National Park Service
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Natural Resource Stewardship and Science

Mojave National Preserve and Castle Mountains National Monument

Geologic and Soil Resources Inventory Summary



On this page: A view of the Providence Mountains from Kelso Cima Road inside Mojave National Preserve. Photo by Matthew Harrington (Colorado State University).

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Abstract

This document summarizes the status of National Park Service (NPS) Geologic Resources Inventory (GRI) and Soil Resources Inventory (SRI) deliverables for Mojave National Preserve (MOJA) and Castle Mountains National Monument (CAMO). It also provides information on current geology and soil resources management concerns with a focus on identified inventory needs related to geologic heritage, geohazards, and related soil features and processes. This document is intended to assist preserve and monument staff with prioritizing technical assistance or new inventory and assessment funding requests in the near term (roughly 1–5 years).

The GRI hosted a baseline scoping meeting for Mojave National Preserve in 2003. Castle Mountains National Monument was created after baseline scoping meetings were completed. Baseline bedrock and surficial geologic maps were delivered to the Preserve in 2011. Surficial mapping is being updated by the USGS over the next few years, and issues with the bedrock data are being triaged. No baseline bedrock or surficial geologic maps have been delivered to the Monument. SRI has not yet delivered any products to the Preserve or Monument.

Geologic heritage resources of particular interest include Indigenous connections, ranching, mining, homesteading, railroading, military, geotourism, paleontology, volcanic features, stratotypes, and Zzyzx. Inventory needs include documenting prominent Indigenous quarries, conducting paleontological surveys, inventorying military trackway scars, and documenting prominent geologic features.

Soils in the Preserve and Monument have been mapped by the Natural Resources Conservation Service. Inventory needs include mapping the extent of desert pavement, assessing the rate of soil erosion following large fires, and monitoring biological soil crusts following restoration efforts.

Geohazards include extreme erosion from large precipitation events, rockfalls, earthquakes, mining hazards, and flash flooding. Inventory needs include drafting risk assessment maps for preserve and monument infrastructure in floodplains and flood event impact assessments.

Additional guidance for preserve and monument staff regarding proposal processes and timeframes for the new Inventories and Assessment (I&A) program is available on the GSRI and I&A SharePoint sites.

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Background of the GSRI

The Geologic and Soil Resources Inventory (GSRI) is a new program encompassing the legacy Geologic Resources Inventory (GRI) and Soil Resources Inventory (SRI) programs. To inform park management decisions and planning, GSRI aids in the collection of new data and derives new information from existing data regarding the presence, absence, abundance, distribution, and significance of geologic or soil features or processes.

In the late 1990s, the GRI and SRI programs were established as two of the 12 original baseline inventories in the Inventory and Monitoring (I&M) program. These baseline inventories compiled existing information, acquired new information, and helped establish a minimum level of data across more than 270 parks with significant natural resources, which served as a common starting point for natural resource stewardship. For both GRI and SRI, the primary deliverable was a digital (GIS) map.

Between the 1990s and early 2020s, GRI scoping summaries, geologic map posters, and GRI reports were also produced for most of the 270 parks. GRI and SRI baseline inventory products are available through the NPS Geodiversity Atlas**.** These products are designed to enhance stewardship of park resources by providing valuable information about soils, geologic formations, hazards, and links between geology, history, and other natural resources. As of 2024, the I&M program is transitioning from a baseline inventory strategy to a park-proposed inventory strategy.

The GRI and SRI are now unified as one inventory program, GSRI, and will be integrated into the new Inventories & Assessment (I&A) Program. Through the new I&A program, parks will submit geology- and soil-related project requests in PMIS during the Servicewide Comprehensive Call (SCC). This transition will begin in FY25, with new guidance enacted for GSRI. See the GSRI SharePoint site for more information regarding this transition. During this transition period, 13 "priority" parks, including Mojave National Preserve, were identified as missing a baseline GRI report (Castle Mountains National Monument was included at the request of the Preserve). This GSRI summary serves as a substitute for a baseline GRI report and is intended to support the park's participation in the new inventories program. As such, it summarizes the status of GRI and SRI deliverables for Mojave National Preserve and provides information on current geology and soils resource management concerns with a focus on identified inventory needs. Information in this summary was compiled from existing reports, meetings with park staff, and the best professional judgment from GSRI and WASO Geologic Resources Division (GRD) geoscientists.

Baseline GSRI Products

Geology

The most recent GRI GIS release for the Mojave National Preserve (referred to as the "Preserve" herein) was the unpublished digital geologic map of the Preserve in 2011. There are some known data and geology issues with the bedrock map, and the USGS is triaging those; more information should be available soon. There is an NPS-access-only unpublished surficial geology map of the Preserve from 2011 available on the NPS DataStore. Updated surficial mapping is ongoing and

should be completed over the next few years. GRI has not delivered any products to the Castle Mountains National Monument (referred to as the "Monument" herein).

Geologic GIS Data: https://irma.nps.gov/DataStore/Reference/Profile/2174400

Soils

The SRI has not yet delivered any products to the Preserve or to the Monument. Soil maps provide information on soil types, including scores of different characteristics and management considerations including linear extensibility ("shrink-swell") potential, erosion potential, soil stability, suitability for site development, suitability for recreation development (e.g., trails), and many other topics. Perrone (2023) provides an overview of the use of soil data at the NPS WASO level and lists soil data currently available in Web Soil Survey along with NPS-specific uses for the data.

The most up-to-date soils data is available via the Natural Resources Conservation Service (NRCS) Web Soil Survey website, and management-focused maps for potential project areas can be developed on-demand at that site. The Web Soil Survey homepage gives instructions for how to view and download soil data.

The Web Soil Survey data is broken down into county-level soil survey areas. Mojave National Preserve and Castle Mountains National Monument encompass 4 soil survey areas. Each soil survey area is assigned a code and a name (Table 1). The soil survey is partially complete. The NRCS plans to complete all soil survey areas in the US by 2026 (Thompson et al. 2020). Table 1 lists the soil survey areas and their completion status. To view the soil data on the Web Soil Survey website, use the navigation pane on the left side of the main webpage to select the soil survey area or the NPS unit and set it as the "area of interest" using the "AOI" icon along the top of the map. Use the "Soil Map" tab at the top to view the soil map and the "Soil Data Explorer" tab to view additional soil data including linear extensibility and suitability for development. See additional Web Soil Survey guidance and FAQs or contact the NRCS state soil scientist for technical assistance.

Table 1. List of soil survey areas and their completion status.

Web Soil Survey Area Code	Web Soil Survey Area Name	Status
CA795	Mojave National Preserve Area, California	Complete
CA805	Mojave Desert Area, Northeast Part, California	Complete
CA695	Mojave Desert Area, California	Incomplete
NV755	Clark County Area, Nevada	Complete

Future GSRI Products

As the GSRI becomes integrated into the I&A program, future GSRI products will be determined by the project proposals submitted by the parks. The GSRI will fund projects such as the following:

- Collect new data or derive new information from existing data regarding the presence, absence, abundance, distribution, and significance of geologic heritage, soil features or processes, or geohazards.
- Include features or processes at an individual feature or landscape scale.
- Include groups of features or maps of multiple features in a defined area of management needs.
- Are a snapshot in time and may establish a baseline for monitoring or assessment.
- Typically include a geospatial (GIS) component.

GSRI project examples:

- Features and processes eligible for funding through the GSRI program include cave/karst, geothermal, paleontological resources (fossils), landslides and rockfall, other geohazards (e.g., volcanoes, earthquakes, sinkholes), eolian, erosion, soil suitability and limitations for use, soil properties and qualities, ecological site descriptions, and other geologic or soil features or processes of management interest.
- Features and processes covered by other sources of funding and ***not*** eligible for GSRI funding are Abandoned Mineral Lands (AML), orphaned oil and gas wells, contaminated lands, etc.
- The GSRI will also accept proposals for new baseline products, including a geologic (geologic or surficial) or soil map or report, especially for parks outside the original 270 I&M parks. Parks requesting these products will need to indicate a management need the baseline data will support. MOJA is still missing the baseline bedrock geologic map, and CAMO is missing the baseline geologic map and soil map. These are baseline products that are eligible for proposals.

Park Significance and Establishment

At 6,271 km^2 (1.55 million acres), the Mojave National Preserve is the third-largest unit of the National Park System in the contiguous United States. It protects the vast, open landscapes of the Mojave Desert and over 10,000 years of human history. The Preserve is in southeastern California, central to many popular desert parks and destinations: the entrance on Ivanpah Road is only 96 km (60 miles) south of Las Vegas, Nevada; 113 km (70 miles) southwest of Lake Mead National Recreation Area; the entrance on Cima Road is 225 km (140 miles) southeast of Death Valley National Park; and the Kelbaker Road entrance is 113 km (70 miles) north of Joshua Tree National Park (Figure 1). Before the Preserve was officially designated as a unit of the National Park System in 1994, it was known as the East Mojave National Scenic Area, managed by the Bureau of Land Management (BLM).



Figure 1. Mojave National Preserve lies in the heart of the Mojave Desert, surrounded by other prominent NPS sites. Many people unknowingly drive alongside the Preserve on interstates 15 and 40 without ever visiting. Castle Mountains National Monument is located in the small gap between Mojave National Preserve and the Nevada state border. NPS map.

Castle Mountains National Monument was created in 2016 by presidential proclamation (US President 2016). At just over 85 km^2 (21,025.5 acres), the Monument is bounded on three sides by the Preserve (north, south, and west) and possesses outstanding natural, cultural, and historical values representing some of the finest characteristics of the eastern Mojave Desert (US President 2016). The Monument connects wildlife corridors to the Preserve and completes its boundary along the California-Nevada border.

The Preserve and the Monument contain numerous mountain ranges, wide valleys, and dense, interspersed Joshua Tree (*Yucca brevifolia*) forests. Wide-ranging geologic features on the landscape, including lava tubes, cinder cones, and sand dunes, highlight the geologic diversity of the two park units, attracting both professional and amateur geologists alike. The prevalence of the geologic features and their connections to continuous occupation and use of the landscape are listed as foundational aspects of the Preserve's formation (National Park Service 2013).

Geologic History

The diverse geologic history of the Preserve and Monument is vast, spanning over 1.75 billion years of active volcanism, metamorphism, tectonism, and erosion. From roughly 1.75 billion to 1.1 billion years ago, a series of igneous intrusions (the process of emplacement of magma into preexisting rock which produces rocks like granite) cut into the underlying metamorphosed gneisses (a foliated metamorphic rock with alternating bands of dark and light minerals) that form the oldest rocks in the Preserve. Over the next 850 million years, spanning the late Proterozoic Era, Paleozoic Era, and early Mesozoic Era, sedimentary strata were deposited unconformably (a type of geologic contact that represents a break in time in an otherwise continuous rock record) atop the Proterozoic gneisses and granites. Many of the oldest sedimentary units have undergone extreme deformation, limiting useful interpretation.

Beginning in the Triassic Period (251.9 million–201.3 million years ago) and continuing in pulses throughout the Mesozoic Era, widespread magmatism, folding, and faulting deformed the landscape and deposited both volcanic (an igneous rock that has been erupted onto the surface of the Earth) and plutonic (an igneous rock or intrusive body formed at great depth beneath Earth's surface) rocks. While no Paleogene-aged rocks (66 million–23 million years ago) are documented within the Preserve or monument, the Miocene Epoch (23.0 million–5.3 million years ago) consisted of intense volcanism and faulting, producing pediment domes (formed by erosional and weathering processes that create rounded, low-sloping surfaces such as Cima Dome in the Preserve; Figure 2) and the Cima Volcanic Field in the Preserve. Volcanism continued through the Pliocene Epoch (5.3 million–2.6 million years ago) and the Pleistocene Epoch (2.6 million–11,700 years ago), with the most recent eruption occurring sometime between 30,000 and 100,000 years ago (Phillips 2003). The increased availability of moisture during the Quaternary (2.58 million years ago to the present) allowed large pluvial (resulting from precipitation) lakes to form, depositing thick layers of eroded sediments from surrounding mountains, pediments (a gently sloping, erosional bedrock surface at the foot of a mountain or plateau escarpment), and domes (Johnson et al. 2023). The retreat of continental glaciations transformed the climate to the arid, desert conditions found today. More detailed information on the geologic history of the Preserve can be found in Theodore (2007).



Figure 2. Cima Dome as seen from Teutonia Peak. Pediment domes are formed by erosional and weathering processes that create rounded, low-sloping surfaces. Photo by Matthew Harrington (Colorado State University).

Geologic Heritage

Geologic heritage (also called “geoheritage”) evokes the idea that the geology of a place is an integral part of its history and cultural identity. In 2015, the National Park Service's GRD, in cooperation with the American Geosciences Institute, published a booklet introducing the American experience of geoheritage, geodiversity, and geoconservation: America's Geologic Heritage: An Invitation to Leadership. This publication introduces key principles and concepts of America's geoheritage, which are the focus of ongoing collaboration and cooperation on geologic conservation in the United States. That booklet introduced the American experience of geologic heritage and outlined key principles and concepts, including the following five big ideas:

- America’s geologic landscape is an integral part of its history and cultural identity, and Americans have a proud tradition of exploring and preserving geologic heritage.
- America’s geologic heritage, as shaped by geologic processes over billions of years, is diverse and extensive.
- America’s geologic heritage holds abundant values—aesthetic, artistic, cultural, ecological, economic, educational, recreational, and scientific—for all Americans.
- America’s geologic heritage benefits from established conservation methods developed around the world and within the United States.
- America’s geologic heritage engages many communities, and involvement by individuals will ensure its conservation for future generations.

This section highlights the Preserve and Monument’s geoheritage and draws connections between geologic resources and key principles outlined above. The Preserve and Monument’s significant geologic features, landforms, and landscapes are part of a rich geologic heritage that is, in part, the reason for the park’s establishment.

Indigenous Connections

As the last ice age waned 11,000 years ago, increased moisture from cooler and wetter weather patterns formed lakes and flowing streams in what are currently dry playas. These conditions allowed

plant and animal life to flourish, and with them, early humans. Archeologists have identified various intervals of human occupation in the region, beginning at least 7,000 years ago and continuing to the present. Although evidence of their existence is limited, over 1,300 cultural resources, including chipped stones and rock images (both petroglyphs and pictographs; Figure 3), have been uncovered in the Preserve (Nystrom 2003).

The Preserve recognizes the Pipa Aha Macav (Mojave) and the Nuwu (Chemehuevi) as the original stewards of the land. Utilizing the floodplain to plant crops, the Mojave frequently hunted in and traveled through the region of the Preserve and Monument, even serving as guides to some of the first non-Indigenous visitors, leading groups to water sources (Nystrom 2003). The Mojave utilized local geology frequently, blending sedimentary clay, crushed sandstone, and quartzites to create pottery with painted geometric designs serving diverse functions (National Park Service 2023a). Rhyolite and silicate quarries show evidence of on-site lithic reduction (the process of fashioning stones or rocks from their natural state into tools and weapons by removing some parts) and distribution of stone creations across the Preserve (Dave Nichols, Mojave National Preserve and Castle Mountains National Monument, Archeologist, follow-up call, 13 May 2024).

Potential inventory needs:

- A map of likely exposures for units known to be associated with quarries.

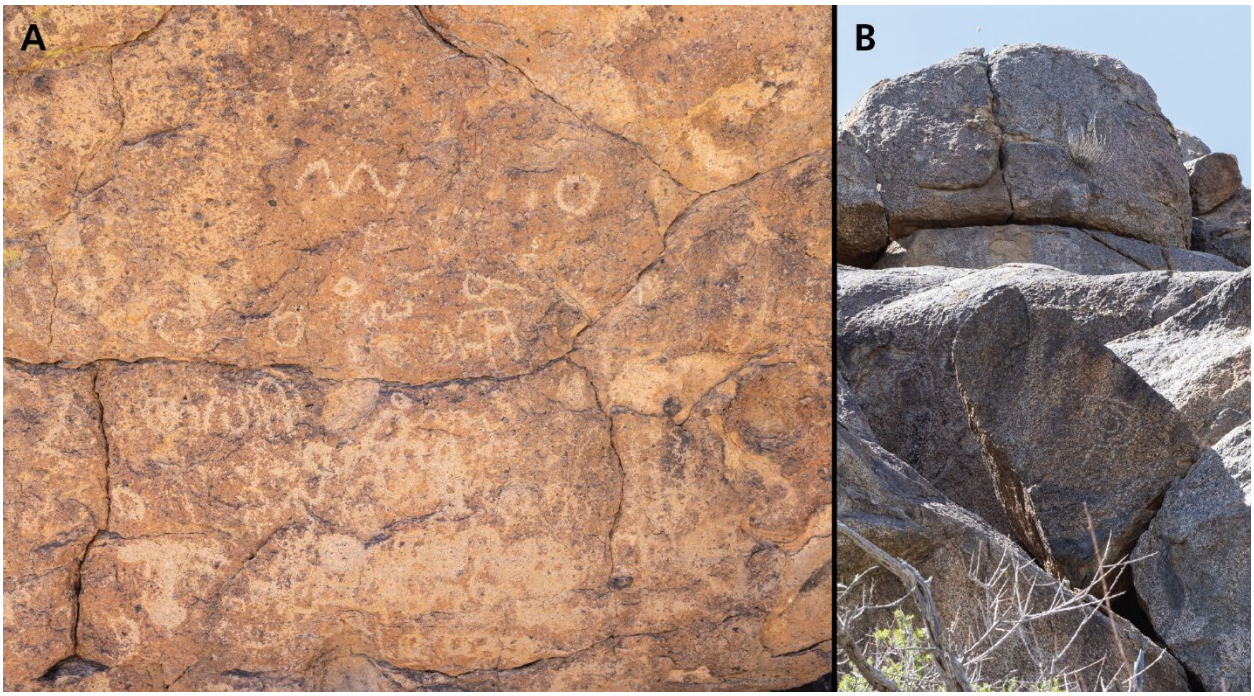


Figure 3. Petroglyphs carved into the desert varnish on rocks can be found throughout the Preserve. These petroglyph photos were taken near Hole-in-the-Wall (A) and Rock Spring (B). Photos by Matthew Harrington (Colorado State University).

Ranching

For roughly the past 150 years, cattle have been continuously grazed within the boundaries of the Preserve. Early Euro-American travelers traversed through the Preserve, utilizing water made available by natural springs along travel routes to sustain their herds. As miners, and later railroad workers and homesteaders, began to populate the area, entrepreneurs set up multiple ranches across the Preserve at springs, including Rock Spring, Marl Springs, and Kessler Spring (Nystrom 2003). Many of the corrals constructed near springs are still standing today and are often utilized as primitive camping sites (National Park Service 2023b). Ranching within the Preserve continues to this day, although water access has evolved beyond simple reliance on natural springs.

Potential inventory needs:

- An assessment of the impact of ranching on soils within the Preserve.

Mining

The prevalence of faulting at the convergence of two tectonic plates created ideal conditions for mineralization and rich ore deposits in the region of the Preserve and Monument. Both fractures caused by faulting and joints in bedrock allowed mineralized water to flow toward the surface, leaving precipitated minerals and precious metals behind in veins. A diverse array of minerals has been extracted from the Preserve and Monument, including gold, silver, lead, zinc, copper, tungsten, vanadium, iron, clay, and cinders (Figure 4; Nystrom 2003).



Figure 4. A view of the Castle Mountain Gold Mine from within the Monument. The mine has historically extracted gold from the rock, and current management aims to revamp extraction. Photo by Matthew Harrington (Colorado State University).

The onset of the California Gold Rush in the mid-1800s and the passing of the General Mining Law of 1872 allowed individuals to stake a claim on an area of land where a mineral deposit was discovered (National Park Service 2024). Mines were rapidly established across the region, but most mines in the Preserve lacked long-term profitability, as many veins were rich in ore but small (Nystrom 2003).

From the 1950s to the 1990s, extraction of cinders (glassy, vesicular, pyroclastic fragments that fall to the ground in an essentially solid condition) from the Cinder Cone Lava Beds area of the Preserve (see "Volcanic Features" below) played an essential role in the construction of buildings within the budding city of Las Vegas and as roadway materials, landscaping, and decoration (National Park Service 2023c). During the cinder mines' history, over 60,000 truckloads of cinders totaling 1.5 million tons were extracted (National Park Service 2023c). Massive conveyor belts and other mining equipment can still be seen around the cinder cones at Aiken Mine, allowing visitors to envision what the operation may have looked like during peak production.

The Vulcan Mine, located just under 16 km (10 mi) southeast of Kelso in the Preserve, was the most profitable mine in the Preserve's history. In the 1940s, the mine produced over $7 million worth of iron, which was used to construct Liberty ships for the World War II war effort (see the "Military" section of this report; National Park Service 2023c). By 1944, after extracting nearly half of the total estimated iron from the mine, production ceased due to the increased costs of extracting the remaining iron from deep underground. While a fence was installed in 2009 along the pit's edge for visitor safety, the mine can still be viewed by visitors (NPS 2023c).

The legacy of mining is evident within both the Preserve and Monument. Evidence of mining operations can be seen in most areas of the Preserve and Monument and includes mine openings including, adits, shafts, inclines, tailings, waste rock, abandoned equipment, storage tanks, and miscellaneous objects left behind by miners (Figure 5). While many of these features are harmless to visitors, others, particularly open pits, contaminated tailings, and abandoned equipment, can pose risks to visitors. Additional information on the hazards of abandoned mines can be found in the "Mining Hazards" section of this report.

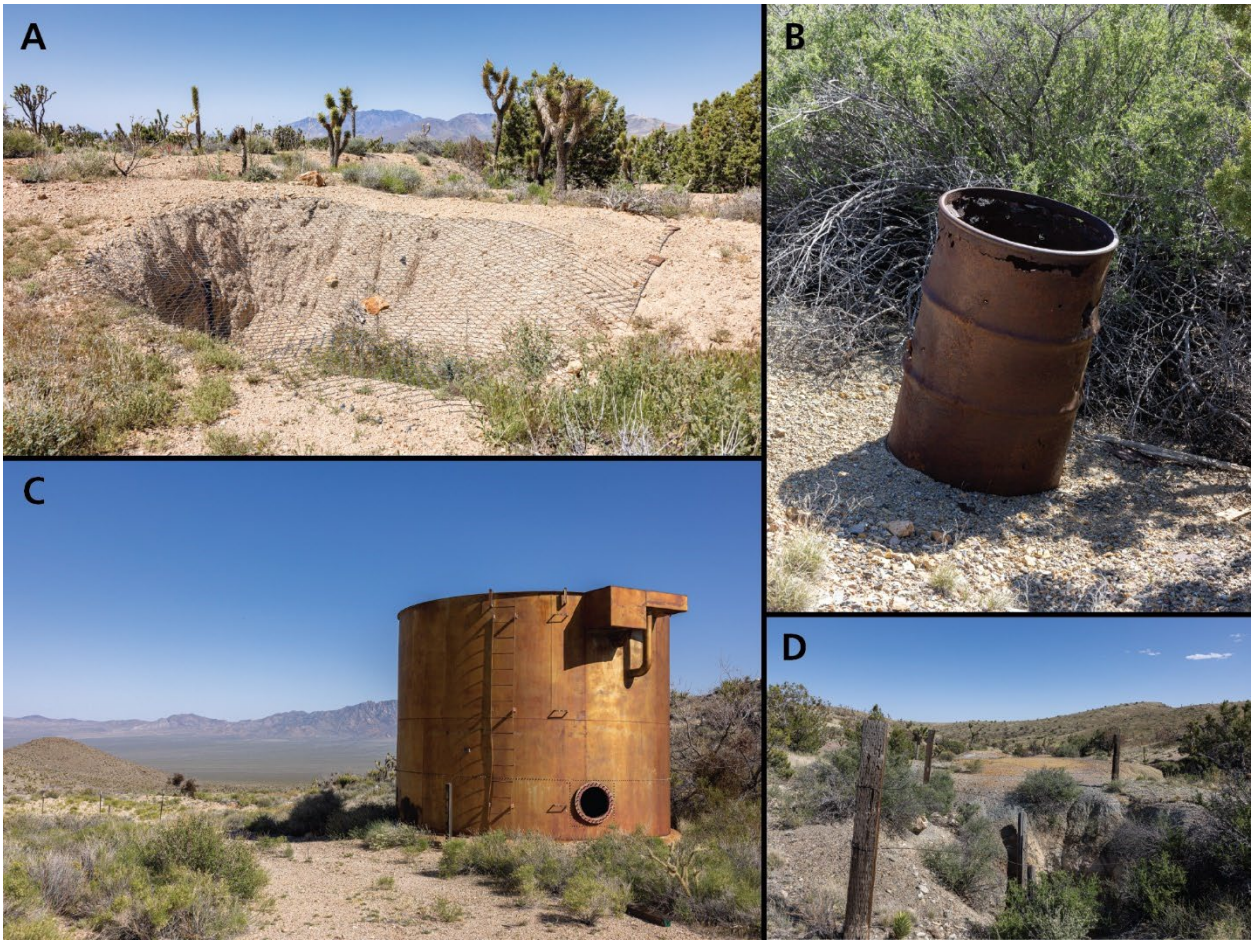


Figure 5. Images of historical mining activities across the Preserve. A) An abandoned mining pit at Teutonia Mine, sealed by metal netting. B) A rusted oil drum near old mining pits at Golden Quail Mine. C) A large, abandoned water tank at the Valgold Mine ore processing area overlooking Ivanpah Valley. D) An abandoned mine pit at Golden Quail Mine that has been blocked off by wooden posts and barbed wire. Photos by Matthew Harrington (Colorado State University).

Military

Some of the earliest military expeditions across the Mojave Desert provided the names of many features along the modern Mojave Road. Lieutenant Amiel Whipple's 1854 expedition to Los Angeles across the Mojave Trail (large parts of the trail became the Mojave Road, which bisects what is now the Preserve) provided names to Piute Springs, Rock Spring, Marl Springs, and Soda Lake (near Zzyzx; Casebier 2007). The need for the Mojave trail to be upgraded into a wagon road was solidified when gold was discovered in the mountains of central Arizona in the early 1860s: Arizona was dependent upon supplies from California, and a reliable path was essential (Casebier 2007). The use of the Mojave Road peaked in the 1860s and 1870s, when the road was traversed by countless wagons, stagecoaches, and troops (Casebier 2007). The route was preferred due to its higher elevation, lower average temperatures, and more reliable water sources than lower and hotter desert routes in the region (Casebier 2007).

The military maintained a handful of forts and camps along the Mojave Road, including a camp at Rock Spring. After the US mail changed routes and violent encounters with Indigenous people had diminished, the army abandoned the camp in 1868.

Despite the abandonment of the military camp, Rock Spring continued as an important landscape feature in the Preserve. While fighting in Europe during World War I, soldier Bert Smith was exposed to poison gases and returned to the US with damaged lungs and a poor prognosis (NPS interpretive sign). He moved to the Mojave Desert, seeking the health benefits of dry air. In 1929, he constructed the Rock House (Figure 6) out of nearby rocks and ended up living another 25 years at the home (NPS interpretive sign). The Rock House was built near Rock Spring along the Mojave Road.



Figure 6. Rock Spring House was built by WWI veteran Bert Smith in 1921, using rocks from the landscape. The house still stands today as a testament to its solid construction and impact on the Preserve's history. Photo by Matthew Harrington (Colorado State University).

When the United States entered World War II, regional mining operations pivoted from precious metals to industrial materials. In addition to the mass amounts of raw iron extracted from the Vulcan Mine (see "Mining" section), the Evening Star Mine (in the Preserve) produced tin and tungsten, and several smaller mines produced copper (Nystrom 2003).

Beyond mineral extraction, the US military utilized the Mojave Desert as a training ground for troops during World War II. General George S. Patton established the Desert Training Center and stationed troops across the region (National Park Service 2015a). While most activity took place south of the Preserve and Monument, Camp Goffs existed on the eastern edge of the Preserve. Roughly 15,000 soldiers spent time at Camp Goffs, and over one million soldiers were stationed across the Mojave Desert. The soldiers trained in maneuvers with tanks and other military vehicles. These exercises left permanent scars on the desert landscape, cutting into desert pavement (see "Biological Soil Crust, Soils, and Desert Pavement" below) and leaving trackways that can still be seen today. Rock alignments from huge tent camps are still found across the Preserve, particularly in the southeastern corner (Nystrom 2003). In areas of heavy use, soil compaction from heavy foot and vehicle traffic altered the natural ecology of the desert.

The presence of the military did, however, provide future benefits to the Preserve. The US military systematically mapped the entire Mojave Desert for the first time, utilizing both aerial photography and land-based methods to enhance their training operations (Nystrom 2003). In the late 1940s and early 1950s, the USGS utilized military mapping data to produce a series of 15-minute quadrangle maps of the Mojave Desert (Nystrom 2003). The presence of so many soldiers accelerated interest in recreational use of the Mojave Desert, where they utilized surplus jeeps and camping gear alongside newly published maps to explore the region.

Potential inventory needs:

- An inventory of known military trackway scars and debris (documentation and mapping of Camp Goffs already exists).

Geotourism

The diverse geological features within the Preserve and Monument have become popular destinations for geotourism (tourism based on geological features or character). Many of the most popular and recognizable destinations in the Preserve are major geologic landmarks, including the Kelso Dunes, lava tubes, and Hole-in-the-Wall (Figure 7). Sites such as Hole-in-the-Wall, which hosts a visitor center, allow information on local geology to be shared with visitors as they actively explore these features. Visitation to the Preserve has grown considerably, from 450,000 annual visitors in the early 2000s to over 1.1 million visitors in 2023 (National Park Service n.d.). As more people continue to visit and utilize the Preserve, documenting the most heavily visited areas and the impacts seen from such visitation will aid in preserving the important features of the Preserve.

Potential inventory needs:

- An inventory of known high-interest geological features in the Preserve and Monument.
- Monitoring of visitation numbers at specific geologic "hot spots."
- An integrated map or document with geological features and their ties to other Preserve and Monument inventories or management needs.

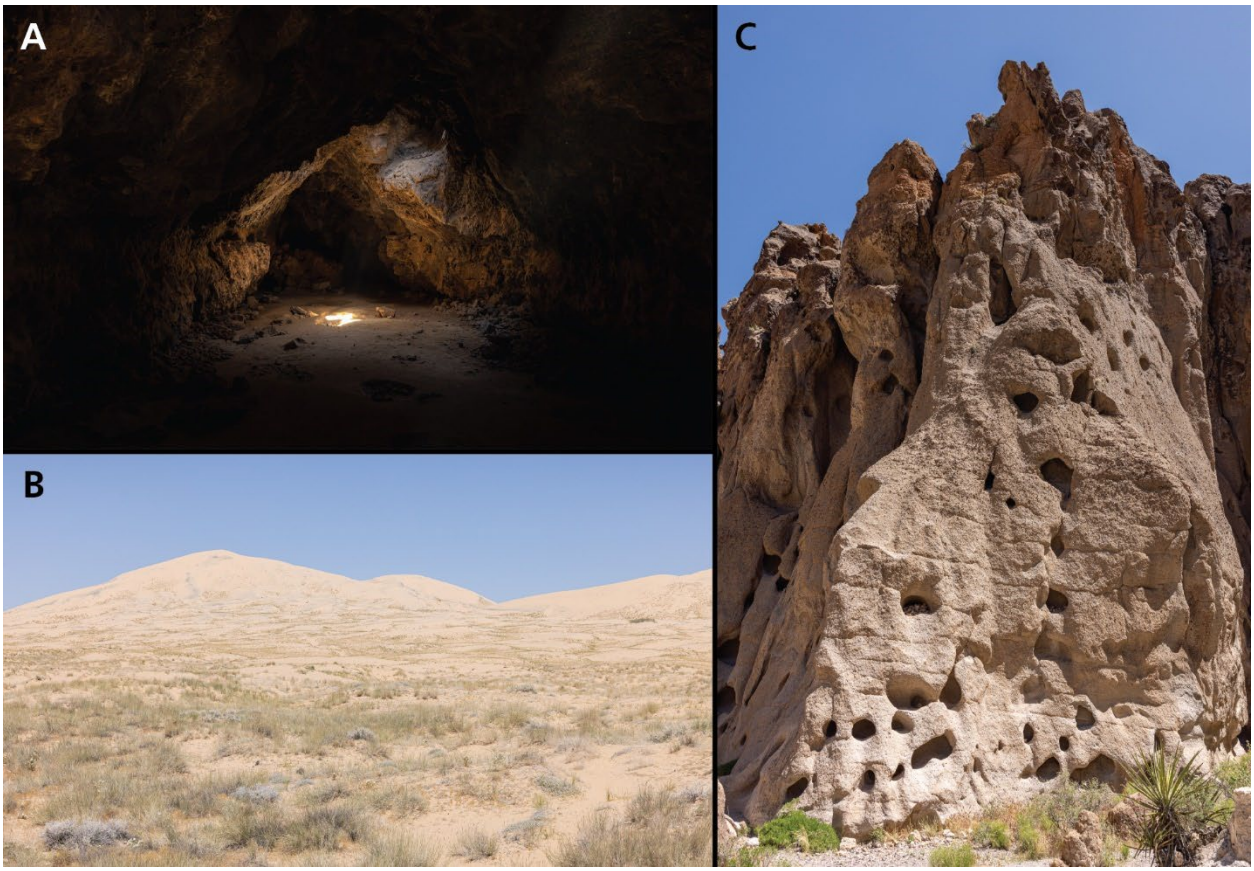


Figure 7. Primary geotourism features of the Preserve. A) This lava tube formed when the top of the lava flow hardened, allowing the molten lava below to drain away. A ladder down into the lava tube allows visitors to explore this feature. B) The Kelso Dunes are a large dune field in the Preserve located southwest of Kelso. C) Hole-in-the-Wall offers an exciting hike to visitors who want to scramble through rhyolite tuff uniquely pocketed with tafoni-style weathering (where weathering creates small, rounded openings in rock faces). Photos by Matthew Harrington (Colorado State University).

Stratotypes

A stratotype is the original or subsequently designated standard of reference for a named layered stratigraphic unit or of a stratigraphic boundary. Stratotypes are important geologic reference exposures that help identify, define, and correlate geologic units from one location to another. When geologists propose or describe a new layer or body of rock, a stratotype is assigned to exposures containing all (or most) of the unique diagnostic criteria. Stratotypes have significant scientific value and are often easily accessible, world-class locations to study outcrops of rock. The Preserve contains two formally recognized stratotypes: the Cambrian Latham Shale and the Cambrian Bonanza King Formation (Figure 8). The Latham Shale type section is in the western Providence Mountains and consists of greenish-gray, platy shale and thin layers of sandy limestone (Henderson et al. 2021). The Bonanza King Formation type locality is located at Bonanza King Mine in the eastern Providence Mountains and consists of reddish-brown sandy dolomite, light to dark gray dolomite, dolomitized limestone, and chert (Henderson et al. 2021). While not yet formally designated as stratotypes, the Jurassic Sands Granite and Fountain Peak Rhyolite; the Cretaceous Mid Hills Adamellite and

Teutonia Quartz Monzonite; and the Miocene Tortoise Shell Mountain Rhyolite, Wild Horse Mesa Tuff, and Hackberry Spring Volcanics are all recognized geologic units named after features within the Preserve. The Monument has not yet been inventoried for stratotypes. For additional information on stratotypes within the Preserve, see Henderson et al. (2021).

Potential inventory needs:

- An inventory of known or potential stratotypes in the Monument.



Figure 8. Two stratotypes exist within the Preserve: the Cambrian Latham Shale and the Cambrian Bonanza King Formation. A & B) The Latham Shale is a fossiliferous unit that has accessible outcrops in the Preserve. C) The Wild Horse Mesa Tuff is not yet a formally designated stratotype, but the unit is named after features within the Preserve, and stratotype designation is recommended. Photos by Matthew Harrington (Colorado State University).

Zzyzx Mineral Springs and Soda Lake

Around 2 million to 5 million years ago, the Mojave River began flowing from west to east, filling a large, ancient lake known as Lake Manix (National Park Service 2022). Roughly 25,000 years ago, just before the peak of the last ice age, Lake Manix drained eastward, forming Lake Mojave. As the

climate began to dry, Lake Mojave water levels dropped, splitting the ancient lake into Silver Lake (north of Baker, CA) and Soda Lake (in the Preserve). As the final water levels dropped and evaporated, thick salt crusts were left behind, giving Soda Lake a bright white appearance (Figure 9). The lake is now ephemeral with periods of flooding, evapoconcentration, and desiccation. On the edge of the ephemeral lakebed, Soda Springs creates a natural oasis, having provided water access to the Mojave and Chemehuevi people for generations. These springs, including MC Spring, West Pond, and Lake Tuendae, host the federally endangered fish, Mohave Tui Chub (*Siphateles bicolor mohavensis*).



Figure 9. Soda Lake's bright white color is attributed to thick salt crusts that were left behind as water levels in the former lake evaporated. Photo by Matthew Harrington (Colorado State University).

Geologic Resources, Management Issues, and Inventory Needs

This section briefly summarizes significant geologic resources and any associated hazards, issues, and inventory needs that have been identified by discussions with Preserve and Monument staff. Significant geologic resources include features that are essential to the geologic story, landscape, or creation of the Preserve and Monument. These resources are highlighted to summarize what is currently known and what needs may exist for future projects. Geologic hazards refer to notable hazards stemming from geologic features or processes that may require active management. Geologic issues refer to problems that result in the damage or theft of geologic resources. The following sections are discussed alphabetically.

Inventory Needs

The following table (Table 2) presents several geologic and soil resources inventory needs that were identified during the 2024 follow-up meeting, in NPS planning documents, or through literature review.

Table 2. A list of identified geologic and soil resource inventory needs for MOJA and CAMO. The purpose of this table is to list all potential needs, not just those that are currently feasible. This summary recognizes that the ability to undertake many inventory and monitoring projects is often limited by financial or staffing constraints.

Subject	Inventory Need(s)	Reference(s)
Geoheritage	Condition assessments and/or monitoring of known petroglyph and pictograph sites to better understand rates of erosion on varying rock surfaces (MOJA & CAMO)	Follow-up Call Original Scoping Meeting Author Recommendation
Geoheritage	A map of likely exposures for units known to be associated with quarries (MOJA & CAMO) An assessment of the impact of ranching on soils (MOJA)	Follow-up Call Original Scoping Meeting Author Recommendation
Geoheritage	An inventory of known military trackway scars and debris (MOJA)	Follow-up Call Original Scoping Meeting Author Recommendation
Geoheritage	An inventory of known high-interest geological features (MOJA & CAMO)	Follow-up Call Original Scoping Meeting Author Recommendation
Geoheritage	An inventory of known high-interest geological features (MOJA & CAMO)	Follow-up Call Original Scoping Meeting Author Recommendation
Geoheritage	Monitoring of visitation numbers at specific geologic “hot spots” (MOJA)	Follow-up Call Original Scoping Meeting Author Recommendation
Geoheritage	An integrated map or document with geological features and their ties to other preserve and monument inventories or management needs (MOJA & CAMO)	Follow-up Call Original Scoping Meeting Author Recommendation

Subject	Inventory Need(s)	Reference(s)
Geoheritage	Monitoring of high visitation sites and high-priority resource sites for any vandalism or theft (MOJA)	Follow-up Call Original Scoping Meeting Author Recommendation
Abandoned mineral lands	Monitoring of safety features around open mine pits (structural stability, damage, erosion, etc.) (MOJA & CAMO)	Original Scoping Call Follow-up Call
Water Resources	Assessing potential damage to structures in floodplains and near ephemeral washes during 100-year, 500-year, or 1000-year flood events (MOJA & CAMO)	Follow-up Call
Water Resources	Assessing the impact of increasingly variable precipitation patterns (MOJA & CAMO)	Follow-up Call
Water Resources	Monitoring of springs and spring levels (MOJA & CAMO)	Follow-up Call
Water Resources	Creating a risk assessment map for structures/facilities/high visitation areas that are most at risk during varying levels of storms (MOJA)	Follow-up Call
Geoscience Research	Monitoring the magnitude, duration, and frequency of dust storms (MOJA & CAMO)	Original Scoping Meeting Follow-up Call
Geoscience Research	Monitoring the growth/decline rates of the Kelso Dunes (MOJA)	Original Scoping Meeting Follow-up Call
Geoscience Research	Inventorying all volcanic features to determine management needs (MOJA & CAMO)	Original Scoping Meeting Follow-up Call
Soils and Desert Pavement	Assessing the amount and impacts of increased nitrogen deposition (MOJA & CAMO)	Follow-up Call Original Scoping Meeting
Soils and Desert Pavement	Analyzing the compaction of soils near oases (MOJA & CAMO)	Follow-up Call Original Scoping Meeting
Soils and Desert Pavement	Inventorying the total area of disturbed lands (MOJA & CAMO)	Follow-up Call Original Scoping Meeting
Soils and Desert Pavement	Inventorying the locations of desert pavements (MOJA & CAMO)	Follow-up Call Original Scoping Meeting
Soils and Desert Pavement	Inventorying nonnative grasses (MOJA & CAMO)	Follow-up Call Original Scoping Meeting
Soils and Desert Pavement	Monitoring or assessing the impact of erosion on soils following large fires (MOJA & CAMO)	Follow-up Call Original Scoping Meeting
Soils and Desert Pavement	Assessments of soil crust or desert pavement damage to prioritize potential restoration projects (MOJA & CAMO)	Follow-up Call Original Scoping Meeting
Mapping	Bedrock mapping (CAMO)	Follow-up Call
Mapping	Funding for bedrock mapping (MOJA)	Follow-up Call
Paleontology	A baseline paleontological inventory (CAMO)	Author Recommendation MOJA Paleontological Inventory
Paleontology	Assessments of erosional risk for known fossil sites (MOJA & CAMO)	Author Recommendation MOJA Paleontological Inventory
Paleontology	Monitoring known fossil sites (MOJA)	Author Recommendation MOJA Paleontological Inventory

Subject	Inventory Need(s)	Reference(s)
Paleontology	Updated paleontological inventories for potential fossil sites (MOJA)	Author Recommendation MOJA Paleontological Inventory
Paleontology	Inventories of high-priority fossil sites to protect against vandalism and theft (MOJA)	Author Recommendation MOJA Paleontological Inventory
Stratotypes	An inventory of known or potential stratotypes (CAMO)	Author Recommendation

Biological Soil Crust, Soils, and Desert Pavement

Although much of the Preserve and Monument consist of exposed bedrock and boulders, soils exist within many areas. Among the most important is a living groundcover called biological soil crust (also known as desert crust). Primarily composed of cyanobacteria, some biological soil crusts also contain lichens, mosses, green algae, microfungi, and bacteria (National Park Service 2015b). These crusts bind soil particles and rock together, stabilizing the soil and increasing its resistance to wind and water erosion. Water, nutrients, and organic matter are trapped and stored within biological soil crust, providing accessible resources to plants. Even after the living organisms within the soil crust die, the structural integrity of the soil crust can continue to provide stability to the soil.

Unfortunately, soil crusts are fragile, and human activity can be extremely damaging. Foot traffic and off-road driving are the primary threats to soil crusts within the Preserve and Monument. Off-road driving is particularly damaging, as tire trackways increase erosion from wind and water and can lead to channelization, permanently destroying the soil crust. The Preserve has manipulated flooding, evapoconcentration, and desiccation cycles in salt crust to remove vehicle tracks, as well as raked and vertically mulched vehicle tracks in vegetation and dirt (Sofia Andeskie, Mojave National Preserve and Castle Mountains National Monument, Chief of Science and Resource Stewardship Division, personal communication, 13 February 2025). Pietrasiak et al. (2011) inventoried and assessed soil crusts within Joshua Tree National Park and determined that geology plays an essential role in driving crust distribution and predicting its occurrence. Future inventories or assessments should utilize known geologic features to increase the understanding of soil crusts within the Preserve and Monument. An enhanced understanding of visitor use in areas with known soil crusts and the recovery rate of soil crusts will also assist in the management of these resources. While the park has not yet restored disturbed soil crusts, regrowth is currently being studied by multiple research permits (Sofia Andeskie, Mojave National Preserve and Castle Mountains National Monument, Chief of Science and Resource Stewardship Division, personal communication, 13 February 2025). Analyses of the impact of future road projects on soil crusts is one helpful tool to mitigate damage.

Historically, soils across the Mojave Desert have been nitrogen-poor, and native plants have adapted to overcome this issue. However, increased nitrogen deposition from air and water influx from the growing metropolitan centers (primarily Los Angeles and Las Vegas) has led to a significant increase in soil nitrogen. This has allowed nonnative plants that were historically incapable of survival to

encroach into the Preserve and Monument. The increase in some nonnative grasses, particularly red brome (*Bromus rubens*), has negatively altered the fire regime. Up until the 1980s, fires were considered relatively rare within the Mojave Desert, and as such, Joshua tree forests are not well adapted to wildfires (Vamstad and Rotenberry 2010). Increased fire activity stemming from encroaching nonnative grasses has threatened Joshua tree stands and burned vast areas of the Preserve and Monument, as seen in the 2020 Cima Dome fire.

Desert pavement is a naturally occurring, slow-forming concentration of wind-polished, closely packed pebbles, boulders, and other rock fragments that cover a desert surface where wind action or sheetwash has removed all the smaller particles. When disrupted, the landscape loses its stability and is more prone to erosion. Desert pavement is a high-priority resource for the Preserve and Monument; once it has been destroyed, it is gone forever. Currently, there are no methods available for restoring desert pavements.

Potential inventory needs:

- Assessing the amount and impacts of increased nitrogen deposition.
- Analyzing the compaction of soils near oases.
- Inventorying the total area of disturbed lands.
- Inventorying the locations of desert pavements within the Preserve and Monument.
- Inventorying nonnative grasses.
- Monitoring or assessing the impact of erosion on soils following large fires.

Geoheritage Resources: Theft and Damage

Theft and vandalism at old mine sites and ranches are a concern. The loss of historical items from a site diminishes the history and heritage provided by these items. In many cases, these items are irreplaceable. Theft of paleontological or cultural resources is also a concern. Paleontological resources from the Latham Shale were illegally extracted and stolen in May of 2020 (Sofia Andeskie, Mojave National Preserve and Castle Mountains National Monument, Chief of Science and Resource Stewardship Division, personal communication, 1 May 2024). The thief used a rock saw to cut out chunks from an exposure and acquire fossils (Figure 10). The suspect was apprehended, and no further events have transpired. Occasional monitoring of high-priority paleontological sites may prove effective in avoiding similar incidents.

Illegal murals and graffiti on exposed rock or historic structures are an issue at the Preserve and Monument (Figure 11). Vandals can deface entire boulders with graffiti in a short time, requiring Preserve and Monument staff to clean and remove the illegal activity. For illegal inscriptions on rock faces, the cleaning process can alter the rock, increasing the erosion of the rock face. In cases where water must be used for cleaning, introduced water outside of precipitation events can alter the vegetation and impact erosion around the graffiti site.

Damage from off-highway vehicles (OHVs) is a major threat to Preserve and Monument resources. OHV damage typically occurs either as illegal OHVing or when visitors take personal vehicles off designated roads. In attempts to prevent visitors from taking their personal vehicles off-road, the Preserve and Monument staff have elevated the shoulder of the roads throughout most of the Preserve and Monument. Off-road activities damage desert pavement, trample vegetation, and open the roadway up to increased sedimentation during rain events by damaging the raised shoulders. Trackway scars from off-road vehicles do not dissipate on their own and damage floral communities, desert pavement, and biological soil crust (see the "Biological Soil Crust, Soils, and Desert Pavement" section of this summary), and can potentially damage fossil resources. Trackway scars left by vehicles in the 1940s can still be seen today.

Potential inventory needs:

- Monitoring of high visitation sites and high-priority resource sites for any vandalism or theft.
- Inventorying known trackway scars or damaged areas.
- Assessing soil crust or desert pavement damage to prioritize potential restoration projects.



Figure 10. Evidence of illegal extraction from the Latham Shale in the Preserve. A rock saw was used to cut away fossils from the shale, leaving behind permanent scars in the outcrop. Photo by Matthew Harrington (Colorado State University).



Figure 11. An example of graffiti found alongside old foundations and ruins at Rock Spring. Graffiti can occur on rock faces, historical structures and objects, or modern facilities. Photo by Matthew Harrington (Colorado State University).

Mining Hazards

The Preserve has 595 abandoned mineral lands (AML) sites (10.9% of all NPS sites) and 11,557 AML features (29.1% of all NPS features, the highest of any NPS site; Rebecca Port, NPS Geologic and Soil Resources Inventory, personal communication, 22 August 2024). The Monument currently has zero sites or features listed in the AML database; however, sites were inventoried via a task agreement with the California Department of Conservation and will show in the AML database when it is updated (Sofia Andeskie, Mojave National Preserve and Castle Mountains National Monument, Chief of Science and Resource Stewardship Division, personal communication, 13 February 2025).The Monument likely has AML sites and features based upon their abundance in the Preserve.

The abundance of abandoned mining sites continues to pose serious management challenges to the Preserve and the Monument. The risks associated with abandoned mines are many. Hazards include vertical shafts, adits (horizontal shafts), inclines (angled shafts), rotted ladders, cave-ins, abandoned explosives, deadly gases accumulated within shafts, mine tailings contaminated with mercury and cyanide, rusted structures, deteriorating buildings, and abandoned heavy machinery and debris.

Due to the Preserve's vast number of AML sites and features, the strategy for sealing mine openings varies. Factors such as the historic value of the mine, the hazard level of the mine, cost, and the

opportunity for the abandoned site to benefit local wildlife are all considered (National Park Service 2023c). Due to limited funding, many mining hazards are given temporary solutions, including fencing and signage (National Park Service 2023c). For some of the larger openings, large metal grates have been installed to prevent visitor access while still providing opportunistic wildlife, such as bats, snakes, or desert tortoises, access to the artificial caves. In addition, wire nets, cupolas, graded culverts, or fences are also used (Figure 12). However, the weathering, rusting, erosion, and vandalism of these features over decades may occasionally require decisions about the replacement, enhancement, or reinforcement of safety measures at these openings.

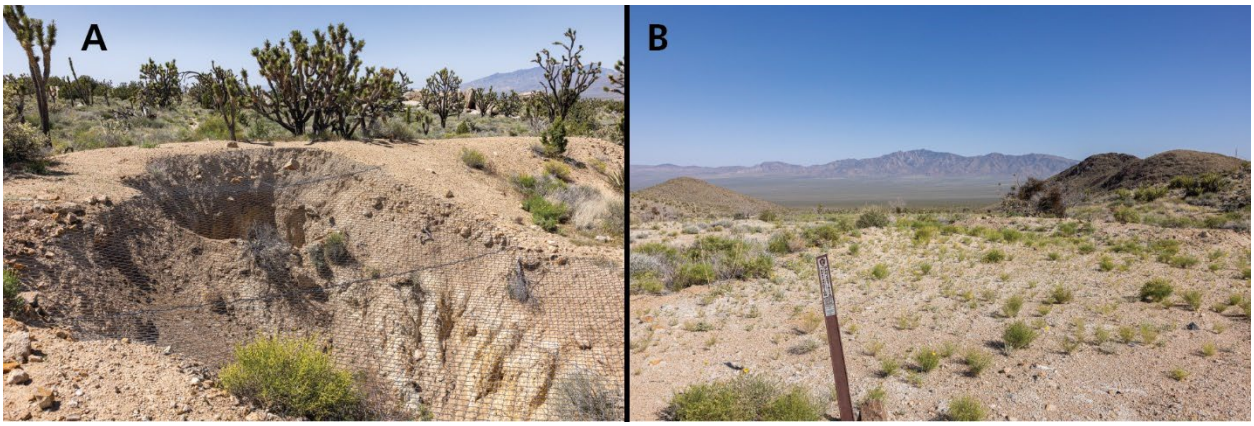


Figure 12. Abandoned mineral lands dot the Preserve and Monument, with the Preserve hosting the highest number of AML features in the entire National Park System. A) A metal net covers an old mining pit at the Teutonia Mine. B) A sign indicates that restoration is in progress for a formerly contaminated piece of land at the Valgold Mine ore processing area. Photos by Matthew Harrington (Colorado State University).

Another strategy for sealing AML sites/features is the application of expanding polyurethane foam (PUF) and topping the PUF with dirt to conceal the opening. PUF is lightweight, inexpensive, and does not leach hazardous chemicals. The plug is also removable if access to the mine is necessary in the future. Mines plugged by PUF can still showcase depressions in the landscape where historical mining occurred while minimizing risk to visitors. However, the Preserve and Monument generally prefer not to use PUF, as mines are typically part of the cultural landscape. For mines that are not found eligible for listing on the National Registry, PUF remains an option that can be decided upon by the management team at the Preserve and Monument (David Nichols, Mojave National Preserve and Castle Mountains National Monument, Archeologist, personal communication, 13 February 2025).

In addition to the hazards of the physical mines themselves, contamination from former mines into ephemeral washes and soil remains an ongoing issue for the Preserve and Monument. Signage can inform visitors to stay away from these areas. Fencing off contaminated and potentially contaminated sites allows preserve and monument staff to protect visitors while determining proper strategies for clean-up, removal, or mitigation.

Potential inventory needs:

- Monitoring safety precautions placed around mining hazards.

Paleontological Resources

Paleontological resources (fossils) are any evidence of life preserved in a geologic context (Santucci et al. 2009). They may be body fossils (any remains of the actual organism such as bones, teeth, shells, or leaves) or trace fossils (evidence of an organism's activity such as nests, burrows, tracks, or coprolites [fossil feces]). All fossils are nonrenewable. Fossils in NPS areas occur in situ in rocks or unconsolidated deposits, in museum collections, and in cultural contexts such as building stones or archeological resources.

The paleontological record within the Preserve and Monument is vast, extending from the late Proterozoic Eon (550 million years ago) to the Holocene Epoch (11,700 years ago to the present). Fossil remains include Ediacaran fauna, Paleozoic marine fauna, and Cenozoic flora and fauna. A paleontological resource inventory completed in 2023 (Johnson et al. 2023) summarized historical paleontological research in the Preserve, field-checked known localities, and created a baseline of paleontological resource data for the Preserve.

Additional paleontological resources in the Preserve and Monument are packrat (*Neotoma* spp.) middens. Packrat middens are piles of debris (pollen, seeds, leaves, bones, shells, and other materials) accumulated by packrats in hidden middens. Over time, packrat urine cements the materials together into a solid mass that maintains fantastic preservation, primarily in arid climates or humidity-controlled caves. Middens are an essential resource for determining environmental change over time, as they preserve an array of both plant and animal materials on the landscape at the time of formation. These materials are often prime subjects for isotopic analysis and dating, providing accurate climatic data to pair with physical evidence. For more detailed information on paleontological resources within the Preserve and Monument, refer to the paleontological resource inventory (Johnson et al. 2023).

Potential inventory needs:

- A baseline paleontological inventory for the Monument.
- Assessments of erosional risk for known fossil sites.
- Monitoring known fossil sites.
- Updated paleontological inventories for potential fossil sites across the Preserve.
- Inventories of high-priority fossil sites to protect against vandalism and theft.

Sand Dunes, Wind Erosion, and Deposition

The Kelso Dunes (Figure 13) are one of the most prominent dune systems in California and, at over 183 m (600 feet high), are the third highest dune system in North America (Covington 2003). The dune field is roughly 4.8 km (3 mi) wide and 8 km (5 mi) long. The Kelso Dunes are unique among dune fields of the western United States in that they contain a wide variety of dune forms and are still partially active (possess ongoing movement of sand by wind; Muhs et al. 2016). Attempts to mine heavy metals within the dune field have occurred, but with little to no success (Covington 2003). The dunes have been closed off to off-road vehicles since 1973 (Covington 2003). The source of the dunes is likely more complex in its origin than solely the Mojave River, as was historically thought. For a more detailed breakdown of the origin and geomorphology of the Kelso Dunes, see Muhs et al. (2016).



Figure 13. The Kelso Dunes are the third highest dune system in North America. The dunes are still active today and contain a wide variety of different dune forms. Photo by Matthew Harrington (Colorado State University).

Dust storms and the deposition of their materials are essential parts of the Preserve and Monument's ecology. In the Mojave Desert, dust deposition provides essential nutrients for soil formation and aids in the formation of desert crusts and desert pavement (Covington 2003). Dust storms can also carry pathogens or radioactive materials, potentially creating health concerns for endemic plants and animals. Historically, the region has been a dust donor, not a recipient, as wind has transported dust to the southeast, contributing to the formation of more fertile soils in that area (Covington 2003). However, dust storms can also erode geoheritage features within the Preserve or Monument. Pictographs and petroglyphs can be slowly eroded away by such storms, and historical objects can be covered or hidden.

Potential inventory needs:

- Monitoring the potential impact of dust.
- Monitoring the magnitude, duration, and frequency of dust storms in the Preserve and the Monument.
- Monitoring the growth/decline rates of the Kelso Dunes.

Seismicity

Many of the faults within the Preserve and Monument are no longer active; most activity ceased in the Pliocene (5.3 million to 2.6 million years ago) or early Pleistocene (2.6 million to 2 million years ago). At present, the Preserve and Monument are impacted by seismicity along the San Andreas Fault System, the Garlock Fault, and the Eastern California Shear Zone (US Geological Survey 2009). Each of these fault zones possesses regional right-lateral shearing forces with displacements ranging into the hundreds of kilometers. For up-to-date and real-time data on earthquakes within California, the Preserve and Monument staff are directed to the Caltech Southern California Earthquake Data Center (SCEDC; https://scedc.caltech.edu/index.html) and the UC Berkeley Seismology Lab (BSL; https://seismo.berkeley.edu/). In the event of a large earthquake, it is recommended that Preserve and Monument staff monitor the impact of seismic activity on roadways, infrastructure, and historic features.

Volcanic Features

The Preserve and Monument contain evidence of a volcanic past in the form of cinder cones, lava tubes, columnar jointing, lava flows, and pyroclastic deposits. Volcanic activity occurred frequently throughout the Late Neogene (23 million to 2.6 million years ago) and Quaternary (2.6 million years ago to present), with eruptions associated with the Lava Beds and Cinder Cone areas beginning around 7 million years ago (US Geological Survey 2009). The last volcanic episode occurred roughly 8,000 years ago (US Geological Survey 2009). The impact of recent volcanic activity is evident on the landscape today, with many recent lava flows remaining uncolonized by vegetation.

The cinder cones (Figure 14) have been extensively mined, with almost every cinder cone in the Preserve showing evidence of some form of mining. The Cinder Cones area of the Preserve is listed as a National Natural Landmark.

Potential inventory needs:

- Inventorying all volcanic features within the Preserve and Monument to determine management needs.



Figure 14. The cinder cones in the Preserve were essential in the construction of Las Vegas, where over 1.5 million tons of cinders were mined and utilized. Photo by Matthew Harrington (Colorado State University).

Water Resources

Typical of a desert ecosystem, perennial streams are nonexistent within the Preserve and Monument. However, the presence of ephemeral springs and seeps provides flora and fauna with essential access to water in an otherwise arid environment. Most springs and seeps exist along the southwest–northwest trending Providence, Granite, New York, and Castle Mountains (National Park Service 2015c). Primarily discharging from perched aquifers (an aquifer that is separated from the water table by an unsaturated zone), water levels are controlled by seasonal precipitation along mountains and hillsides. Spring and seep activity peaks during the wettest months of the year (late fall through late spring) and decreases throughout summer into early fall (National Park Service 2015c). Because many of the springs and seeps flow independently of regional water tables, years with no summer monsoon and winter droughts can lead to the drying up of most ephemeral springs. Historically, some active springs became hubs for Indigenous groups for water resources, trading, and travel. Later, springs were essential sources of water for railroads, ranchers, miners, homesteaders, and military outposts and forts (Figure 15).



Figure 15. Access to freshwater at Rock Spring made the location a popular stop for Indigenous people on hunting and trading trips, a pit stop for historic travelers, a location for a small military post and mail, and a site for homesteaders. Photo by Matthew Harrington (Colorado State University).

When precipitation falls within the Preserve and Monument, sheets of water flow down mountain and hill slopes across vast pediments, carrying water toward drainages and into basins. As pediments are actively eroded during precipitation events, thin layers of eroded gravel and sediment overlying the bedrock wash downslope. When Preserve and Monument roadways cut across pediments, sheet flow can deposit heavy amounts of sediment on the roads, sometimes requiring full road closures for maintenance. In areas where roads cross washes, summer monsoons have caused catastrophic damage to large stretches of roadways with sloughing, erosion, and rapid water flows. Ephemeral washes near Preserve and Monument facilities, such as housing, administrative buildings, historic structures, and campgrounds, can also pose threats. If an intense monsoon hits the Preserve or Monument at the right place, these washes can swell with water and destroy any of the aforementioned infrastructure.

To add to the risk, many of these facilities are built on floodplains, placing them directly in the path of water drainage during large storms. Assessments for the potential damage that could be caused by 100-year, 500-year, or 1000-year flood events may prove beneficial for management planning. As these types of floods become more common because of climate change, having a baseline and a management plan to deal with potential damage will be useful.

Potential inventory needs:

- Assessing potential damage to preserve and monument structures in floodplains and near ephemeral washes during 100-year, 500-year, or 1000-year flood events
- Assessing the impact of increasingly variable precipitation patterns across the Preserve and Monument.
- Monitoring springs and spring levels.
- Creating a risk assessment map for structures/facilities/high visitation areas that are most at risk during varying levels of storms.

Legislatively Required Geologic Inventories

The GRD provides a webpage that summarizes laws, regulations, and policies that specifically apply to NPS minerals and geologic resources.

Series: Geology & Minerals—Resource Laws, Regulations, and Policies (nps.gov)

At Mojave National Preserve and Castle Mountains National Monument, the following apply:

- Cave and Karst Systems
- Paleontology
- Recreational Collection of Rocks and Minerals
- Mining Claims
- Federal Mining Leasing
- Common Variety Mineral Materials
- Climate Change
- Upland and Fluvial Processes
- Soils

Summary of Geologic and Soil Hazards

The dynamic landscapes of many National Park System units present various natural hazards that threaten NPS facilities, staff, visitors, or resources. Many of these natural hazards are geologic (e.g., volcanoes, earthquakes, and landslides). The Addressing Climate Change and Natural Hazards Handbook (National Park Service 2015d, 2023d), grounded in NPS Policy Memorandum 15-01 (Jarvis 2015), provides information and a process to help teams and decision-makers identify, avoid, and mitigate risks associated with environmental change hazards and effects on proposed and planned facility investments. The handbook supports NPS planning guidance, policy directives, and executive orders and does not supersede existing mandated compliance processes and policies.

Additional guidance for facility management, e.g., Climate-Smart Planning Principles and Recommended Practices, has been developed to support effective decision-making.

According to PM 15-01, managers should apply the handbook guidance to identify options to manage natural hazard and climate change risks throughout all levels of facility planning and design. Project teams are required to submit the completed Natural Hazards Checklist (Table 3) as part of Regional and Bureau Investment Review Board submissions. This information can also be used as part of the updated (2024) Automated Investment Review Board (AIRB) submittal process at the Investment Concept (IC) stage. Table 3 includes selected geologic and soils hazards listed in Part 1 of National Park Service (2023d). The GSRI team has added additional hazards where appropriate for the Preserve and the Monument. If needed, Part 2 of the handbook could inform the completion of the checklist, such as whether a hazard is applicable. Contact the GRD with any questions.

Table 3. Geologic and soil hazards checklist. This checklist includes selected hazards listed in part 1 of National Park Service (2023d) is a screening tool to be used at the investment concept stage to help teams determine potential climate change effects and natural hazards to a proposed facilities investment. The checklist shall be completed for all investment concepts and schematic designs that require Investment Review Board review at the regional and/or bureau-wide levels. Its use is encouraged for all infrastructure investments. This table is a synthesis of existing GRI- or SRI- compiled map data and information, as well as published DOI, USGS, NPS, or state geological survey information. It is appropriate for use at park-scale discussions and assessments. It is not a substitute for site-specific investigations or National Environmental Policy Act (NEPA) analysis. Ground-disturbing activities should neither be approved nor denied based upon the information here.

Hazard	Examples of Risk or Secondary Hazard	Best Professional Judgment	Source(s) of Information
Flash Flood	Sudden rising water, e.g., in a dry wash or canyon. Loss of life due to unexpected flooding. Destruction of infrastructure, e.g., through impact or saturation. Reduced or precluded visitation. Power failure due to areawide power outages. Geologic heritage resources (e.g., petroglyphs, paleontological features, historic mining equipment) may be washed away or covered.	Known hazard (extreme; SHIRA)	DOI Strategic Hazard Identification and Risk Assessment (SHIRA) SHIRA - Home (sharepoint.com) Climate Toolbox: Climate Mapper (for Western US) https://marine.usgs.gov/coastalchangehazardsportal/ FEMA: NFHL https://www.fema.gov/flood-maps/national-flood-hazard-layer
Riverine Flood	Inundation. Destruction of infrastructure, e.g., through impact or saturation. Stream channel migration and streambank erosion. Water quality effects. Water supply diminished. Reduced or precluded visitation.	Not applicable (no perennial rivers in the park; see Flash Flood)	DOI Strategic Hazard Identification and Risk Assessment (SHIRA) SHIRA - Home (sharepoint.com) Climate Toolbox: Climate Mapper (for Western US) https://marine.usgs.gov/coastalchangehazardsportal/ FEMA: NFHL https://www.fema.gov/flood-maps/national-flood-hazard-layer
Lake and Reservoir Level Change	Water supply diminished. Flooding and erosion impacts to infrastructure. Diminished or lost recreational opportunities.	Not applicable	University of Michigan: Great Lakes Integrated Science and Assessments (for Great Lakes only) https://glisa.umich.edu/ NOAA: Lake Level Viewer (for Great Lakes only) https://coast.noaa.gov/llv/ USGS: Lakes and reservoirs dataset https://waterdata.usgs.gov/nwis/current/?type=lake&group_key=state_cd US Bureau of Reclamation Water Operations https://www.usbr.gov/main/water/#GP

Hazard	Examples of Risk or Secondary Hazard	Best Professional Judgment	Source(s) of Information
Precipitation: Increased Extreme Events	Surface erosion. Floods. Water damage to structures from driven rain. Unstable saturated soils. Reduced or precluded visitation. Power failure due to areawide power outages.	Known hazard	NPS: National Park historical and projected climate change trends https://irma.nps.gov/DataStore/Reference/Profile/2266988 Climate Toolbox: Climate Mapper (for Western US) https://marine.usgs.gov/coastalchangehazardsportal/ NASA: DAYMet gridded climate data https://daymet.ornl.gov/ DOI Strategic Hazard Identification and Risk Assessment (SHIRA) SHIRA - Home (sharepoint.com)
Precipitation: Altered Patterns and Changing Humidity	Local flooding. Mold growth. Wood decay. Drought. Fire. Water supply change.	Known hazard	NPS: National Park historical and projected climate change trends https://irma.nps.gov/DataStore/Reference/Profile/2266988 Climate Toolbox: Climate Mapper (for Western US) https://marine.usgs.gov/coastalchangehazardsportal/ NASA: DAYMet gridded climate data https://daymet.ornl.gov/
Drought: Increased Frequency, Intensity, Magnitude, and Duration	Limited water supply for visitor, staff, and operational needs (e.g., potable and fire suppression water). Increased competition for available water and water supply impacts (e.g., water supply curtailment by state agencies). Crack/heave damage in drier soils. Increased vulnerability to wildfire.	Known hazard (high; SHIRA)	Climate Toolbox: Climate Mapper (for Western US) https://marine.usgs.gov/coastalchangehazardsportal/ FEMA: Drought risk https://hazards.fema.gov/nri/drought University of Nebraska-Lincoln: Drought Monitor https://droughtmonitor.unl.edu/ DOI Strategic Hazard Identification and Risk Assessment (SHIRA) SHIRA - Home (sharepoint.com)
Permafrost Dynamics	Thawing. Surface collapse. Increased landslide susceptibility. Road/service disruption. Frost heave.	Not applicable	NASA: Permafrost dataset https://neo.gsfc.nasa.gov/view.php?datasetId=PermafrostNSIDC NPS: Central Alaskan Network Permafrost Protocol Dataset https://irma.nps.gov/DataStore/Reference/Profile/2288714 DOI Strategic Hazard Identification and Risk Assessment (SHIRA) SHIRA - Home (sharepoint.com)
Landslide	Rockfall. Mud or debris slides or flows onto or from under structures. Reduced or precluded visitation.	Known hazard (susceptible to landslides)	FHWA Unstable Slope Management Program (USMP): Geologic and Geotechnical Services | FHWA (dot.gov). FEMA: Landslide risk https://hazards.fema.gov/nri/landslide USGS: Emergency Assessment of Post-Fire Debris-Flow Hazards https://landslides.usgs.gov/hazards/postfire_debrisflow/ DOI Strategic Hazard Identification and Risk Assessment (SHIRA) SHIRA - Home (sharepoint.com)

Hazard	Examples of Risk or Secondary Hazard	Best Professional Judgment	Source(s) of Information
Earthquake	Falling objects. Collapsing structures. Inoperability of major building systems, e.g., power, sewer, water. Liquefaction - loss of strength to foundations, silt deposition, standing water. Trigger to other hazards, e.g., landslides, debris flows.	Known hazard (very high; SHIRA)	USGS: Earthquake Probability Mapping https://www.usgs.gov/natural-hazards/earthquake-hazards/hazards FEMA: Earthquake risk https://hazards.fema.gov/nri/earthquake DOI Strategic Hazard Identification and Risk Assessment (SHIRA) SHIRA - Home (sharepoint.com) Caltech Southern California Earthquake Data Center https://scedc.caltech.edu/index.html) UC Berkeley Seismology Lab (https://seismo.berkeley.edu/).
Tsunami	Coastal area inundation.	Not applicable	State Tsunami Inundation Mapping FEMA: Tsunami risk https://hazards.fema.gov/nri/tsunami DOI Strategic Hazard Identification and Risk Assessment (SHIRA) SHIRA - Home (sharepoint.com)
Shrink/Swell Soils	Damage to structure. “Heaving” of ground beneath structure. Increased landslide susceptibility.	Potential hazard (low; SHIRA)	NPS: Soil Resources Inventory https://irma.nps.gov/DataStore/Reference/Profile/2190302 USDA: Soils Survey https://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/survey/ (look for “linear extensibility” interpretation) DOI Strategic Hazard Identification and Risk Assessment (SHIRA) SHIRA - Home (sharepoint.com)
Volcanic Eruption	Lava flows. Fire. Tsunamis. Toxic gas releases. Ash and air quality degradation. Reduced or precluded visitation.	Not applicable	USGS: Volcano Hazards Program https://www.usgs.gov/volcano FEMA: Volcanic activity risk https://hazards.fema.gov/nri/volcanic-activity Red Cross: Map of Volcano Risk Areas https://maps.redcross.org/website/maps/arc_map_links.html DOI Strategic Hazard Identification and Risk Assessment (SHIRA) SHIRA - Home (sharepoint.com)
Hydrothermal Activity (e.g., geysers)	Toxic gas release. Explosion. Boiling water. Steam. Surface collapse into void.	Not applicable	NREL: Geothermal resource data, tools, and maps https://www.nrel.gov/gis/geothermal.html USGS: Geothermal resources https://www.usgs.gov/programs/energy-resources-program/science/science-topics/geothermal DOI Strategic Hazard Identification and Risk Assessment (SHIRA) SHIRA - Home (sharepoint.com)
Subsurface Hazards: Abandoned Mineral Lands Cave/Karst (sinkholes)	Surface collapse. Contamination.	Known hazard	State geological hazards maps USGS: Karst in the United States: A Digital Map Compilation and Database (Weary and Doctor 2014) Evaluation of cave and karst programs and issues at US national parks (Land et al. 2013) DOI Strategic Hazard Identification and Risk Assessment (SHIRA)

Prior NRSS-Supported Work

This section provides tables (Table 4 and Table 5) of prior NRSS-supported geology and soils work at Mojave National Preserve and Castle Mountains National Monument. These research permits and TARs can be used to determine if a project has already been undertaken or if gaps in knowledge exist. The Monument did not have any research permits when this summary was written due to its new status within the NPS.

Castle Mountains National Monument

TAR: Assist MOJA/CAMO in working with Newcastle Gold (mining operation)

Mojave National Preserve

Table 4. A chronological list of geologic research permits from Mojave National Preserve.

Year	Geologic Research Permits from RPRS
1964	A geologic reconnaissance in the southeastern Mojave Desert
1971	Clark Mountain thrust complex in the Cordillera of southeastern California: geologic summary and field trip guide
1987	Mineral Resources of the Fort Piute Wilderness Study Area, San Bernardino County, California (Chapter C)
2001–2002	Geologic mapping and landscape studies to quantify vulnerability and recoverability of desert landscapes and produce a geologic map of Mojave National Preserve
2003–2004, 2006–2015	Stratigraphy and correlation of Paleozoic strata in selected parts of the Mojave National Preserve
2003–2004	A. Geologic mapping and landscape studies to quantify vulnerability and recoverability of desert landscapes and produce a geologic map of Mojave National Preserve. B. Installation of instruments for long-term monitoring of meteorology and soil moisture
2004–2005	Soil moisture studies for combined geospatial models in the Mojave Desert
2004–2007	Using a salt-flat-endemic spider (Araneae; *Saltonia*) to infer paleoriver routes
2004	Deformation, metamorphism and tectonic history of 1.7 Ga orogenic events in Proterozoic gneisses of the Mojave Province, Providence Mountains, SE California
2005–2006	Geomorphic study of storage, stability, and transport of sediment in desert basins during periods of paleoclimate change
2005–2019	Plate Boundary Observatory (PBO) component in Mojave National Preserve to monitor tectonic and magmatic processes using high precision Global Positioning Systems (GPS)
2005	Monitoring land-surface change and understanding wind erosion at Mojave National Preserve
2008	Hydrogeologic investigation of Henry Spring, Mojave Desert, California
2011	Unpublished digital geologic map of Mojave National Preserve, California (NPS, GRD, GRI, MOJA, MOJA digital map) adapted from the US Geological Survey Bulletin by Theodore, Hodges, Tosdal, Miller, Wooden, Conway, Haxel, Rytuba, Dohrenwend, and others (2007)
2011	Unpublished digital surficial geologic map of Mojave National Preserve, California (NPS, GRD, GRI, MOJA, MOJS digital map) adapted from the unpublished US Geological Survey data by Miller, Bedford, Phelps, Schmidt, Lidke, and McMackin (2002)
2012–2013	TextureCam: Automated Image Texture Analysis
2013–2015	Proposal for geophysical studies within the Mojave National Preserve with the goal of characterizing the geologic and structural setting of the Eastern Mojave Desert
2014	Using igneous bodies of the Mojave National Preserve and their tectonic and geochemical connection to ore body formation to identify buried metal ore bodies

Year	Geologic Research Permits from RPRS
2014–2020	Blueprint Earth: Mission Mojave
2015–2016	Expansion of spring-fed wetlands during the Little Ice Age, Mojave National Preserve, California
2015	CSUF Mojave Desert archaeology project: Soda Mountains geologic specimen collection for XRF
2016	Paleontological resource inventory and monitoring: Mojave Desert Network
2018–2019	Deep fault structure beneath the Mojave from a high density, passive seismic profile
2019–2023	Geophysical studies within the Mojave National Preserve
2019–2021	Geologic mapping in the Mountain Pass, California Focus Area
2021	Mapping the Teutonia batholith: the missing link to the Cretaceous Magmatic Arc
2023	Mojave National Preserve: paleontological resource inventory (public version)
2023	Mojave National Preserve: paleontological resource inventory (sensitive version)
2023	Geologic mapping of Piute Valley
2023	Geologic and Hyperspectral Thermal Emission Spectrometer (HyTES) studies at Cima Volcanic Field
2024	Age and tectonic setting of Neoproterozoic-Cambrian strata of western Laurentia in the Old Dad, Kelso, and Providence Mountains
In progress	Geologic resources inventory project for Mojave National Preserve

Table 5. A chronological list of soils research permits from Mojave National Preserve.

Year	Soils Research Permits from RPRS
1990, 2001, 2004	Sex expression in *Atriplex hymenelytra* (Chenopodiaceae): patterns, processes, and consequences
2001–2002	Geologic mapping and landscape studies to quantify vulnerability and recoverability of desert landscapes and produce a geologic map of Mojave National Preserve
2001–2003	Soil vegetation changes related to livestock removal at Mojave National Preserve and Great Basin National Park
2002	Survey of mycorrhizal association with dune plants in the Kelso Dunes
2003–2004	A. Geologic mapping and landscape studies to quantify vulnerability and recoverability of desert landscapes and produce a geologic map of Mojave National Preserve B. Installation of instruments for long-term monitoring of meteorology and soil moisture
2004–2005	Soil moisture studies for combined geospatial models in the Mojave Desert
2004–2007	Instrumentation for meteorological data in support of DOI Landscape Science Objectives 1, 2, and 3
2004–2006, 2011	Climatic and anthropogenic influences on dust emission in desert terrains
2004–2006, 2008–2010	Integrated forecasting of desert terrain conditions for military operations
2005–2008, 2018	Fire effects on seedbanks and vegetation in the Eastern Mojave Desert
2005–2006	Investigation of the occurrence and distribution of naturally-produced perchlorate in areas of minimal anthropogenic impact
2005–2006	Geomorphic study of storage, stability, and transport of sediment in desert basins during periods of paleoclimate change
2005	Monitoring land-surface change and understanding wind erosion at Mojave National Preserve
2006	Investigation of Fire Stimulated Germination in Postfire Herbs Recruiting After the Hackberry Fire

Year	Soils Research Permits from RPRS
2007–2010, 2013–2015	Where does dust originate? Geomorphic and climatic control on the evolution of dust sources in the Mojave Desert, USA
2008–2016, 2019–2021	Mojave soil microorganisms
2008–2011	Linking land-surface characteristics to soil and ecosystem dynamics in the Clark Mountains, Mojave National Preserve
2008	Hydrogeologic investigation of Henry Spring, Mojave Desert, California
2009	Isotopic assessment of sources of nitrate in Mojave Desert pavements
2010	Expanded survey of free-living and plant-parasitic nematodes from the Mojave National Preserve
2010, 2012	Investigation of the spatial relationships of bacteria associated with rock varnish
2010	Effects of livestock removal on recovery of Mojave NR plant communities
2011–2022	Soil Survey of Mojave National Preserve
2011	Jepson Herbarium Workshop: Lichens and Soil Crusts of the Eastern Mojave
2011	Carbon, nitrogen and aggregate stability properties of biological soil crusts in the Mojave Desert
2011–2012	Climate change, plant-soil feedbacks, and diversity decline in three grassland systems
2012–2013, 2015, 2016	Correlating soil properties with nematode and desert crust biodiversity on an alluvial fan of Clark Mountains
2012–2013, 2015–2016, 2022–2024	Integrated upland monitoring of the Mojave Desert Network
2013	Mojave Desert Network integrated upland monitoring: 2012 pilot study for Mojave National Preserve
2014–2016	Impact of climate change and altered vegetation management on the conservation and recovery of the Blunt-nosed Leopard Lizard
2015–2016	Expansion of spring-fed wetlands during the Little Ice Age, Mojave National Preserve, California
2016–2017, 2019, 2024	The role of climate on the soil carbon cycle in the Mojave National Preserve, and projected impacts due to 21st century climate change
2018, 2022	DNA characterization of soil microbes associated with degradation of borate-treated wood in geographic regions with high levels of naturally occurring borates
2018	Overcoming the nematode taxonomic impediment through integration of novel tools for species discovery and phylogeny: Cephaloboidea as a case-study
2018–2019	Quantifying dust emissions from common desert landforms, Mojave Desert, USA
2018–2019	Evolution of cleptoparasite-host interactions between the blister beetle *Meloe franciscanus* (Coleoptera: Meloidae) and its hosts, the solitary bees in the genus *Habropoda*. Nesting biology and pollination ecology of the solitary bee *Calliopsis puella*. Soil nematode community interactions
2019	Adaptation to climate and soil in *Eriogonum umbellatum*
2020–2022	Understanding how time and climate influence mechanical weathering
2020	Frontiers in dust mineralogical composition and its effects upon climate (FRAGMENT)
2020–2023	Linking microbial succession to biogeochemical cycling and Joshua tree regeneration after the Dome Fire
2021–2023	Mojave National Preserve vegetation analysis pre- and post-Dome Fire, August 2020
2021–2023	Developing biocrust rapid assessment tools for conservation and restoration
2021–2023	Digging into soil carbonate formation processes in a hyper-arid climate with triple oxygen isotopes
2022	Assessing the efficacies of passive versus active restoration on heavily disturbed cattle-grazing sites in the Mojave National Preserve

Year	Soils Research Permits from RPRS
2022–2023	Exploring biological soil crust sensitivity to climate change across the Mojave Desert
2022–2024	Combating weeds, fire and soil erosion with biocrust restoration
2022–2023	Exploring biological soil crust recovery post-fire in Joshua tree woodlands along a seventy year chronosequence
2022	Community resilience of fungi in extreme environments
2022–2023	Effect of landscape features and site conditions on drought response by vegetation and soil microbial communities
2022	Dust composition and climate - understanding drylands soil mineralogy from remote sensing
2023	Combating weeds, fire and soil erosion with biocrust restoration, Phase 2
2023	Mojave soil microorganisms and the dry limit of life
2023	Untangling the dry limit for microbial life in rock-inhabiting communities of US Western drylands (Acronym: DRYLIFE)
2024	Exploring biological soil crust and plant assemblage recovery post-fire in Joshua tree woodlands along a one hundred year chronosequence
In progress	National Park Service - SRI - Soil Survey Geographic (SSURGO) for Mojave National Preserve, California - In Progress

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