m (3 ft) long, known as "Noonday tubes", have sometimes been interpreted as burrows, but appear instead to be features that formed between stromatolites as they grew (Marenco et al. 2002; Corsetti and Grotzinger 2005).

Johnnie Formation (Neoproterozoic)

Description: The Johnnie Formation in MOJA has sometimes been included in the Prospect Mountain Quartzite, along with the overlying Stirling Quartzite and Wood Canyon Formation (Stewart 1970). In the Providence Mountains, the Johnnie Formation is about 35 to 40 m (110 to 130 m) thick. The basal 5 m (16 ft) is composed of olive brown silty to pebbly quartzite, fining upwards to a greenish gray siltstone, interpreted as fluvial to shallow marine deposits. This is followed by 16 to 18 m (52 to 59 ft) of carbonates including microbial laminations, representing peritidal deposition and storm events. The upper part of the formation is composed of 13 to 15 m (43 to 49 ft) beds of banded dark green to gray siltstone and quartzite with some carbonate rocks, deposited beneath tidal influence but above storm wave base. The section in the Kelso Mountains is thicker and finer grained (Bahde et al. 1997). The Johnnie Formation exposed within MOJA is not the entire sequence, because some of the lower portion is thought to be absent. The entire formation represents two transgression-regression cycles (Bahde et al. 1997). Deposition occurred approximately 580 to 550 Ma (Bergmann et al. 2011). The North American continent had recently rifted from another landmass outboard of the MOJA area, leading to a passive margin (Kaufman et al. 2007).

Fossils found within MOJA: Microbial laminations are present in the Providence Mountains (Traub and Cooper 1993; Bahde et al. 1997).

Fossils found outside of MOJA: Fossils that have been reported from the Johnnie Formation elsewhere include wrinkle structures that may be microbial in origin (Hagadorn and Bottjer 1999), filaments in stromatolites (Pierce and Cloud 1979), and stromatolites (Trower and Grotzinger 2010; Bergmann et al. 2011), and possible coprolites (Waggoner 2001). Some of the stromatolites are reworked clasts, at least some apparently from a now-lost Johnnie Formation bed that eroded during a hiatus in deposition of the formation (Trower and Grotzinger 2010).

Stirling Quartzite (Neoproterozoic)

Description: The Stirling Quartzite is more resistant to erosion than the underlying Johnnie Formation and the overlying Wood Canyon Formation (Stewart 1970). Stewart (1970) correlated his A and C members with rocks in the Providence Mountains, along with an overlying undivided unit. Bahde et al. (1997) described these units as the lower, middle, and upper members of the Stirling Quartzite in the Kelso and Providence Mountains. The lower member is composed of about 55 m (180 ft) of quartzite divided into two intervals, the upper being coarser and capped by a thin conglomerate. This conglomerate member is interpreted as having been deposited in distal fluvial to upper marine shoreface settings. The overlying middle member is about 45 m (150 ft) of dark gray siltstone in the Kelso Mountains and 30 m (100 ft) of quartzitic siltstone in the Providence Mountains, deposited in tidal flat to shallow subtidal settings. No upper member is recognized in the Providence Mountains, but in the Kelso Mountains, this unit grades into an upper member about 12 m (39 ft) thick (Bahde et al. 1997); note, though, that the presence of an upper member in the Kelso

Mountains seems to be incompatible with their statements regarding a burrowed siltstone bed (see below). Stone et al. (2017), who did not attempt to divide the Stirling Quartzite from the Wood Canyon Formation, recognized the Stirling Quartzite of the Providence Mountains as primarily thick-bedded to massive light gray quartzite with a middle interval of darker gray finer quartzite and siltstone. Issues with the local stratigraphic definition of the Stirling Quartzite may be connected to difficulties locating the contact with the Wood Canyon Formation, which is reportedly inconspicuous (Stewart 1970; Stone et al. 2017). Deposition of the formation occurred during a marine transgression-regression cycle (Bahde et al. 1997), presumably shortly before the Cambrian. The upper contact with the Wood Canyon Formation is disconformable (Keller et al. 2012).

Fossils found within MOJA: There is one reference to possible fossils in the Stirling Quartzite within MOJA reported by Barretta et al. (1994); a thin siltstone in the middle part of the formation at the Providence Mountains has burrows, marking the oldest evidence of metazoans in the area. However, this bed, which is also present in the Kelso Mountains, has since been placed in the overlying Wood Canyon Formation (Bahde et al. 1997). The authors' intention is clearly to place the bed in the Wood Canyon Formation, which is followed here. Therefore, the Stirling Quartzite is not currently known to be fossiliferous in MOJA.

Fossils found outside of MOJA: Few fossils have been reported from the Stirling Quartzite from other areas. They include wrinkle structures that may be microbial in origin (Hagadorn and Bottjer 1999), sparse Ediacaran-like fossils (Hagadorn and Waggoner 1998), conical fossils attributed to the enigmatic cloudiniids (Corsetti and Hagadorn 2000; Hagadorn and Waggoner 2000; Hagadorn et al. 2000), and invertebrate trace fossils like *Planolites* (Hagadorn and Waggoner 2000).

Wood Canyon Formation (Neoproterozoic–lower Cambrian)

Description: Stewart (1970) and Bahde et al. (1997) provided detailed descriptions of the Wood Canyon Formation in MOJA. The latter authors transferred some of Stewart's underlying Stirling Quartzite to the Wood Canyon Formation. Per their descriptions, the Wood Canyon Formation of MOJA consists of the middle and upper members, including a unique "lower middle member" which incorporates rocks formerly assigned to the upper Stirling Quartzite. The "lower middle member" is composed of a basal conglomerate overlain by a thin burrowed siltstone interval, followed by about 35 m (110 ft) of siltstone and interbedded quartzite, and then an interval of coarser quartzite and interbedded siltstone. This unit is interpreted as a combination of shallow marine, deltaic, and fluvial deposition. The Precambrian–Cambrian boundary (approximately 539 Ma) occurs in the lower Wood Canyon Formation (Keller et al. 2012).

The "classic middle member" above is composed of about 140 m (460 ft) of coarse quartzite and interbedded siltstone, with the top of the member marked by a "piperock" of vertical burrows (*Skolithos*) (Stewart 1970; Bahde et al. 1997). This unit is interpreted as representing a transition from fluvial to deltaic to shallow marine deposition. Lying conformably above the middle member is the upper member, composed of about 45 m (150 ft) of mudstone, siltstone, and burrowed quartzite, with more mud in the Kelso Mountains than the Providence Mountains. This member is interpreted as a storm-influenced marine shelf shallowing over time to a tidal flat (Bahde et al. 1997). The upper contact with the Zabriskie Quartzite is conformable and gradational (Dunne 1972).

MOJA staff completed a detailed measured section of the middle and upper members of the Wood Canyon Formation in the Kelso Mountains in 2022. 1.5 m (4.9 ft) of the middle member is exposed and is composed of yellow to orangish-brown sandstone. Sedimentary characteristics include well-sorted, medium to coarse sized sand grains with coarse sand and pebbles at the base of the outcrop. There is faint cross-bedding. No fossils were observed. The middle member has a sharp contact with the overlying upper member of the Wood Canyon Formation.

The upper member is approximately 20 m (66 ft) thick and composed of interbedded mudstone and sandstone (Figure 3). The fine-grained sandstone is light gray to dark gray in color with a red iron oxide coating. The mudstone is dark brown in color. Both the sandstone and mudstone are well-sorted. Sandstone beds are 10–25 cm (4–10 in) thick. Mudstone beds are 1–7 cm (0.4–3 in) thick. Mudstone and sandstone beds are cyclic and there are sharp contacts between sandstone and mudstone beds. Some sandstone beds have planar laminations. Observed fossils include vertical burrows ~1 cm (0.4 in) in diameter and ~2 cm (0.8 in) long. Diagenetic features include red iron coating on weathered surfaces of dark gray sandstone and in fractures and white, powdery, ~1 cm (0.4 in) diameter, blob-shaped coatings on certain beds.

Figure 3. Erin Eichenberg (left), Lauren Parry (crouched right of Erin), and Emily Johnson (left-center) at a strongly banded outcrop of the upper Wood Canyon Formation in the Kelso Mountains (NPS/JUSTIN TWEET).

<u>Fossils found within MOJA</u>: The Wood Canyon Formation is paleontologically notable because it spans the Precambrian–Cambrian boundary, preserving fossils from the early radiation of animals with hard parts. There are several reports of fossils in the Wood Canyon Formation of MOJA. Stewart (1970) reported the presence of *Skolithos* ichnofossils burrows in the upper member and

similar structures in the middle member in the Providence Mountains. Bahde et al. (1997) found invertebrate burrows and other traces to be common features of the formation in the Kelso and Providence Mountains, including: a siltstone interval low in the "lower middle member" with horizontal burrows such as *Treptichnus* (formerly *Phycodes*) *pedum*, the oldest metazoan fossils in the area; a *Skolithos* "piperock" near the top of the middle member; and general burrowing throughout the quartzite of the upper member in the Providence Mountains. There is some inconsistency about the placement of the burrowed siltstone bed versus the underlying Stirling Quartzite, but it is accepted as being in the Wood Canyon Formation here; see the Stirling Quartzite section for more discussion. Most notably, Hagadorn et al. (2000) published on a site in MOJA that has produced fossils of soft-bodied enigmatic "Ediacaran" organisms, among others. This site has yielded specimens of the late-surviving Ediacaran organism cf. *Swartpuntia* sp., archaeocyathid sponges, trilobites, and several types of invertebrate traces. Invertebrate traces are found both near the base and in the upper part of the Wood Canyon Formation here, while body fossils have only been found in the upper part of the formation (Hagadorn et al. 2000). Fedo and Cooper (2001) found trace fossils to be present in the lower part of the formation in the Kelso and Providence Mountains and included a photo of a trace fossil (*Taphrhelminthopsis*) in situ in the Kelso Mountains.

Fossils found outside of MOJA: Fossils attributed to the Wood Canyon Formation over its entire depositional area, not just MOJA, include: wrinkle structures that may be microbial in origin (Hagadorn and Bottjer 1999); cyanobacteria (*Epiphyton* and *Renalcis*) (Signor and Savarese 1988); Ediacaran forms such as *Ernietta* and *Swartpuntia* (Corsetti and Hagadorn 2000; Hagadorn and Waggoner 2000; Hagadorn et al. 2000); reef-building archaeocyathid sponge (Signor 1994; Corsetti and Hagadorn 2000; Hagadorn et al. 2000); brachiopod (Diehl 1974); hyolith (Signor 1994; Corsetti and Hagadorn 2000); trilobites (Mount 1976); helicoplacoids (Durham 1993); various enigmatic small invertebrates, such as cloudiniids (Hagadorn and Fedo 2000), *Volborthella* (Signor 1994; Hagadorn and Waggoner 2002), *Hyolithellus* (Signor and Savarese 1988), and other nebulous "small shelly fossils" (McMenamin et al. 2013); and diverse invertebrate burrows and trails (Klein 1975; Signor 1994; Corsetti and Hagadorn 2000; Hagadorn and Waggoner 2000; Hagadorn et al. 2000; Jensen et al. 2002). The Wood Canyon Formation has distinct assemblages at different levels. The Ediacaran forms *Ernietta* and *Swartpuntia*, the enigmatic cloudiniids, and certain invertebrate trace fossils are common near the base of the Proterozoic section, while archaeocyathids, hyoliths, trilobites, and different trace fossils are found higher up (Corsetti and Hagadorn 2000).

Zabriskie Quartzite (lower Cambrian)

Description: The Zabriskie Quartzite of MOJA is composed primarily of medium to coarse yellowish to pinkish gray cliff-forming quartzite (Stewart 1970). It is about 21 m (70 ft) thick in the Providence Mountains (Stewart 1970) and Kelso Mountains (Dunne 1972). The Zabriskie Quartzite has sometimes been lumped with the underlying Wood Canyon Formation in the Prospect Mountain Quartzite, or identified with the Tapeats Sandstone, a formation better known to the west on the Colorado Plateau (Mount 1976). The depositional environment is interpreted to have transitioned from inner shelf marine to shoreface marine to fluvial braid plains over time (Keller et al. 2012). The upper contact with the Carrara Formation/Latham Shale is disconformable (Bahde et al. 1997; Keller et al. 2012). The Zabriskie Quartzite dates to the early Cambrian based on the ages of underlying and overlying rocks.

MOJA staff completed detailed descriptions of the Zabriskie Quartzite in the Kelso Mountains in MOJA in 2022 (Figure 4). This formation is 20 m (66 ft) thick and composed of white to yellow sandstone. The sandstone beds are well-sorted and composed of fine-grained sand. Most units are massive. Some units have faint laminations. No fossils were observed. Diagenetic features include red coatings in small (1–2 mm [0.04–0.08 in] wide) fractures.

Figure 4. An outcrop of the Zabriskie Quartzite in the Kelso Mountains (NPS/SOFIA ANDESKIE).

<u>Fossils found within MOJA</u>: The Zabriskie Quartzite is fossiliferous within MOJA, having examples of trace fossils. Dunne (1972) reported abundant vertical tubes (perhaps *Skolithos*) in horizons in the upper half of the formation in the Devils Playground. Bedford (2003) also reported *Skolithos*, in the

nearby Kelso 7.5′ Quadrangle. Bahde et al. (1997) reported unspecified trace fossils in the Zabriskie Quartzite of the Providence Mountains, and Fedo and Cooper (2001) reported unspecified trace fossils at both the Kelso and Providence Mountains.

<u>Fossils found outside of MOJA</u>: Considering the Zabriskie Quartzite over its entire depositional area, including areas outside of MOJA, trace fossils are the main fossils known (Barnes and Klein 1975; Prave 1992; Foster 2011a). Mount (1980) also reported trilobites from unspecified locations.

Latham Shale (lower Cambrian)

<u>Description</u>: The lower to middle Cambrian rocks at MOJA have been known under three major naming systems in the literature. One system divides them, in ascending order, into the Latham Shale (or Kelso Shale in the oldest works), Chambless Limestone, and Cadiz Formation (e.g., Hazzard 1938, 1954; Stewart 1970; Palmer and Halley 1979; Stone et al. 1983; Gaines and Droser 2002; Keller et al. 2012). Another system groups these three units as the Carrara Formation (e.g., Dunne 1972, 1977; Brown 1989; Theodore 2007). Finally, a third system identifies this interval as the Bright Angel Shale (e.g., Hewett 1956; Haskell 1959; Dobbs 1961; Burchfiel and Davis 1977). Sometimes the Pioche Shale is used, especially west of the Mesquite fault that runs through MOJA (Hewett 1956; Yelverton 1963; Evans 1971). The Latham–Chambless–Cadiz system will be used here, on the basis that three shorter, more focused sections are easier to follow than one long section. The Latham Shale is thought to be equivalent to the lowest three members of the Carrara Formation, in ascending order the Eagle Mountain Shale, Thimble Limestone, and Echo Shale Members (Palmer and Halley 1979). The Carrara Formation, present to the north and west of MOJA in DEVA, is typically a mix of shale and limestone, but toward the south carbonate deposition is greatly reduced, and the interval can be divided into the Latham–Chambless–Cadiz system (Stewart 1970; Keller et al. 2012).

In the Providence Mountains, the Latham Shale consists of about 17–23 m (55–75 ft) of fossiliferous greenish gray shale with thin sandy limestone layers (Hazzard 1954). This unit and the overlying Chambless and Cadiz Formations are interpreted to have been deposited on a marine shelf, from subtidal to supratidal depths (Foster 2011a). Oxygenation levels fluctuated in the bottom waters, affecting the activities of bottom-dwelling bioturbators. Storm deposits are recognized by the presence of shell accumulations (Gaines and Droser 2002). Based on biostratigraphy, the Latham Shale was deposited in the early Cambrian (Palmer and Halley 1979). The Latham Shale type section is within MOJA (Henderson et al. 2021).

MOJA staff completed detailed descriptions of the Latham Shale in the Kelso Mountains in MOJA in 2022 (Figure 5). The Latham Shale is 35 m (115 ft) thick and composed of mudstone. The mudstone is dark gray, brown, and greenish gray in color. The mudstone contains laminations, as well as flute and scour marks. Fossils are found in the upper section of the Latham Shale, which is composed of dark gray and fissile rocks. Fossils include brachiopods, trilobites, and soft-bodied organisms.

Figure 5. An outcrop of the Latham Shale in the Kelso Mountains (NPS/EMILY JOHNSON).

Fossils found within MOJA: The Latham Shale is fossiliferous within MOJA. Among the fossils found in MOJA are cyanobacteria, a possible cnidarian, brachiopods, hyoliths, an undescribed worm, radiodont arthropods, trilobites, eocrinoids, enigmatic wrinkled patches, and invertebrate burrows and fecal trails (Figure 6). Mount (1976, 1980) included photographs of specimens from the Latham Shale of MOJA, including University of California–Riverside (UCR) 7002/1, part of a radiodont, and UCR 7003/1, an unnamed worm. The radiodont specimen was later figured and described in Briggs and Mount (1982) as *Anomalocaris* sp., along with a specimen collected for the University of California Museum of Paleontology (UCMP; Berkeley, California), UCMP 37470. It was also figured in Gaines and Droser (2002). Collection records from University of California–Riverside (UCR) regarding UCR 7002 show that not only was UCR 7002/1 (*Anomalocaris* sp.) collected there, but also UCR 7002/4, trilobite *Olenellus clarki*, and UCR 7002/6, trilobite *Olenellus mohavensis*. These two trilobites were illustrated in Lieberman (1999). Pates et al. (2021) reassigned UCR 7002/1 to the related radiodont *Ramskoeldia consimilis*?. The worm was later figured in Conway Morris and Peel (2010), who had been part of a party to relocate the original site in the hope of finding more specimens. The only fossil located was the counterpart of the original worm specimen, now also at UCR. It represents a palaeoscolecid, a type of extinct armored non-annelid worm (Conway Morris and Peel 2010). Liang et al. (2020, 2022) illustrated soft-tissue preservation in brachiopod specimens from UCR 7002, one of which had what appears to be an attached *Sphenothallus* (a possible cnidarian, related to corals). In a dissertation, Wilbur (2005) described a new species of eocrinoid, "*Gogia fowleri*", from near the top of the formation in MOJA. Because Wilbur (2005) is a non-peer reviewed dissertation, the name is considered informal. The proposed type specimens are at the Texas Memorial Museum (University of Texas at Austin, Austin, Texas) as UT TMM 2047TX1a and 1b (Wilbur 2005). To date, this species has not been formally described.

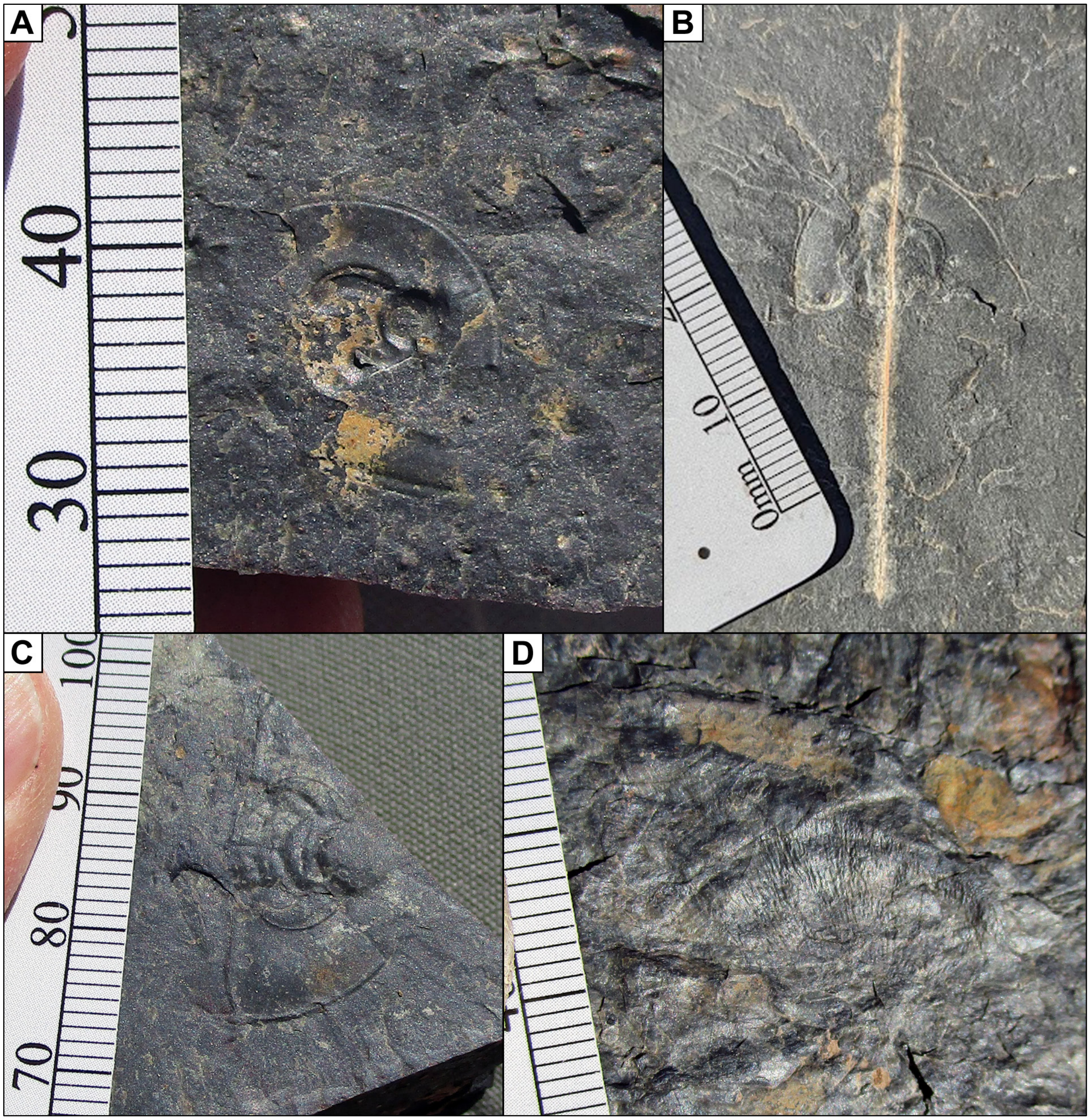

Figure 6. Latham Shale fossils from MOJA. **A–C.** Trilobite cephalons in the Latham Shale. **D.** Enigmatic wrinkled patch in the Latham Shale (NPS).

Aside from UCR 7002 and 7003, there are three other UCR localities reported from the Latham Shale: UCR 7313; UCR 7895, from the same area as UCR 7002 and 7003; and UCR 7580. UCR collections from the Providence Mountains were featured briefly in Webster et al. (2003) and Webster (2009). UCR records record the following kinds of fossils from their sites (J. Miller-Camp, University of California–Riverside museum scientist, pers. comm. to JST, November 2015; L. English, UCR museum scientist, pers. comm., April 2022):

- UCR 7002: *Anomalocaris canadensis* (now *Ramskoeldia consimilis*?); trilobites *Bristolia bristolensis*, *Olenellus* (now *Bristolia*) *mohavensis*, *O. clarki*, *O. nevadensis*, and *Onchocephalus* n. sp.; algae (sic; cyanobacteria) *Morania* n. sp.; and "fecal trails"
- UCR 7003: annelid (sic; palaeoscolecid) n. gen. and sp.; trilobites *Bristolia* n. sp. B and *Olenellus mohavensis*; and a hyolith
- UCR 7313: trilobites *Bristolia insolens* and *B. mohavensis*
- UCR 7580: numerous trilobites
- UCR 7895: trilobites *Olenellus clarki*, *O. fremonti* (now *Mesonacis*), *O. gilberti*, and *O. nevadensis*

Other Latham Shale fossils have been observed in MOJA. Hazzard (1933, 1954) reported on brachiopods and trilobites from several localities in the Providence Mountains now within MOJA; they were not identified as the Latham Shale until the later publication (Hazzard 1954). Stewart (1970) noted the presence of indistinct invertebrate trace fossils in quartzitic sandstone of the Latham Shale in the Providence Mountains. Bedford (2003) noted the local presence of shell fragments in a sandy limestone bed near the top of the formation in the Kelso 7.5′ Quadrangle. Gaines and Droser (2002), describing the Latham Shale of the Providence Mountains, observed five beds of trilobite fragments, four or more beds of shell lags, and tens of shell pavements, with brachiopods, hyoliths, and trilobites represented. Burrows were also present.

In addition to these finds, there are several reports of fossils from MOJA ascribed to the undivided Bright Angel Shale or Carrara Formation. Hewett (1956) reported trilobites from the Bright Angel Shale and "algal" markings on Bright Angel Shale dolomite. Dunne (1972), describing the geology of Devils Playground, reported trilobite hash and casts and molds in the Carrara Formation.

<u>Fossils found outside of MOJA</u>: Fossils from the Latham Shale, including areas outside of MOJA (primarily the Marble Mountains), include the enigmatic frond-like fossil *Margaretia* (Waggoner and Hagadorn 2004), the enigmatic conical fossils *Cambrorhytium* (perhaps related to jellyfish) and *Lathamoserpens* (perhaps a hyolith) (Waggoner and Hagadorn 2005), brachiopods, hyoliths, palaeoscolecid worms, radiodonts, trilobites, eocrinoids, and invertebrate pellets and other trace fossils (Mount 1976, 1980; Gaines and Droser 2002; Foster 2011a). Among the trace fossils are examples of *Bergaueria* (Alpert 1973; Mount 1976, 1980), mound-like structures that are interpreted as resting traces of sea anemones. Coprolites from the formation include crushed fragments of brachiopods, hyoliths, and trilobites, showing the presence of significant predators (Hagadorn 2009).

Chambless Limestone (lower Cambrian)

<u>Description</u>: The Chambless Limestone of the Providence Mountains consists of 52–67 m (170–220 ft) of light to dark gray limestone with common "algal" nodules (Hazzard 1954). The Chambless Limestone is thought to correlate to the Gold Ace Limestone Member of the Carrara Formation, which is similar but does not have the same abundance of "algal" oncoids and skeletal fragments (Palmer and Halley 1979). Deposition of this marine unit may have occurred in a "localized offshore

or barrier carbonate complex" (Foster 2011a). Based on fossils, the Chambless Limestone was deposited during the early Cambrian (Palmer and Halley 1979).

MOJA staff completed a detailed measured stratigraphic section of the Chambless Limestone at the Kelso Mountains. The Chambless Limestone is a hard, ridge-forming, light to dark gray limestone (Figure 7). The limestone alternates between massive and thickly bedded sections. Massive sections of lighter gray limestone contain an abundance of ~2–4 cm (0.8–1.6 in) dark gray "algal" nodules (oncoids), which have been strained by tectonic stresses. Dark gray bedded sections have little to no fossils and are more intensely weathered. The limestone also contains pitted to crinkly weathering textures and fractures filled with granular carbonate mineralogy.

Figure 7. An outcrop of the Chambless Limestone in the Kelso Mountains. Barrel cacti are 30–60 cm (1–2 ft) tall (NPS/EMILY JOHNSON).

<u>Fossils found within MOJA</u>: The Chambless Limestone is fossiliferous within MOJA, with abundant microbial structures, brachiopods, hyoliths, gastropods, trilobites, and eocrinoids. Hazzard (1954) reported *Girvanella*, brachiopods, hyoliths, and trilobites from MOJA. *Girvanella*, fossil sheaths of cyanobacteria, is commonly described as a builder of "algal" mounds and nodules (oncoids), such as those commonly found in the Chambless Limestone. The term "*Girvanella*" is sometimes used as shorthand for these structures. Stewart (1970) noted the presence of *Girvanella* in the Chambless Limestone in the Providence Mountains, and 10% to 30% of the formation in the Kelso 7.5′ Quadrangle consists of dark blue gray "algal" nodules (Bedford 2003). UCR collection records show that Chambless Limestone locality UCR 7311 is within MOJA. It yielded specimens including UCR 7311/1, eocrinoid ?*Gogia* sp.; UCR 7311/2, trilobite *Olenellus puertoblancoensis*; and UCR 7311/3, brachiopod *Acrothele spurri*. UCR 7311/2 and /3 were illustrated in Mount (1976), and UCR 7311/1 was illustrated in Mount (1974). Several other species of brachiopods and trilobites, as well as apparent hyoliths, have also been found at this site (J. Miller-Camp, pers. comm. to JST, November

2015; L. English, pers. comm., April 2022). An unpublished locality in the Providence Mountains includes oncoids and gastropods, and another yielded brachiopods and *Girvanella* (D. Burdette, MOJA emeritus, pers. comm. to JST, January 2016).

Fossils found outside of MOJA: Like the Latham Shale, fossils in the Chambless Limestone are best known from the Providence Mountains in MOJA and Marble Mountains south of MOJA. The fossil assemblage of the formation, including areas outside of MOJA, has yielded trace fossils of oncoids (i.e., *Girvanella*) (Mount 1976, 1980; Foster 2011a), unusual cup-like structures and possible borings or bioclaustrations on the oncoids (Unal and Zinsmeister 2005), and unidentified trace fossils (Foster 2011b). Body fossils include remains of archaeocyathid sponge (Foster 2011a), brachiopods, hyoliths, trilobites, and eocrinoids (Mount 1976, 1980; Foster 2011a).

Cadiz Formation (lower–middle Cambrian)

Description: The Cadiz Formation of the Providence Mountains is composed of about 160–210 m (540–690 ft) of buff and gray muddy limestone, purplish and reddish shale, and greenish-gray shale and quartzite (Hazzard 1954). The upper 30 m (100 ft) of the formation is composed of alternating layers of thin-bedded gray limestone and yellowish-brown mudstone, more resistant than the underlying shale, siltstone, and sandstone (Stone et al. 2017). It is correlated to the upper five members of the Carrara Formation, in ascending order the Pyramid Shale, Red Pass Limestone, Pahrump Hills Shale, Jangle Limestone, and Desert Range Limestone Members. The equivalents of the limestone members are not thick, and in some cases are represented only by thin oolite beds (Palmer and Halley 1979). Deposition occurred in a number of environments associated with shallow marine shelves and carbonate shoals (Foster 1994). The formation spans the early–middle Cambrian boundary (Hazzard 1954; Foster 2011a). The upper contact with the Bonanza King Formation is gradational (Keller et al. 2012).

Fossils found within MOJA: The Cadiz Formation is fossiliferous within MOJA, having yielded brachiopods, hyoliths, trilobites, and trace fossils. Hazzard and Mason (1936) reported middle Cambrian trilobites from an unspecified locality or localities in the Providence Mountains. Hazzard (1954) reported lower and middle Cambrian fossils from three localities in the Providence Mountains of MOJA, with lower Cambrian brachiopods, hyoliths, and trilobites, and middle Cambrian trilobites. Judging by the citations and taxa reported, these probably include the fossils cited in Hazzard and Mason (1936). UCR has three localities listed as from the Cadiz Formation in MOJA: UCR 7620, 7881, and 7894. Specimens could not be located for UCR 7260. UCR 7881 yielded trace fossils. UCR 7894 yielded the trilobite *Olenellus* ?*terminatus* (J. Miller-Camp, pers. comm. to JST, November 2015; L. English, pers. comm., April 2022).

Fossils found outside of MOJA: Fossils reported from the Cadiz Formation, primarily from the Marble Mountains south of MOJA, include the enigmatic sponge-like *Chancelloria* (Mason 1935; Hazzard and Mason 1936), *Palaelophacmaea*, once thought to be a gastropod but now interpreted as a float structure of a planktonic cnidarian (Waggoner and Collins 1995), brachiopods, hyoliths, trilobites (Mason 1935; Hazzard and Mason 1936; Mount 1976; Foster 2011a), possible echinoderms (Foster 2011a), oncoids encrusting other fossils (Unal and Zinsmeister 2005), and invertebrate trace fossils (Foster 1994, 2011a).

Bonanza King Formation (middle–upper Cambrian)

Description: The Bonanza King Formation, named for the Bonanza King Mine in MOJA, and overlying Nopah Formation are commonly identified in older reports as the Goodsprings Dolomite or Goodsprings Formation. The Goodsprings Dolomite includes rocks of several formations from the Cambrian to the Devonian. The lower half of the "Goodsprings Dolomite" is essentially the Bonanza King Formation (Hazzard and Mason 1936; Gans 1974). Hazzard (1954), describing the geology of the Providence Mountains, reported the Bonanza King Formation to include unnamed upper and lower dolomite members sandwiching the Silver King Member. This scheme was expanded in Stone et al. (2017), who divided the formation into (in ascending order) the Papoose Lake Member, Banded Mountain Member, Silver King Dolomite Member, and an unnamed upper member. The Papoose Lake Member is approximately 220 m (720 ft) thick and composed of a lower interval of medium to dark gray thin-bedded limestone grading upward into dolomite, and an upper interval of light to medium gray laminated dolomite and sandy dolomite. The Banded Mountain Member is approximately 300 m (980 ft) thick and composed primarily of strongly bedded and laminated dolomite in thin to thick beds, with alternating gray, brownish-gray, and yellowish-gray layers. The Silver King Dolomite Member is approximately 100 m (320 ft) thick and composed of generally massive black to dark gray dolomite, with patches of lighter dolomite. Finally, the unnamed upper member is approximately 80 m (260 ft) thick and composed of generally light gray medium- to thick-bedded dolomite (Stone et al. 2017). Deposition of the formation occurred in shallow marine shelf settings (Foster 2011a) and spanned the middle–late Cambrian boundary (Palmer and Hazzard 1956; Keller et al. 2012). The upper contact with the Nopah Formation may be disconformable (Hazzard 1954). The type section for the Bonanza King Formation is in MOJA (Henderson et al. 2021).

Fossils found within MOJA: There are few reports of fossils in the Bonanza King Formation within MOJA. Hazzard and Mason (1936) reported trilobites in the basal part of the formation most likely in the Providence Mountains. UCR locality 7554 has yielded possible stromatolites. Stone et al. (2017) reported bioclastic fragments in the limestone of the Papoose Lake Member in the Providence Mountains, and observed possible stromatolites in the Banded Mountain Member and possible burrow mottling in the Silver King Dolomite Member.

Fossils found outside of MOJA: The Bonanza King Formation is sparsely fossiliferous in general. Fossils reported from the formation include sponge–microbial reefs (Shapiro and Rigby 2004), bacterial filament microfossils (Haukedahl et al. 2008), microbial structures, fragmentary brachiopods and trilobites (Foster 2011a), and invertebrate trace fossils and bioturbation (Droser and Bottjer 1985). Most of its fossils are microbial traces, such as stromatolites and oncoids (Miller and Sundberg 1984). Examples of the sponge–microbial reef association have been found in the upper part of the formation just outside of MOJA. Trilobite fossils were also found here (Shapiro and Rigby 2004).

Nopah Formation (upper Cambrian)

Description: The Nopah Formation of MOJA is commonly identified in older reports as the Goodsprings Dolomite or Goodsprings Formation. Most of the upper part of the "Goodsprings" represents the Nopah Formation (Gans 1974). The Nopah Formation interval has also been identified as the Cornfield Springs Formation (Hazzard and Mason 1936), or as an unnamed sedimentary sequence (Hazzard 1954). Hazzard (1954) described the rocks recognized here as the Nopah Formation as composed of several units. At the base is 15 m (50 ft) of buff-weathering sandy dolomite and greenish shale, followed by 180 m (600 ft) of alternating dark and light gray dolomite, and then 23 to 30 m (75 to 100 ft) of light and dark gray dolomite with a sandy lower zone and a local basal sandstone or quartzite. Hazzard interpreted this upper part as Devonian in age. More recent publications divide the Nopah Formation into three named members, in ascending order the Dunderberg Shale Member (mixed brown shale and gray limestone), Halfpint Member (gray and tan carbonate rocks), and Smoky Member (mixed light gray microbial mound carbonates and dark gray shallow subtidal carbonates) (Keller et al. 2012). The Dunderberg Shale Member is sometimes described as its own formation (Gans 1974; Stone et al. 2017). Stone et al. (2017) did not use the Nopah Formation name in the Providence Mountains, instead employing the Dunderberg Shale name for 10–30 m (33–100 ft) of light brown to yellowish-brown medium- to thick-bedded dolomite and thin-bedded siltstone and sandstone over dark greenish-brown to yellowish-brown shale. The overlying rocks were included in an undivided Cambrian–Devonian unit, which Stone et al. (2017) interpreted as including equivalents to the Cambrian "Cornfield Springs Formation", Ordovician–Devonian Mountain Springs Formation, and Valentine and Ironside Members of the Ironside Member of the Sultan Limestone (Stone et al. 2017). Deposition of the Nopah Formation in the MOJA area is thought to have begun with muds deposited in intertidal to deep subtidal settings, followed by lagoonal and microbial bank deposition (Cooper et al. 1981). The Nopah Formation was deposited during the late Cambrian (Keller et al. 2012). The upper contact with the Sultan Limestone is disconformable (Hazzard 1954).

Fossils found within MOJA: The Nopah Formation is fossiliferous within MOJA. Hazzard and Mason (1936) reported a fauna from a sandy horizon at the base of their Cornfield Springs Formation likely within the Providence Mountains. This assemblage included a sponge, a brachiopod species, three trilobite species, and a "cystoid" plate (potentially an eocrinoid instead). Hazzard (1954) found trilobites in the basal 15 m (50 ft) of sandy dolomite and shale at several localities in MOJA. James Hagadorn (Denver Museum of Nature and Science, pers. comm. to JST, February 2016) reported that brachiopods and trace fossils are also present. Cooper et al. (1981) interpreted the deposition of the Halfpint Member in the MOJA area to have taken place primarily in a microbial bank. Among the sections they examined were locations in the New York and Providence Mountains, but they did not detail these sections.

Fossils found outside of MOJA: Outside of MOJA, the Nopah Formation has a limited assemblage of upper Cambrian marine fossils. The Dunderberg and Halfpint Members have mostly body fossils, while the Smoky Member has mostly microbial fossils such as oncoids and stromatolites (Miller and Sundberg 1984). Body fossils include *Chancelloria*, the sponge *Hintzespongia* (Miller et al. 1981), archaeocyathid sponges (Hazzard and Mason 1936), brachiopods (Miller et al. 1981), the early chiton relative *Matthevia* (Yochelson et al. 1965), gastropods (Miller and Sundberg 1984), trilobites, eocrinoids (Miller et al. 1981), and conodonts (Miller and Paden 1976). Trace fossils include various microbial structures (Cooper et al. 1981) and invertebrate trace fossils and bioturbation (Droser and Bottjer 1985), the latter including predatory borings on shells (Miller and Sundberg 1984). Shapiro and Awramik (2006) named the thrombolite *Favosamaceria cooperi* from a fossil found in the Smoky Member just outside of MOJA.

Sultan Limestone (Middle–Upper Devonian)

Description: The Devonian rocks of MOJA have historically been assigned to the Sultan Limestone (e.g., Hazzard 1954), divided into three members. As described by Hazzard (1954), the Ironside Dolomite Member at the base is composed of 15 to 23 m (50 to 75 ft) of very dark gray dolomite. Above it is the Valentine Limestone Member, composed of 60+ m (200+ ft) of dark gray dolomite beneath 110 to 120 m (350 to 400 ft) of light and dark gray limestone in massive beds alternating with thinly bedded layers and two sandstone beds low in this section. The upper unit, the Crystal Pass Limestone Member, is composed of 76 to 91 m (250 to 300 ft) of porcelain-like light creamy gray limestone (Hazzard 1954). The Crystal Pass Limestone Member is noted for the "tinkling" sound produced by its fragments (Dobbs 1961). More recently, Stone et al. (2017) did not map the Sultan Limestone in the Providence Mountains but interpreted various intervals as equivalent to the members of the formation. Their undivided Cambrian–Devonian dolomite, sandy dolomite, and quartzite includes discontinuous black dolomite beds that are equivalent to the Ironside Member and overlying dolomite and quartzite attributed to the lower Valentine Member. Above this, an unnamed limestone, dolomite, and quartzite unit is attributed primarily to the upper Valentine Member and Crystal Pass Member, plus some quartzite beds at the top previously placed in the Monte Cristo Limestone (Stone et al. 2017).

Regardless of the name, the rocks are interpreted as shallow marine units. The Ironside Member is interpreted as a shallow marine shelf setting. The Valentine Limestone Member is interpreted as having been deposited mostly under intertidal and subtidal water. The Crystal Pass Limestone Member is also interpreted as intertidal and subtidal, with some areas of more restricted marine deposition (Bereskin 1982). Deposition occurred during the Middle and Late Devonian (Givetian to Famennian stages, about 385–359 Ma), with the oldest rocks being older in the west than in the east (Bereskin 1982). The upper contact with the Monte Cristo Limestone is disconformable (Hazzard 1954).

Fossils found within MOJA: The Sultan Limestone is fossiliferous within MOJA, having yielded reef-building stromatoporoid sponges, tabulate and rugose corals, brachiopods, gastropods, crinoids, and conodonts. Hazzard (1954) reported stromatoporoid sponges, rugose corals, and gastropods from Valentine Limestone Member localities in the Providence Mountains within MOJA. Hewett (1956) discussed two more fossiliferous localities in the Valentine Limestone Member that seem to map within MOJA. However, Hewett's work predated the extension of the township/range grid through the entire area, and it appears more likely that the sites are outside of MOJA. This also better accords with geologic maps. Hewett (1956) reported tabulate and rugose corals, brachiopods, and gastropods from these sites. Dobbs (1961), working in the Clark Mountains, reported fossils in the Sultan Limestone from unspecified locations probably within MOJA. These included corals, brachiopods, and crinoid stems in the Ironside Dolomite Member, and corals, brachiopods, and crinoid fragments in the Valentine Limestone Member. The Ironside Dolomite Member fossils were usually poorly preserved and replaced by silica and would weather in relief from the surrounding rock. Yelverton

(1963) reported Sultan Formation fossils from Old Dad Mountain in MOJA. These included unspecified fossils from the upper Ironside Dolomite Member, corals, brachiopods, and crinoids from the Valentine Limestone Member, and echinoderm fragments from near the base of the Crystal Pass Limestone Member. Evans (1971) found stromatoporoids, tabulate corals, and brachiopods in the middle of the Valentine Limestone Member near MOJA, and "silicified corals" (potentially stromatoporoids again) in the Ironside Dolomite Member at Striped Mountain. Burchfiel and Davis (1977) observed "ghosts" of silicified stromatoporoids in the Valentine Limestone Member in the New York Mountains in MOJA. Miller (1983) reported brachiopods and conodonts from the Providence Mountains. Brown (1989) also observed stromatoporoids in the Valentine Limestone Member of the New York Mountains. Stone et al. (2017) reported poorly preserved stromatoporoids in black dolomite considered equivalent to the Ironside Member in the Providence Mountains, and stromatoporoids, corals, brachiopods, and gastropods in the beds attributed to the upper Valentine Member and Crystal Pass Member.

MOJA collection records identify two unpublished localities tentatively assigned to the Sultan Limestone. Crinoids were found at both sites. UCR collection records attribute four conodont localities within MOJA to the Sultan Limestone, UCR 9233 through 9236 from the Providence Mountains (J. Miller-Camp, pers. comm. to JST, November 2015; L. English, pers. comm., April 2022). Some of the specimens were illustrated in Miller (1983). There is some chance that some of the material from UCR 9236 is from the Monte Cristo Limestone, because the conodonts include Lower Mississippian forms. Another UCR locality, UCR 9102 from the Striped Mountains, is attributed to the "Goodsprings Dolomite" with a possible Silurian age, but the only fossil reported from it is the tabulate coral *Syringopora*, generally more abundant in younger rocks, so the locality is potentially in the Sultan Limestone.

Fossils found outside of MOJA: The Sultan Formation is also notably fossiliferous just outside of MOJA. At Mohawk Hill, Evans (1958) found stromatoporoids in the Ironside Dolomite Member and stromatoporoids, tabulate corals, and brachiopods in the Valentine Limestone Member. Bereskin (1982) reported stromatoporoids, tabulate and rugose corals, brachiopods, and echinoderms from the Ironside Dolomite Member at Mohawk Hill, and stromatoporoids, corals, brachiopods, gastropods, and echinoderms in the Valentine Limestone Member. Suek and Bereskin (1982) described flat layered stromatoporoid reefs from north of Mesquite Pass, a few km/mi north of the Clark Mountain parcel. These rocks also included invertebrate trace fossils and body fossils of foraminifera, red algae, green algae, calcispheres, tabulate and rugose corals, tentaculitids, brachiopods, gastropods, trilobites, ostracodes, crinoids, and echinoids.

The Sultan Formation fossils from in and around MOJA cover essentially all of the higher-level diversity known from the formation in its entire depositional area; the only group that seems to have not been reported is nautiloids, known from the Sultan Formation in southern Nevada (Harrington 1987). Most Sultan Formation fossils are from the Valentine Limestone Member. The Ironside Dolomite Member has similar but less abundant fossils; most of its fossils have been destroyed by alteration from limestone to dolomite. Fossils are rare in the Crystal Pass Limestone Member (Bereskin 1982).

Monte Cristo Limestone (Lower–Middle Mississippian)

Description: The Monte Cristo Limestone is a fossiliferous limestone unit (Figure 8). It is usually described as divisible into four or five members, in ascending order the Dawn Limestone, Anchor Limestone, Bullion Limestone, Arrowhead Limestone (in some reports), and Yellowpine Limestone Members. They are sometimes raised to formations in their own right, with the Monte Cristo Formation raised to a group. Hazzard (1954) and Stone et al. (2017) reported the presence of all except the Arrowhead Limestone Member in the Providence Mountains (although noting that the Yellowpine Limestone Member was locally absent and may be lenticular rather than continuous). This member may not have been identified because of thinness; Hewett (1956) reported all five from the same general region, with the Arrowhead Limestone Member only being 3 m (10 ft) thick. In MOJA, the Dawn Limestone Member is about 73 m (240 ft) of light and dark gray limestone beds up to 6 m (20 ft) with cherty upper beds (Hazzard 1954); Hazzard (1954) also reported an interval of about 3 to 5 m (10 to 15 ft) of white to brownish sandstone and quartzite at the base, not assigned to any member. Stone et al. (2017) assigned this interval to the upper part of their undivided Devonian unit and suggested it correlates to the Quartz Spring Member of the Lost Burro Formation, as seen in DEVA. Hewett (1956) found that the Dawn Limestone Member had been mostly altered to dolomite north of the Providence Mountains. The Anchor Limestone Member consists of 30 to 46 m (100 to 150 ft) of light gray crinoidal limestone with brown chert (Hazzard 1954). The Bullion Limestone Member consists of 76 to 110 m (250 to 350 ft) of light gray to cream crinoidal limestone (Hazzard 1954). Hewett (1956) found it to be mostly dolomite north of the Providence Mountains, forming a cliff. The 3 m (10 ft)-thick Arrowhead Limestone Member is composed of alternating layers of fine limestone and thin shale (Hewett 1956). Finally, the Yellowpine Limestone Member is 23 to 38 m (75 to 125 ft) of very dark gray limestone (Hazzard 1954). These members were deposited in shallow marine settings (Brown 1989), during the Early to Middle Mississippian (Kinderhookian to Meramecian stages, between about 359 and 333 Ma) (Haskell 1959; Webster and Lane 1987). The upper contact with the Bird Spring Formation is disconformable (Hazzard 1954).

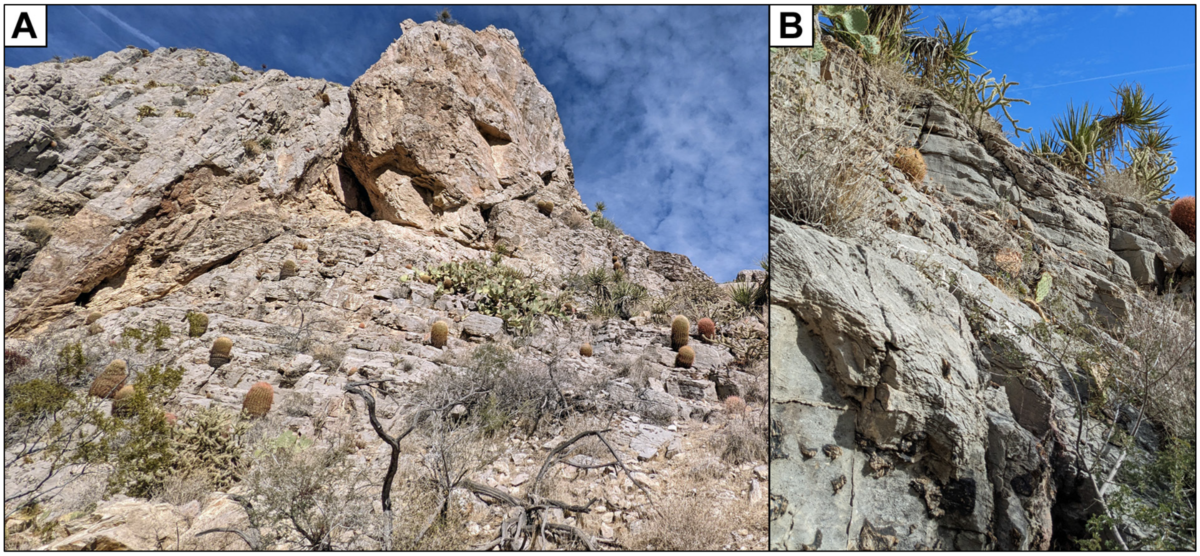

Figure 8. The Monte Cristo Limestone. **A.** Crinoid material and chert lenses at this outcrop indicate it is the Anchor Limestone Member. **B.** A close-up of the outcrop (NPS/EMILY JOHNSON).

<u>Fossils found within MOJA</u>: The Monte Cristo Limestone is fossiliferous in a number of places within and just outside of MOJA, with all five members producing fossils. The assemblage includes tabulate and rugose corals, bryozoans, brachiopods, bivalves, ammonoids, nautiloids, gastropods, trilobites, ostracodes, crinoids, and possibly echinoids. Hazzard (1954) found some types of fossils to be abundant enough to include in general descriptions of the members, including crinoids in the Anchor and Bullion Members, and rugose corals in the Yellowpine Limestone Member. He also reported collections of fossils from the Dawn and Anchor Members at several localities in MOJA. These sites yielded rugose corals, bryozoans, brachiopods, and crinoids. Hewett (1956) reported a number of fossils from the Anchor Limestone Member, but as with Hewett's Sultan Limestone sites, it is more likely that the site is near but outside of MOJA. The fossils included brachiopods, bivalves, ammonoids, nautiloids, gastropods, trilobites, ostracodes, and crinoids. Haskell (1959), like Hazzard (1954), reported crinoids to be an integral part of the Dawn and Anchor Members in the New York Mountains–Lanfair Valley area, and also found rugose corals to be common in the middle part of the formation. Barca (1960, 1966) found crinoid fragments to be abundant in the Bullion Limestone Member of the Old Dad Mountain area. Dobbs (1961) reported a number of fossils from the various members on the east flank of Clark Mountain, at least in part within MOJA. These included tabulate and rugose corals and crinoids in the Dawn and Anchor Members, tabulate corals in the Bullion Limestone Member, corals in the Arrowhead Limestone Member, and corals, brachiopods, and gastropods in the Yellowpine Limestone Member. Yelverton (1963) reported tabulate and rugose corals, bryozoans, brachiopods, bivalves, cephalopods, and crinoids from the formation on Old Dad Mountain, with crinoid fragments prominent in the Anchor Limestone Member. Dunne (1972), working in the Devils Playground area of MOJA, reported crinoid columnals in the Dawn, Anchor, and Bullion Members, and a few unspecified fossils in the Yellowpine Member. Dunne (1977) reported crinoids in the Bullion Limestone Member at Old Dad Mountain. Brown (1989), describing limestone units in the New York Mountains of MOJA, reported the presence of crinoid debris in the Dawn, Anchor, and Bullion Members. Stone et al. (2017), working in the Providence Mountains, observed corals, crinoid debris, and other marine fossils in the Dawn Limestone Member and locally abundant solitary corals, colonial corals, and brachiopods in the Yellowpine Limestone Member. Also, just outside of MOJA, Evans (1958) reported corals in the Yellowpine Limestone Member in the Mescal Range.

<u>Fossils found outside of MOJA</u>: Much of the higher-level paleontological diversity known from the Monte Cristo Limestone can be found in and near MOJA. Types of fossil organisms known from the Monte Cristo Limestone but not yet reported from MOJA include sponges (Hansen 1979), blastoids, echinoids (Hewett 1931), conodonts, trace fossils including bioturbation and apparent fecal pellets (Hansen 1979), foraminifera, algae, and calcispheres (Hansen 1979).

Bird Spring Formation (Pennsylvanian–lower Permian)

<u>Description</u>: The Bird Spring Formation is the youngest Paleozoic formation identified within MOJA. Hazzard (1938) proposed dividing the MOJA-area rocks now included in the Bird Spring Formation into the Pennsylvanian Providence Mountains Limestone and the lower Permian Mount Edgar Limestone, but neither name has become accepted. Occasionally an author includes additional

Permian formations above the Bird Spring Formation in the northern part of the MOJA area (Hewett 1956; Evans 1959, 1971; Walker 1987), principally the Kaibab Formation.

The Bird Spring Formation of MOJA can be close to 900 m (3,000 ft) thick. Hazzard (1954) made an arbitrary division between Pennsylvanian and Permian rocks. He assigned the lowest 251 m (825 ft) to the Pennsylvanian, and the upper 650+ m (2,130+ ft) to the Permian. The Pennsylvanian interval includes very dark gray to light creamy gray limestone, locally dolomitized, with minor sandstone, sandy limestone, and shale, and cherty and fossiliferous zones in the lower half. The Permian interval is made up of gray limestone with sandstone and chert. The fossiliferous gray limestone is massively bedded (Hall 2007). Rather than divide by age, Stone et al. (2017) regarded the formation as lithologically divisible into thirds. The lower third is composed of medium- to dark-gray thick-bedded to massive limestone with abundant lenses and nodules of dark brown chert. The middle third is composed of fossiliferous light- to medium-gray thin- to thick-bedded or massive limestone and some grayish-orange silty limestone to limy siltstone. The upper third is composed of light-gray thin- to medium-bedded dolomite and dolomitic limestone, with some light- to medium-gray limestone and grayish-orange silty limestone to limy siltstone (Stone et al. 2017).

The rocks contain diagenetic orange to brown and black chert, as both stringy and nodular inclusions and in veiny networks filling fractures (Sharp and Glazner 1993). In some locations, vertically exposed bedding planes and widespread fracturing left these rocks highly susceptible to chemical weathering from groundwater and rainwater (Sharp and Glazner 1993). Caves formed in the Bird Spring Formation (Figure 9) when groundwater percolated through fractures in the limestone and dissolved holes in the rocks before the late Miocene. As these holes grew larger, water diverted from smaller nearby fractures and flow was focused into the larger channels, which grew into caverns (Sharp and Glazner 1993).

The Bird Spring Formation is recognized as a shallow marine unit (Gordon 1964; Brown 1989; Stevens and Stone 2007). Deposition occurred on a shelf, with the shore to the east. The lower Permian fossils indicate warm tropical to subtropical waters of normal marine salinity (Stevens and Stone 2007). Deposition of the formation took place over a relatively long time, perhaps from the Late Mississippian to the early Permian in the MOJA area (Evans 1971). Pennsylvanian and lower Permian fossils have been attributed to the formation at MOJA (Hazzard 1954; Yelverton 1963; Law 1969; Stevens and Stone 2007; Stone et al. 2017). The upper contact with the Moenkopi Formation is disconformable (Hazzard 1954) and represents the transition from Paleozoic to Mesozoic strata at MOJA.

<u>Fossils found within MOJA</u>: The Bird Spring Formation is abundantly fossiliferous in and around MOJA. Types of fossils that have been found at sites within MOJA include the coral-like sponge *Chaetetes*, tabulate and rugose corals, bryozoans, brachiopods, bivalves, nautiloids, ammonoids, gastropods, annelids, trilobites, ostracodes, crinoids, echinoids, holothurians, conodonts, fish fragments, and foraminifera including fusulinids. Fossil groups probably present in MOJA include rostroconchs, echinoids, and microbial features such as stromatolites. Some of the described fossils from the MOJA area come from the Providence Mountains, including the enclave of state-managed land. Because the fossils are of marine invertebrates, which generally have widespread distribution

within formations, it is likely that any types of fossils found in the Bird Spring Formation on state-managed land in the Providence Mountains will probably be found in surrounding areas in MOJA, and vice-versa. Reports include the following:

Figure 9. The Bird Spring Formation at the entrance to Mitchell Caverns in the Providence Mountains State Recreation Area (NPS/EMILY JOHNSON).

Thompson and Hazzard (1946) described lower Permian fusulinid foraminifera from the Providence Mountains, mostly from the state land enclave, but at least some of the material is from areas now in MOJA. For reference, the new taxa named from the state land enclave were *Dunbarinella concisa*, *Pseudoschwagerina arta*, *P. roeseleri*, *P. uber*, *Schubertella masoni*, *Schwagerina aculeata*, *S. aculeata* var. *plena*, *S. modica*, *S. providens*, *S.*? *multispira*, and *Triticites californicus*. Thompson and Hazzard's research was briefly mentioned in an abstract before the paper (Thompson and Hazzard 1940). Hazzard (1954) identified fossils from a number of locations in the Providence Mountains. Some of the localities and sections are at least partially within the state-managed land enclave, and he did not specify which fossils came from which sites. Hazzard reported that the Pennsylvanian portion of the formation yielded brachiopods, ammonoids, and trilobites from sites in MOJA. The Permian portion yielded tabulate and rugose corals, bryozoans, brachiopods, gastropods, echinoids, and fusulinid foraminifera. Hewett (1956) reported fossils from two MOJA localities, including fossils of corals, bryozoans, and brachiopods. He also noted that other sites in the area had fossils of bivalves, nautiloids, gastropods, trilobites, and ostracodes.

Evans (1958) noted the presence of fusulinid foraminifera just outside of MOJA; these are probably the same as the foraminifera reported in Evans (1971). Easton (1960) reported the rugose coral *Lonsdaleia* (now *Durhamina*) *cordillerensis* from a site within the state land enclave. Any fossils from this site, University of Southern California (USC) 344, would now be at the Natural History Museum of Los Angeles County. Haskell (1959) found that the Bird Spring Formation of the New York Mountains–Lanfair Valley area had abundant but poorly preserved fossils, including rugose corals. Barca (1960) reported the presence of fusulinid foraminifera, the sponge *Chaetetes* (replaced by chert), tabulate and rugose corals, and fragments of bryozoans, brachiopods, and crinoids at Cowhole Mountain. Yelverton (1963) reported various fossils from the Old Dad Mountain area. These included Lower or Middle Pennsylvanian examples of *Chaetetes*, tabulate and rugose corals, bryozoans, brachiopods, and crinoids, and Upper Pennsylvanian and lower Permian *Chaetetes*, tabulate and rugose corals, bryozoans, brachiopods, bivalves, nautiloids, gastropods, crinoids, and fusulinid foraminifera. Gordon (1964) reported the presence of the ammonoid *Paralegoceras texanum* (previously identified as *Gastrioceras* cf. *G. cancellatum* by Hazzard [1954]) within MOJA. Law (1969), in a study focused on conodonts, reported a variety of fossils primarily from the Pennsylvanian interval, among them tabulate corals, solitary and colonial rugose corals, bryozoans, brachiopods, bivalves, gastropods, scolecodonts, ostracodes, crinoids, holothurian plates, conodonts, fish fragments, and foraminifera.

Dunne (1972) found fusulinid foraminifera at Old Dad Mountain. Wilson (1978) reported fossiliferous zones in the Bird Spring Formation of the Seventeenmile Point area. Plas (1972) and Erwin (1988) mentioned an undescribed species of gastropod found in the lower Permian rocks of the formation in the Providence Mountains. Brown (1989) found crinoid fragments in the lower part of the formation in the New York Mountains. Kaasa (1990), in an abstract, reported on a lower Permian stromatolite in the Providence Mountains. This domal structure included fragments of rostroconchs, bivalves, gastropods, and foraminifera in its structures, and was associated with bryozoan colonies, brachiopods, and echinoderm fragments.

Wilson (1994a, 1994b) reported on lower Permian corals from the state land enclave, and described the new species *Heritschioides mckassoni*, *Neomultithecopora providens*, and *Paraheritschioides applegatei*. Also present at these sites near MOJA were bryozoans, brachiopods, gastropods and other mollusks, crinoids, echinoids, and fusulinid foraminifera (Wilson 1994a). Stevens and Stone (2007) described fusulinid foraminifera from a number of localities in MOJA and the state enclave. The general areas include Cowhole Mountain, the Providence Mountains, and Old Dad Mountain. They named four species from localities in MOJA: *Cuniculinella mojavensis* (holotype USNM 531309); *Pseudochusenella hazzardi* (holotype USNM 531314); *Stewartina magnifica* (holotype USNM 531301); and *Stewartina ultimata* (holotype USNM 531304). These fusulinid zones date to the early Permian. Stevens and Stone also mentioned the presence of corals, brachiopods, and gastropods in the lower two-thirds of the Bird Spring Formation in the Providence Mountains, colonial corals at Cowhole Mountain, and unidentified marine fossils at Old Dad Mountain. Stone et al. (2017) reported probable algal coatings, tabulate and rugose corals, bryozoans, gastropods, possible ostracodes, crinoid debris, fusulinid and other foraminifera, and fossil debris in the Bird Spring Formation of the Providence Mountains in MOJA.

UC–Riverside has several localities from the Bird Spring Formation within or just outside of MOJA. Localities within MOJA include UCR 5026, which may have produced fusulinid foraminifera; UCR

7962, which appears to have yielded "reef-forming organisms, a big fusulinid, and crinoid stem segments"; and UCR 9103, which has produced the gastropod *Bellerophon* sp. and the echinoid *Echinocrinus* sp. UCR 5231 and 5232 may be within MOJA or the northeastern part of the state land enclave in the Providence Mountains. They are not definitely attributed to the Bird Spring Formation, but they produced typical Permian fusulinid foraminifera, so they are included here. Finally, UCR 5020, 5021, and 5229 are within the state land enclave. They have produced brachiopods, echinoids, and fusulinids (J. Miller-Camp, pers. comm. to JST, November 2015; L. English, pers. comm., April 2022).

Fossils found outside of MOJA: The above fossils indicate that the Bird Spring Formation of MOJA and the immediate vicinity includes representatives of most of the known higher-level diversity of the formation. Types of fossils so far only reported from outside of MOJA include radiolarians, encrusting algae (Stone et al. 2014), tree roots (*Stigmaria*) (Langenheim et al. 1962), invertebrate trace fossils including pellets and possible burrows (Stone et al. 2014), and teeth of cartilaginous fish (Langenheim et al. 1962).

Moenkopi Formation (Lower Triassic)

Description: Isolated outcrops identified as the Moenkopi Formation are scattered throughout MOJA, from Clark Mountain and the Mescal Range, to the northern Providence Mountains, to the New York Mountains, to Cowhole Mountain (Walker 1987; Theodore 2007). In the northern outcrops, the rocks are correlated to the Shnabkaib Member of the Moenkopi Formation, and include a conglomerate (Walker 1987). The unit is about 120 to 150 m (400 to 500 ft) thick, mostly composed of light blue gray limestone with some shale (Hewett 1956). The Providence Mountains section is described differently by Hazzard (1954), Walker (1987), and Stone et al. (2017). Hazzard described it as including four unnamed members: a basal unit about 66 m (217 ft) thick composed of maroon, red, and brown sandstone, clay shale, and conglomerate; then 47 m (115 ft) of light gray to tan fossiliferous limestone; then 47 m (115 ft) of olive-drab thin clay shale and dark gray fossiliferous limestone; finally, 143+ m (470+ ft) of light and dark gray nodular limestone with some shale. Walker described the rocks as including a basal conglomerate, a sandstone and shale interval, a fossiliferous limestone that may represent the Virgin Limestone Member, another sandstone and shale interval, and finally a limestone interval with some metamorphism. Stone et al. (2017) employed a simpler division of a sandstone member beneath a limestone member, with no proposed correlations. The sandstone member is approximately 110 m (360 ft) thick and mostly composed of light-brown thin-bedded calcareous sandstone to siltstone, with lesser shale and limestone. The overlying limestone member is approximately 150 m (490 ft) thick and composed of light- to medium-gray thin- to medium-bedded limestone with some sandstone; this member is almost entirely confined to the state-managed lands (Stone et al. 2017). In the New York Mountains, the Moenkopi Formation consists of marble and other metamorphosed sedimentary rocks followed by quartzite (Walker 1987). Some authors find the New York Mountains section to be too metamorphosed to definitely attribute to the Moenkopi Formation (Burchfiel and Davis 1977; Miller and Wooden 1993). Finally, the Devils Playground/Cowhole Mountain section is less firmly correlated but includes a section of hornfels followed by quartzite that may represent the Moenkopi Formation. To the north and west, in the Soda Mountains area, the Moenkopi Formation is replaced by the Silver

Lake Formation (Walker 1987). Small outcrops attributed to the Upper Triassic Chinle Formation (Hewett 1956; Evans 1958, 1971; Reynolds 1989, 2006) and the Lower Jurassic Moenave–Kayenta Formation (Reynolds 1989, 2006) are sometimes reported above the Moenkopi Formation in the Mescal Range just outside of MOJA.

The Moenkopi Formation is generally interpreted as a coastal and tidal flat formation with marine incursions (Stewart et al. 1972), but this interpretation is more applicable to the Four Corners area of Arizona–Colorado–New Mexico–Utah. In the MOJA area, the marine influence was much greater. The fossiliferous limestones are interpreted as representing shelf environments above storm wave base (Pruss and Payne 2009), as part of a transition from a retreating ocean margin to rivers (Reynolds 1989). Deposition occurred during the Early Triassic in the MOJA area (Walker 1987). The upper contact of the various Moenkopi sections with overlying sedimentary or volcanic rocks is generally disconformable (Walker 1987).

Fossils found within MOJA: The Moenkopi Formation should be regarded as fossiliferous within MOJA, although the few published reports are all from localities in the state land enclave or the Mescal Range just outside of MOJA. These reports are of marine invertebrates, and it is highly likely that the same kinds of fossils are present in MOJA if they are present within distances of less than a kilometer in an area surrounded entirely by the preserve. The various reports indicate that microbial fossils, brachiopods, bivalves, ammonoids, gastropods, and invertebrate trace fossils should be anticipated in MOJA. Hazzard (1954) reported bivalves and ammonoids from the state land enclave. Brachiopods and bivalves have been reported from just outside of MOJA, and bivalves and gastropods have been found northeast of the Clark Mountain parcel (Hewett 1956). Pruss and Bottjer (2004a) described invertebrate burrows and trails from just outside of MOJA near Mountain Pass, and Pruss and Payne (2009) described microbial spheroids from the same site. They also found mollusk and crinoid fossils there. Stone et al. (2017) observed shell fragments in the limestone member.

Fossils found outside of MOJA: The Moenkopi Formation has a wide variety of fossils over its depositional area, but not all of them are relevant for the rocks in southeastern California. Because the Virgin Limestone Member and Shnabkaib Member have been cited as potentially correlating to rocks in MOJA, their fossil assemblages are cited here for reference. The Virgin Limestone Member's assemblage includes sponges (Bonde et al. 2018), bryozoans, brachiopods, bivalves, ammonoid and nautiloid cephalopods, gastropods, ostracodes, the crustacean *Halicyne*, crinoids (Poborski 1954; Hintze 1986; Jenson 1986; Stewart et al. 1972), asteroids (Santucci and Kirkland 2010), echinoids (Moffat and Bottjer 1999), stromatolites, oncoids (Sanderson 1967; Pruss and Bottjer 2004a, 2004b), microbial wrinkle structures (Pruss et al. 2004), several types of invertebrate trace fossils (Pruss and Bottjer 2004a), probable microbial spheroids (Pruss and Payne 2009), and "algal" filaments (Sanderson 1967). The Shnabkaib Member has produced brachiopods, bivalves, ammonoids, gastropods, crinoids, stromatolites, invertebrate trace fossils, and "algal" filaments (Lambert 1984). Microbial structures are common, but fossils are otherwise rare (Lambert 1984).

Mesozoic volcanic and associated sedimentary rocks (various ages, Triassic–Cretaceous)

Description: There are a variety of Mesozoic-age volcanic rocks in MOJA, some of which are associated with sedimentary rocks. The rocks represent a range of ages. Examples include: unnamed Triassic volcanic rocks and quartzite in the Devils Playground (Dunne 1972, 1977); volcanic rocks and conglomerates above the Moenkopi Formation in the northern Providence Mountains and the New York Mountains (Walker 1987; Stone et al. 2017 [identified as the Fountain Peak Rhyolite in the Providence Mountains and dated to the late Middle Jurassic]); unnamed Mesozoic sedimentary rocks of Sagamore Canyon in the New York Mountains (Burchfiel and Davis 1977); fluvial sandstone associated with the 167 Ma Cowhole Volcanics (Busby et al. 2002), and the Delfonte Volcanics in the Mescal Range, dated to 100 ± 2 Ma (Busby et al. 2002).

Fossils found within MOJA: Fossils have not yet been reported from these scattered outcrops, but it is not impossible that something may be found in them, perhaps comparable to the terrestrial trace fossils and reworked Paleozoic fossils known from the Aztec Sandstone in and near MOJA.

Fossils found outside of MOJA: None to date.

Aztec Sandstone (Middle Jurassic)

Description: Rocks attributed to the Aztec Sandstone are present in two areas of western MOJA: Cowhole Mountain and Old Dad Mountain. Similar rocks are also exposed in the eastern Mescal Range within about 3 km (2 mi) of MOJA (Theodore 2007). This primarily sandstone unit can be 200 to 800 m (660 to 2,600 ft) thick in western MOJA. It also includes volcanic rocks (Busby et al. 2002). The rocks represent eolian deposition (Busby et al. 2002), deposited locally in two basins (Wadsworth et al. 1995). In the Mescal Range, the rocks include eolian dune sandstones and brown silty sandstones attributed to delta or basin settings (Reynolds and Mickelson 2006). The Aztec Sandstone is historically considered to be the western expression of a giant dune system (also known as a "sand sea" or erg) found across several states of the Southwest. Equivalent formations are called the Navajo and Nugget Sandstones (Bonde et al. 2008). This dune system is the largest erg known from North America (Blakey 2008), and Kocurek (2003) identifies it as the largest known on Earth. The Navajo and Nugget Sandstones, and usually the Aztec Sandstone in southeastern Nevada, are accepted as Early Jurassic in age; however, the Aztec Sandstone of Cowhole Mountain includes a Middle Jurassic igneous flow dated to 172 ± 6 Ma and is stratigraphically lower than other flows dated to 167 Ma (Busby et al. 2002). It is not entirely clear that the rocks identified as the Aztec Sandstone in and around MOJA are correlative to rocks identified as the Aztec Sandstone in southern Nevada, which would explain the discrepancy (Busby et al. 2002). The name is retained here for convenience and consistency, but the potential relationship to the accepted Aztec–Navajo–Nugget system should be investigated further.

Fossils found within MOJA: At Cowhole Mountain, Marzolf and Cole (1987) found that the basalmost Aztec Sandstone is a limestone breccia fills paleochannels in the underlying rock. Among the rocks in this basal layer are reworked Paleozoic rocks with fusulinid foraminifera and brachiopods. Novitsky-Evans (1978) found burrows and possible fecal pellets in the basal Aztec Sandstone of Cowhole Mountain.

<u>Fossils found outside of MOJA</u>: Near MOJA, the Aztec Sandstone of the Mescal Range preserves the only Mesozoic dinosaur tracks in California (Reynolds 1983). First reported by Evans (1958, 1971), the track sites preserve examples of about a dozen forms of vertebrate tracks and two types of invertebrate traces. The vertebrate tracks are dominated by quadrupeds. Reportedly there are six kinds of equidimensional tracks (including mammal or "mammal-like reptile" tracks called *Brasilichnium* and dinosaur tracks called *Navahopus*), two kinds of elongate tracks (including *Pteraichnus*, pterosaur tracks), and gracile tracks probably produced by a lizard-like animal, as well as three kinds of bipedal theropod dinosaur tracks (Reynolds 2006). Observation at the site suggests that the diversity may be overstated, or at least very subtle (JST, pers. obs., November 2021). Invertebrate traces include vertical "worm burrows" (*Skolithos*) and arachnid tracks (*Octopodichnus*). Impressions of horsetails have also been found (Reynolds 2006). The tracks are only found in eolian beds, not the silty beds (Reynolds and Mickelson 2006). At least 116 track sites have been found (Reynolds and Weasma 2002), and people have tried to remove some of the tracks (Reynolds 2006).

Jurassic intrusive rocks (Jurassic)

<u>Description</u>: Jurassic intrusive rocks of various compositions are present at and near many locations in MOJA (east of Cima Dome, the Clipper Mountains, Devils Playground, Granite Mountains, Ivanpah Mountains, Mescal Range, Providence Mountains, and Striped Mountain) (Theodore 2007).

<u>Fossils found within MOJA</u>: Nonfossiliferous (intrusive igneous rocks); included for completeness.

<u>Fossils found outside of MOJA</u>: Nonfossiliferous.

Cretaceous igneous rocks (Upper Cretaceous)

<u>Description</u>: Cretaceous igneous rocks of various compositions are present at and near many locations in MOJA (Baker, Cima Dome, Cowhole Mountain, the Fenner Hills, Halloran Wash, Horner Mountains, Ivanpah, Kelso Mountains, Piute Mountains, Piute Range, and Soda) (Grose 1959; Dunne 1972; Novitsky-Evans 1978; Miller et al. 1982; DeWitt et al. 1984; Theodore 2007).

<u>Fossils found within MOJA</u>: Nonfossiliferous; included for completeness.

<u>Fossils found outside of MOJA</u>: Nonfossiliferous.

Miocene igneous rocks (Miocene)

<u>Description</u>: Miocene igneous rocks include intrusive and extrusive rocks of diverse composition (Theodore 2007).

<u>Fossils found within MOJA</u>: Nonfossiliferous; included for completeness.

<u>Fossils found outside of MOJA</u>: Nonfossiliferous.

Pre-Quaternary sedimentary rocks (Miocene–Pliocene)

<u>Description</u>: The upper Cenozoic of MOJA and the immediate vicinity is a mosaic of interfingering local sedimentary and volcanic units, representing alluvial fan, eolian, fluvial, lacustrine, and landslide deposition with intervening volcanic flows and explosive eruptions. The Miocene volcanic and sedimentary rocks of MOJA can be as much as 370 m (1200 ft) thick and may include andesitic

and dacitic tuffs, andesitic and basaltic flows, tuff-rich sandstones, conglomerates, and tuff-rich lacustrine limestones. They may be overlain by limestone breccias (possibly created by landslides) and fanglomerate gravels, then finally unconsolidated sand, gravel, and boulders of Quaternary age (Hazzard 1954). Hazzard (1954) described these deposits in the Providence Mountains, Miller and Wooden (1993) described them in the New York Mountains, Nielson and Nakata (1993) described them in the Piute Range, Nielson et al. (1993) described them in the Castle Mountains and Castle Peaks, Nielson (1998) described them in the Grotto Hills area, and Bedford (2003) described them in the Kelso area. Similar sequences of Pliocene and Quaternary volcanic and sedimentary rocks are also present elsewhere, such as in the area of the late Miocene–Holocene Cima Volcanic Field (Wilshire 1992a, 1992b, 1992c, 1992d).

<u>Fossils found within MOJA</u>: The best-known Miocene fossils from MOJA come from the Lanfair Valley area. As described by Reynolds et al. (1995), the geology in this area consists of the 18.5 Ma Peach Springs Tuff, the rocks of the Woods Mountains volcanic center (18.5 to 17.6 Ma), basalt flows to as late as 10.2 Ma, and fluvial and lacustrine sedimentary rocks at the margins and between flows. The Woods Mountains volcanic center began with eruptions from 18.5 to 17.8 Ma (the Hackberry Spring volcanic rocks), followed by the eruption of the caldera-forming Wild Horse Mesa Tuff at 17.8 Ma, additional eruptions associated with the caldera from 17.75 to 17.73 Ma, and post-caldera eruptions of 17.6 Ma. Hobby rock and fossil collectors found the first reported vertebrate fossils in this area in the 1960s. Workers from the San Bernardino County Museum (SBCM; Redlands, California) worked here during the 1970s and 1980s. They defined two local faunas: the Wild Horse Mesa local fauna (SBCM 1.18.2), from between the Peach Springs Tuff and Wild Horse Mesa Tuff, and the Hackberry Wash local fauna (SBCM locality 1.26.1), associated with the Wild Horse Mesa Tuff. These sites represent lacustrine deposition near volcanoes; the rocks are sometimes identified as the informal Winkler Formation. The Wild Horse Mesa assemblage includes logs and wood of *Sequoia langsdorfii*, other conifer wood and needles (Reynolds et al. 1995), grasses and reed-like fossils (SBCM records), ostracodes, and flamingo tracks (Reynolds et al. 1995). The *Sequoia* and ostracodes were first reported by Hazzard (1954). The Hackberry Wash local fauna includes fossils of a rodent (cf. *Trogomys*), a pika, the canid *Metatomarctus* cf. *M. canavus*, a felid, a rhino (*Menoceras barbouri*), camelids (*Protolabis* sp. and cf. *Hesperocamelus*), and the small deer-like artiodactyl *Aletomeryx occidentalis* (Reynolds et al. 1995; Tedford et al. 2004). These fossils were found in silicified shale interbedded with jasper (Reynolds et al. 1995).

Other fossils have not received as much press. Cenozoic petrified wood has been reported (Santucci et al. 2004). It is likely that petrified wood built into structures at Mitchell Caverns came from Cenozoic deposits within MOJA, but the exact source locality or localities is unknown. Nielson and Nakata (1993) mentioned but did not describe Pliocene? and younger vertebrate fossils in playa deposits in the Piute Range. Post-middle Miocene limestone beds in the northern Lanfair Valley, in an area including MOJA and CAMO, are known to include “algal” filaments (Capps and Moore 1997), but localities are not stated, and it is not known if these fossils are from one or both of CAMO and MOJA.

For this report, MOJA staff observations of "reed-like" fossils were noted, but reeds are not a confirmed identification. The fossils vary in thickness from 5 to 17 mm (0.2 to 0.7 in), have a defined outer stem, and then were filled in with a later isopachous calcite cement. No other fossils were identified.

Fossils found outside of MOJA: In the Shadow Valley basin, north and west of MOJA in the vicinity of Valley Wells, lacustrine sediments of a similar age to the two Lanfair Valley local faunas have produced fossils of minnows and rodents (Reynolds 1994; Reynolds et al. 2003), and younger deposits (about 13 to 10 Ma) include fossils of stromatolites, rootlets, burrows, and tracks of birds and mammals (Friedmann 1999).

Upper Cenozoic volcanic rocks (upper Miocene–Pleistocene)

Description: Upper Cenozoic volcanic rocks include basalt lava flows and basalt cinder deposits.

Fossils found within MOJA: Nonfossiliferous; included for completeness.

Fossils found outside of MOJA: Nonfossiliferous.

Quaternary rocks and deposits (Pleistocene–Holocene)

Description: The Pleistocene and Holocene Quaternary deposits of MOJA consist of clay-, silt-, sand-, and gravel-sized sediment that is poorly sorted and unconsolidated. Sediments were deposited by alluvial fans, ephemeral rivers, and ephemeral lakes.

Fossils found within MOJA: Quaternary fossils in southeastern California are typically found in packrat middens, caves, or unconsolidated sediments (often fluvial, lacustrine, or wetland in origin). MOJA has examples of midden fossils and fluvial and lacustrine fossils, and extensive cave assemblages are known from just outside of the preserve. Additional information on Quaternary vertebrate sites in the region can be found in Jefferson (1991a) and "Pleistocene Vertebrates of Southwestern USA and Northwestern Mexico", an Internet compendium maintained by Arthur Harris (University of Texas–El Paso) (https://www.utep.edu/leb/pleistNM/).

Packrat middens are collections of plant material and food waste constructed by packrats (*Neotoma* spp.) and cemented by their viscous urine. They can be well-preserved in dry caves and rock shelters and illustrate the environment of the builder's foraging range. Middens are important tools for reconstructing the ecology and climate of the late Pleistocene and Holocene of the southwestern United States (Strickland et al. 2001). Additional information on packrat middens on NPS lands, including those from MOJA, can be found in Tweet et al. (2012). Small middens of unknown but presumably usually recent age can be found throughout MOJA in protected rock shelters. Clark Mountain has been known to host large midden deposits since 1948 (Mehringer and Ferguson 1969). Mehringer and Ferguson (1969), writing on bristlecone pines in the Mojave Desert, described three middens from a rock shelter on the southeast side of Clark Mountain. This site is probably either just within or just outside of the boundaries of MOJA. The three middens were dated to 28,720 ± 1,800 radiocarbon years before present (36,660 to 29,210 calibrated years before present), 23,600 ± 950 radiocarbon years before present (29,810 to 25,990 calibrated years before present), and 12,460 ± 190 radiocarbon years before present (15,280 to 14,040 calibrated years before present). (Note that radiocarbon dates are not the same as calendar dates, and must be calibrated to approximate calendar years. Dates can be calibrated using a calibration program such as Calib 8.2 [http://calib.org/calib/] if error ranges are provided. "Present" in "before present" is 1950.) The two older middens were mostly made up of bristlecone pine and limber pine needles, with minor amounts of *Abies concolor* and *Juniperus osteosperma* fossils, while the most recent midden was mostly made up of *Juniperus osteosperma* and single-leaf pinyon fossils, with minor amounts of *Abies concolor* and pine fossils. These three middens show clear differences with modern vegetation: bristlecone and limber pine are no longer found at Clark Mountain, and *Abies concolor* is only found in an isolated stand. In addition, characteristics of the pinyon wood indicate moister conditions than found anywhere on Clark Mountain today. During the Pleistocene, these trees could survive at lower elevations because of the different climate (Mehringer and Ferguson 1969). Spaulding (1977) described midden material filling the floor of a cave on Clark Mountain. This material is intermediate in age to Mehringer and Ferguson's middens at 19,900 ± 1,500 radiocarbon years before present (27,180 to 20,530 calibrated years before present), and also contained bristlecone and limber pine fossils. The midden assemblages show overlap of pinyon-juniper woodland with limber pine and *Abies concolor* during late glacial times, followed by takeover by pinyon-juniper woodland before the beginning of the Holocene (Wells 1983). A much more recent midden was described by Koehler et al. (2005), probably just outside of MOJA. This example was found at an elevation of 305 m (1,000 ft) and was dated to 1,880 ± 80 radiocarbon years before present (1,990 to 1,690 calibrated years before present). Further investigations of rock shelters and caves at MOJA would probably produce a detailed long-term record of Pleistocene–Holocene climate and biological changes in the preserve.

There are a few reports of fossils in the fluvial and lacustrine sediments of MOJA. Balkwill (1965) found specimens of the freshwater bivalve *Pisidium* in middle–upper Pleistocene fanglomerate deposits of the New York Mountains. Medall (1964) also found a *Pisidium* valve in similar sediments in the northern Lanfair Valley area, but the record is not detailed enough to distinguish between MOJA or CAMO. Vertebrate fossils have been reported from upper Pleistocene lacustrine sediments in southwestern MOJA (Jefferson 1991b; Reynolds et al. 2003). MOJA locality records indicate that mammoth, horse, and camel fossils had been recovered from several sites, and specimens of the fish *Siphateles bicolor* and the rodents *Neotoma* sp. and *Reithrodomtys* [sic; *Reithrodontomys*] sp. (harvest mouse) have been found at another location. Bivalves and gastropods have been collected from Soda Lake deposits in western MOJA (SBCM records).

<u>Fossils found outside of MOJA</u>: Comparable fossils have been found at several sites in the vicinity, including the Valley Wells wetlands sites, the assemblages of the Pleistocene lakes Lake Manix and Lake Mojave, and the lacustrine sediments of Piute Valley.

The Valley Wells fossil sites are on the north side of Interstate 15, across from MOJA. Previously this area was thought to have evidence of Pliocene, early Pleistocene, and late Pleistocene faunas from lake sediments, but later stratigraphic work and re-identification of some specimens showed that the deposits were produced by groundwater discharge and the site's fossils were all late Pleistocene to early Holocene in age, from about 60,000 to 8,000 years ago. The beds correlate to Members B, D, and E of Tule Springs Fossil Beds National Monument (TUSK) (Pigati et al. 2011;

Springer et al. 2018). Fossils found here are friable, fragmentary, and encrusted with carbonates (Springer et al. 2011). Animals known from Valley Wells include fossils identified to freshwater and terrestrial snails (Roth and Reynolds 1990), slugs, ostracodes, frogs, toads, lizards, snakes, rodents, rabbits, canids, felids, mammoths, horses, camels, llamas, and pronghorns (Pigati et al. 2011; Springer et al. 2011). Plants are represented by root voids (Pigati et al. 2011). The site represents successive wetland sequences, with the wetlands supporting meadows and a riparian forest (Pigati et al. 2011).

Deposits of the former Pleistocene lakes Lake Manix and Lake Mojave near MOJA have proven productive. Lake Manix, the larger and longer-lived of the two lakes, is represented by four laterally equivalent members made up of fanglomerate, alluvial, fluvial, lacustrine, and deltaic sediments, in turn overlying older Mojave River sediments (Jefferson 2003). Diverse fossils of lake and terrestrial organisms have been found in these deposits, including fossils of oncoidal stromatolites (Reynolds 2004), wood and leaves (Seiple 1994), freshwater bivalves and gastropods, ostracodes, and bones of chubs, sticklebacks, pond turtles, water birds, eagles, shorebirds, owls, sloths, rodents, rabbits, mammoths, dire wolves, coyotes, *Arctodus* and other bears, mountain lions, scimitar-tooth cats, horses, camels, llamas, pronghorns, mountain sheep, and bison (Jefferson 2003). Most of the vertebrates are thought to have lived around 290,000 years ago, with other clusters around 195,000 years ago and 60,000 to 19,000 years ago. Shell beds formed around 49,000 and 19,000 years ago (Seiple 1994). Life still flourished in the former Lake Manix basin after it drained. West of Silver Lake, fossils identified to fishes, frogs or toads, lizards, snakes, birds, rodents, rabbits, and deer show a community living along the Mojave River between about 17,000 and 10,000 years ago (Reynolds 2004). Lake Mojave is not as well known, but its deposits are also fossiliferous. Most of the Lake Mojave research has been done at Silver Lake, but similar fossils should be present at Soda Lake in MOJA. Fossils reported from Silver Lake identified to diatoms (Wells et al. 2003), reproductive structures of the green algae *Chara* (stonewort), bivalves, gastropods, ostracodes, and bony fishes (Leatham and Wilcox 1997). In addition, the tufa there was precipitated by cyanobacteria (Reynolds et al. 2003). Recent Lake Manix and Lake Mojave events have frequently been dated by radiocarbon dates on shells of the bivalve *Anodonta* (Ore and Warren 1971; Berger and Meek 1992; Reynolds et al. 2003; Reheis et al. 2015). A paleontology resource inventory conducted in support of maintenance of a fiber-optic line skirting the northwestern boundary of MOJA identified *Anodonta* shells at an aggregate quarry at the north end of Soda Lake, but the original stratigraphy has been lost (Chambers Group, Inc. 2013).

The locality information for Jefferson's late Pleistocene Piute Valley fossils is sparse (Piute Valley, 42 km [26 mi] south of Searchlight, Nevada), but it appears that the fossils came from a few km/mi east of MOJA. These fossils came from lacustrine sediments on the west side of the valley, and include body fossils identified to birds, rodents, rabbits, the American lion *Panthera atrox*, horses, camels, and bison (Jefferson 1991a).

There are several fossiliferous cave localities immediately outside of MOJA or in the state land enclave: Antelope Cave, Kokoweef Cave, Mescal Cave, Mitchell Caverns, and Quien Sabe Cave. MOJA itself has at least 45 small caves, and similar fossils may be present in its caves (Santucci et al. 2001). Antelope Cave has preserved a late Pleistocene assemblage including cyprinid fishes, tortoises, lizards, raptors, perching birds, bats, shrews, rodents, pikas, rabbits, coyotes, foxes, bears, mustelids, skunks, horses, camels, deer, pronghorns, and bighorn sheep (Jefferson 1991a; Reynolds et al. 1991a). Kokoweef Cave spans the Pleistocene–Holocene boundary. There is one date of 9,830 ± 150 radiocarbon years before present (11,760 to 10,990 calibrated years before present), with most fossils found lower than the dated horizon. This site's assemblage appears to stem from a combination of accidental falls and biological "collectors" such as raptors, packrats, and carnivorans (Goodwin and Reynolds 1989). Kokoweef Cave includes fossil identified to hackberry (*Celtis*), freshwater and terrestrial snails (Roth and Reynolds 1990), cyprinid fish, toads, tortoises, lizards, snakes, various birds, shrews, rodents, pikas, rabbits, bats, coyotes, foxes, ringtails, mustelids, skunks, bobcats, horses, camels, deer, pronghorns, and bighorn sheep (Jefferson 1991a; Reynolds et al. 1991b), as well as packrat middens (Goodwin and Reynolds 1989). Mescal Cave has yielded late Pleistocene and Holocene fossils of plants, tortoises, lizards, snakes, rodents, pikas, rabbits, canids, bobcats, ringtails, skunks, horses, and bighorn sheep, as well as packrat droppings (Jefferson 1991a; Stegner 2015). The fossil record here goes back to around 34,000 years ago. These fossils were primarily accumulated by packrats (Stegner 2015). Mitchell Caverns is notable as the only cave in the area with fossils of the ground sloth *Nothrotheriops*. Aside from the sloth, this site also has fossils of tortoises, birds, rodents, rabbits, foxes, felids, ringtails, horses, camels, and bighorn sheep, dating to the late Pleistocene–early Holocene (Jefferson 1991a). Quien Sabe Cave has Holocene fossils of vertebrates including shrews, rodents, and bats (Whistler 1991; Stegner 2015). Fossils from NPS caves are described in Santucci et al. (2001), which also briefly discusses the five sites near MOJA.

Taxonomy

Further work is needed to refine taxonomic identifications of some fossils in MOJA collections. The fossils included in this section encompass those housed in MOJA collections, in addition to those housed in other repositories, and those recorded in the field that have not been collected. Not all known fossils include provenance data. See Appendix A for a full list of taxa.

Fossil Plants

Petrified palm wood, palm roots, reed-like fossils (Figure 10), and other unidentified wood material have been known to collectors since at least the early 1960s. Logs and wood of *Sequoia langsdorfii* as well as other conifer wood and needles have been reported (Reynolds et al. 1995), and grass and reed-like fossils are also present (San Bernardino County Museum records). *Sequoia langsdorfii* material has also been reported in the Providence Mountains (Strong 1966; R. Reynolds, pers. comm. in Santucci et al. 2004). Plant macrofossils of Pleistocene to Holocene age are found in packrat middens. Mehringer and Ferguson (1969) recorded juniper, pine, and fir needles and twigs in packrat middens in the Clark Mountains.

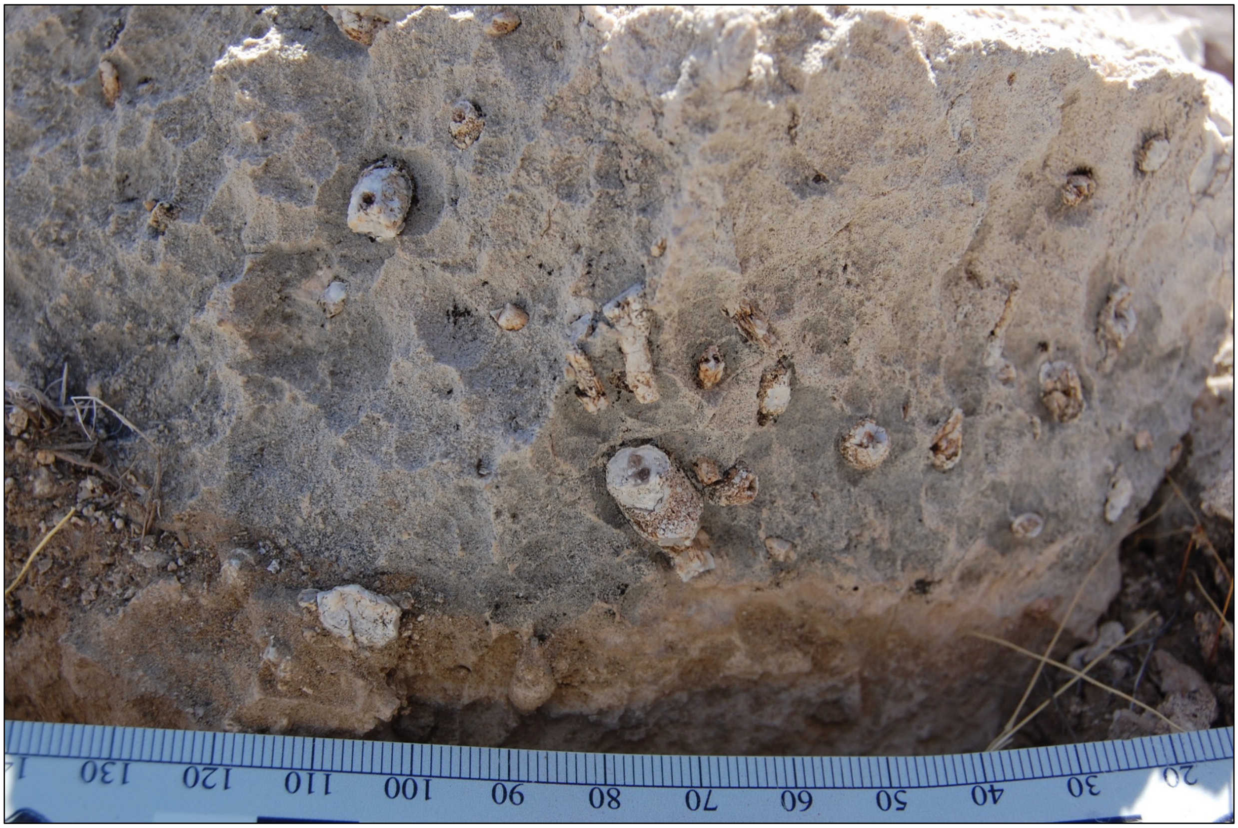

Figure 10. Reed-like fossils preserved in the Wild Horse Mesa Tuff (NPS/SOFIA ANDESKIE).

Fossil Invertebrates

Invertebrates represent the majority of known fossil resources within MOJA. They are found primarily in Carboniferous (Mississippian–Pennsylvanian) and lower Cambrian units. Invertebrate fossil resources are known from the Wood Canyon, Latham Shale, Chambless Limestone, Cadiz, Nopah, Sultan Limestone, Monte Cristo Limestone, and Bird Spring Formations. The Latham Shale, Monte Cristo Limestone, and Bird Spring Formation are particularly productive.

Phylum Porifera (sponges)

Archaeocyathid sponges were noted by Hagadorn et al. (2000) in the Wood Canyon Formation of the Kelso Mountains. The demosponge *Chaetetes* sp., which superficially resembles tabulate corals, has been reported in the Bird Spring Formation of the Cowhole Mountains (Barca 1960) and Old Dad Mountain (Yelverton 1963). Stromatoporoids are preserved near the base of the Valentine Member of the Sultan Limestone in the New York Mountains (Brown 1989). Undetermined sponges have been observed in upper Paleozoic clasts in the preserve (Figure 11).

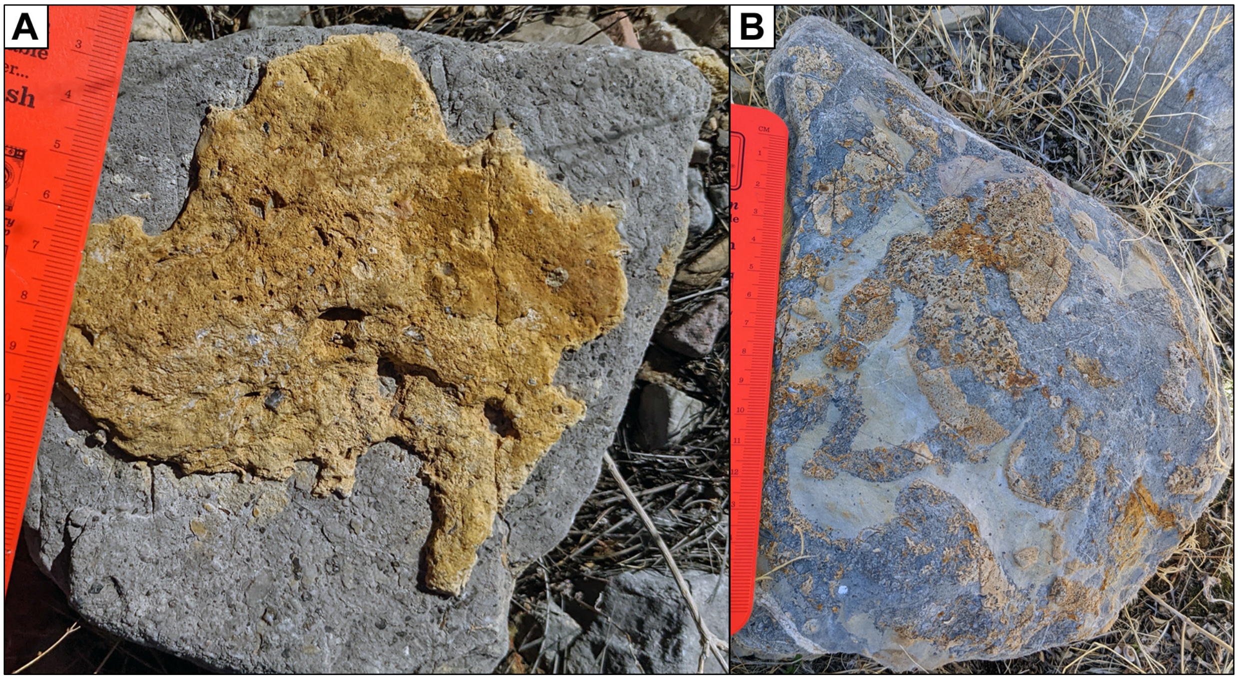

Figure 11. Sponges in crinoidal limestone, Providence Mountains (NPS/EMILY JOHNSON).

Phylum Cnidaria (jellyfish and corals)

Tabulate and rugose corals are found within MOJA in the Sultan Limestone, Monte Cristo Limestone, and Bird Spring Formation.

Tabulata

At Old Dad Mountain, Yelverton (1963) reported *Cladopora* sp.? in the Sultan Limestone and *Syringopora surcularia* in the Monte Cristo Formation. Stone et al. (2017) reported *Bayhaium merriamorum* and *Syringopora* sp. in the Bird Spring Formation of the Providence Mountains, and Barca (1960) reported *Syringopora* sp. in the Bird Spring Formation of the Cowhole Mountains. *Syringopora*-type tabulates have been observed in various units and in rubble throughout MOJA (Figures 12 and 13). "Honeycomb coral" (cf. *Favosites*) has also been observed in float (Figure 14A).

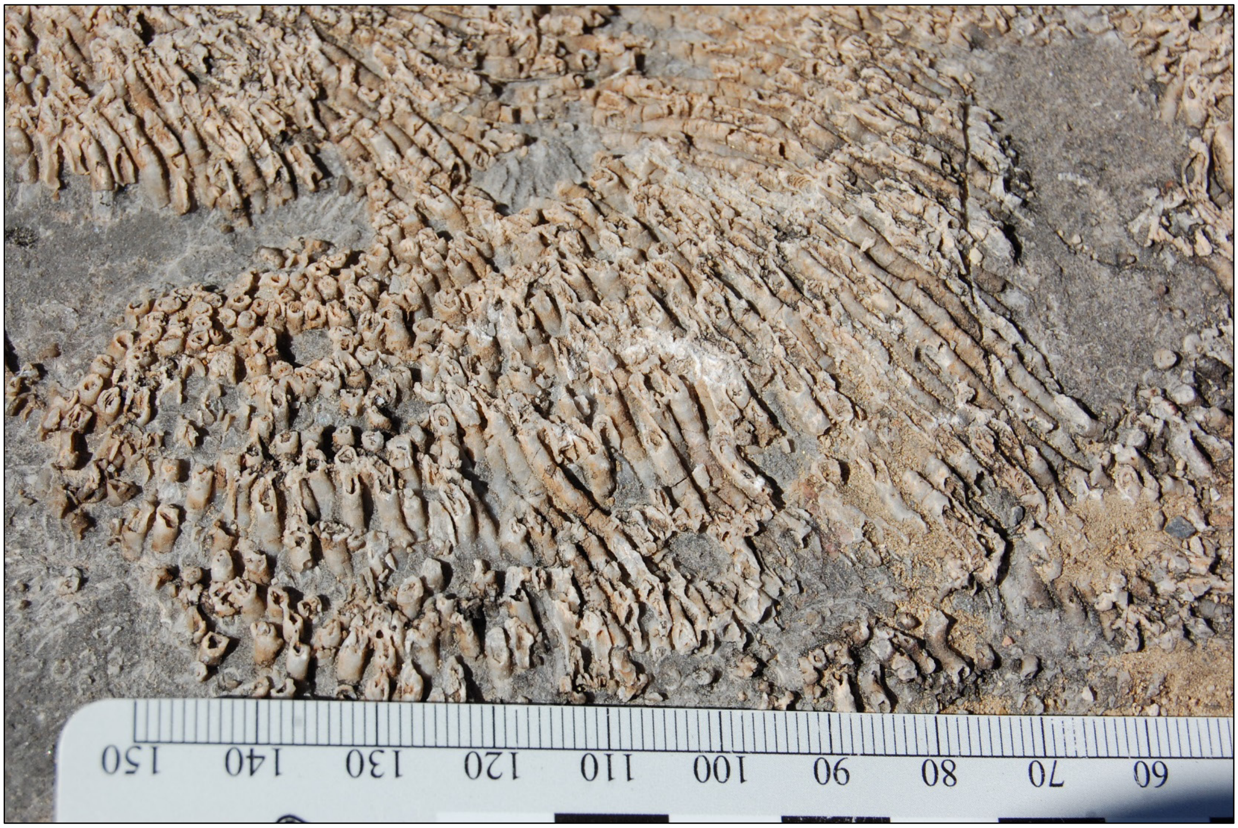

Figure 12. *Syringopora*-type tabulate coral in the Monte Cristo Formation of the Providence Mountains (NPS/SOFIA ANDESKIE).

Figure 13. *Syringopora*-type tabulate coral in limestone float washing out from the eastern Providence Mountains (NPS/EMILY JOHNSON).

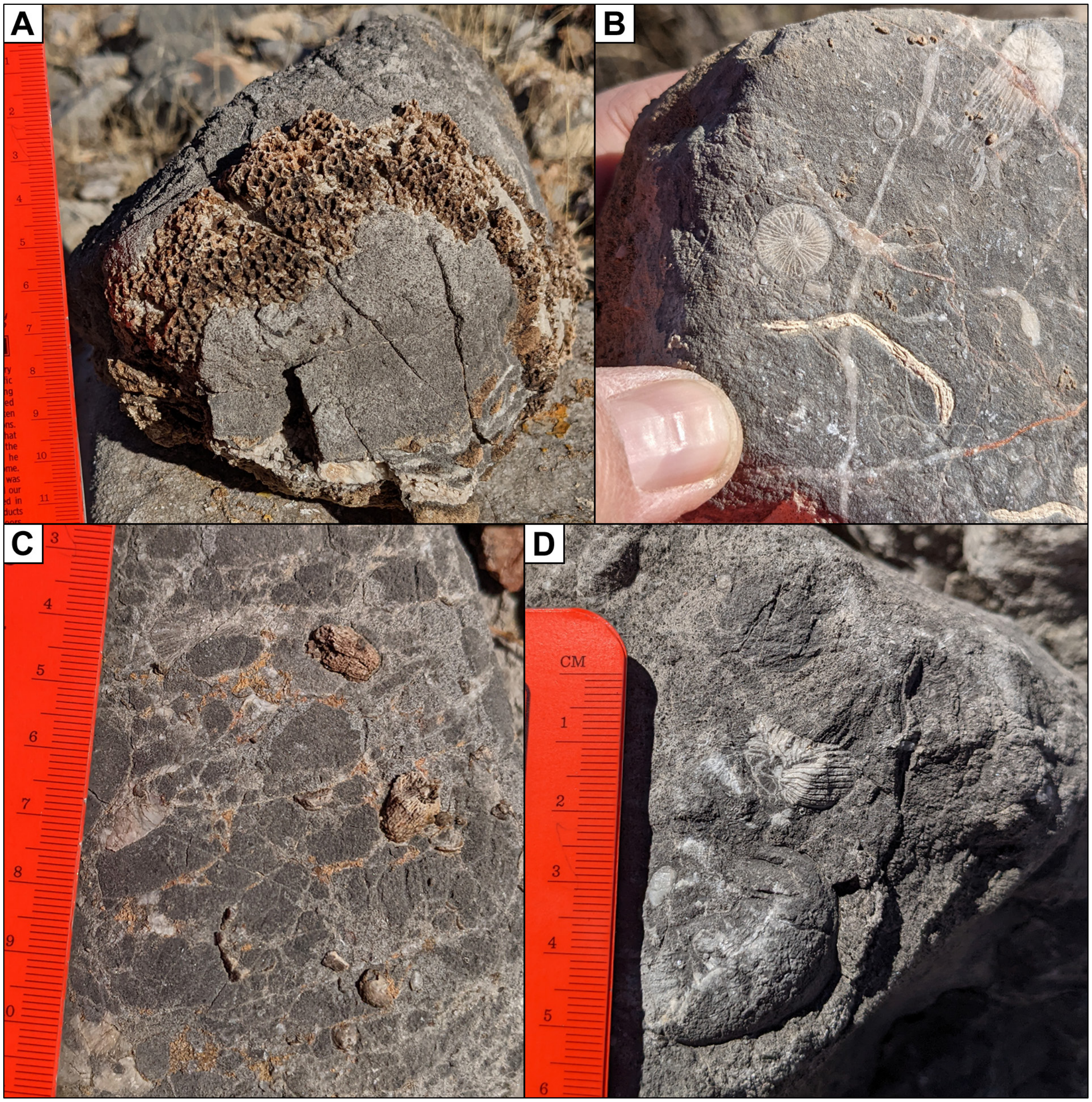

Figure 14. Coral specimens in limestone found in float in the Providence Mountains. **A.** *Favosites*-type tabulate coral. **B–D.** Horn corals (NPS/EMILY JOHNSON).

Rugosa

Hazzard (1954) reported *Disphyllum lonense?* and "*Cyathophyllum*" *flexum?* in the Valentine Member of the Sultan Limestone of the Providence Mountains, and *Caninophyllum* sp. in the Providence Mountains, in the Yellowpine Member of the Monte Cristo Limestone. Haskell (1959) reported *Homalophyllites crassus* in the Monte Cristo Formation of the New York Mountains. *Homalophyllites* sp. and *Triplophyllites* sp. are present in the Monte Cristo Formation of the northern Providence Mountains according to Hazzard (1954).

Yelverton (1963) reported *Amplexocarinia* sp. and *Lophophyllidium* sp. in the Bird Spring Formation, and *Zaphrentis*? sp. in the Monte Cristo Formation of Old Dad Mountain. *Amplexocarinia*? sp. was also reported in the Bird Spring Formation of the Cowhole Mountains by Barca (1960). Stone et al. (2017) reported *Siphonodendron warreni* in the Monte Cristo Formation of the Providence Mountains. Horn corals are encountered in float in the preserve as well (Figure 14B–D).

Phylum Bryozoa (moss animals)

Bryozoans are known to be present within MOJA in the Monte Cristo Limestone and the Bird Spring Formation. *Polypora* sp. is found in the Bird Spring Formation of the Providence Mountains (Hewett 1956). Yelverton (1963) reported the presence of *Fenestella* sp. in the Monte Cristo Limestone and Bird Spring Formation of Old Dad Mountain. Bryozoan fragments have also been recorded in the Bird Spring Formation of the Cowhole Mountains (Barca 1960).

Phylum Brachiopoda (lamp shells)

Brachiopods are found in within MOJA in the Latham Shale, Chambless Limestone, Cadiz Formation, Nopah Formation, Sultan Limestone, Monte Cristo Limestone, and the Bird Spring Formation. The Bird Spring Formation is known to be particularly productive.

Several Cambrian formations have brachiopods, mostly belonging to phosphatic-shelled "inarticulate" lineages (Figure 15). The phosphatic composition often gives the shells a superficially fingernail-like appearance. *Acrothele spurri* was reported in the Chambless Limestone by Mount (1976, 1980), and *Paterina prospectensis* is present in the Latham Shale and Chambless Limestone according to Hazzard (1954). Gaines and Droser (2002) described acrotretid brachiopods in the Latham Shale of the Providence Mountains. Hazzard (1954) also reported *Nisusia* sp. in the Cadiz Formation, and *Obolus* sp. has been reported in the Nopah Formation (Hazzard and Mason 1936).

Brachiopods from younger formations at MOJA are calcitic-shelled "articulate" forms (Figure 16). *Atrypa* sp. has been identified in the Valentine Member of the Sultan Limestone in the Mescal Range (Evans 1971) and Old Dad Mountain (Yelverton 1963). On Clark Mountain, Dobbs (1961) reported spirifer and productid brachiopods in the Ironside Dolomite Member of the Sultan Limestone, as well as unspecified brachiopods in the Valentine Member of Sultan and the Anchor Member of the Monte Cristo Formation. Hazzard (1954) identified several brachiopods in the Bird Spring Formation of the Providence Mountains, including species of *Derbyia*, *Dictyoclostus*, *Composita*, and *Marginifera*. In the Bird Spring Formation of Old Dad Mountain, Yelverton (1963) reported species of *Composita*, *Derbyia*, and *Linoproductus*.

Figure 15. Phosphatic brachiopod shell partially exposed in a specimen from the Kelso Mountains. It is among the group of specimens recovered from May 2020 looting (NPS/JUSTIN TWEET).

Figure 16. Brachiopod shell (lower left) in situ in the Monte Cristo Limestone of the Providence Mountains (NPS/EMILY JOHNSON).

Phylum Mollusca: Class Bivalvia (clams, oysters, etc.)

At Old Dad Mountain, Yelverton (1963) identified the bivalves *Myalina* sp.? and *Parallelodon* sp.? in the Monte Cristo Limestone and *Myalina* sp.? and undetermined bivalves in the Bird Spring Formation. Medall (1964) found a single valve of the freshwater clam *Pisidium* sp. in fanglomerate of the New York Mountains. *Anodonta californiensis* is present in Quaternary Soda Lake deposits (San Bernardino County Museum records).

Phylum Mollusca: Class Cephalopoda (octopuses, squids, nautiloids, etc.)

Ammonoids are present in the Bird Spring Formation of the Providence Mountains. Gordon (1964) described an ammonite questionably identified as *Paralegoceras texanum* in a Bird Spring Formation block in the Providence Mountains. This specimen was collected by Hazzard, who initially identified the ammonite as *Gastrioceras* cf. *G. cancellatum* (Hazzard 1954). The nautiloid *Orthoceras* sp. was reported by Yelverton (1963) in the Bird Spring Formation near Old Dad Mountain; this identification is likely shorthand for a straight-shelled (orthoconic) nautiloid, as *Orthoceras* is both a "wastebasket" taxon and only definitely known from much older rocks.

Phylum Mollusca: Class Gastropoda (snails)

A small number of gastropod taxa have been reported from the upper Paleozoic rocks of MOJA (Figure 17). An unnamed snail referred to as *Glyptospira* sp. A was reported by both Plas (1972) and Erwin (1988) in the Bird Spring Formation of the Providence Mountains. Plas (1972) additionally reported *Amaurotoma zappa* and species of *Anomphalus* in middle Wolfcampian rocks in the Providence Mountains. *Bulimorpha* sp.? is present in the Bird Spring Formation near Old Dad Mountain according to Yelverton (1963), and *Bellerophon* sp. in the same unit in the Striped Mountain area (UC–Riverside records). Hazzard (1954) identified *Platyschisma ambiguum* in the Valentine Member of the Sultan Limestone in the Providence Mountains. Stone et al. (2017) further reported undetermined gastropods in the Monte Cristo Limestone and the Bird Spring Formation of the Providence Mountains. *Planorbella tenuis* is present in Quaternary Soda Lake deposits (San Bernardino County Museum records).

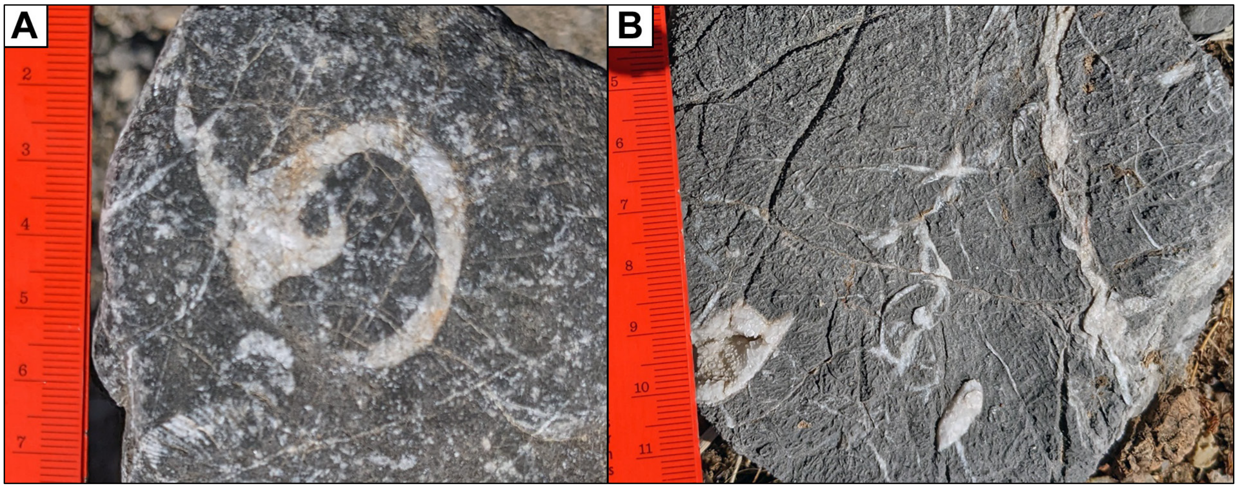

Figure 17. Gastropods in limestone in float (NPS/EMILY JOHNSON).

Phylum Arthropoda: Class Trilobita

Trilobite fossils are abundant in the Latham Shale of the Kelso and Providence Mountains (Figures 18 and 19), and more rarely reported in the Wood Canyon Formation, Zabriskie Quartzite, Chambless Limestone (Figure 20), Cadiz Formation, Bonanza King Formation, Nopah Formation, and Bird Spring Formation.

The Latham Shale is a source of trilobite fossils in the Kelso and Providence Mountains. Redlichiid trilobites of the genera *Olenellus*, *Bristolia*, *Mesonacis*, and *Peachella* have all been documented. Hagadorn et al. (2000) reported nevadiid trilobites in the Wood Canyon Formation of the Kelso Mountains. In the Chambless Limestone, *Olenellus, Bristolia*, and *Mesonacis* have been reported. Hazzard and Mason (1936) and Hazzard (1954) reported trilobites including corynexochids, ptychopariids, and agnostids in the Cadiz Formation and ptychopariids, agnostids, and elviniids in the Nopah Formation. Hazzard (1954) also reported the trilobite *Griffithides* sp. in the Bird Spring Formation of the Providence Mountains.

Figure 18. Complete *Olenellus clarki* specimen, Latham Shale, Providence Mountains (NPS).

Figure 19. Olenellid trilobite in a Latham Shale slab, Kelso Mountains (NPS/JUSTIN TWEET).

Figure 20. Trilobite fragments in the Chambless Limestone of the Providence Mountains (NPS).

Phylum Arthropoda: Class Radiodonta

The radiodont *Ramskoeldia consimilis*? (Pates et al. 2021), initially interpreted as *Anomalocaris canadensis* (Briggs and Mount 1982), has been found in the Latham Shale. Specimens from MOJA are housed in UCR and UCMP collections (Figure 21).

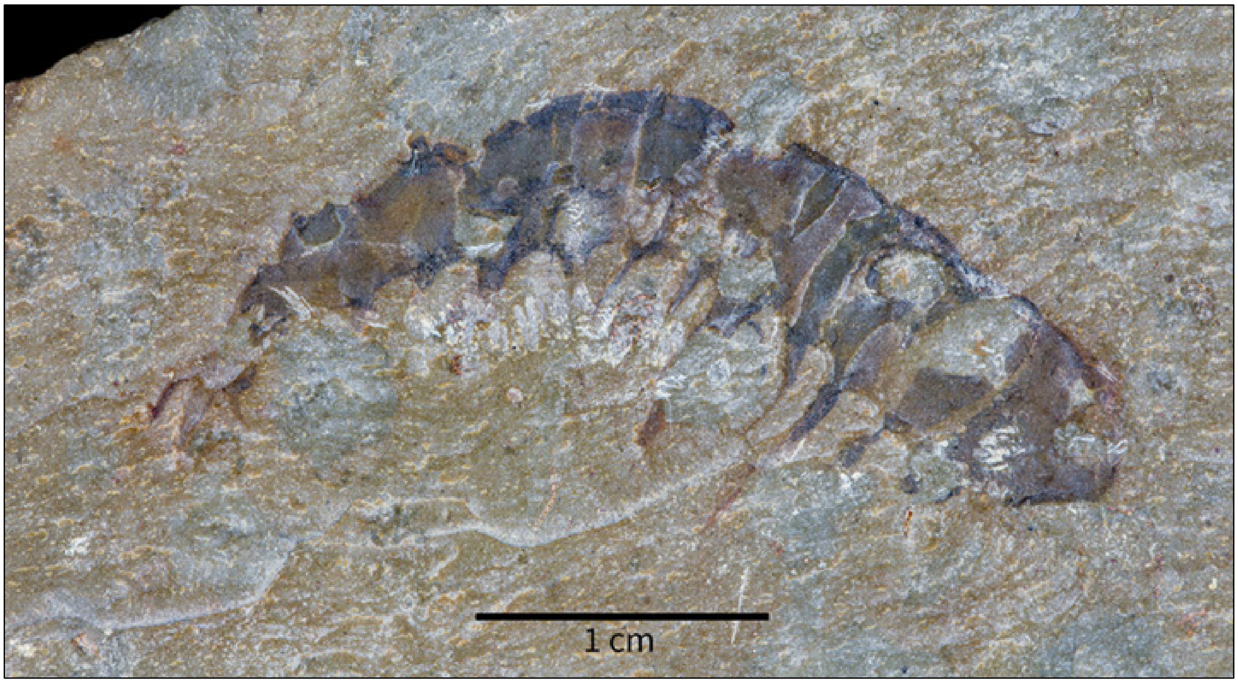

Figure 21. *Ramskoeldia consimilis*?, UCMP 37470 (UCMP/DAVE STRAUSS).

Phylum Echinodermata (sea stars, brittle stars, sea lilies, sea urchins, etc.)

Crinoids are the most common type of echinoderm preserved within MOJA (Figure 22), found in the Sultan Limestone, Monte Cristo Formation, and the Bird Spring Formation. Crinoid stalk fragments are present in the Dawn, Anchor, and Bullion Members of the Monte Cristo Formation in the Providence Mountains, the Cowhole Mountains, Old Dad Mountain, and Striped Mountain. In the Providence Mountains the crinoid-bearing limestone grades to encrinite. Crinoids and echinoderm debris are also present in the Bird Spring Formation of the Providence Mountains and the New York Mountains.

Of other echinoderms, Mount (1976, 1980) reported the eocrinoid ?*Gogia* sp. from the Latham Shale. In a thesis, Wilbur (2005) informally described the MOJA taxon as new species “*Gogia fowleri*.” Novitsky-Evans (1978) described “pelmatozoan” columnals in the Dawn and Anchor Members of the Monte Cristo Formation in the Cowhole Mountains. Holothurian (sea cucumber) plates were among the microfossils reported by Law (1969) from Pennsylvanian-aged Bird Spring Formation rocks, which is of note as the only report of holothurian fossils to date from an NPS-managed unit (they are doubtless more widespread but, being microfossils, are more difficult to observe than macroscopic fossils). The echinoid *Echinocrinus* sp. is present in the Bird Spring Formation in the Striped Mountain area (UC–Riverside records).

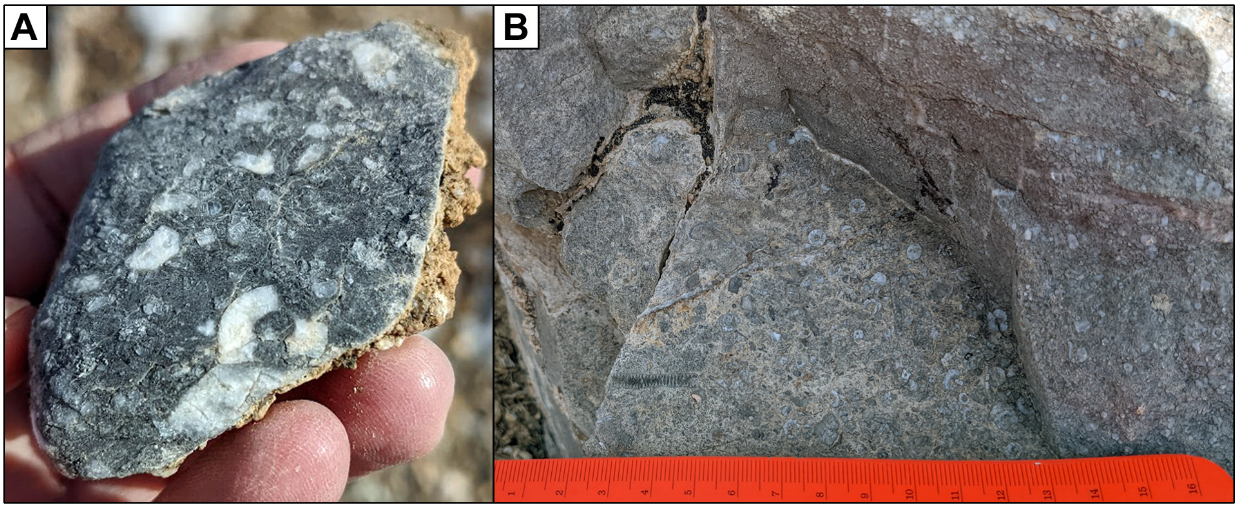

Figure 22. Crinoid fossils in MOJA. **A.** Crinoid fragments in limestone float, Striped Mountain. **B.** Encrinite in Bonanza King Canyon, Providence Mountains (NPS/EMILY JOHNSON).

Other Invertebrates

Hyoliths have been reported from the Latham Shale, Chambless Limestone, and Cadiz Formation in MOJA. Undetermined hyoliths were recorded by Gaines and Droser (2002) in storm deposits in the upper Latham Shale of the Providence Mountains. Hazzard (1954) reported *Hyolithes* sp. in the Chambless Limestone and Cadiz Formation of the Providence Mountains.

A palaeoscolecid worm was collected and described by Mount (1976, 1980) from the Latham Shale and figured in Conway Morris and Peel (2010).

The ostracod *Bairdia* sp. was reported in the Sultan Limestone of the Ivanpah Quadrangle by Hewett (1956), along with unspecified ostracodes in the Bird Spring Formation. Hazzard (1954) reported unspecified ostracodes in Miocene tuffs. Reynolds et al. (1995) mentioned the presence of undetermined ostracodes in the Winkler Formation.

Fossil Vertebrates

Class Mammalia

Reynolds et al. (1995) reported Miocene vertebrate fossils in MOJA in “silicified shale interbedded with jasper.” Rhino (*Menoceras*) remains including a humerus, patella, metacarpals, multiple lower jawbones, and a compressed skull were collected. The authors also reported a deer-like artiodactyl resembling *Aletomeryx* sp., as well as the camels *Miolabis* and *Aepycamelus*. Other paleontological finds include small rodent teeth, felid remains including a forelimb, and teeth and bones of *Tomarctus* sp., a coyote-sized dog. The age of the specimens is well-constrained by the underlying Peach Springs Tuff (18.5 Ma) and the overlying Wild Horse Mesa Tuff (17.8 Ma) (Reynolds et al. 1995). Updated identifications of most of the taxa were included in Tedford et al. (2004) (see Appendix A below).

Pleistocene mammal fossils have also been recorded within the preserve. In the early 2000s, MOJA staff collected a late Pleistocene horse (cf. *Equus*) limb bone and mammoth (*Mammuthus* sp.) tooth fragment in float; these bones are currently housed at SBCM. A harvest mouse (*Reithrodontomys* sp.) proximal femur fragment and *Neotoma* (packrat) caudal vertebra were collected in 2002 and are currently housed at MOJA headquarters in Barstow.

Other Vertebrates

In a study of Devonian stratigraphy of the Providence Mountains, Miller (1983) identified numerous conodonts in the Sultan Limestone including species of *Patrognathus*, *Polygnathus*, and *Spathognathodus*. Law (1969) reported a number of conodont species in the Bird Spring Formation.

A Tui chub (*Siphateles bicolor*) vertebra was collected in 2002 and is currently housed at MOJA headquarters in Barstow.

Ichnofossils

Microbial trace fossils are represented by various structures. Stromatolitic dolostone was reported in pre-Johnnie Formation rocks referred to as the “Seventeenmile Point Formation” by Wilson (1978). Wilson described an oncolitic upper interval, and stromatolites and cryptalgal lenses in the middle interval. Oncoids, referred to by Bedford (2003) as *Girvanella* sp., are present in the Chambless Limestone within MOJA (Figure 23) and can be considered characteristic of the formation.

Figure 23. Oncoids in Chambless Limestone in float in the Kelso Mountains (NPS/JUSTIN TWEET).

Ichnofossils associated with invertebrates are particularly common in the Wood Canyon Formation and the Latham Shale. Tracks, burrows, and tubes are present throughout the formation (Figures 24 and 25). Invertebrate-associated ichnofossils *Taphrhelminthopsis* isp., *Treptichnus pedum*, and other arthropod traces were described in the Wood Canyon Formation of the Kelso Mountains by Hagadorn et al. (2000). *Treptichnus pedum* is an index fossil for the beginning of the Cambrian. *Skolithos* isp. “piperock” is present at the top of the middle member of the Wood Canyon Formation in the Providence and Kelso Mountains. *Cruziana* isp., the elongate bilobate trackways of trilobites and similar arthropods, as well as their resting trace *Rusophycus* isp. have been observed in the Wood Canyon Formation of the Kelso Mountains (Figure 26). Fecal trails, *Cruziana* isp., algal markings, and unspecified invertebrate burrows are found in the Latham Shale.

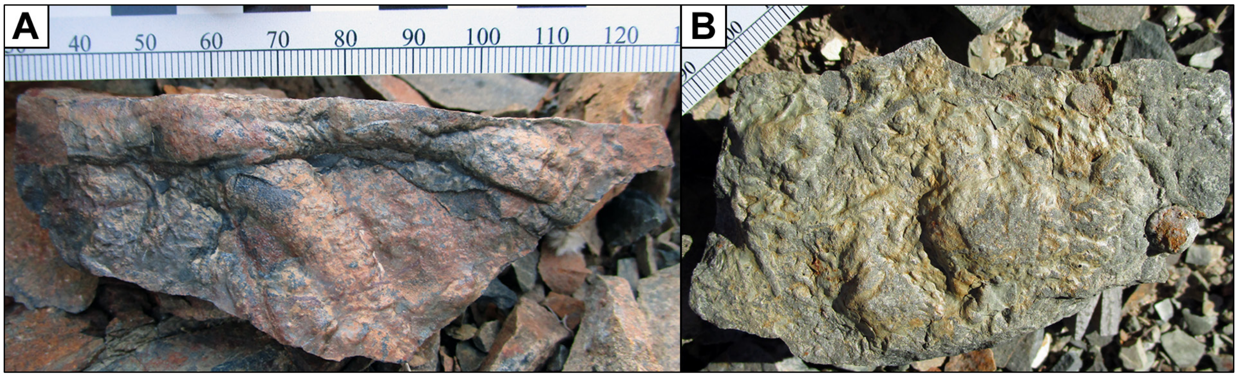

Figure 24. Wood Canyon Formation ichnofossils (NPS/JUSTIN TWEET). **A.** *Cruziana*-type trackways. **B.** Bioturbated surface.

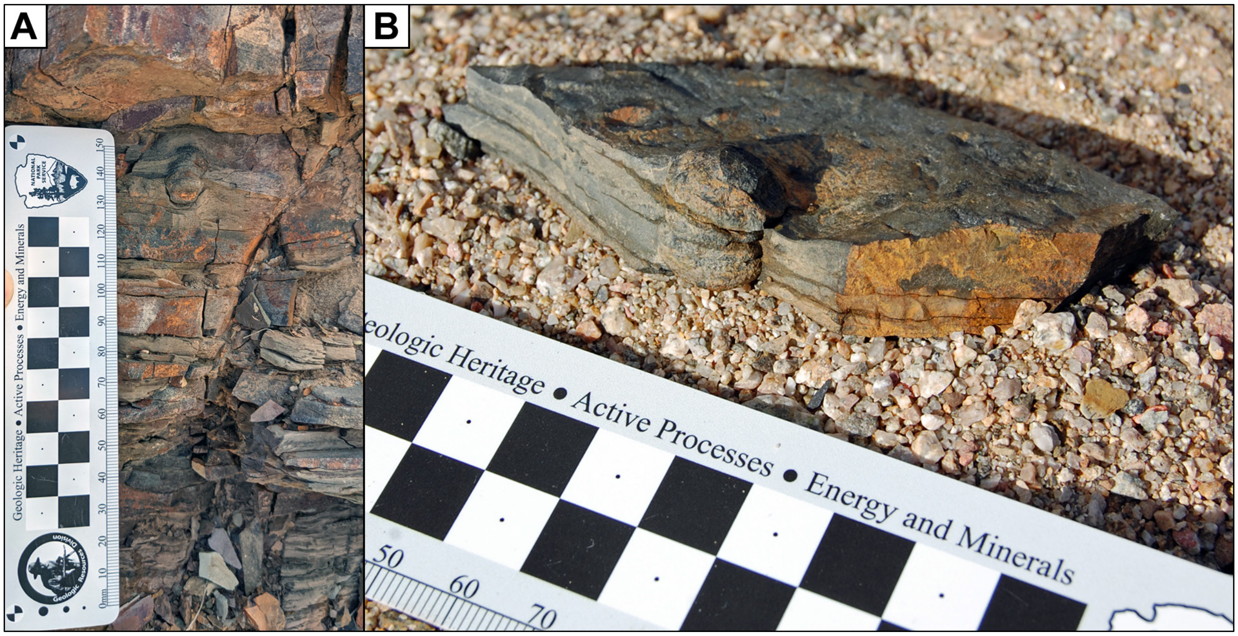

Figure 25. Cylindrical burrows in situ and in float in the upper Wood Canyon Formation (NPS/EMILY JOHNSON).

Figure 26. *Cruziana* isp. and *Rusophycus* isp. trackways in a block from the Wood Canyon Formation (NPS/EMILY JOHNSON).

Flamingo-like footprints produced by a large wading bird were reported in the Winkler Formation by Reynolds et al. (1995).

Other Fossils

The frond-like Ediacaran organism *Swartpuntia* sp. was reported by Hagadorn et al. (2000) in the Latham Shale of the Kelso Mountains. This is of note because almost no Ediacaran organisms persisted beyond the Precambrian–Cambrian boundary. *Morania* n. sp. colonies are present in the Latham Shale according to UCR records.

Fusulinid foraminifera are abundant in the Bird Spring Formation of the Providence Mountains (Figure 27), as well as Old Dad Mountain and the Cowhole Mountains. Identified foraminifera include species of *Leptotriticites*, *Parafusulina*, *Pseudoschwagerina*, *Schwagerina*, *Stewartina*, and *Triticites* (Stevens and Stone 2007; Stone et al. 2017). They are useful for determining the relative ages of the rocks containing them.

Figure 27. Fusulinid foraminifera in limestone float in the eastern Providence Mountains alluvial fan (NPS/EMILY JOHNSON).

Fossil Localities

An important component of this paleontological resource inventory was to compile geospatial data for existing fossil sites as well as new fossil sites. A table of field-checked localities can be found in Appendix F. Details on MOJA localities are available to qualified researchers.

Paleontological Localities Near MOJA

Mescal Track Site

This locality is in the Mescal Range on BLM-administered land. The rocks exposed at the site are sandstones of various colors, compositions, and resistance to erosion. The lowest exposed interval is reddish-orange and ledgy. Higher up in the exposure the sandstone turns yellow-tan and is more recessive. Further up the rocks turn reddish and ledgy again. This outcrop has been attributed to the Aztec Sandstone; however, this identification is questionable. Similar sandstone in the Cowhole Mountains is intertongued with Middle Jurassic igneous flows dated to 172 ± 6 million years ago by Busby et al. (2002), while the Aztec–Navajo–Nugget sandstone belt is well-established as Early Jurassic in age. This outcrop may instead correlate to younger, Middle Jurassic units recorded in Utah.

Quadruped tracks are abundant in the lower flaggy interval, but only sporadically present higher in the unit. They are typically 1.5 to 2.5 cm (0.6 to 1.0 in) across, and subcircular to elliptical (Figure 28). The tracks have been previously described in several publications. Evans (1958) first reported the presence of quadruped "dinosaur" tracks here in situ and in slabs blasted for quarrying. Reynolds (2006) attributed tracks to three ichnotaxa of bipedal theropods and eight different quadrupedal ichnotaxa. When observed in person, the tracks appeared less diverse than described in Reynolds (2006) and Reynolds and Mickelson (2006). Most of the vertebrate tracks are interpreted as *Brasilichnium*, a small quadrupedal mammal or mammal relative. Pinprick-like arthropod tracks are also present, along with cross-bedding, ripple marks, and raindrop impressions. Horsetail imprints and *Skolithos* have also been reported here but were not observed by the MOJA field team.

Reynolds (2006) reported that people have previously tried to remove some of the tracks, though no obvious evidence of looting was found in 2021. Springer et al. (2009) indicated that curators, employees, and volunteers for the San Bernardino County Museum (SBCM) and the National History Museum of Los Angeles County (LACM) collected trackway slabs in April 2008 for preservation as part of a partnership with the Needles office of the California Bureau of Land Management. Plans were in place to exhibit these trackways at both museums. The excavated specimens were housed at both LACM and SBCM. Trackway panels are on permanent display at the Dinosaur Hall at LACM. Panels are also displayed at SBCM (K. Springer, U.S. Geological Survey, pers. comm., 2022). The field team also found an area with numerous pieces of purplish-brown rhyolite that showed evidence of human working, including an area of debitage, making this both a paleontological site and an archeological site. It appears that the sandstone ridge, with abundant agaves, was a site of agave processing.

Figure 28. Quadruped tracks in situ in Jurassic sandstone (NPS/JUSTIN TWEET).

Mitchell Caverns Natural Preserve

Mitchell Caverns is a complex of three caverns within the Pennsylvanian–Permian Bird Spring Formation. The bedrock contains a variety of marine fossils, and the caves themselves contain fossil vertebrates from the Pleistocene, including a variety of mammals, as well as more recent animals. Two of these caverns, El Pakiva and Tecopa, are connected by a man-made tunnel and are open to public tours led by California State Park rangers. A third cave, Winding Stair, is closed to the public.

The caverns are within the bounds of Mojave National Preserve on the east flank of the northern Providence Mountains, in the Providence Mountains State Recreation Area. They are the only limestone caves in the California State Park system, where carbonate rocks are rare except in the eastern Mojave Desert. Mitchell Caverns is surrounded by MOJA; however, it is important to note that this land is not managed by the National Park Service. The area became part of the California state park system in 1956 and Mitchell Caverns was designated a National Natural Landmark in 1975.

Many marine invertebrate fossils are preserved in the limestone walls of the Mitchell Caverns. Fusulinid foraminifera were common in the shallow and warm Bird Spring Sea 300–250 million years ago, and their grain-like, approximately centimeter- (half-inch-) long tests are well-preserved and particularly widespread near the main cave entrance. Brachiopod shell fragments and crinoid stalks and stems can also be found near entrances and along trails outside the caves (Sharp and Glazner 1993). Bryozoans, mollusks, echinoids, and non-reef-building corals are also present in the Bird Spring Limestone in the Providence Mountains and at Mitchell Caverns (Hall 2007).

Beyond the Pennsylvanian to Permian marine fossils preserved in its limestone walls, terrestrial vertebrate fossils of the Rancholabrean North American Land Mammal age (less than 240,000 years ago to 11,000 years before present) and early Holocene have also been found in Mitchell Caverns. Pleistocene fossils found in the caves include extinct large horses and the extinct camel genus *Camelops* (Jefferson 1991a). Mitchell Caverns is also the source of the area's only fossils of the Shasta ground sloth *Nothrotheriops shastensis* (Harper 1998). The site's numerous Holocene fossils include desert tortoises, as well as those of several avian taxa including great horned owls, greater roadrunners, and ravens (Jefferson 1991b). Small mammalian fossils from Mitchell Caverns represent desert cottontails, hares, ringtails, and various rodent genera including squirrels, mice, and rats. Fossils of foxes, small cats, bobcats, and bighorn sheep have also been found (Jefferson 1991a).

The MOJA field team visited Mitchell Caverns and the surrounding area with California State Parks Interpretive Ranger Andrew Fitzpatrick in November 2021. The cave system contains several packrat middens, both indurated and recent. Amberat is present in an overhead crevice near the El Pakiva Cavern entrance. This is a remnant of what was once a much larger indurated midden which was destroyed when State Parks crews blasted the cave entrance to widen it. Remains of acorns and small bones weather out of the midden. Deeper in the caves, colonial corals are exposed in a solution tube (Figure 29). The MOJA team also observed the location in Tecopa Cavern where a sloth (*Nothrotheriops*) humerus was found. There appears to be additional sediment in the chamber, so perhaps future excavation could uncover more of the sloth or other fossils. Alternatively, the specimen may have been the only part of a carcass transported to the cave by a carnivore.

Invertebrate fossils are exposed in Bird Spring Formation rocks cropping out along the trails between the visitor center and caves. A large gastropod, crinoid columnals, and fusulinid foraminifera were identifiable among the general fossil debris (Figure 30). Inside the visitor center are fossils on display which Fitzgerald collected nearby, including tabulate and colonial rugose corals, gastropods, and several fusulinid-bearing rocks. The walls of the visitor center and cabins were built by Jack Mitchell in the 1930s. These buildings include a wide variety of stones collected by Mitchell, some of which are fossils or fossiliferous (Figure 31). Some are of local provenance; others are from unknown locations. For example, several columns feature large pieces of whitish petrified wood, potentially but not definitely from Cenozoic deposits in MOJA. The corals found in the building walls, both tabulate and colonial rugose, are of types known to be present in the Bird Spring Formation and other local formations. Crinoids and brachiopods were also observed. One unusual piece built into the top of a retaining wall has several small vertebrate tracks, resembling both the Coconino Sandstone of Arizona and the tracks observed by the MOJA team in the Mescal Range.

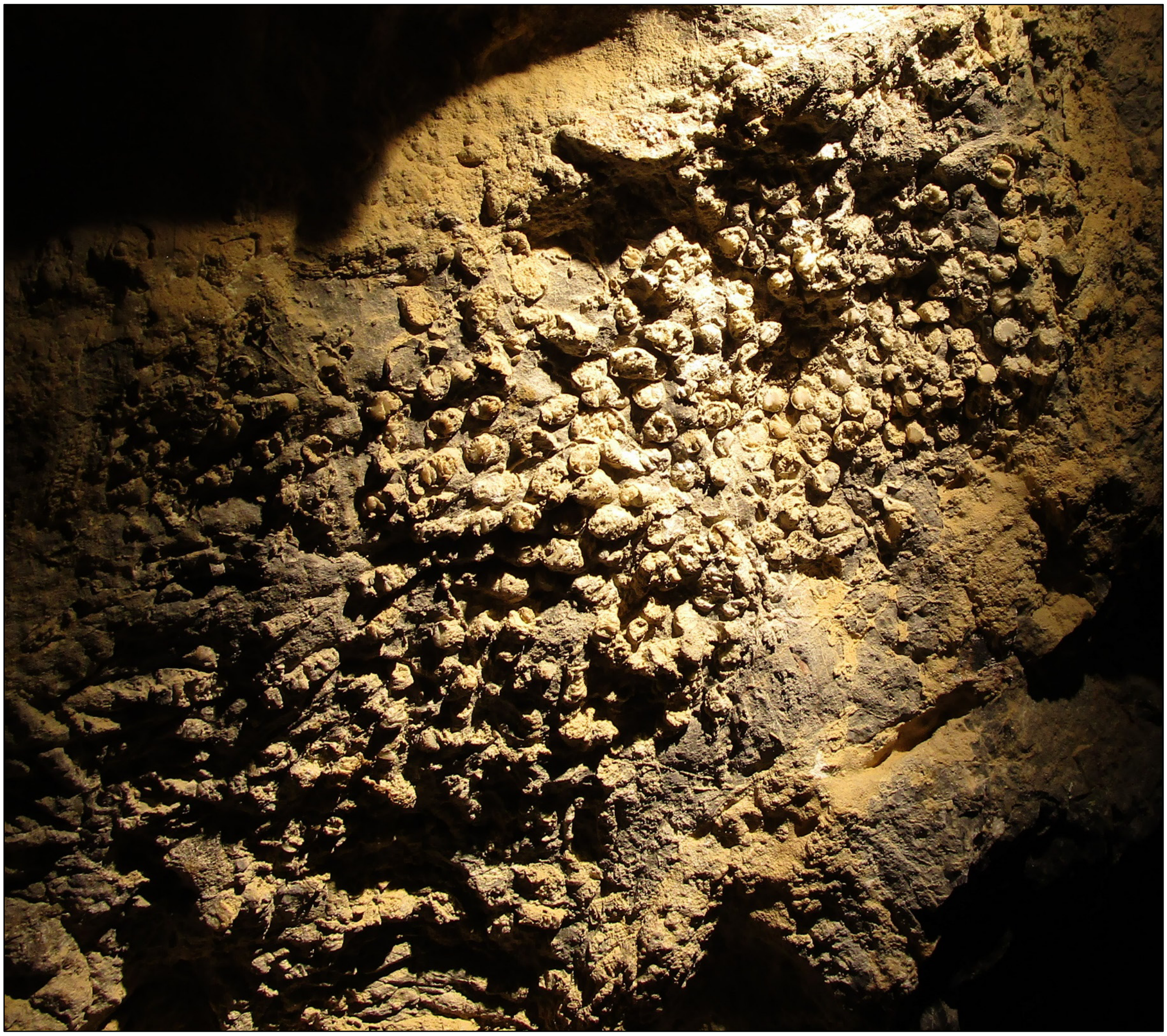

Figure 29. Colonial coral preserved within the Bird Spring Formation walls of Mitchell Caverns (NPS/JUSTIN TWEET).

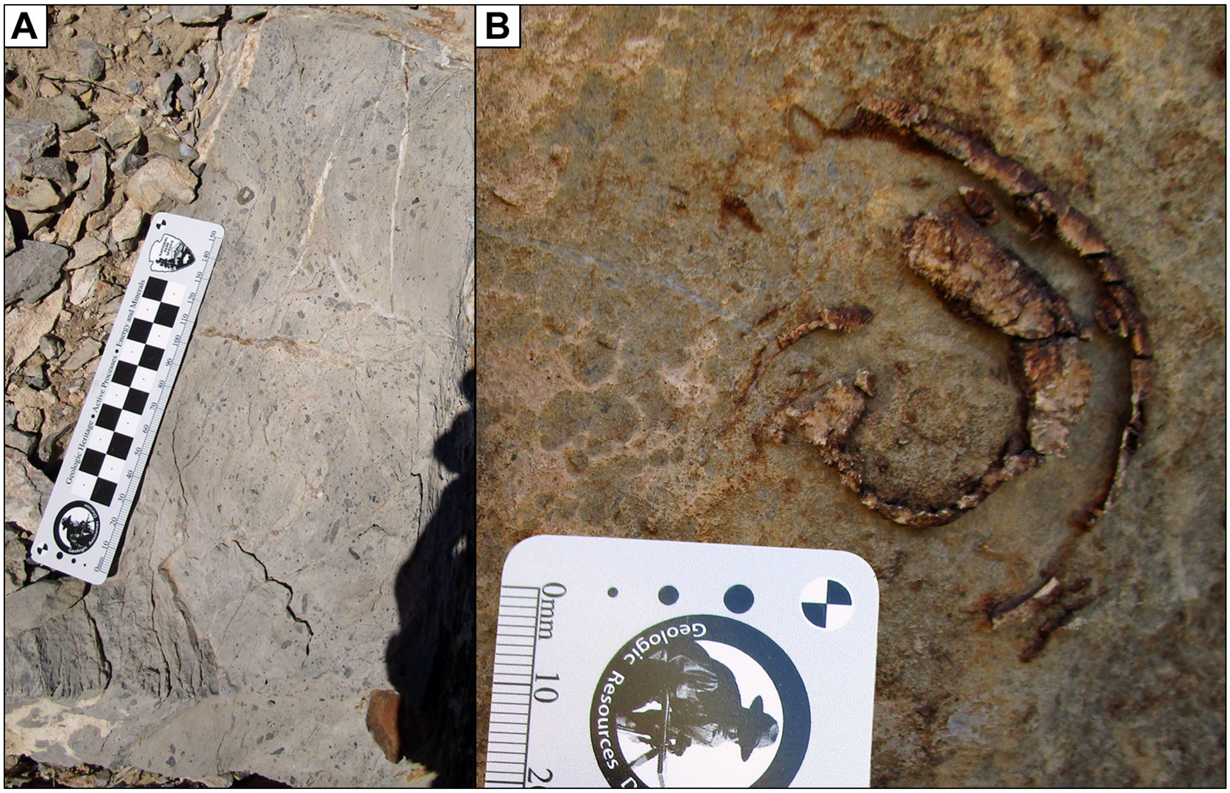

Figure 30. Fossils preserved in the Bird Spring Formation on the path to Mitchell Caverns. **A.** Fusulinid foraminifera and crinoid fragments. **B.** A large gastropod (NPS/JUSTIN TWEET).

Figure 31. Fossils built into the walls of one of Mitchell's cabins (NPS/JUSTIN TWEET).

Cultural Resource Connections

It is estimated that people have been present in the Mojave Desert since the close of the Pleistocene, and have been using potentially fossiliferous rocks, such as chert, to make tools and other artifacts (Knell 2014). With such a long record of human presence, it would not be surprising to find fossils in cultural resource contexts. The most likely types of associations in MOJA are fossiliferous stones used to make artifacts, and remains of flora and fauna at archeological sites.

There are many ways for paleontological resources to have connections to cultural resources. Examples of paleontological resources in cultural contexts include, but are not limited to: fossils used by people for various purposes, such as petrified wood used for tools, spear points, and other artifacts, or fossil shells picked up as charms or simply because they looked interesting; associations of prehistoric humans with paleontological resources, such as kill sites of mammoths, prehistoric bison, and other extinct animals; incorporation of fossils into cultural records, such as fossils in American Indian lore, “tall tales” of mountain men, and emigrant journals; and fossils in building stone. Kenworthy and Santucci (2006) presented an overview and cited selected examples of National Park Service fossils found in cultural resource contexts.

Museum Collections and Paleontological Archives

Museum Collections and Curation

Preserve Collections

MOJA has a formal museum collection curated in Mojave National Preserve Headquarters located in Barstow, California. However, these collections are minimal. These specimens were collected by former MOJA geologist, Ted Weasma. Three Pleistocene specimens, a *Reithrodontomys* sp.? proximal femur fragment, *Neotoma* sp.? caudal vertebra, and a tui chub (*Siphateles bicolor*) vertebra were collected in August 2002. Two specimens containing echinoderm spines and brachiopods in matrix, collected in August 2000, and two *Girvanella* sp.? specimens in matrix, have no locality information. Additionally, several bags of specimens confiscated from a May 2020 looting incident were returned to MOJA staff after being processed by law enforcement and are now stored at preserve headquarters but are not part of the collections. Seventeen of these specimens contain trilobite fossils, seven contain brachiopods, and 35 contain ichnofossils including burrows, *Cruziana*-type trackways, and crinkled surfaces indicative of bioturbation. Interpretive staff have expressed interest in displaying specimens for interpretation and outreach in the visitor centers once the visitor centers are open.

Collections in Other Repositories

MOJA is a relatively new NPS unit, and substantial collections took place before it was incorporated into the NPS. These collections are scattered across various repositories, and some are still being discovered during the inventory process. Along with other repositories, substantial collections are housed at the San Bernardino County Museum, University of California–Berkeley, and University of California–Riverside.

The San Bernardino County Museum (SBCM; Redlands, California) made collections of Miocene fossils within MOJA during the 1970s and 1980s when the land now in MOJA was managed by the BLM (Reynolds et al. 1995). Several localities—SBCM 1.18.2, 6, and 8—have specimens mainly consisting of reed and grass fossils and petrified wood. Collections from lacustrine sediments at SBCM 1.18.2 include *Sequoia langsdorfii* wood and needles, reed and grass fossils, silicified and opalized petrified wood, and flamingo footprints. The other two localities were reported by private collectors and contain assemblages of plant fossils as well as geologic samples.

The collection site described in Reynolds et al. (1995) is SBCM locality 1.26.1. Collections from this locality include a tibia, seven lumbar vertebrae, sacrum, and partial ribs of *Miolabis* sp. in a limestone matrix; a humerus of the extinct hornless rhinoceros *Aphelops* sp.; and a felid ulna, radius, and humerus. Other notable specimens include camelid jaws and an occipital condyle, as well as several *Menoceras* dentaries with teeth. A cast of one of the partial *Menoceras* jaws, specimen A500-1149, is on exhibit in the Hall of Earth Sciences. In addition to the curated specimens, two cabinets associated with SBCM 1.26.1 contain uncatalogued and unprepared materials including a cf. *Metatomarctus* left dentary, canid and felid bones and tooth fragments, camelid bones, and opalized indeterminate bone fragments. Many of the specimens discussed in Reynolds et al. (1995) have not been fully curated and given SBCM specimen numbers, though SBCM curators plan to do so in the future (S. Kottkamp, San Bernardino County Museum curator of Earth science, pers. comm., 2022). Casts of some mammalian specimens were given to the American Museum of Natural History for reference (Wang et al. 1999).

The Pleistocene *Mammuthus* sp. tooth and *Equus* sp. proximal radius collected by MOJA staff are both at SBCM, associated with the locality SBCM 1.62.1. Indeterminate bone fragments were collected at SBCM 1.17.1. Collections from SBCM 1.64.8 include more than 15 valves of the freshwater mussel *Anodonta californiensis* and eight shells of the gastropod *Planorbella tenuis*. Quadruped trackway panels excavated from Jurassic sandstone just outside of MOJA are on display and housed in SBCM collections (K. Springer, pers. comm., 2022).

The University of California Museum of Paleontology (UCMP; Berkeley) records include more than 200 localities from within or just outside of MOJA, although many of the fossils have not been cataloged. Ashley Dineen (UCMP Sr. Museum Scientist, Invertebrate Paleontology) provided information on four of the MOJA localities, all of which yielded invertebrates (pers. comm., August 2022). The locality D7770, in the Cambrian Latham Shale of the Providence Mountains, yielded only one specimen (UCMP 37470), a radiodont impression originally assigned to *Anomalocaris canadensis*. This specimen was collected by Paul and Roberta Kirkland on June 16, 1977, and was figured in Briggs and Mount (1982) and reinterpreted as *Ramskoeldia consimilis*? by Pates et al. (2021). Specimens collected from the three other UCMP localities have not been curated and cataloged, but Dineen provided MOJA with a general summary. Locality A1081, in the Mississippian Monte Cristo Limestone, is located in the Providence Mountains. Collections were made in December of 1932 by Charles Warren Merriam, including rugose corals, bryozoans, brachiopods, trilobites, crinoids, fusulinids, and unspecified microfossils. In 1952, Ralph Langenheim made collections in a unit described as the Cambrian “Kelso Formation” at locality A8700 in the Providence Mountains. Collections here include brachiopods and several species of olenellid trilobites. UCMP locality B2705 lists no collector or specific coordinates but contains collections from the Pennsylvanian Bird Spring Formation, including tabulate and rugose corals, brachiopods, and crinoids.

The University of California–Riverside (UCR; Riverside) has Paleozoic fossils from MOJA (. Miller-Camp, pers. comm. to JST, November 2015; L. English, pers. comm., April 2022), many associated with the work of Jack Mount. Some of these specimens were figured in Mount (1976, 1980). UCR 7002, a Latham Shale locality in the Providence Mountains, has yielded fossils including trilobites, a fragment of the radiodont *Ramskoeldia consimilis*? (UCR 7002/1), and examples of the brachiopod *Paterina prospectensis* which were described in Liang et al. (2020, 2022). Collections associated with UCR 7003 include slab samples containing cephalons of trilobites including the genera *Bristolia*, *Mesonacis*, *Olenellus*, and *Peachella*, as well as the part and counterpart remains of a palaeoscolecid worm (UCR 7003/1). Mount’s GEO 111 class at UCR measured a 14.8 m (48.6 ft) section through 15 stratigraphic levels of the Latham Shale at UCR 7895, near UCR 7003. Other Mount localities from the Providence Mountains include UCR 7311, the source of the *Gogia* sp. specimen described in Mount (1974) as well as hyoliths, trilobites, and the brachiopod *Eothele* (=*Acrothele*) *spurri.* In March 1975, Mount and Harold Meals collected trilobite specimens at UCR

7580 in the Latham Shale of the Kelso Mountains. These specimens include several examples of *Bristolia* sp., *Mesonacis fremonti*, and *Olenellus nevadensis* cephalons, as well as one nearly complete trilobite of unspecified genus. UCR locality 9103 is in the Bird Spring Formation in the Mescal Range. In October 1980, Mount collected specimens here including several partial shells of the gastropod *Bellerophon* sp. and one block containing disarticulated plates and spines of the echinoid *Echinocrinus* sp.

In March 1968, Michael A. Murphy collected blocks containing the silicified fusulinid foraminifera *Triticites* sp. from the Bird Spring Formation of UCR 5021 in the Providence Mountains. UCR collected numerous blocks and slabs of foraminifera from UCR 5026 in the early 1960s, in the Bird Spring Formation. At UCR 5231 and UCR 5232, Bruce Wardlaw collected blocks of Permian limestone containing numerous foraminifera of genera including *Schubertella, Schwagerina,* and *Triticites*. The rock unit is unspecified but presumed to be the Bird Spring Formation. In 1981 Michael J. Miller collected conodont elements at four localities in the Providence Mountains, UCR 9233–9236. Species of *Patrognathus*, *Polygnathus*, and *Spathognathodus* were found here in the Ironside Member of the Sultan Limestone, showing the rock to date to the late Famennian (Late Devonian).

Other repositories have smaller collections. The Natural History Museum of Los Angeles County (LACM; Los Angeles) has another unusual Cambrian fossil from MOJA, a specimen of the Ediacaran organism cf. *Swartpuntia* sp. (LACMIP 12726) (Hagadorn et al. 2000). The Texas Memorial Museum (TMM; University of Texas at Austin) holds the proposed types of an informally described eocrinoid from MOJA (UT TMM 2047TX1a and 1b) (Wilbur 2005). The type material of four fusulinid species from MOJA is in the collections of the National Museum of Natural History (USNM; Washington, D.C.) (Stevens and Stone 2007). Stevens and Stone (2007) also noted that some of the fusulinid fossils from their study area were in the collections of the San Jose State University Museum of Paleontology (SJS; San Jose, California). However, it is not clear that this institution still reposits any fossils; Stevens and Clites (2016) reported that Stevens's fossil coral collection was being transferred primarily to the UCMP, with some specimens going to the USNM, and UCMP records show coral slides from MOJA localities with SJS numbers. Additionally, of the 111 specimens collected during 2006 field work (under permit MOJA-00173), 23 specimens were reposited at Professor Mark Webster's lab at the University of Chicago, and 88 were reposited by Professor Richard Hilton at the Sierra College Natural History Museum in Rocklin, California. The present status of these specimens is unknown.

Some of the older collections from MOJA, such as the material described in Thompson and Hazzard (1946) and Gordon (1964), were formerly in the collections of Stanford University (SU; Stanford, California). For example, the MOJA ammonoid discussed by Gordon was SU 23147. However, Stanford's paleontological specimens were transferred to the California Academy of Sciences (CAS; San Francisco). Christine Garcia (CAS geology collections manager, pers. comm., April 2022) was unable to locate Hazzard's Providence Mountains material, but it is possible that he retained specimens for research or primarily made field identifications. The microfossils from Thompson and

Hazzard (1946), although also originally at Stanford, did not go the CAS. They went to the UCMP (UCMP collection records).

Type Specimens

The type specimens of four fossil species are known to have been found within MOJA (Table 2). They are all species of foraminifera from the Bird Spring Formation. A number of potentially new taxa have been reported but have not been formally described, such as "*Gogia fowleri*" in Wilbur (2005); the palaeoscolecid worm of Mount (1976, 1980) and Conway Morris and Peel (2010); and *Glyptospira* sp. A of Plas (1972) and Erwin (1988). Several more type specimens are known from the state lands in the Providence Mountains from the Bird Spring Formation, representing the fusulinid foraminifera *Dunbarinella concisa*, *Pseudoschwagerina arta*, *P. roeseleri*, *P. uber*, *Schubertella masoni*, *Schwagerina aculeata*, *S. aculeata* var. *plena*, *S. modica*, *S. providens*, *S.*? *multispira*, and *Triticites californicus* (Thompson and Hazzard 1946), and the corals *Heritschioides mckassoni*, *Neomultithecopora providens*, and *Paraheritschioides applegatei* (Wilson 1994a).

Table 2. Fossil taxa named from specimens found within MOJA.

Taxon	Citation	Age, Formation	Type Specimen	Notes
Cuniculinella mojavensis	Stevens and Stone 2007	Permian, Bird Spring	USNM 531309	Fusulinid foraminifera
Pseudochusenella hazzardi	Stevens and Stone 2007	Permian, Bird Spring	USNM 531314	Fusulinid foraminifera
Stewartina magnifica	Stevens and Stone 2007	Permian, Bird Spring	USNM 531301	Fusulinid foraminifera
Stewartina ultimata	Stevens and Stone 2007	Permian, Bird Spring	USNM 531304	Fusulinid foraminifera

Archives

NPS Paleontology Archives

All data, references, images, maps, and other information used in the development of this report are maintained in the NPS Paleontology Archives and Library. These records consist of both park-specific and servicewide information pertaining to paleontological resources documented throughout the NPS. If any resources are needed by NPS staff at MOJA, or additional questions arise regarding paleontological resources, contact the NPS Senior Paleontologist & Paleontology Program Coordinator Vincent Santucci, vincent_santucci@nps.gov. Preserve staff are also encouraged to communicate new discoveries to the NPS Paleontology Program, not only when support is desired, but in general, so that this information can be incorporated into the archives. A description of the Archives and Library can be found in Santucci et al. (2018).

E&R Files

E&R files (from "Examination and Report on Referred Fossils") are unpublished internal USGS documents. For more than a century, USGS paleontologists identified and prepared informal reports on fossils sent to the survey by other geologists, for example to establish the relative age of a formation or to help correlate beds. The system was eventually formalized as a two-part process including a form sent by the transmitting geologist and a reply by the survey geologist. Sometimes the fossil identifications were incorporated into publications, but in many cases this information is unpublished. These E&R files include documentation of numerous fossil localities within current NPS areas, usually predating the establishment of the NPS unit in question and frequently unpublished or previously unrecognized. Extensive access to the original files was granted to the NPS by the USGS beginning in 2014 (Santucci et al. 2014). A small number of E&R files has been found for MOJA, including the earliest report of fossils for the preserve (see "History of Paleontological Resources at MOJA").

Park Paleontological Research

Current and Recent Research

Since 1994, when MOJA was established, 19 permits have been issued for research at MOJA that was either paleontological in focus, or a geological project with paleontological significance.

MOJA1997ATZH, principal investigator Robert Reynolds, project "*Cyclic Prospecting of Paleontologic Resources*", issued for 1997.

MOJA19990045-99, principal investigator David Miller of the U.S. Geological Survey, project "*Geologic mapping and landscape studies to quantify vulnerability and recoverability of desert landscapes and produce a geologic map of Mojave National Preserve*", issued for 1999; this project was continued in 2000 under permit 0045-00, 2001–2002 under permit MOJA-2001-SCI-0018, 2003 under permit MOJA-2003-SCI-0032, and 2004 under permit MOJA-2004-SCI-0015.

MOJA-2003-SCI-0054, principal investigator Paul Stone of the U.S. Geological Survey, project "*Stratigraphy and correlation of Paleozoic strata in selected parts of the Mojave National Preserve*", issued for 2003; this project was continued in 2004 under permit MOJA-2004-SCI-0028, 2005–2006 under permit MOJA-2005-SCI-0009, 2012–2013 under permit MOJA-2012-SCI-2005, and 2014 under permit MOJA-2014-SCI-0003.

MOJA-2009-SCI-0009, principal investigator David Rhode of the Desert Research Institute, project "*Woodrat Midden Collection and Analysis for Support of USGS Paleohydrology Study, Mojave Desert, California*", issued for 2009.

MOJA-2010-SCI-0043, principal investigator Marith Reheis of the U.S. Geological Survey, project "*Paleoclimate Records of Groundwater Discharge and Floods, Mojave National Preserve*", issued for 2011–2013.

MOJA-2011-SCI-0028, principal investigator Mary Allison Stegner of University of California, Berkeley, project "*Measuring Natural Variability of Ecosystem Metrics using the Fossil Record*", issued for 2011.

MOJA-2016-SCI-0029, principal investigator Ronald Amundson of University of California, Berkeley, project "*Quaternary Paleoclimate and Volcanic History of the Cima Volcanics*", issued for 2016–2017.

MOJA-2018-SCI-0051, principal investigator Ryan Manzuk of Princeton University, project "*Lower Cambrian Geology and Paleontology in the Southern Kelso Mountains*", issued for 2019.

MOJA-2019-SCI-0039, principal investigator David Reioux of the California Geological Survey, project "*Geologic Mapping in the Mountain Pass, California Focus Area*", issued for 2019; this project was continued in 2020 under permit MOJA-2019-SCI-0041.

MOJA-2020-SCI-004, principal investigator Judy Fierstein of the U.S. Geological Survey, project "*Eruptive history of the Cima volcanic field*", issued for 2020.

Paleontological Research Permits

See the National Park Service Natural Resource Management Reference Manual DO-77 section on Paleontological Resource Management, subsection on Scientific Research and Collection (https://irma.nps.gov/DataStore/Reference/Profile/572379). NPS Management Policies 2006, section 4.8.2.1 on Paleontological Resources, states that

> *The Service will encourage and help the academic community to conduct paleontological field research in accordance with the terms of a scientific research and collecting permit.*

Any collection of paleontological resources from an NPS area must be made under an approved research and collecting permit. The NPS maintains an online Research Permit and Reporting System (RPRS) database for researchers to submit applications for research in NPS areas. Applications are reviewed at the park level and either approved or rejected. Current and past paleontological research and collecting permits and the associated Investigator's Annual Reports (IARs) are available on the RPRS website (https://irma.nps.gov/rprs/). Additional information on NPS law and policy can be found in Appendix E.

Interpretation

No formal in-person public programming addressing fossils is presented at MOJA because interpretation efforts in the preserve focus on informal interactions between visitors and roving rangers. Interpretive programming at MOJA is presented by roving rangers and via social media, with little formally scheduled programming or informational exhibits available at visitor centers. Interpretive programming regarding fossils in MOJA would be presented via video productions on the preserve's website and social media platforms. MOJA celebrates National Fossil Day via posts on social media channels, and staff have participated in nearby events such as "Pleistocene Palooza" at Tule Springs Fossil Beds National Monument and "Diggin' It" at Victor Valley Museum. Interpretive staff have indicated an interest in establishing a collection of fossils for teaching and interpretation, both as exhibits at visitor centers and as teaching aids for pop up programming presented by roving rangers in the field. Rangers have expressed interest in establishing a paleontology exhibit at Hole-in-the-Wall Visitor Center with fossils on display.

Recommended Interpretive Themes

I. General Paleontological Information

All of the following interpretation topics include a section instructing visitors how to be paleontologically aware while in the preserve. The ranger will provide the visitor with advice on why fossils are important, how paleontologists look for fossils, what to do if fossils are found, and reminders to be aware that fossils exist and should be respected within preserve boundaries.

- Fossils are non-renewable resources that possess scientific and educational information and provide insight into what Earth was like thousands and even hundreds of millions of years ago.
- When paleontologists survey for paleontological resources, the most important tool for planning is a geologic map. Paleontological resources are more common in certain geologic units, so knowing where those units are exposed is important for a successful search. Other tools that a paleontologist takes into the field include a field notebook for recording data and observations, small picks and brushes, consolidants to stabilize fossils, GPS, camera, topographic maps, and appropriate First Aid and safety equipment. It might be helpful to provide examples of these items for visitors when giving an interpretive talk.
- If fossils are found in the preserve by a visitor, the visitor should photograph the specimen in place, record the location on a map or using GIS technology, and notify a ranger of where the resource was found, but most importantly, they should leave the fossil where they found it. It is extremely important for scientific and resource management purposes for locational information to be preserved. Visitors should be informed that NPS fossils are protected by law.

II. Fossils of MOJA

- A program could be developed to educate the public on what types of fossils are present in MOJA and what they tell scientists about Earth's dynamic history. Sections of this report such as the "Geology" section will be useful, in addition to educational content provided by the MOJA Physical Scientist. The goal of this program is to increase visitors' understanding of local geology and paleontology. Therefore, information regarding fossils from the vicinity of MOJA can be included.

III. Caves and Fossil Resources

- Resources for this Interpretation theme are listed in the references section.

IV. Further Interpretation Themes

MOJA should be sure to promote their paleontological resources and provide additional opportunities or programs for visitors to learn about fossils on National Fossil Day, celebrated annually on the Wednesday of the second full week in October (National Earth Science Week). For more information on this event visit: https://www.nps.gov/subjects/fossilday/index.htm. The NPS coordinates the National Fossil Day partnership and hosts fossil-focused events across the country. Conducting one of the suggested paleontology-focused talks on this day would be a perfect opportunity to not only increase public awareness about paleontological resources in MOJA, but also connect with other parks and museums who are also participating in this national event. The NPS Geologic Resources Division can assist with planning for National Fossil Day activities and provide Junior Paleontologist Program supplies including activity booklets, badges, posters and other fossil-related educational resources (https://www.nps.gov/subjects/fossils/junior-paleontologist.htm).

Paleontological Resource Management and Protection

National Park Service Policy

Paleontological resources are non-renewable remains of past life preserved in a geologic context. At present, there are 424 official units of the National Park System, plus national rivers, national trails, and affiliated units that are not included in the official number. Of these, 286 are known to have some form of paleontological resources, and paleontological resources are mentioned in the enabling legislation of 18 units. Fossils possess scientific and educational values and are of great interest to the public; therefore, it is exceedingly important that appropriate management attention be placed on protecting, monitoring, collecting, and curating of these paleontological specimens from federal lands. In March 2009, the Paleontological Resources Preservation Act (PRPA) was signed into law as part of the Omnibus Public Land Management Act of 2009. The new paleontology-focused legislation includes provisions related to inventory, monitoring, public education, research and collecting permits, curation, and criminal/civil prosecution associated with fossils from designated Department of Interior (DOI) lands. More information on laws, policies, and authorities governing NPS management of paleontological resources is detailed in Appendix E. Paleontological resource protection training is available for NPS staff through the NPS Paleontology Program. The Paleontology Program is also available to provide support in investigations involving paleontological resource theft or vandalism.

Between 2009 and 2022 an interagency coordination team including representatives from the Bureau of Land Management (BLM), Bureau of Reclamation (BOR), National Park Service (NPS) and U.S. Fish & Wildlife Service (FWS) developed the DOI final regulations for PRPA. The draft DOI regulations were published in the Federal Register in December 2016 and were available for 60 days to allow for public comment. The interagency team has reviewed public comments provided for the draft regulation and have incorporated these into the final regulation. The final regulation was surnamed by the DOI Solicitor’s Office and each of the four bureau directors. On August 2, 2022, the DOI Paleontological Resources Preservation Act final regulation was published in the Federal Register. After 30 days the Office of Management and Budget approved the final DOI PRPA regulation, which is available at the following website: https://www.federalregister.gov/documents/2022/08/02/2022-16405/paleontological-resources-preservation. For more information regarding this act, visit https://www.nps.gov/subjects/fossils/fossil-protection.htm.

2006 National Park Service Management Policies (section 4.8.2.1) state

> *…Paleontological resources, including both organic and mineralized remains in body or trace form, will be protected, preserved, and managed for public education, interpretation, and scientific research. The Service will study and manage paleontological resources in their paleoecological context (that is, in terms of the geologic data associated with a particular fossil that provides information about the ancient environment).*

> *Superintendents will establish programs to inventory paleontological resources and systematically monitor for newly exposed fossils, especially in areas of rapid erosion. Scientifically significant resources will be protected by collection or by on-site protection and stabilization. The Service will encourage and help the academic community to conduct paleontological field research in accordance with the terms of a scientific research and collecting permit. Fossil localities and associated geologic data will be adequately documented when specimens are collected. Paleontological resources found in an archeological context are also subject to the policies for archeological resources. Paleontological specimens that are to be retained permanently are subject to the policies for museum objects.*
>
> *The Service will take appropriate action to prevent damage to and unauthorized collection of fossils. To protect paleontological resources from harm, theft, or destruction, the Service will ensure, where necessary, that information about the nature and specific location of these resources remains confidential, in accordance with the National Parks Omnibus Management Act of 1998.*
>
> *All NPS construction projects in areas with potential paleontological resources must be preceded by a preconstruction surface assessment prior to disturbance. For any occurrences noted, or when the site may yield paleontological resources, the site will be avoided or the resources will, if necessary, be collected and properly cared for before construction begins. Areas with potential paleontological resources must also be monitored during construction projects.*

Fossils have scientific, aesthetic, cultural, educational, and tourism value, and impacts to any of these values impairs their usefulness. Effective paleontological resource management protects fossil resources by implementing strategies that mitigate, reduce, or eliminate loss of fossilized materials and their relevant data. Because fossils are representatives of adaptation, evolution, and diversity of life through deep time, they have intrinsic scientific values beyond just the physical objects themselves. Their geological and geospatial contexts provide additional critical data concerning paleoenvironmental, paleogeographic, paleoecologic, and a number of other conditions that together allow for a more complete interpretation of the physical and biological history of the earth. Therefore, paleontological resource management must act to protect not only the fossils themselves, but to collect and maintain other contextual data as well.

In general, losses of paleontological resources result from naturally occurring physical processes, by direct or indirect human activities, or by a combination of both. These processes or activities influence the stability and condition of in situ paleontological resources (Santucci and Koch 2003; Santucci et al. 2009). The greatest loss of associated contextual data occurs when fossils are removed from their original geological context without appropriate documentation. Thus, when a fossil weathers and erodes from its surrounding sediments and geologic context, it begins to lose significant ancillary data until, at some point, it becomes more a scientific curiosity than a useful piece of scientific data. A piece of loose fossil “float” can still be of scientific value. However, when a fossil has been completely removed from its original context, such as an unlabeled personal souvenir or a specimen with no provenance information in a collection, it is of very limited scientific utility. Similarly, inadvertent exhumation of fossils during roadway construction or a building excavation may result in the loss or impairment of the scientific and educational values associated with those fossils. It is not necessary to list here all of the natural and anthropogenic factors that can lead to the loss of paleontological resources; rather it is sufficient to acknowledge that anything that disturbs native sediment or original bedrock has potential to result in the loss of the paleontological resources that occur there, or the loss of associated paleontological resource data.

Cave localities are in a distinct class for management due to the close connection with archeological resources and unique issues affecting cave resources. See Santucci et al. (2001) for additional discussion of paleontological resources in cave settings.

Management strategies to address any of these conditions and factors could also incorporate the assistance of qualified specialists to collect and document resources rather than relying solely on staff to accomplish such a large task at MOJA. Active recruitment of paleontological research scientists should also be used as a management strategy.

Baseline Paleontology Resource Data Inventories

A baseline inventory of paleontological resources is critical for implementing effective management strategies, as it provides information for decision-making. This inventory report has compiled information on previous paleontological research done in and near MOJA, taxonomic groups that have been reported within MOJA boundaries, and localities that were previously reported. This report can serve as a baseline source of information for future research, inventory reports, monitoring, and paleontological decisions. The Paleontological Resource Inventory and Monitoring reports for the Mojave Desert I&M Network completed by Santucci et al. (2004) and Tweet et al. (2016) and the references cited within were important baseline paleontological resource data sources for this MOJA-specific report.

Paleontological Resource Monitoring

Paleontological resource monitoring is a significant part of paleontological resource management, and one which usually requires little to implement beyond time and equipment already on hand, such as cameras and GPS units. Monitoring enables the evaluation of the condition and stability of in situ paleontological resources (Santucci and Koch 2003; Santucci et al. 2009). A monitoring program revolves around periodic site visits to assess conditions compared to a baseline for that site, with the periodicity depending on factors such as site productivity, accessibility, and significance of management issues. For example, a highly productive site which is strongly affected by erosion or unauthorized collection, and which can be easily visited by park staff, would be scheduled for more frequent visits than a less productive or less threatened site.

A monitoring program is generally implemented after an inventory has been prepared for a park and sites of concern have been identified, with additional sites added as necessary. Data accumulated via monitoring is used to inform further management decisions, such as the following questions: Is the site suitable for interpretation and education? Does the site require stabilization from the elements? Is collection warranted? Is there a need for some form of law enforcement presence?

Collection is recommended to be reserved for fossils possessing exceptional value (e.g., rare or high scientific significance) or at immediate risk of major degradation or destruction by human activity and natural processes. Therefore, paleontological resource monitoring is a more feasible potential management tool. The first step in establishment of a monitoring program is identification of localities to be monitored, as discussed previously. Locality condition forms are then used to evaluate factors that could cause loss of paleontological resources, with various conditions at each locality rated as good, fair, or poor. Risks and conditions are categorized as Disturbance, Fragility, Abundance, and Site Access. "Disturbance" evaluates conditions that promote accelerated erosion or mass wasting resulting from human activities. "Fragility" evaluates natural conditions that may influence the degree to which fossil transportation is occurring. Sites with elevated fragility exhibit inherently soft rapidly eroding sediment or mass wasting on steep hillsides. A bedrock outcrop that is strongly lithified has low fragility. "Abundance" judges both the natural condition and number of specimens preserved at the locality as well as the probability of being recognized as a fossil-rich area by non-paleontologists, which could lead to unpermitted collecting. "Site Access" assesses the risk of a locality being visited by large numbers of visitors or the potential for easy removal of large quantities of fossils or fossil-bearing sediments. A locality with high access would be in close proximity to public use areas or other access (along trails, at roadcuts, at beach or river access points, and so on).

Each of the factors noted above may be mitigated by management actions. Localities exhibiting a significant degree of disturbance may require either active intervention to slow accelerated erosion, periodic collection, and documentation of fossil materials, or both. Localities developed on sediments of high fragility naturally erode at a relatively rapid rate and would require frequent visits to document and/or collect exposed fossils in order to prevent or reduce losses. Localities with abundant or rare fossils, or high rates of erosion, may be considered for periodic monitoring in order to assess the stability and condition of the locality and resources, in regard to both natural processes and human-related activities. Localities that are easily accessible by road or trail would benefit from the same management strategies as those with abundant fossils and by occasional visits by park staff, documentation of in situ specimens, and/or frequent law enforcement patrols. Further information on paleontological resource monitoring can be found in Santucci and Koch (2003) and Santucci et al. (2009).

Foundation Documents and Resource Stewardship Strategies

Foundation documents and Resource Stewardship Strategies are two types of park planning documents that may contain and reference paleontological resource information. A foundation document is intended to provide basic guidance about a park for planning and management. It briefly describes a given park and its purpose, significance, fundamental resources and values, other importance resources and values, and interpretive themes. Mandates and commitments are also identified, and the state of planning is assessed. Foundation documents may include paleontological information and are also useful as a preliminary assessment of what a park's staff know about their paleontological resources, the importance they place on these resources, and the present state of these non-renewable resources. A foundation document for MOJA has been published (National Park Service 2013).

A Resource Stewardship Strategy (RSS) is a strategic plan intended to help park managers achieve and maintain desired resource conditions over time. It offers specific information on the current state of resources and planning, management priorities, and management goals over various time frames. An RSS for MOJA has not yet been published.

Geologic Maps

A geologic map is the fundamental tool for depicting the geology of an area. Geologic maps are two-dimensional representations of the three-dimensional geometry of rock and sediment at or beneath the land surface (Evans 2016). Colors and symbols on geologic maps correspond to geologic map units. The unit symbols consist of an uppercase letter indicating the age and lowercase letters indicating the formation's name. The American Geosciences Institute website (https://www.americangeosciences.org/environment/publications/mapping) provides more information about geologic maps and their uses. The NPS Geologic Resources Inventory (GRI) has been digitizing existing maps of NPS units and making them available to parks for resource management.

Geologic maps are one of the foundational elements of a paleontological resource management program. Knowing which sedimentary rocks and deposits underlie a park and where they are exposed are essential for understanding the distribution of known or potential paleontological resources. The ideal scale for resource management in the 48 contiguous states is 1:24,000 (maps for areas in Alaska tend to be coarser). Whenever possible, page-sized geologic maps derived from GRI files are included in paleontological resource inventory reports for reference, but it is recommended that GRI source files be downloaded from IRMA for use. The source files can be explored in much greater detail and incorporated into the park GIS database. Links to the maps digitized by the GRI for MOJA can be found in IRMA at https://irma.nps.gov/DataStore/Reference/Profile/2174439. In addition to a digital GIS geologic map, the GRI program also produces a park-specific report discussing the geologic setting, distinctive geologic features and processes within the park, highlighting geologic issues facing resource managers, and describing the geologic history leading to the present-day landscape of the park. A park GRI report has not yet been produced for MOJA.

Paleontological Resource Potential Maps

A map of possible paleontological resources is included in this report (Figure 32). The map shows the distribution of geologic units within a park that are known to have yielded fossils within the park (green on Figure 32), have not yielded fossils within the park but are fossiliferous elsewhere (yellow), or have not yielded fossils (red). The map can serve as readily accessible guidance for determining which areas to survey or monitor, or areas where the discovery of fossils may be of concern during work that disturbs the ground (road work, building construction, etc.).

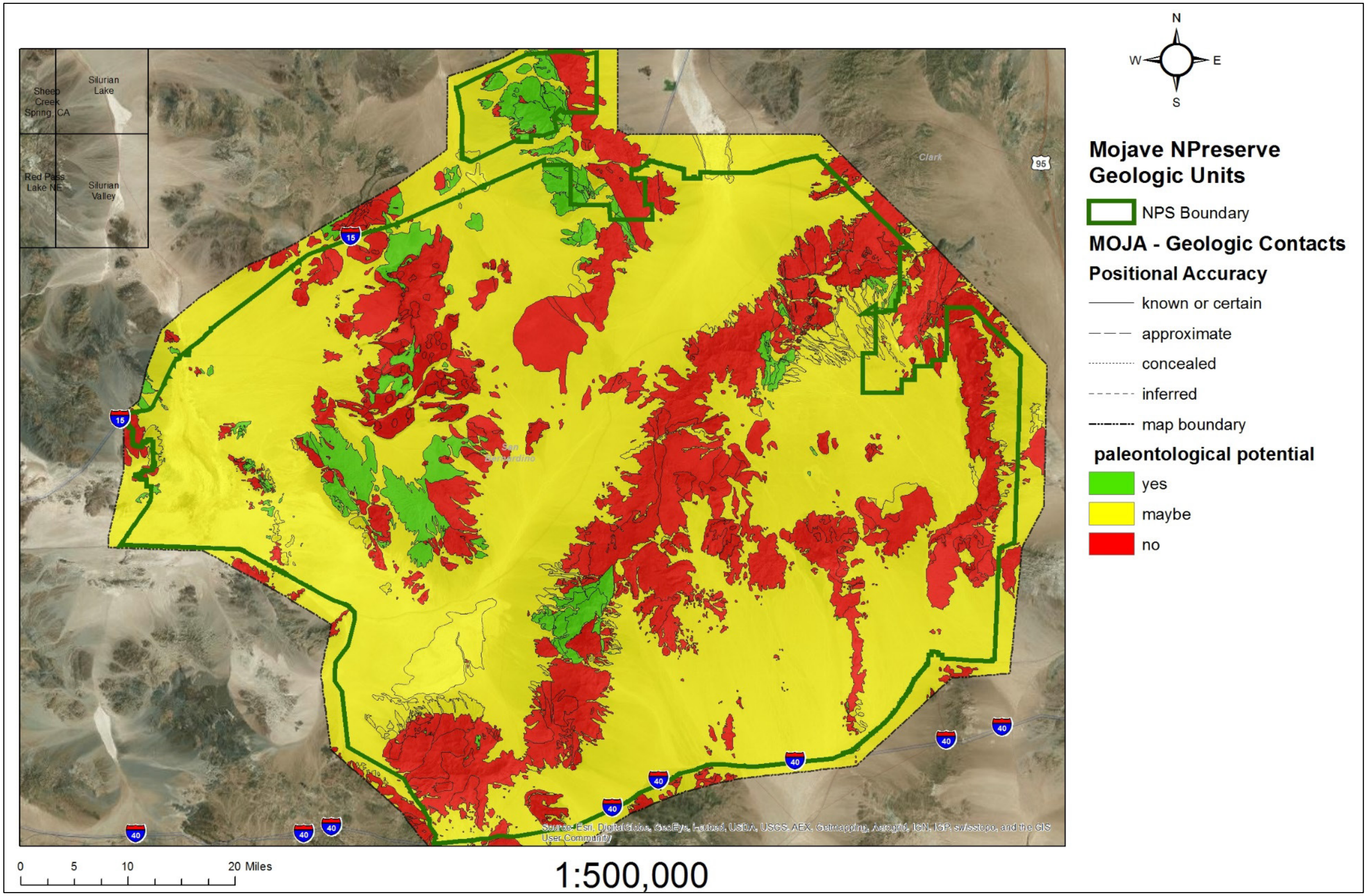

Figure 32. Map indicating paleontological potential of geologic map units in MOJA (NPS/TIM CONNORS).

Paleontological Resource Management Recommendations

The paleontological resource inventory at MOJA has documented rich and previously unrecognized paleontological resources. This report captures the scope, significance, and distribution of fossils at MOJA as well as provides recommendations to support the management and protection of the preserve's non-renewable paleontological resources.

- MOJA staff should be encouraged to observe exposed rocks and sedimentary deposits for fossil material while conducting their usual duties. To promote this, staff should receive guidance from the MOJA Physical Scientist regarding how to recognize common local fossils. When opportunities arise to observe paleontological resources in the field and take part in paleontological field studies with trained paleontologists, staff should take advantage of them, if funding and time permit.
- MOJA staff should photo-document and monitor any occurrences of paleontological resources that may be observed in situ. Fossils and their associated geologic context (surrounding rock) should be documented but left in place unless they are subject to imminent degradation. A Geologic Resource Monitoring Manual published by the Geological Society of America and NPS Geologic Resources Division (GRD) includes a chapter on paleontological resource monitoring (Santucci et al. 2009). Santucci and Koch (2003) also present information on paleontological resource monitoring.
- Fossil theft is one of the greatest threats to the preservation of paleontological resources and any methods to minimize these activities should be utilized by staff. Any occurrence of paleontological resource theft or vandalism should be investigated by a law enforcement ranger. When possible, incidents should be fully documented, and the information submitted for inclusion in the annual law enforcement statistics.
- Fossils found in a cultural context should be documented like other fossils but will also require the input of an archeologist or a cultural resource specialist. Any fossil which has a cultural context may be culturally sensitive as well (i.e., subject to NAGPRA) and should be regarded as such until otherwise established. The Geologic Resources Division can coordinate additional documentation/research of such material.
- The preserve may fund and recruit paleontology interns as a cost-effective means of enabling some level of paleontological resource support. The Scientists in Parks Program is an established program for recruitment of geology and paleontology interns.
- Contact the NPS Paleontology Program for technical assistance with paleontological resource management issues.
- Further field work is suggested at all potentially fossiliferous outcrops.

If fossil specimens are found by MOJA staff, it is recommended they follow the steps outlined below to ensure proper paleontological resource management.

- Photo-document the specimen without moving it from its location if it is loose. Include a common item, such as a coin, pen, or pencil, for scale if a ruler or scale bar is not available.

- If a GPS unit is available, record the location of the specimen. If GPS is not available, record the general location within MOJA and height within the outcrop, if applicable. If possible, revisit the site when a GPS unit is available. Most smartphones also have the ability to record coordinates; if no GPS unit is available, attempt to record the coordinates with a phone.
- Write down associated data, such as rock type, general description of the fossil, type of fossil if identifiable, general location in MOJA, sketch of the fossil, position within the outcrop or if it is loose on the ground, any associated fossils, and any other additional information.
- Do not remove the fossil unless it is loose in an area of heavy traffic, such as a public trail, and is at risk of being taken or destroyed. If the fossil is removed, be sure to wrap in soft material, such as tissue paper, and place in a labeled plastic bag with associated notes.

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Appendix A: Paleontological Species

The following tables (Appendix Table A-1, A-2, and A-3) document the fossil species found at MOJA in stratigraphic context, as reported in the literature, in museum collections, and through personal observations. The tables are divided stratigraphically: Appendix Table A-1 documents Proterozoic and Cambrian formations, Appendix Table A-2 documents Devonian through Jurassic formations, and Appendix Table A-3 documents Neogene and Quaternary tables. In each table, the rows are organized systematically, placing taxa of the same broad groups together. The columns are organized by formation, which are presented in ascending order (oldest to youngest) left to right. The columns also include the taxon (first two columns) and references (last column; included in "Literature Cited" above). If a taxon is present in a given formation at a locality that can be placed within MOJA, that cell is marked "Y"; if there is some question about the formation or whether the locality is within MOJA, the cell is marked "?". Records of uncertain stratigraphy are marked "U". Fossils that have been reworked from an older unit are marked "R". A null record is marked "–".

It is likely that some of the genera and species cited here are actually examples of different authors identifying the same fossils using different names. Also, generic and specific assignments in general change over time with new specimens and research. It is beyond the scope of this document to provide definitive taxonomic updates for all names. Therefore, original usage is preferred to make it easier to use the source documents, except in cases where usage in the source documents has changed. In these cases, the most recent name is preferred. Changes in taxonomy and other notes are listed after the tables.

The terms "aff.", "cf.", "isp.", and "sp." are examples of open nomenclature, in which there is some uncertainty about a classification. The terms "aff." and "cf." can be applied to any level of classification; "aff." indicates an affinity to the cited taxon (genus, species, etc.) and "cf." indicates "compare with", but in practice different authors may use them in approximately the same way. "sp." means "species" and "isp." means "ichnospecies" (for trace fossils), both indicating that a fossil can be classified to a genus but not to a species. Question marks also indicate questionability at whatever level they are applied. Placement and usage of question marks (before or after, within parentheses, with or without spaces) varies by author. "n. sp." indicates a potential new species. Quotation marks around both a genus and species indicate an informal name, while quotation marks around only a genus indicate that the species should be reassigned to another genus.

Formation abbreviations in the tables are after Bedford (2003) and Stone et al. (2017). Those units that were not included in those documents have been given abbreviations in the same style. Formations not yet known to be fossiliferous within the preserve (Stirling Quartzite, Moenkopi Formation) are omitted. Float records from undetermined units (e.g., cf. *Favosites* in Figure 14A) are also omitted.

- Q = Quaternary sediments
- To = other Cenozoic units, including “New York Fanglomerate” (Tn) and “light-gray Tertiary limestone” of Capps and Moore (1997) (Tca)
- Tw = “Winkler Formation”
- Ja = Aztec Sandstone
- PIPb = Bird Spring Formation
- Mm = Monte Cristo Limestone
- Ds = Sultan Limestone
- Cn = Nopah Formation
- Cbk = Bonanza King Formation
- Cc = Cadiz Formation
- Cch = Chambless Limestone
- Cl = Latham Shale
- Cz = Zabriskie Formation
- CZwc = Wood Canyon Formation
- Zj = Johnnie Formation
- Zu = Pre-Johnnie Formation rocks (“Seventeenmile Point Formation”)

Appendix Table A-1. Taxa reported from Proterozoic and Cambrian formations in MOJA.

Group	Taxon	Zu	Zj	CZwc	Cz	Cl	Cch	Cc	Cbk	Cn	References
Invertebrates	**Invertebrates overall**	**–**	**–**	**Y**	**–**	**Y**	**Y**	**Y**	**Y**	**Y**	**–**
Invertebrates: Porifera?: Archaeocyatha	*Ethmophyllum* sp.	–	–	–	–	–	–	–	–	Y	Hazzard and Mason 1936
	Archaeocyatha undetermined	–	–	Y	–	–	–	–	–	–	Hagadorn et al. 2000
Invertebrates: Cnidaria?	*Sphenothallus* sp.?	–	–	–	–	Y	–	–	–	–	Liang et al. 2022
Invertebrates: Brachiopoda	*Acrothele spurri*	–	–	–	–	–	Y	–	–	–	Mount 1976, 1980
	Nisusia sp.	–	–	–	–	–	–	Y	–	–	Hazzard 1954
	Obolus sp.	–	–	–	–	–	–	–	–	Y	Hazzard and Mason 1936
	Paterina prospectensis	–	–	–	–	Y	Y	–	–	–	Hazzard 1954; Liang et al. 2020, 2022
	Acrotretida undetermined	–	–	–	–	–	–	–	–	–	Gaines and Droser 2002
	Brachiopoda undetermined	–	–	–	–	Y	–	–	–	Y	Gaines and Droser 2002; Liang et al. 2022; J. Hagadorn, pers. comm. to JST
Invertebrates: Hyolitha	*Hyolithes* sp.	–	–	–	–	–	Y	Y	–	–	Hazzard 1954
	Hyolitha undetermined	–	–	–	–	Y	–	–	–	–	Gaines and Droser 2002
Invertebrates: Palaeoscolecida	Unnamed palaeoscolecid	–	–	–	–	Y	–	–	–	–	Mount 1976, 1980; Conway Morris and Peel 2010
Invertebrates: Arthropoda	**Arthropoda overall**	**–**	**–**	**Y**	**–**	**Y**	**Y**	**Y**	**Y**	**Y**	**–**
Invertebrates: Arthropoda: Radiodonta	*Ramskoeldia consimilis*?	–	–	–	–	Y	–	–	–	–	Mount 1976, 1980; Briggs and Mount 1982; Gaines and Droser 2002; Pates et al. 2021
Invertebrates: Arthropoda: Trilobita	**Trilobites overall**	**–**	**–**	**Y**	**–**	**Y**	**Y**	**Y**	**Y**	**Y**	**–**
	Agnostus sp.	–	–	–	–	–	–	–	–	Y	Hazzard and Mason 1936
	Agraulus sp.	–	–	–	–	–	–	Y	–	–	Hazzard 1954
	Alokistocare n. sp.	–	–	–	–	–	–	–	–	Y	Hazzard and Mason 1936
	Alokistocare sp.	–	–	–	–	–	–	Y	–	–	Hazzard and Mason 1936; Hazzard 1954
	Bathyuriscus? aff. *B. bithus*	–	–	–	–	–	–	Y	–	–	Hazzard and Mason 1936
	Bristolia anteros	–	–	–	–	Y	–	–	–	–	Webster et al. 2003

Appendix Table A-1 (continued). Taxa reported from Proterozoic and Cambrian formations in MOJA.

Group	Taxon	Zu	Zj	CZwc	Cz	Cl	Cch	Cc	Cbk	Cn	References
Invertebrates: Arthropoda: Trilobita (continued)	*Bristolia bristolensis*	–	–	–	–	Y	Y	–	–	–	Hazzard 1954; Webster et al. 2003
	Bristolia harringtoni	–	–	–	–	Y	–	–	–	–	Lieberman 1999; Webster et al. 2003
	Bristolia insolens	–	–	–	–	Y	–	–	–	–	Hazzard 1933; Lieberman 1999; Webster et al. 2003
	Bristolia cf. *B. insolens*	–	–	–	–	Y	–	–	–	–	Hewett 1956
	Bristolia n. sp. B	–	–	–	–	Y	–	–	–	–	UCR records
	Bristolia mohavensis	–	–	–	–	Y	–	–	–	–	Hazzard 1933; Lieberman 1999; Webster et al. 2003
	Clavaspidella aff. *C. bela*	–	–	–	–	–	–	Y	–	–	Hazzard and Mason 1936
	Clavaspidella sp.	–	–	–	–	–	–	Y	–	–	Hazzard 1954
	Dellea sp.	–	–	–	–	–	–	–	–	Y	Hazzard 1954
	Elvinia sp.	–	–	–	–	–	–	–	–	Y	Hazzard 1954
	cf. *Geragnostus tumidosus*	–	–	–	–	–	–	–	–	Y	Hazzard 1954
	Glossopleura sp.	–	–	–	–	–	–	Y	–	–	Hazzard 1954
	Inglefieldia cf. *I. affinis*	–	–	–	–	–	–	Y	–	–	Hazzard 1954
	Kochaspis sp.	–	–	–	–	–	–	Y	–	–	Hazzard 1954
	Kochiella sp.	–	–	–	–	–	–	Y	–	–	Hazzard 1954
	Mesonacis fremonti	–	–	–	–	Y	Y	–	–	–	Hazzard 1954; Hewett 1956; Webster et al. 2003
	Mesonacis sp. A	–	–	–	–	Y	–	–	–	–	Webster et al. 2003
	Mesonacis sp. indet.	–	–	–	–	Y	–	–	–	–	Hazzard 1933
	Olenellus clarki	–	–	–	–	Y	–	–	–	–	Hazzard 1933, 1954; Lieberman 1999; Webster et al. 2003
	Olenellus aff. *O. gilberti* A	–	–	–	–	–	–	–	–	–	Webster et al. 2003
	Olenellus nevadensis	–	–	–	–	Y	–	–	–	–	Hazzard 1954; Hewett 1956; Webster et al. 2003

Appendix Table A-1 (continued). Taxa reported from Proterozoic and Cambrian formations in MOJA.

Group	Taxon	Zu	Zj	CZwc	Cz	Cl	Cch	Cc	Cbk	Cn	References
Invertebrates: Arthropoda: Trilobita (continued)	*Olenellus puertoblancoensis*	–	–	–	–	–	Y	–	–	–	Mount 1976, 1980
	Olenellus ?terminatus	–	–	–	–	–	–	Y	–	–	UCR records
	Olenellus aff. *O. terminatus*	–	–	–	–	Y	–	–	–	–	Webster et al. 2003
	Olenellus n. sp. near *O. bristolensis*	–	–	–	–	Y	–	–	–	–	Hewett 1956
	Onchocephalus n. sp.	–	–	–	–	Y	–	–	–	–	UCR records
	Peachella iddingsi	–	–	–	–	Y	–	–	–	–	Webster et al. 2003; Webster 2009
	Proliostracus cf. *P. noenygaardi*	–	–	–	–	–	–	Y	–	–	Hazzard 1954
	Pterocephalia?? sp.	–	–	–	–	–	–	–	–	Y	Hazzard 1954
	Zacanthoides sp.	–	–	–	–	–	–	Y	–	–	Hazzard 1954
	Olenellida undetermined	–	–	–	–	Y	–	–	–	–	Gaines and Droser 2002
	New trilobite genus	–	–	–	–	–	–	–	–	Y	Hazzard and Mason 1936
	Trilobita undetermined	–	–	Y	–	Y	U	U	Y	–	Hazzard and Mason 1936; Dunne 1972; Hagadorn et al. 2000; Gaines and Droser 2002
Invertebrates: Echinodermata	“Cystoid” plate	–	–	–	–	–	–	–	–	Y	Hazzard and Mason 1936
	“*Gogia fowleri*”	–	–	–	–	Y	–	–	–	–	Wilbur 2005
	?*Gogia* sp.	–	–	–	–	–	Y	–	–	–	Mount 1976, 1980
Invertebrates: Other	Undetermined invertebrate fossils	–	–	–	–	Y	–	–	–	–	Gaines and Droser 2002; Bedford 2003
Ichnofossils	**Ichnofossils overall**	**Y**	**Y**	**Y**	**Y**	**Y**	**U**	**Y**	**–**	**Y**	**–**
	“Algal” markings	–	–	–	–	Y	–	–	–	–	Hewett 1956
	Arthropod traces	–	–	Y	–	–	–	–	–	–	Hagadorn et al. 2000
	Bergaueria isp.?	–	–	Y	–	–	–	–	–	–	Inventory
	Bioturbation	–	–	–	–	U	U	U	–	–	Dunne 1972
	Cruziana isp./*Rusophycus* isp.	–	–	Y	–	–	–	–	–	–	Inventory

Appendix Table A-1 (continued). Taxa reported from Proterozoic and Cambrian formations in MOJA.

Group	Taxon	Zu	Zj	CZwc	Cz	Cl	Cch	Cc	Cbk	Cn	References
Ichnofossils (continued)	Cryptalgal / microbial laminations	Y	Y	–	–	–	–	–	–	–	Wilson 1978; Bahde et al. 1997
	“Fecal trails”	–	–	–	–	Y	–	–	–	–	UCR records
	Oncolites	Y	–	–	–	–	–	–	–	–	Wilson 1978
	Planolites isp.	–	–	Y	–	–	–	–	–	–	Hagadorn 1998
	Skolithos isp.	–	–	Y	Y	–	–	–	–	–	Stewart 1970; Dunne 1972; Bahde et al. 1997; Hagadorn et al. 2000; Fedo and Cooper 2001; Bedford 2003
	Stromatolites	Y	–	–	–	–	–	–	–	–	Wilson 1978
	Taphrhelminthopsis isp.	–	–	Y	–	–	–	–	–	–	Hagadorn et al. 2000; Fedo and Cooper 2001
	Treptichnus pedum	–	–	Y	–	–	–	–	–	–	Bahde et al. 1997; Hagadorn et al. 2000
	Unspecified invertebrate burrows	–	–	Y	–	Y	–	–	–	–	Stewart 1970; Dunne 1972; Bahde et al. 1997; Gaines and Droser 2002
	Unspecified invertebrate tracks	–	–	Y	–	–	–	–	–	–	Dunne 1972
	Unspecified trace fossils	–	–	Y	Y	–	–	Y	–	Y	Bahde et al. 1997; Fedo and Cooper 2001; UCR records; J. Hagadorn, pers. comm. to JST
Other Fossils	*Girvanella* sp.	–	–	–	–	–	Y	–	–	–	Hazzard 1954; Stewart 1970; Bedford 2003
	Morania n. sp.	–	–	–	–	Y	–	–	–	–	UCR records
	cf. *Swartpuntia* sp.	–	–	Y	–	–	–	–	–	–	Hagadorn 1998; Hagadorn et al. 2000
	Enigmatic wrinkled patch	–	–	–	–	Y	–	–	–	–	Inventory
	Fossil debris	–	–	–	–	–	–	–	Y	–	Stone et al. 2017

Appendix Table A-2. Taxa reported from Devonian through Jurassic formations in MOJA.

Group	Taxon	Ds	Mm	PIPb	Ja	References
Invertebrates	**Invertebrates overall**	**Y**	**Y**	**Y**	**R**	**–**
Invertebrates: Porifera	*Chaetetes* sp.	–	–	Y	–	Barca 1960; Yelverton 1963
	Stromatopora sp.	Y	–	–	–	Hazzard 1954; Novitsky-Evans 1978
	Stromatoporoidea undetermined	Y	–	–	–	Burchfiel and Davis 1977; Brown 1989; Stone et al. 2017
Invertebrates: Cnidaria: Anthozoa	**Anthozoa overall**	**Y**	**Y**	**Y**	**R**	**–**
	Undetermined colonial corals	–	–	Y	–	Stevens and Stone 2007; Stone et al. 2017
	Undetermined corals	?	?	Y	–	Barca 1960; Dobbs 1961; Yelverton 1963; Evans 1971; Stevens and Stone 2007
Invertebrates: Cnidaria: Anthozoa: Tabulata	*Bayhaium merriamorum*	–	–	Y	–	Stone et al. 2017
	Cladopora sp.?	Y	–	–	–	Yelverton 1963
	Syringopora surcularia	–	Y	–	–	Yelverton 1963
	Syringopora sp.	?	?	Y	–	Barca 1960; Dobbs 1961; Yelverton 1963; Law 1969; Evans 1971; Stone et al. 2017
Invertebrates: Cnidaria: Anthozoa: Rugosa	*Amplexocarinia* sp.	–	–	Y	–	Yelverton 1963
	Amplexocarinia? sp.	–	–	Y	–	Barca 1960
	Caninophyllum sp.	–	–	Y	–	Hazzard 1954
	“Cyathophyllum” *flexum*?	Y	–	–	–	Hazzard 1954
	Disphyllum lonense?	Y	–	–	–	Hazzard 1954
	Homalophyllites crassus	–	Y	–	–	Haskell 1959
	Homalophyllites sp.	–	Y	–	–	Hazzard 1954
	Lithostrotion sp.	–	–	Y	–	Law 1969
	Lophophyllidium sp.	–	–	Y	–	Yelverton 1963
	Siphonodendron warreni	–	Y	–	–	Stone et al. 2017

Appendix Table A-2 (continued). Taxa reported from Devonian through Jurassic formations in MOJA.

Group	Taxon	Ds	Mm	PlPb	Ja	References
Invertebrates: Cnidaria: Anthozoa: Rugosa (continued)	*Triplophyllites* sp.	–	Y	–	–	Hazzard 1954
	Triplophyllum sp.	–	–	Y	–	Hewett 1956
	Tschussovskenia connorsensis	–	–	Y	–	Stone et al. 2017
	Zaphrentis sp.	–	?	–	–	Dobbs 1961; Evans 1971
	Zaphrentis sp.?	–	Y	–	–	Yelverton 1963
	Undetermined horn corals	–	Y	Y	R	Haskell 1959; Barca 1960; Law 1969
Invertebrates: Bryozoa	*Fenestella* sp.	–	–	Y	–	Yelverton 1963
	Fenestella sp.?	–	Y	–	–	Yelverton 1963
	Polypora sp.	–	–	Y	–	Hewett 1956
	Fenestellidae undetermined	–	Y	Y	–	Hazzard 1954; Law 1969
	Ramose bryozoans	–	–	Y	–	Law 1969
	Bryozoa undetermined	–	Y	Y	–	Hazzard 1954; Barca 1960; Yelverton 1963; Stone et al. 2017
Invertebrates: Brachiopoda	**Brachiopoda overall**	**Y**	**Y**	**Y**	**R**	**–**
	Atrypa sp.?	Y	–	–	–	Yelverton 1963
	Chonetes sp.	–	Y	–	–	Yelverton 1963
	Cleiothyridina sublamellosa	–	–	Y	–	Hewett 1956
	Composita sp.	–	–	Y	–	Yelverton 1963
	Derbyia sp.	–	Y	–	–	Hazzard 1954
	Derbyia sp.?	–	–	Y	–	Yelverton 1963
	Dictyoclostus portlockianus	–	–	Y	–	Hazzard 1954
	Dielasma sp.	–	Y	–	–	Hazzard 1954
	?*Enteletes hemiplicatus*	–	–	Y	–	Hazzard 1954

Appendix Table A-2 (continued). Taxa reported from Devonian through Jurassic formations in MOJA.

Group	Taxon	Ds	Mm	PIPb	Ja	References
Invertebrates: Brachiopoda (continued)	*Juresonia nebrascensis*	–	–	Y	–	Hazzard 1954
	Linoproductus sp.	–	–	Y	–	Yelverton 1963
	Marginifera muricatina	–	–	Y	–	Hazzard 1954
	Marginifera aff. *M. muricatina*	–	–	Y	–	Hewett 1956
	Productus sp.	–	Y	–	–	Hazzard 1954
	Reticularia sp.?	–	Y	–	–	Yelverton 1963
	Rhipidomella sp.?	–	Y	–	–	Yelverton 1963
	Schizophoria? sp.	–	–	Y	–	Hewett 1956
	Spirifer centronatus	–	Y	–	–	Hazzard 1954
	Spirifer cf. *S. logani*	–	Y	–	–	Hazzard 1954
	Spirifer cf. *S. opimus*	–	–	Y	–	Hazzard 1954
	Productida undetermined	?	–	Y	R	Dobbs 1961; Law 1969; Marzolf and Cole 1987
	Spiriferida undetermined	?	–	–	–	Dobbs 1961
	Brachiopoda undetermined	?	Y	Y	–	Barca 1960; Dobbs 1961; Yelverton 1963; Law 1969; Evans 1971; Stevens and Stone 2007
Invertebrates: Mollusca	**Mollusca overall**	**Y**	**Y**	**Y**	**–**	**–**
Invertebrates: Mollusca: Bivalvia	*Myalina* sp.?	–	–	Y	–	Yelverton 1963
	Parallelodon sp.?	–	Y	–	–	Yelverton 1963
	Schizodus sp.?	–	Y	–	–	Yelverton 1963
	Bivalvia undetermined	–	–	Y	–	Yelverton 1963; Law 1969
Invertebrates: Mollusca: Cephalopoda	Cephalopoda undetermined	–	Y	–	–	Yelverton 1963
Invertebrates: Mollusca: Cephalopoda: Ammonoidea	*Paralegoceras texanum*	–	–	Y	–	Hazzard 1954; Gordon 1964

Appendix Table A-2 (continued). Taxa reported from Devonian through Jurassic formations in MOJA.

Group	Taxon	Ds	Mm	PlPb	Ja	References
Invertebrates: Mollusca: Cephalopoda: Nautiloidea?	"*Arthoceras* sp.?" [*Orthoceras*?]	–	–	Y	–	Yelverton 1963
Invertebrates: Mollusca: Gastropoda	*Amaurotoma zappa*	–	–	?	–	Plas 1972
	Anomphalus sp.	–	–	?	–	Plas 1972
	Bellerophon sp.	–	–	Y	–	UC–Riverside records
	Bulimorpha sp.?	–	–	Y	–	Yelverton 1963
	Glyptospira sp. A	–	–	?	–	Plas 1972; Erwin 1988
	Platyschisma ambiguum	Y	–	–	–	Hazzard 1954
	Gastropoda undetermined	–	Y	Y	–	Dobbs 1961; Law 1969; Stevens and Stone 2007; Stone et al. 2017; inventory
Invertebrates: Annelida	Scolecodont elements	–	–	Y	–	Law 1969
Invertebrates: Arthropoda: Trilobita	*Griffithides* sp.	–	–	Y	–	Hazzard 1954
Invertebrates: Arthropoda: Ostracoda	Ostracoda undetermined	–	–	Y	–	Law 1969
	Possible ostracodes	–	–	Y	–	Stone et al. 2017
Invertebrates: Echinodermata	*Echinocrinus* sp.	–	–	Y	–	UC–Riverside records
	Crinoidea undetermined	Y	Y	Y	R	Hazzard 1954; Haskell 1959; Barca 1960; Yelverton 1963; Dobbs 1961; Balkwill 1965; Law 1969; Evans 1971; Dunne 1972; Brown 1989; Stone et al. 2017
	Echinoidea undetermined	–	?	–	–	Inventory
	Holothuroidea undetermined	–	–	Y	–	Law 1969
	Pelmatozoa undetermined	–	Y	–	–	Novitsky-Evans 1978
	Echinodermata undetermined	Y	–	–	–	Yelverton 1963

Appendix Table A-2 (continued). Taxa reported from Devonian through Jurassic formations in MOJA.

Group	Taxon	Ds	Mm	PlPb	Ja	References
Invertebrates: Other	Corals or stromatoporoids	Y	–	–	–	Evans 1971
	Shell debris	Y	–	–	–	Evans 1971
Vertebrates	**Vertebrates overall**	**Y**	**–**	**Y**	**–**	**–**
Vertebrates: Conodonta	*Adetognathus gigantus*	–	–	Y	–	Law 1969
	Adetognathus lautus	–	–	Y	–	Law 1969
	Adetognathus missouriensis	–	–	Y	–	Law 1969
	Apatognathus? sp.	–	–	Y	–	Law 1969
	Gnathodus bassleri	–	–	Y	–	Law 1969
	Gnathodus roundyi	–	–	Y	–	Law 1969
	Gnathodus n. sp.	–	–	Y	–	Law 1969
	Hibbardella acuta	–	–	Y	–	Law 1969
	Hibbardella sp.	–	–	Y	–	Law 1969
	Hindeodella asiatica	–	–	Y	–	Law 1969
	Hindeodella cf. *H. delicatula*	–	–	Y	–	Law 1969
	Hindeodella multidenticulata	–	–	Y	–	Law 1969
	Hindeodella sp. A	–	–	Y	–	Law 1969
	Hindeodella sp.	–	–	Y	–	Law 1969
	Hindeodus alatoides	–	–	Y	–	Law 1969
	Idiognathodus delicatus	–	–	Y	–	Law 1969
	Idiognathoides convexa	–	–	Y	–	Law 1969
	Idiognathoides corrugata	–	–	Y	–	Law 1969
	Idiognathoides nodulifera	–	–	Y	–	Law 1969
	Idiognathoides sinuata	–	–	Y	–	Law 1969

Appendix Table A-2 (continued). Taxa reported from Devonian through Jurassic formations in MOJA.

Group	Taxon	Ds	Mm	PIPb	Ja	References
Vertebrates: Conodonta (continued)	*Kladognathus*? sp.	–	–	Y	–	Law 1969
	Ligonodina hanaii	–	–	Y	–	Law 1969
	Ligonodina cf. *L. roundyi*	–	–	Y	–	Law 1969
	Ligonodina sp.	–	–	Y	–	Law 1969
	Lonchodina? *obtusa*	–	–	Y	–	Law 1969
	Lonchodina? sp.	–	–	Y	–	Law 1969
	Metalonchodina bidentata	–	–	Y	–	Law 1969
	Metalonchodina sp.	–	–	Y	–	Law 1969
	Neoprioniodus conflexus	–	–	Y	–	Law 1969
	Neoprioniodus cf. *N. camurus*	–	–	Y	–	Law 1969
	Neoprioniodus loxus	–	–	Y	–	Law 1969
	Neoprioniodus scitulus	–	–	Y	–	Law 1969
	Ozarkodina delicatula	–	–	Y	–	Law 1969
	Ozarkodina cf. *O. compressa*	–	–	Y	–	Law 1969
	Patrognathus variabilis or *andersoni*	Y	–	–	–	Miller 1983
	Polygnathus collinsoni	Y	–	–	–	Miller 1983
	Polygnathus linguiformis linguiformis	Y	–	–	–	Miller 1983
	Polygnathus zenapolensis	Y	–	–	–	Miller 1983
	Roundya cf. *R. costata*	–	–	Y	–	Law 1969
	Spathognathodus cristula	–	–	Y	–	Law 1969
	Spathognathodus cf. *S. echigoensis*	–	–	Y	–	Law 1969

Appendix Table A-2 (continued). Taxa reported from Devonian through Jurassic formations in MOJA.

Group	Taxon	Ds	Mm	PIPb	Ja	References
Vertebrates: Conodonta (continued)	*Spathognathodus minutus*	–	–	Y	–	Law 1969
	Spathognathodus (*Ozarkodina*—P element)	Y	–	–	–	Miller 1983
	Streptognathodus elegantulus	–	–	Y	–	Law 1969
	Streptognathodus elongatus	–	–	Y	–	Law 1969
	Streptognathodus expansus	–	–	Y	–	Law 1969
	Streptognathodus suberectus	–	–	Y	–	Law 1969
	Synprioniodina microdenta	–	–	Y	–	Law 1969
	Conodonta undetermined	–	–	Y	–	Law 1969
Vertebrata: Other	Fish fragments	–	–	Y	–	Law 1969
Ichnofossils	Invertebrate burrows	–	–	–	Y	Novitsky-Evans 1978
	Possible fecal pellets	–	–	–	Y	Novitsky-Evans 1978
Other Fossils	**Other fossils overall**	**Y**	**Y**	**Y**	**R**	**–**
Other Fossils: Foraminifera	*Ammodiscus* sp.	–	–	Y	–	Law 1969
	Cuniculinella mojavensis	–	–	Y	–	Stevens and Stone 2007
	Eoparafusulina linearis	–	–	Y	–	Stevens and Stone 2007
	Eoparafusulina sp.	–	–	Y	–	Stevens and Stone 2007
	Fusulina (*Triticites*) *secalica*	–	–	Y	–	Yelverton 1963
	Leptotriticites californicus	–	–	Y	–	Stevens and Stone 2007
	Leptotriticites cf. *L. californicus*	–	–	Y	–	Stone et al. 2017

Appendix Table A-2 (continued). Taxa reported from Devonian through Jurassic formations in MOJA.

Group	Taxon	Ds	Mm	PIPb	Ja	References
Other Fossils: Foraminifera (continued)	*Leptotriticites glenensis*	–	–	Y	–	Stevens and Stone 2007; Stone et al. 2017
	Leptotriticites aff. *L. gracilitatus*	–	–	Y	–	Stevens and Stone 2007
	Leptotriticites aff. *L. gracilitatus*?	–	–	Y	–	Stevens and Stone 2007
	Leptotriticites aff. *L. hatchetensis*	–	–	Y	–	Stevens and Stone 2007; Stone et al. 2017
	Leptotriticites cf. *L. hughesensis*	–	–	Y	–	Stevens and Stone 2007; Stone et al. 2017
	Leptotriticites cf. *L. panamintensis*	–	–	Y	–	Stone et al. 2017
	Leptotriticites cf. *L. varius*	–	–	Y	–	Stevens and Stone 2007; Stone et al. 2017
	Leptotriticites wetherensis	–	–	Y	–	Stevens and Stone 2007; Stone et al. 2017
	Leptotriticites sp.	–	–	Y	–	Stone et al. 2017
	Leptotriticites sp. 2	–	–	Y	–	Stevens and Stone 2007; Stone et al. 2017
	Parafusulina cf. *P. bakeri*	–	–	Y	–	Stevens and Stone 2007
	Parafusulina aff. *P. durhami*	–	–	Y	–	Stevens and Stone 2007
	Parafusulina cf. *P. shaksgamensis crassimarginata*	–	–	Y	–	Stevens and Stone 2007
	Parafusulina splendens	–	–	Y	–	Stevens and Stone 2007
	Parafusulina sp.	–	–	Y	–	Thompson and Hazzard 1946
	Parafusulina sp. 1	–	–	Y	–	Stevens and Stone 2007
	Paraschwagerina fairbanksi	–	–	Y	–	Stevens and Stone 2007
	Pseudochusenella hazzardi	–	–	Y	–	Stevens and Stone 2007

Appendix Table A-2 (continued). Taxa reported from Devonian through Jurassic formations in MOJA.

Group	Taxon	Ds	Mm	PlPb	Ja	References
Other Fossils: Foraminifera (continued)	*Pseudoschwagerina arta*	–	–	Y	–	Stevens and Stone 2007; Stone et al. 2017
	Pseudoschwagerina arta?	–	–	Y	–	Stevens and Stone 2007
	Pseudoschwagerina cf. *P. gerontica*	–	–	Y	–	Stevens and Stone 2007; Stone et al. 2017
	Pseudoschwagerina roeseleri	–	–	Y	–	Stone et al. 2017
	Pseudoschwagerina roeseleri?	–	–	Y	–	Stone et al. 2017
	Pseudoschwagerina cf. *P. roeseleri*	–	–	Y	–	Stone et al. 2017
	Pseudoschwagerina uddeni	–	–	Y	–	Stevens and Stone 2007; Stone et al. 2017
	Pseudoschwagerina sp.	–	–	Y	–	Thompson and Hazzard 1946; Barca 1960; Yelverton 1963; Dunne 1972; Stone et al. 2017
	Pseudoschwagerina sp. 1	–	–	Y	–	Stevens and Stone 2007
	Schubertella kingi	–	–	Y	–	Thompson and Hazzard 1946
	Schwagerina aculeata	–	–	Y	–	Stevens and Stone 2007; Stone et al. 2017
	Schwagerina aculeata plena	–	–	Y	–	Stevens and Stone 2007; Stone et al. 2017
	Schwagerina aff. *S. davisi*	–	–	Y	–	Stevens and Stone 2007
	Schwagerina cf. *S. colemani*	–	–	Y	–	Stone et al. 2017
	Schwagerina cf. *S. elkoensis*	–	–	Y	–	Stevens and Stone 2007
	Schwagerina cf. *S. menziesi*	–	–	Y	–	Stevens and Stone 2007
	Schwagerina modica	–	–	Y	–	Stone et al. 2017

Appendix Table A-2 (continued). Taxa reported from Devonian through Jurassic formations in MOJA.

Group	Taxon	Ds	Mm	PlPb	Ja	References
Other Fossils: Foraminifera (continued)	*Schwagerina* aff. *S. modica*	–	–	Y	–	Stone et al. 2017
	Schwagerina providens	–	–	Y	–	Stevens and Stone 2007; Stone et al. 2017
	Schwagerina providens?	–	–	Y	–	Stevens and Stone 2007
	Schwagerina cf. *S. pugunculus*	–	–	Y	–	Stevens and Stone 2007
	Schwagerina wellsensis	–	–	Y	–	Stone et al. 2017
	Schwagerina aff. *S. wellsensis*	–	–	Y	–	Stevens and Stone 2007; Stone et al. 2017
	Schwagerina cf. *S. wellsensis*	–	–	Y	–	Stevens and Stone 2007; Stone et al. 2017
	Schwagerina vervillei	–	–	Y	–	Stevens and Stone 2007
	Schwagerina sp.	–	–	Y	–	Thompson and Hazzard 1946; Barca 1960; Yelverton 1963
	Schwagerina sp. 4	–	–	Y	–	Stone et al. 2017
	Schwagerina? sp. 1	–	–	Y	–	Stevens and Stone 2007
	Schwagerina? sp. 2	–	–	Y	–	Stevens and Stone 2007
	Stewartina convexa	–	–	Y	–	Stevens and Stone 2007; Stone et al. 2017
	Stewartina convexa?	–	–	Y	–	Stevens and Stone 2007
	Stewartina magnifica	–	–	Y	–	Stevens and Stone 2007
	Stewartina texana	–	–	Y	–	Stevens and Stone 2007
	Stewartina uber	–	–	Y	–	Stevens and Stone 2007
	Stewartina uber?	–	–	Y	–	Stevens and Stone 2007
	Stewartina ultimata	–	–	Y	–	Stevens and Stone 2007
	Stewartina sp.	–	–	Y	–	Stone et al. 2017
	Stewartina sp. 1	–	–	Y	–	Stevens and Stone 2007
	Triticites bensonensis	–	–	Y	–	Stevens and Stone 2007; Stone et al. 2017

Appendix Table A-2 (continued). Taxa reported from Devonian through Jurassic formations in MOJA.

Group	Taxon	Ds	Mm	PlPb	Ja	References
Other Fossils: Foraminifera (continued)	*Triticites bensonensis*?	–	–	Y	–	Stevens and Stone 2007; Stone et al. 2017
	Triticites californicus	–	–	Y	–	Thompson and Hazzard 1946; Stevens and Stone 2007; Stone et al. 2017
	Triticites aff. *T. californicus*	–	–	Y	–	Stevens and Stone 2007; Stone et al. 2017
	Triticites cellamagnus	–	–	Y	–	Stevens and Stone 2007; Stone et al. 2017
	Triticites elegantoides	–	–	Y	–	Stevens and Stone 2007; Stone et al. 2017
	Triticites gigantocellus	–	–	Y	–	Stevens and Stone 2007; Stone et al. 2017
	Triticites hermanni	–	–	Y	–	Stevens and Stone 2007; Stone et al. 2017
	Triticites muddiensis	–	–	Y	–	Stevens and Stone 2007; Stone et al. 2017
	Triticites aff. *T. rothi*	–	–	Y	–	Stevens and Stone 2007; Stone et al. 2017
	Triticites sp.	–	–	Y	–	Dunne 1972
	Triticites sp. 1	–	–	Y	–	Stevens and Stone 2007
	Triticites? sp.	–	–	Y	–	Barca 1960
	Fusulinida undetermined	–	–	Y	R	Barca 1960; Yelverton 1963; Law 1969; Marzolf and Cole 1987
	Undetermined small foraminifera	–	–	Y	–	Stone et al. 2017
	Foraminifera undetermined	–	–	Y	–	Law 1969
Other Fossils: Other	Probable coatings by *Osagia*	–	–	Y	–	Stone et al. 2017
	Unspecified fossils and fossil debris	Y	Y	Y	–	Hazzard and Mason 1936; Haskell 1959; Yelverton 1963; Dunne 1972; Novitsky-Evans 1978; Wilson 1978; Stevens and Stone 2007; Stone et al. 2017

Appendix Table A-3. Taxa reported from Neogene and Quaternary formations in MOJA.

Group	Taxon	Tw	To	Q	References
Plants	**Plants overall**	**Y**	**Y**	**Y**	**–**
Plants: Pinopsida	*Abies concolor*	–	–	Y	Mehringer and Ferguson 1969; Wells 1983; midden database
	Juniperus osteosperma	–	–	Y	Mehringer and Ferguson 1969; Wells 1983
	Pinus flexilis	–	–	Y	Mehringer and Ferguson 1969; Spaulding 1977; Wells 1983
	Pinus longaeva	–	–	Y	Mehringer and Ferguson 1969; Spaulding 1977; Wells 1983
	Pinus monophylla	–	–	Y	Mehringer and Ferguson 1969; Wells 1983
	Sequoia langsdorfii	Y	Y	–	Hazzard 1954; Reynolds et al. 1995
	Conifer needles	Y	–	–	Reynolds et al. 1995
Plants: Magnoliophyta	*Agropyron* sp.	–	–	Y	USGS midden database
	Artemisia tridentata-type	–	–	Y	USGS midden database
	Berberis sp.	–	–	Y	USGS midden database
	Chrysothamnus sp.	–	–	Y	USGS midden database
	Cirsium sp.	–	–	Y	USGS midden database
	Descurainia sp.	–	–	Y	USGS midden database
	Euphorbia sp.	–	–	Y	USGS midden database
	Leptodactylon sp.	–	–	Y	USGS midden database
	Muhlenbergia sp.	–	–	Y	USGS midden database
	Undetermined grasses	Y	–	–	SBCM records
	Undetermined reeds	Y	–	–	SBCM records
Other plants	Reed-like fossils	Y	–	–	Strong 1975; inventory
	Unspecified wood	Y	Y	–	Reynolds et al. 1995; Santucci et al. 2004
Invertebrates	**Invertebrates overall**	**Y**	**Y**	**Y**	**–**
Invertebrates: Mollusca: Bivalvia	*Anodonta californiensis*	–	–	Y	SBCM records
	Pisidium sp.	–	Y (Tn)	–	Medall 1964
Invertebrates: Mollusca: Gastropoda	*Planorbella tenuis*	–	–	Y	SBCM records
Invertebrates: Arthropoda	Ostracoda undetermined	Y	Y	–	Hazzard 1954; Reynolds et al. 1995
Vertebrates	**Vertebrates overall**	**Y**	**U**	**U**	**–**
Vertebrates: Actinopterygii	*Siphateles bicolor*	–	–	Y	Santucci et al. 2004; MOJA records
Vertebrates: Mammalia	*Neotoma* sp.	–	–	Y	Santucci et al. 2004; MOJA records
	Reithrodontomys sp.	–	–	Y	Santucci et al. 2004; MOJA records
	cf. *Trogomys*	Y	–	–	Reynolds et al. 1995; Tedford et al. 2004
	Ochotonidae undetermined	Y	–	–	Reynolds et al. 1995; Tedford et al. 2004

Appendix Table A-3 (continued). Taxa reported from Neogene and Quaternary formations in MOJA.

Group	Taxon	Tw	To	Q	References
Vertebrates: Mammalia (continued)	*Metatomarctus* cf. *M. canavus*	Y	–	–	Reynolds et al. 1995; Wang et al. 1999; Tedford et al. 2004
	Felidae undetermined	Y	–	–	Reynolds et al. 1995
	Mammuthus sp.	–	–	Y	MOJA records; SBCM records
	Menoceras barbouri	Y	–	–	Reynolds et al. 1995; Tedford et al. 2004
	Equus sp.	–	–	Y	Reynolds et al. 2003; MOJA records; SBCM records
	cf. *Hesperocamelus*	Y	–	–	Reynolds et al. 1995; Tedford et al. 2004
	Protolabis sp.	Y	–	–	Reynolds et al. 1995; Tedford et al. 2004
	Camelidae undetermined	–	–	Y	Reynolds et al. 2003; MOJA records
	Aletomeryx occidentalis	Y	–	–	Reynolds et al. 1995; Tedford et al. 2004
Vertebrates: Other	Vertebrata unspecified	–	U	U	Nielson and Nakata 1993
Ichnofossils	Probable root traces	Y	–	–	Inventory
	Flamingo tracks	Y	–	–	Reynolds et al. 1995
	Neotoma droppings	–	–	Y	Mehringer and Ferguson 1969
	Neotoma middens	–	–	Y	Mehringer and Ferguson 1969; Spaulding 1977; Wells 1983
Other Fossils	Filamentous algae	–	? (Tca)	–	Capps and Moore 1997

Notes

- Bright Angel Shale of Hewett (1956) attributed to Latham Shale
- Basal Cornfield Springs Formation of Hazzard and Mason (1936) and basal shale of unnamed Cambrian–Devonian interval of Hazzard (1954) attributed to Nopah Formation
- Unnamed Devonian limestone of Stone et al. (2017) interpreted as Sultan Limestone here
- References to “cup corals” are interpreted as horn corals (solitary Rugosa)
- Miocene mammal identifications after Tedford et al. (2004)
- *Aepycamelus*? of Reynolds et al. (1995) = cf. *Hesperocamelus* of Tedford et al. (2004)
- *Agraulos* of Hazzard (1954) assumed to be typo for *Agraulus*
- *Aletomeryx* sp. of Reynolds et al. (1995) = *Aletomeryx occidentalis* of Tedford et al. (2004)
- *Derbya* is a spelling variant of *Derbyia*
- *Eothele spurri* = *Acrothele spurri*
- *Gastrioceras* cf. *G. cancellatum* of Hazzard (1954) = *Paralegoceras texanum*
- *Gila bicolor* = *Siphateles bicolor*
- *Marginifera muricatus* = *Marginifera muricatina*

- *Menoceras* like *M. falkenbachi* of Reynolds et al. (1995) = *Menoceras barbouri* of Tedford et al. (2004)
- *Mesonacis bristolensis* = *Olenellus bristolensis* = *Bristolia bristolensis*
- *Mesonacis insolens* = *Olenellus insolens* = *Bristolia insolens*
- *Miolabis* of Reynolds et al. (1995) = *Protolabis* sp. of Tedford et al. (2004)
- *Olenellus fremonti* = *Mesonacis fremonti*
- *Paedumias clarki* = *Olenellus clarki*
- *Paedumias mohavensis* = *Olenellus mohavensis* = *Bristolia mohavensis*
- *Paedumias nevadensis* = *Olenellus nevadensis*
- *Phycodes pedum* = *Treptichnus pedum*
- *Pinus aristata* of Mehringer and Ferguson (1969) = *Pinus longaeva* of Wells (1983)
- Providence Mountains annelid = unnamed palaeoscolecid of Conway Morris and Peel (2010)
- Providence Mountains *Anomalocaris* sp. = *Ramskoeldia consimilis*? (Pates et al. 2021)
- *Schwagerina* sp. 3 of Stevens and Stone (2007) = *Schwagerina* cf. *S. wellsensis*
- *Tomarctus* sp. of Reynolds et al. (1995) = *Metatomarctus* cf. *M. canavus* of Tedford et al. (2004)
- *Trogomys* sp. of Reynolds et al. (1995) = cf. *Trogomys* of Tedford et al. (2004)

Appendix B: South Kelso Mountains Measured Section

Appendix Table B-1. Stratigraphic description of units in the South Kelso Mountains measured section.

Formation	Thickness	Strike/ Dip	Lithology	Sedimentary Structures	Diagenetic Features	Fossils Present
Middle Wood Canyon Formation	1.5 m (4.9 ff) to bottom of outcrop	5/30S	Yellow to orange-brown, well-sorted, medium- to coarse-grained sandstone. Potentially pebbles at base of outcrop.	Possible cross-bedding.	None observed	None observed
Upper Wood Canyon Formation	20 m (66 ft)	11/45S	Interbedded light gray sandstone, dark gray sandstone with red iron oxide coatings, and dark brown mudstone. Sandstone beds are fine-grained and well-sorted.	Some sandstone beds have planar lamination. Sandstone beds are 10–25 cm (3.8–9.8 in) thick. Mudstone beds are 1–7 cm (0.4–2.8 in) thick. Sharp contacts between sandstone and mudstone beds.	Red iron coating on weathered surface of dark gray sandstone and in fractures. White, powdery, ~1 cm (0.4 in) diameter, blob-shaped coating on certain beds.	Vertically oriented, ~1 cm (0.4 in) diameter burrows, arthropod trails
Zabriskie Quartzite	20 m (66 ft)	27/64S	White to yellow, well-sorted, medium-grained to crystalline quartz sandstone.	Mostly massive, some faint laminations.	Red coating in small (1–2 mm [0.04–0.08 in] wide) fractures	None observed
Latham Shale	27 m (89 ft)	37/58S	Dark gray, brown, and greenish-gray well-sorted fissile mudstone.	Laminations to beds of mudstones. Flute and scour marks.	Red iron coating on fissile shale	Fossils are found in the upper section of the Latham Shale that is dark gray and fissile. Fossils include trilobites (primarily cephalons), potential soft-bodied organisms, and brachiopods
Chambless Limestone	N/A	N/A	Light gray and massive to dark gray and thickly bedded ridge-forming oncolite limestone	Dark gray sections have thick bedding	Fractures filled with sandy carbonate veins and small rock fragments	2–3 cm (0.8–1.2 in)-wide oncoids

Appendix C: Repository Contact Information

Contact information for institutions known to have collections from MOJA are included below. Addresses, links, and email addresses to departments are included as available. This information is subject to change, particularly hyperlinks.

CALIFORNIA ACADEMY OF SCIENCES
55 Music Concourse Drive
San Francisco, CA 94118
(415) 379-8000
https://www.calacademy.org/
https://www.calacademy.org/scientists/department-of-invertebrate-zoology-and-geology-history

NATURAL HISTORY MUSEUM OF LOS ANGELES COUNTY
900 Exposition Blvd
Los Angeles, CA 90007
(213) 763-3466
https://nhm.org/
https://nhm.org/research-collections/departments/invertebrate-paleontology (Invertebrate Paleontology)
invpaleo@nhm.org (Invertebrate Paleontology general contact)
https://nhm.org/research-collections/departments/vertebrate-paleontology (Vertebrate Paleontology)
vertpaleo@nhm.org (Vertebrate Paleontology general contact)

SAN BERNARDINO COUNTY MUSEUM
2024 Orange Tree Lane
Redlands, CA 92374
909-798-8608
https://museum.sbcounty.gov/
museum@sbcounty.gov

SMITHSONIAN INSTITUTION, NATIONAL MUSEUM OF NATURAL HISTORY
Department of Paleobiology
P.O. Box 37012
NHB MRC 121
Washington, D.C. 20013
https://naturalhistory.si.edu/research/paleobiology
paleodept@si.edu

TEXAS MEMORIAL MUSEUM
2400 Trinity Street
Mail Stop D1500
Austin, TX 78712
512-471-1604
https://tmm.utexas.edu/
tmminfo@austin.utexas.edu

UNIVERSITY OF CALIFORNIA MUSEUM OF PALEONTOLOGY
Museum of Paleontology
University of California
1101 Valley Life Sciences Building
Berkeley, CA 94720-4780
(510) 642-1822
https://ucmp.berkeley.edu/
https://ucmp.berkeley.edu/contact-ucmp/

UNIVERSITY OF CALIFORNIA–RIVERSIDE
900 University Ave
Riverside, CA 92521
951-827-3182
https://epsci.ucr.edu/

WESTERN SCIENCE CENTER
2345 Searl Pkwy
Hemet, CA 92543
(951) 791-0033
https://www.westernsciencecenter.org/

Appendix D: Glossary

Alkaline: When applied to bodies of water, this refers to a pH greater than 7.0.

Alluvial (adjective), **alluvium** (noun)**:** A general term for unconsolidated terrestrial sediment moved by water and not attributed to a more specific process (i.e., not fluvial, glacial, or lacustrine).

Amberat: Crystallized urine of the rodent *Neotoma* (packrats, woodrats, trade rats); may also sometimes be used in a general sense for undefined *Neotoma* midden contents.

Ammonoid: An extinct shelled cephalopod. Most but not all ammonoids had planispiral, tightly coiled shells. Ammonoids are also sometimes called "ammonites", although that term more strictly applies to a subgroup of ammonoids.

Andesite: A feldspar-rich extrusive igneous rock.

Angiosperm: Any of the flowering plants.

Anoxic: When applied to bodies of water, this refers to waters depleted of oxygen.

Arachnid: Any of the Arachnida, an arthropod group including mites, scorpions, spiders, ticks, and relatives.

Archaeocyathid: An extinct coral-like sponge known only from Cambrian rocks.

Arkose: Sandstone rich in grains of feldspar minerals.

ARPA: Archaeological Resources Protection Act.

Arthropod: Any of a diverse group of invertebrates with exoskeletons, segmented bodies, and jointed appendages. Insects, arachnids, and crustaceans are modern examples.

Articulate brachiopod: A brachiopod with a shell hinge featuring hard "teeth" and "sockets."

Artiodactyl: An even-toed ungulate mammal (e.g., bison, camels, deer, pigs, sheep).

Asteroid: An echinoderm familiar for its five radiating arms; also known as a "sea star" or "starfish".

Baddeleyite: A mineral composed of zirconium oxide (ZrO_2).

Basin (geological): A geologic downwarp formed by folding and faulting; geologic basins can often be identified by rock strata dipping to a central point, a bull's-eye pattern of rocks in a geologic map with the youngest rocks at the center, or an anomalous area of young rocks at the same elevation as older rocks in the vicinity. An eroded geologic basin does not necessarily form a physical depression.

Bellerophont: An extinct mollusk with a planispiral shell and a flaring aperture. Bellerophonts are usually classified with snails but at least some may be monoplacophorans.

Bilobate: Having two lobes.

Bioclast: A clast of biological origin; biological remains functioning as sedimentary particles. Any fossil can technically be considered a bioclast, but the term is most often used for skeletal fragments of marine organisms.

Bioclaustration: A trace fossil of an organism embedded in another organism.

Biostratigraphy: Using fossils to identify the relative positions and relative ages of rocks.

Bioturbation: Disturbance of sediment by organisms to the extent that sedimentary features such as bedding and stratification are destroyed.

Bivalve: A mollusk with two shells; bivalves are also sometimes known as pelecypods, to reduce confusion (the term "bivalve" in a general sense also applies to other groups, such as brachiopods and some arthropods). Examples include clams, oysters, mussels, and scallops.

Blastoid: An extinct stalked echinoderm resembling a crinoid but with a nut-shaped body bearing numerous small filtering appendages, rather than a cup-shaped body with a smaller number of large appendages. Blastoids are sometimes identified informally as "sea buds".

BLM: Bureau of Land Management.

Brachiopod: A marine filter-feeding animal with two shells, resembling bivalve mollusks but more closely related to bryozoans. Brachiopods are sometimes known as "lamp shells" because some of them resemble ancient oil lamps.

Breccia: A rock composed of large angular fragments in a fine-grained matrix.

Bryozoan: A filter-feeding aquatic colonial animal. Bryozoans are sometimes known as "moss animals" because they often encrust objects.

Calcareous: Mostly or partly composed of calcium carbonate; lime-rich.

Calcisphere: An enigmatic microfossil, possibly an algal cyst.

Calcite: A mineral made of calcium carbonate; found in limestone and some fossils.

Calcium carbonate: $CaCO_3$, a mineral-forming compound. Calcite is a common form.

Caldera: A basin landform formed from the collapse of a magma chamber following eruption.

Cambrian: The first geologic period of the Paleozoic Era, noted for the abrupt diversification of life ("Cambrian explosion"); approximately 539 to 487 Ma.

Camelid: A member of the group of mammals including camels and relatives.

CAMO: Castle Mountains National Monument.

Canid: A member of the group of mammals including dogs and relatives.

Carbonate: In geology, a general term for minerals containing carbonate ions (CO_3^{-2}), such as calcite, and rocks containing these minerals, such as dolomite and limestone.

Carboniferous: Internationally, the fifth geologic period of the Paleozoic Era, usually divided into the Mississippian and Pennsylvanian in North America; approximately 359 to 299 Ma.

Carnivoran: A member of the group of mammals including most of the living flesh-eating forms (e.g., felines, canines, bears, raccoons, weasels, seals, etc.).

Cenozoic: A geologic era, dated approximately 66 Ma to the present, noted for the diversification of mammals; the term means "new life".

Cephalon: The head shield of a trilobite.

Cephalopod: A mollusk with a prominent head fringed by tentacles. Examples include squids, octopuses, *Nautilus*, and many extinct forms, especially ammonoids.

Chert: A rock made of silica lacking obvious macroscopic crystals. Flint is a variety of chert found in chalk and marly limestone.

Clast: A rock fragment of any size. A rock made up of clasts, such as sandstone or shale, is called clastic.

Cloudiniid: An enigmatic conical tubular fossil.

Cnidarian: Any of a group of invertebrates noted for capturing prey using stinging cells. Most fossil cnidarians are corals.

Columnal: Individual segments of an echinoderm's stalk, particularly crinoids. They resemble doughnuts, sprockets, or gears.

Conifer: A general term for non-flowering plants that produce seeds and pollen from cones.

Conodont: An extinct eel-like chordate, known primarily from jaw elements.

Contact: In geology, the horizon or plane where two formations meet.

Coprolite: Fossil feces.

Cretaceous: The third and last geologic period of the Mesozoic Era, noted for the rise of flowering plants and the extinction of many groups at the end of the period; approximately 143 to 66 Ma.

Crinoid: An echinoderm, also known as a sea lily, featuring a cup-like body with feathery tentacular arms, usually but not always attached to a surface with a stalk.

Cyanobacteria: Photosynthetic bacteria, also known informally as "blue-green algae".

Cystoid: An extinct echinoderm similar to a crinoid but with an ovoid body, instead of cup-like.

Dacite: An extrusive igneous rock composed primarily of quartz and feldspar.

Debitage: An archeological term for rock debris produced by working stones to produce tools and weapons.

DEVA: Death Valley National Park.

Devonian: The fourth geologic period of the Paleozoic Era; approximately 419 to 359 Ma.

Diagenesis: Physical and chemical changes produced in sediments after deposition.

Diatoms: Algae that secrete cell walls of silica. Diatoms are common microfossils.

Disconformity: An unconformity where the strata above and below the geologic contact are parallel, but the contact itself shows evidence of erosion or nondeposition.

DOI: Department of the Interior or, in references, digital object identifier.

Dolomite: A mineral made of calcium-magnesium carbonate, and a rock (alternatively **dolostone**) composed primarily of this mineral. Most dolomite is formed by the replacement of some of the calcium ions in calcium carbonate by magnesium, a process called dolomitization.

Dolomitization: The conversion of calcium carbonate to dolomite by the replacement of calcium ions with magnesium. This process involves recrystallization and is destructive to fossils made of calcium carbonate, although not all such fossils are affected the same way: mollusk shells are more vulnerable than brachiopod and bryozoan specimens, which in turn are more vulnerable than echinoderm columnals and plates.

Echinoderm: Any of a group of invertebrates noted for their five-fold symmetry. Sea stars (asteroids) and sea urchins (echinoids) are familiar echinoderms.

Echinoid: An echinoderm, also known as a sea urchin, commonly having a globose body covered in spines.

Ediacaran: (Geochronology) A geological period that spans 96 million years from the end of the Cryogenian Period 635 million years ago (Mya), to the beginning of the Cambrian Period 538.8 Mya. It marks the end of the Proterozoic Eon, and the beginning of the Phanerozoic Eon. (Paleontology) A general adjective for soft-bodied, often frond-like organisms that flourished during this period.

Encrinite: A grain-supported sedimentary rock in which the majority of the grains are crinoid fragments.

Eocrinoid: An extinct stalked echinoderm of the early Paleozoic, somewhat similar to crinoids but not closely related.

Eolian: Wind-blown transport or an environment where wind transport dominates.

Erg: A sand-covered desert at least 125 km^2 (48 mi^2) in area; may also be called a dune sea if dunes are abundant.

Extrusive: In igneous rocks, “extrusive” refers to rocks erupted at the surface of the Earth.

Facies: A body of rock that is distinct from the surrounding rock, due to specific aspects of deposition and setting; facies are generally invoked when there are differences within a formation or member that are not suitable for mapping (i.e., not laterally persistent).

Fanglomerate: A gravel-rich conglomerate that originated as a debris flow on an alluvial fan.

Feldspar: One of a number of minerals composed of crystals including various metal ions, aluminum, silicon, and oxygen.

Felid: A member of the group of mammals including cats and relatives.

Fissile: In geology, a rock that has a tendency to split along flat planes of weakness.

Flaggy: A rock that splits into flagstone-like blocks and surfaces.

Float: In geology, eroded material resting on the surface, not attached to an outcrop.

Flute cast: An elongate filled scour projecting from the underside of a bed.

Fluvial: A river as depositional environment or mode of transport.

Foraminifera: A “shelled amoeba”; “foraminifera” is often used for both singular and plural, although some authorities prefer “foraminiferan” for singular and “foraminiferans” or “foraminifers” for plural, and others use the more informal “foram” and “forams.” Foraminifera, which still exist today, are well-known as microfossils from their tests, usually composed of calcium carbonate or tiny sediment grains (agglutinated).

Formation: A group of rocks that share some characteristics and can be depicted on a geological map; the basic unit of stratigraphy.

Fossiliferous: A rock or deposit that yields fossils.

Friable: Rocks and deposits that are easily crumbled.

Fusulinid: A variety of extinct foraminifera noted for their chambered, relatively enormous tests (as much as several cm long). In the field, they may resemble rice or other similar grains, and can be abundant in rocks of Pennsylvanian or Permian age.

Ga: An abbreviation for “giga-annum,” but more easily understood as “million years ago”.

Gneiss: A high-grade metamorphic rock characterized by banding of light-colored (quartz) and dark minerals.

Granite: An igneous rock formed at depth, composed primarily of light-colored quartz and feldspar minerals with small quantities of dark minerals.

GRD: Geologic Resources Division of the National Park Service.

GRI: Geologic Resources Inventory.

Hardground: Naturally cemented seafloor; hardening occurred before the seafloor was buried. Hardgrounds were inhabited by assemblages specialized to live on or in the hard surface.

Helicoplacoid: An extinct sac-shaped echinoderm with a body made up of small mineralized plates.

Holocene: The second and most recent epoch of the Quaternary Period, following the Pleistocene and the last glacial maximum; approximately 11,700 years ago to the present.

Holothurian: A sac-shaped echinoderm also known as a sea cucumber.

Holotype: A name-bearing specimen for an organism. Some species are based on multiple specimens, which are called cotypes (outdated; sometimes "co-types") or syntypes.

Horn coral: A solitary rugose coral. The name refers to the animal-horn-like hard structure.

Hornfels: Sedimentary rocks altered by contact metamorphism caused by nearby hot igneous intrusions.

Humerus: The upper bone of the forelimb or arm.

Hyolith: An extinct animal with an elongate triangular shell, apparently close to the ancestry of brachiopods, mollusks, or both.

***Hyolithellus*:** A conical worm-tube-like fossil.

Ichnofossil: Fossilized remains of biological activity of an organism, including traces of footprints, tracks, burrows, trails, and other biogenically produced features.

Ichnogenus, ichnospecies, ichnotaxon: A scientific name used for a trace fossil, existing in parallel to the names used for body fossils.

In situ: When describing fossils, this means found in place at an outcrop.

Inarticulate brachiopod: A brachiopod with a shell hinge lacking hard structures to keep it closed, instead relying on muscles.

Intertidal: Within the range from low tide to high tide.

Intraclast: A clast representing material that was redeposited after being partially lithified.

Intrusive: In igneous rocks, "intrusive" refers to rocks that cooled from a molten state below the surface of the Earth.

Isopachous: Having an even thickness.

Jurassic: The second geologic period of the Mesozoic Era; approximately 201 to 143 Ma.

Lacustrine: A lake as depositional environment or mode of transport.

LAKE: Lake Mead National Recreation Area

Lithified: A sedimentary deposit that has become rock.

Lithology: The variety or varieties of rock in a formation, member, bed, or other division.

Locality: A distinct site, especially one known to field fossils or other unique features.

Ma: An abbreviation for “mega-annum,” but more easily understood as “million years ago.”

Macrofossil: A fossil that can be studied with the naked eye or a hand lens.

Marl: Calcium carbonate mud or mudstone that commonly forms in lakes.

Massive: In geology, this describes rocks without visible stratification or other bedding features.

Member: A subdivision of a formation.

Mesoproterozoic: The second geologic era of the Proterozoic Eon; 1600 to 1000 Ma.

Mesozoic: A geologic era, dated approximately 252 to 66 Ma, noted for the dominance of dinosaurs on land and the appearance of birds, mammals, and flowering plants; the term means “middle life”.

Metacarpal: One of the long bones of the hand, making up the palm in humans.

Metazoan: Formerly used to refer to multicellular animals, now synonymous with Animalia following the reassignment of single-celled forms.

Microfossil: A fossil, typically a millimeter (0.04 inches) or less in size, that must be studied with a microscope.

Miocene: The first epoch of the Neogene Period; approximately 23 to 5.33 Ma.

Mississippian: In North America, the de facto fifth geologic period of the Paleozoic Era (internationally a subperiod of the Carboniferous Period); approximately 359 to 323 Ma.

MOJA: Mojave National Preserve.

MOJN: Mojave Desert Inventory & Monitoring Network.

Mold: An impression of an organism left in sediment.

Mollusk: Any of a diverse group of invertebrates noted for their combination of a muscular foot, a shell, and a mantle that covers the innards and secretes the shell. Examples include bivalves, cephalopods, and gastropods (snails).

Monera: The group including single-celled organisms without a nucleus.

Monoplacophoran: A type of mollusk; most monoplacophorans have a cap-like or limpet-like shell, but some extinct forms had planispiral shells.

Mustelid: A member of the group of mammals including badgers, otters, weasels, and relatives.

NAGPRA: Native American Graves Protection and Repatriation Act.

Nautiloid: A member of the cephalopod group Nautiloidea, represented today by species of chambered nautilus, but in the past including various straight (**orthoconic**) and coiled forms.

Neogene: The second geologic period of the Cenozoic Era; approximately 23 to 2.58 Ma.

Neoproterozoic: The third and final geologic era of the Proterozoic Eon; approximately 1000 to 539 Ma.

NPS: National Park Service.

Oligocene: The third and final epoch of the Paleogene Period; approximately 34 to 23 Ma.

Oncoid: A concentrically laminated structure formed by microbes; rocks made of oncoids are oncolites.

Oolite: An inorganic spherical concentrically layered carbonate grain, that can be confused for an organic microbial fossil.

Opalite: In geology, opal that does not exhibit play-of-color.

Ordovician: The second geologic period of the Paleozoic Era, following the Cambrian; approximately 487 to 443 Ma.

Organic: Made of organic compounds (i.e., molecules of carbon, hydrogen, nitrogen, and oxygen); pollen, spores, and cysts, all of which can be fossilized, have organic walls.

Orogeny: A mountain-building event.

Ostracode: Also spelled "**ostracod**;" a shelled crustacean, generally microscopic. Ostracodes are known informally as "seed shrimp."

Palaeoscolecidan: An extinct armored worm bearing phosphatic plates.

Paleocene: The first epoch of the Paleogene Period; approximately 66 to 56 Ma.

Paleogene: The first geologic period of the Cenozoic Era; approximately 66 to 23 Ma.

Paleoproterozoic: The first geologic era of the Proterozoic Eon; 2500 to 1600 Ma.

Paleozoic: A geologic era, dated approximately 539 to 252 Ma, noted for the diversification of invertebrates and the appearance of vertebrates and land plants; the term means "early life".

Patella: A bone protecting the knee joint.

Pelmatozoan: A general term for any echinoderm with a "stalk" or "stem", made up of columnals; the majority are crinoids, but several other groups of pelmatozoans existed during the Paleozoic.

Pennsylvanian: In North America, the de facto sixth geologic period of the Paleozoic Era (internationally a subperiod of the Carboniferous Period); approximately 323 to 299 Ma.

Peritidal: From just below to just above tidal range.

Permian: The seventh and final geologic period of the Paleozoic Era, ended by the largest mass extinction event in Earth's history; approximately 299 to 252 Ma.

Phanerozoic: The fourth and final geologic eon of Earth's history; approximately 539 Ma to the present.

Phosphate: In geology, a general term for minerals containing phosphate (PO_4^{-3}), such as apatite, found in bones and some shells (the phosphatic shells of some inarticulate brachiopods, for example).

Planispiral: A shell coiled in a flat plane, like a *Nautilus* shell.

Planktonic: An organism that floats freely but cannot swim against a current.

Playa: A dry lake bed.

Pleistocene: The older of two epochs in the Quaternary Period, noted for ice ages; approximately 2.58 Ma to 11,700 years ago.

Pliocene: The second and final epoch of the Neogene Period; approximately 5.33 to 2.58 Ma.

Precambrian: Time before the Cambrian, before approximately 539 Ma.

Proterozoic: The third and final geologic eon of the Precambrian; approximately 2500 to 539 Ma.

Protist: Informally, either a single-celled organism with a nucleus, or an organism that has one or more nucleated cells that is not an animal, fungus, or plant.

PRPA: Paleontological Resources Preservation Act (2009).

Pygidium: The "tail" section of a trilobite. This section detached readily when the exoskeleton was shed, so pygidia are common fossils.

Quartz: A common mineral composed of silica.

Quartzite: 1) Moderately metamorphosed quartz sandstone in which the quartz sand grains have recrystallized into an interlocking mosaic (also known as **metaquartzite**); 2) Unmetamorphosed quartz-cemented quartz sandstone (also known as **orthoquartzite**).

Quaternary: The most recent geologic period, third and last in the Cenozoic Era, noted for multiple ice ages; approximately 2.58 Ma to the present.

Radiocarbon: Carbon-14 (^{14}C), a radioactive isotope of carbon with a half-life (the time required for half of a sample to decay) of 5,700 ± 30 years, used to date organic materials younger than approximately 50,000 years.

Radiocarbon years: Uncalibrated radiocarbon dates are presented as radiocarbon years before present (defined as 1950).

Radiodont: A member of Radiodonta, a group of extinct early arthropods including forms such as *Anomalocaris*.

Radiolarian: A microscopic planktic organism with a test made of silica.

Radius: One of two bones of the forearm, it does not articulate with the upper arm (humerus).

(Marine) Regression (noun), **regressive** (adjective)**:** a marine retreat, exposing land.

Reworked: A fossil that has been eroded from an older rock unit and redeposited in a younger unit.

Riparian: Pertaining to a riverbank setting.

Rhyolite: A quartz-rich extrusive igneous rock.

Rostroconch: An extinct mollusk noted for a “taco”-like single folded shell, resembling a bivalve.

Rugose coral: An extinct type of coral, with the name in reference to the wrinkled surfaces of their fossils. Rugose corals included both colonial and solitary forms, with the solitary forms known as horn corals.

Sacrum: Two or more fused vertebrae supporting the hip.

Scolecodont: A jaw element of a bristle worm, a common microfossil.

Scour mark: A filled erosive scour preserved on the underside of a bed.

Shoreface: The sloping zone between a horizonal offshore bottom and low tide.

Silica: The compound SiO_2, the building block of the common mineral quartz.

Silicate mineral: A mineral with a framework of silica. Quartz and felspar minerals are common silicates.

Silicification: The replacement of a non-silicate mineral with a silicate mineral.

Sill: A tabular igneous intrusion, emplaced along beds or layers of older rock units.

Silurian: The third geologic period of the Paleozoic Era, following the Ordovician; approximately 443 to 419 Ma.

Skarn: A metamorphic rock formed by alteration via hydrothermal fluids.

Stratigraphy: The study of rock layers.

Stromatolite: A layered microbial mat, typically columnar or domal.

Stromatoporoid: A coral-like sponge; seemingly extinct although some modern sponges are similar.

Structure: In geology, structures are various three-dimensional features such as folds and faults.

Subtidal: Below low tide.

Supratidal: Above high tide.

Tabulate coral: A type of extinct colonial coral, commonly encrusting other fossils; fossils may resemble honeycombs.

Talus: Broken rock shed from cliffs through rock falls; also known as scree.

Taxonomy: The classification of organisms.

Tectonics: The movements and interactions of Earth's plates.

Tentaculitid: A type of extinct "tube worm" of uncertain affinities, known for mm- to cm-scale ribbed shells.

Terrane: A fragment of crustal material that has broken off of one plate and become attached to another.

Test: The formal name for the shells of foraminifera, echinoids, and some other marine organisms.

Thrombolite: A clotted microbial structure.

Trace fossil: Fossils of biological activity, such as root casts; burrows, tracks, and eggshells; also known as ichnofossils.

(**Marine) Transgression** (noun), **transgressive** (adjective)**:** A marine encroachment, submerging land.

Triassic: The first geologic period of the Mesozoic Era; approximately 252 to 201 Ma.

Trilobite: An extinct marine arthropod with a roughly oval body featuring an axial lobe and two lateral lobes (the three lobes of the name), also divided into three sections (cephalon for the head, thorax, and pygidium for the tail); trilobites vaguely resembled woodlice (roly-poly bug or pillbug).

Tufa: In sedimentology, calcareous deposits formed by precipitation from a body of water.

Tuff: A rock that contains more than 75% volcanic ash. Rock with significant but lesser ash content (25% to 75%) is called tuffaceous.

Turbidite: A deposit of a submarine density current.

TUSK: Tule Springs Fossil Beds National Monument.

Type section: A geologic exposure that serves as the basis of definition for a stratigraphic unit.

Unconformity: A general term for any erosional or non-depositional surface between two rock units.

Ungulate: In general usage, a hoofed mammal (Ungulata also includes whales and relatives).

USGS: United States Geological Survey.

Valve: A shell; the term is usually applied to mollusks but sometimes to brachiopods as well. Snails and monoplacophorans are univalved (one shell) and bivalves and brachiopods are bivalved (two shells).

***Volborthella*:** A conical tubular fossil of agglutinated sediment.

Appendix E: Paleontological Resource Law and Policy

The following material is reproduced in large part from Henkel et al. (2015); see also Kottkamp et al. (2020).

In March 2009, the Paleontological Resources Preservation Act (PRPA) (16 USC 460aaa) was signed into law (Public Law 111–11). This act defines paleontological resources as

> *…any fossilized remains, traces, or imprints of organisms, preserved in or on the [E]arth's crust, that are of paleontological interest and that provide information about the history of life on [E]arth.*

The law stipulates that the Secretary of the Interior should manage and protect paleontological resources using scientific principles. The Secretary should also develop plans for

> *…inventory, monitoring, and deriving the scientific and educational use of paleontological resources.*

The Department of Interior's final regulation for the Paleontological Resources Preservation Act was published in the Federal Register on August 2, 2022 (https://www.federalregister.gov/documents/2022/08/02/2022-16405/paleontological-resources-preservation) and approved by the Office of Management and Budget on September 1, 2022.

Paleontological resources are considered park resources and values that are subject to the "no impairment" standard in the National Park Service Organic Act (1916). In addition to the Organic Act, PRPA will serve as a primary authority for the management, protection and interpretation of paleontological resources. The proper management and preservation of these non-renewable resources should be considered by park resource managers whether or not fossil resources are specifically identified in the park's enabling legislation.

The Paleontological Resources Management section of NPS Reference Manual 77 provides guidance on the implementation and continuation of paleontological resource management programs. Administrative options include those listed below and a park management program will probably incorporate multiple options depending on specific circumstances:

- **No action**—no action would be taken to collect the fossils as they erode from the strata. The fossils would be left to erode naturally and over time crumble away, or possibly be vandalized by visitors, either intentionally or unintentionally. This is the least preferable plan of action of those listed here.
- **Surveys**—will be set up to document potential fossil localities. All sites will be documented with the use of GPS and will be entered into the park GIS database. Associated stratigraphic and depositional environment information will be collected for each locality. A preliminary fossil list will be developed. Any evidence of poaching activity will be recorded. Rates of erosion will be estimated for the site and a monitoring schedule will be developed based upon this information. A NPS Paleontological Locality Database Form will also be completed for each locality. A

standard version of this form will be provided by the Paleontology Program of the Geologic Resources Division upon request and can be modified to account for local conditions and needs.

- **Monitoring**—fossil-rich areas would be examined periodically to determine if conditions have changed to such an extent that additional management actions are warranted. Photographic records should be kept so that changes can be more easily ascertained.
- **Cyclic prospecting**—areas of high erosion which also have a high potential for producing significant specimens would be examined periodically for new sites. The periodicity of such cyclic prospecting will depend on locality-specific characteristics such as rates of sediment erosion, abundance or rarity of fossils, and proximity to visitor use areas.
- **Stabilization and reburial**—significant specimens which cannot be immediately collected may be stabilized using appropriate consolidants and reburied. Reburial slows down but does not stop the destruction of a fossil by erosion. Therefore, this method would be used only as an interim and temporary stop-gap measure. In some situations, stabilization of a locality may require the consideration of vegetation. For example, roots can destroy in situ fossils, but can also protect against slope erosion, while plant growth can effectively obscure localities, which can be positive or negative depending on how park staff want to manage a locality.
- **Shelter construction**—it may be appropriate to exhibit certain fossil sites or specimens in situ, which would require the construction of protective shelters to protect them from the natural forces of weathering and erosion. The use of shelters draws attention to the fossils and increases the risk of vandalism or theft, but also provides opportunities for interpretation and education.
- **Excavation**—partial or complete removal of any or all fossils present on the surface and potentially the removal of specimens still beneath the surface which have not been exposed by erosion.
- **Closure**—the area containing fossils may be temporarily or permanently closed to the public to protect the fossil resources. Fossil-rich areas may be closed to the public unless accompanied by an interpretive ranger on a guided hike.
- **Patrols**—may be increased in areas of known fossil resources. Patrols can prevent and/or reduce theft and vandalism. The scientific community and the public expect the NPS to protect its paleontological resources from vandalism and theft. In some situations a volunteer site stewardship program may be appropriate (for example the “Paleo Protectors” at Chesapeake & Ohio Canal National Historical Park).
- **Alarm systems/electronic surveillance**—seismic monitoring systems can be installed to alert rangers of disturbances to sensitive paleontological sites. Once the alarm is engaged, a ranger can be dispatched to investigate. Motion-activated cameras may also be mounted to visually document human activity in areas of vulnerable paleontological sites.

National Park Service Management Policies (2006; Section 4.8.2.1) also require that paleontological resources, including both organic and mineralized remains in body or trace form, will be protected, preserved, and managed for public education, interpretation, and scientific research. In 2010, the National Park Service established National Fossil Day as a celebration and partnership organized to promote public awareness and stewardship of fossils, as well as to foster a greater appreciation of their scientific and educational value (https://www.nps.gov/subjects/fossilday/index.htm). National Fossil Day occurs annually on Wednesday of the second full week in each October in conjunction with Earth Science Week.

Related Laws, Legislation, and Management Guidelines

National Park Service Organic Act

The NPS Organic Act directs the NPS to manage units

> *…to conserve the scenery and the natural and historic objects and the wildlife therein and to provide for the enjoyment of the same in such a manner as will leave them unimpaired for the enjoyment of future generations.* (16 U.S.C. § 1).

Congress reiterated this mandate in the Redwood National Park Expansion Act of 1978 by stating that the NPS must conduct its actions in a manner that will ensure no

> *…derogation of the values and purposes for which these various areas have been established, except as may have been or shall be directly and specifically provided by Congress.* (16 U.S.C. § 1 a-1).

The Organic Act prohibits actions that permanently impair park resources unless a law directly and specifically allows for the acts. An action constitutes an impairment when its impacts

> *…harm the integrity of park resources or values, including the opportunities that otherwise would be present for the enjoyment of those resources and values.* (Management Policies 2006 1.4.3).

Paleontological Resources Protection Act (P.L. 111-011, Omnibus Public Land Management Act of 2009, Subtitle D)

Section 6302 states

> *The Secretary (of the Interior) shall manage and protect paleontological resources on Federal land using scientific principles and expertise. The Secretary shall develop appropriate plans for inventory, monitoring, and the scientific and educational use of paleontological resources, in accordance with applicable agency laws, regulations, and policies. These plans shall emphasize interagency coordination and collaborative efforts where possible with non-Federal partners, the scientific community, and the general public.*

Federal Cave Resources Protection Act of 1988 (16 USC 4301)

This law provides a legal authority for the protection of all cave resources on NPS and other federal lands. The definition for "Cave Resource" in Section 4302 states

> *Cave resources include any material or substance occurring naturally in caves on Federal lands, such as animal life, plant life, paleontological deposits, sediments, minerals, speleogens, and speleothems.*

NPS Management Policies 2006

NPS Management Policies 2006 include direction for preserving and protecting cultural resources, natural resources, processes, systems, and values (National Park Service 2006). It is the goal of the NPS to avoid or minimize potential impacts to resources to the greatest extent practicable consistent with the management policies. The following is taken from section 4.8.2.1 of the NPS Management Policies 2006, "Paleontological Resources and their contexts":

> *Paleontological resources, including both organic and mineralized remains in body or trace form, will be protected, preserved, and managed for public education, interpretation, and scientific research. The Service will study and manage paleontological resources in their paleoecological context (that is, in terms of the geologic data associated with a particular fossil that provides information about the ancient environment).*
>
> *Superintendents will establish programs to inventory paleontological resources and systematically monitor for newly exposed fossils, especially in areas of rapid erosion. Scientifically significant resources will be protected by collection or by on-site protection and stabilization. The Service will encourage and help the academic community to conduct paleontological field research in accordance with the terms of a scientific research and collecting permit. Fossil localities and associated geologic data will be adequately documented when specimens are collected. Paleontological resources found in an archeological context are also subject to the policies for archeological resources. Paleontological specimens that are to be retained permanently are subject to the policies for museum objects.*
>
> *The Service will take appropriate action to prevent damage to and unauthorized collection of fossils. To protect paleontological resources from harm, theft, or destruction, the Service will ensure, where necessary, that information about the nature and specific location of these resources remains confidential, in accordance with the National Parks Omnibus Management Act of 1998.*
>
> *Parks will exchange fossil specimens only with other museums and public institutions that are dedicated to the preservation and interpretation of natural heritage and qualified to manage museum collections. Fossils to be deaccessioned in an exchange must fall outside the park's scope of collection statement. Systematically collected fossils in an NPS museum collection in compliance with 36 CFR 2.5 cannot be outside the scope of the collection statement. Exchanges must follow deaccession procedures in the Museum Handbook, Part II, chapter 6.*
>
> *The sale of original paleontological specimens is prohibited in parks.*
>
> *The Service generally will avoid purchasing fossil specimens. Casts or replicas should be acquired instead. A park may purchase fossil specimens for the park museum collection only after making a written determination that*

- *The specimens are scientifically significant and accompanied by detailed locality data and pertinent contextual data;*
- *The specimens were legally removed from their site of origin, and all transfers of ownership have been legal;*
- *The preparation of the specimens meets professional standards;*
- *The alternatives for making these specimens available to science and the public are unlikely;*
- *Acquisition is consistent with the park's enabling legislation and scope of collection statement, and acquisition will ensure the specimens' availability in perpetuity for public education and scientific research.*

> *All NPS construction projects in areas with potential paleontological resources must be preceded by a preconstruction surface assessment prior to disturbance. For any occurrences noted, or when the site may yield paleontological resources, the site will be avoided or the resources will, if necessary, be collected and properly cared for before construction begins. Areas with potential paleontological resources must also be monitored during construction projects.*

(See Natural Resource Information 4.1.2; Studies and Collections 4.2; Independent Research 5.1.2; Artifacts and Specimens 10.2.4.6. Also see 36 CFR 2.5.)

NPS Director's Order-77, Paleontological Resources Management

DO-77 describes fossils as non-renewable resources and identifies the two major types, body fossils and trace fossils. It describes the need for managers to identify potential paleontological resources using literature and collection surveys, identify areas with potential for significant paleontological resources, and conduct paleontological surveys (inventory). It also describes appropriate actions for managing paleontological resources including: no action, monitoring, cyclic prospecting, stabilization and reburial, construction of protective structures, excavation, area closures, patrols, and the need to maintain confidentiality of sensitive location information.

Excerpt from Clites and Santucci (2012):

Monitoring

An important aspect of paleontological resource management is establishing a long-term paleontological resource monitoring program. National Park Service paleontological resource monitoring strategies were developed by Santucci et al. (2009). The park's monitoring program should incorporate the measurement and evaluation of the factors stated below.

Climatological Data Assessments

These assessments include measurements of factors such as annual and storm precipitation, freeze/thaw index (number of 24-hour periods per year where temperature fluctuates above and below 32 degrees Fahrenheit), relative humidity, and peak hourly wind speeds.

Rates of Erosion Studies

These studies require evaluation of lithology, slope degree, percent vegetation cover, and rates of denudation around established benchmarks. If a park does not have this information, there may be opportunities to set up joint projects, because erosion affects more than just paleontological resources.

Assessment of Human Activities, Behaviors, and Other Variables

These assessments involve determining access/proximity of paleontological resources to visitor use areas, annual visitor use, documented cases of theft/vandalism, commercial market value of the fossils, and amount of published material on the fossils.

Condition Assessment and Cyclic Prospecting

These monitoring methods entail visits to the locality to observe physical changes in the rocks and fossils, including the number of specimens lost and gained at the surface exposure. Paleontological prospecting would be especially beneficial during construction projects or road repair.

Periodic Photographic Monitoring

Maintaining photographic archives and continuing to photo-document fossil localities from established photo-points enables visual comparison of long-term changes in site variables.

Appendix F: Paleontological Locality Data

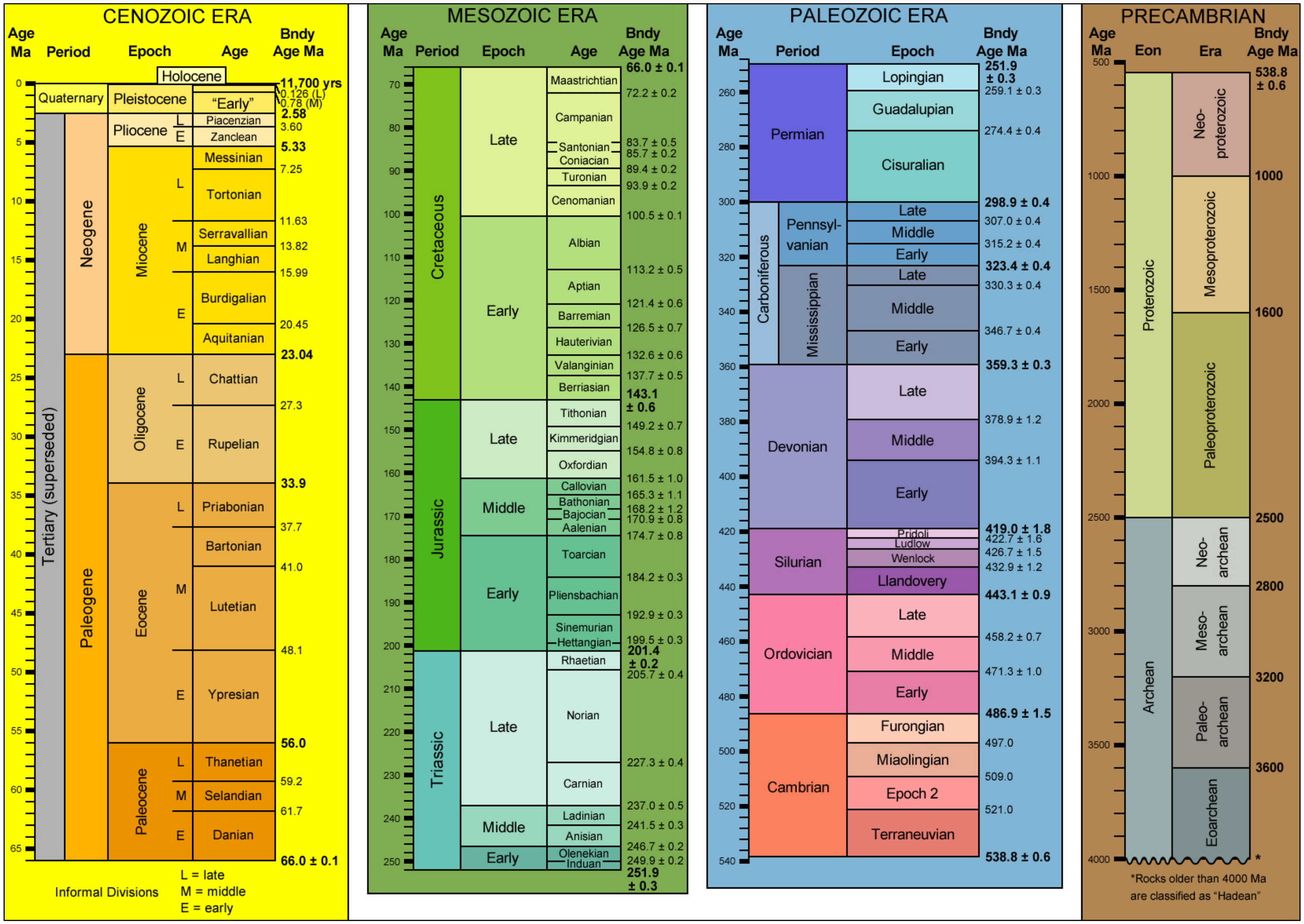
Appendix Table F-1. MOJA paleontological locality data. *=Bird Spring Formation, Monte Cristo Formation, or Sultan Limestone. **=Photo numbers represent zipped folder of photos.

Locality #	Stratigraphy	Taxa	Lithology	Photos**
MOJA 001	Upper Wood Canyon Formation	Ichnofossil tracks and burrows. Cylindrical 1 cm (0.4 in) diameter burrows commonly observed in float and rarely present vertically oriented in situ. Bioturbated blocks in float have a distinct crinkly and glossy surface. *Cruziana* and *Rusophycus*-type arthropod trails.	Interbedded sandstone and mudstone of varying thickness. Light gray to dark gray fine-grained sandstone beds are 10–25 cm (3.9–9.8 in) thick. Red diagenetic iron coating on weathered surface of dark gray sandstone beds and in fractures. White, powdery, blobby coating on some surfaces. Mudstone beds are 1–7 cm (0.4–2.8 in) thick and in sharp, non-gradational contact with the sandstone beds.	MOJA 001 (1)–(64)
MOJA 002	Latham Shale	Trilobites, brachiopods	Dark gray greenish to brown laminated mudstone. Fissile and weathered, breaks into thin angular slabs. Fossils are found in float in the upper section of the Latham that is dark gray and fissile.	MOJA 002 (1)–(64)
MOJA 003	Chambless Limestone	1–3 cm (0.4–1.2 in) oncoids (*Girvanella*? sp.), packrat middens	Weathered, ridge-forming, massive to bedded gray limestone. Pitted to crinkly weathering, fractures filled with sandy-looking carbonate veins and bits of rock. Dark gray bedded parts have little to no fossils and are more intensely weathered. Recrystallized carbonate layers fill fractures between beds. Section then repeats, from massive and fossiliferous to bedded.	MOJA 003 (1)–(36)
MOJA 004	Permian–Devonian limestone*	Crinoids, brachiopods	Dark gray, finely crystalline limestone	MOJA 004 (1)–(23)
MOJA 005	Alluvial fan deposits	Fusulinids, crinoids, gastropods, brachiopods, colonial coral	Float in alluvial fan east of the Providence Mountains. Cobble to boulder-sized, rounded limestone blue-gray and dark gray limestone.	MOJA 005 (1)–(77)
MOJA 006	Monte Cristo Limestone	Crinoid stalk fragments in situ. In float down slope and in nearby wash, fusulinids, shell imprints, sponges, colonial and solitary corals	Light gray crystalline crinoidal limestone forming canyon wall. Pitted weathering.	MOJA 006 (1)–(106)
MOJA 007	Monte Cristo Limestone	Crinoids, solitary horn corals, brachiopod fragments	Light gray crinoidal limestone to encrinite, with dark brown to black chert lenses several cm/in thick	MOJA 007 (1)–(59)
MOJA 008	Float	Crinoids, brachiopods	Dark gray to light gray limestone float, pebbles to cobbles	–

Appendix Table F-1 (continued). MOJA paleontological locality data. *=Bird Spring Formation, Monte Cristo Formation, or Sultan Limestone. **=Photo numbers represent zipped folder of photos.

Locality #	Stratigraphy	Taxa	Lithology	Photos**
MOJA 009	Upper Wood Canyon Formation	Ichnofossil burrows, bioturbated surfaces	Dark brown to dark gray interbedded sandstone and mudstone with ripple marks, intraclasts, flute and scour marks	MOJA 009 (1)–(13)
MOJA 010	Permian–Devonian limestone*	Suspect stromatolites	White to light gray fine crystalline limestone	MOJA 010 (1)–(12)
MOJA 011	Wild Horse Mesa Tuff	Reed-like fossils	Light gray volcanic tuff	MOJA 011 (1)–(36)
MOJA 012	Permian–Devonian limestone*	Crinoids	Dark gray crinoidal limestone	MOJA 012 (1)–(19)
MOJA 013	Monte Cristo Limestone	Colonial coral	Light gray limestone	MOJA 013 (1)–(23)

Appendix G: Geologic Time Scale



Ma=Millions of years old. **Bndy Age**=Boundary Age. Layout after 1999 Geological Society of America Time Scale (https://rock.geosociety.org/net/documents/gsa/timescale/timescl-1999.pdf). Dates after Gradstein et al. (2020).

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