National Park Service
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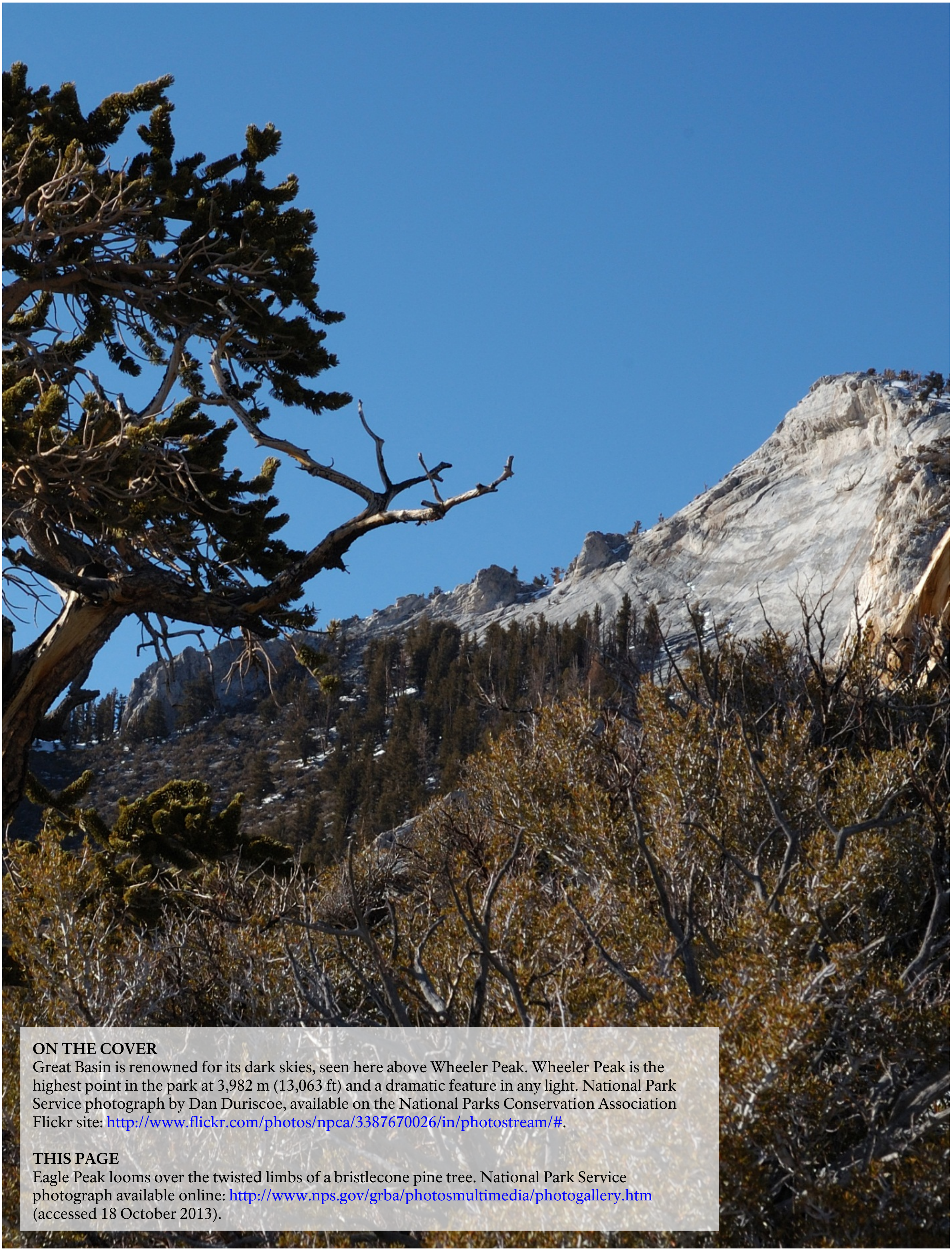
Natural Resource Stewardship and Science

Great Basin National Park

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2014/762



ON THE COVER
Great Basin is renowned for its dark skies, seen here above Wheeler Peak. Wheeler Peak is the highest point in the park at 3,982 m (13,063 ft) and a dramatic feature in any light. National Park Service photograph by Dan Duriscoe, available on the National Parks Conservation Association Flickr site: http://www.flickr.com/photos/npca/3387670026/in/photostream/#.

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Eagle Peak looms over the twisted limbs of a bristlecone pine tree. National Park Service photograph available online: http://www.nps.gov/grba/photosmultimedia/photogallery.htm (accessed 18 October 2013).

Great Basin National Park

Geologic Resources Inventory Report

Natural Resource Report NPS/NRSS/GRD/NRR—2014/762

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The Natural Resource Report Series is used to disseminate high-priority, current natural resource management information with managerial application. The series targets a general, diverse audience, and may contain NPS policy considerations or address sensitive issues of management applicability.

All manuscripts in the series receive the appropriate level of peer review to ensure that the information is scientifically credible, technically accurate, appropriately written for the intended audience, and designed and published in a professional manner. This report received informal peer review by subject-matter experts who were not directly involved in the collection, analysis, or reporting of the data.

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Executive Summary

The Geologic Resources Inventory (GRI) is one of 12 inventories funded by the National Park Service (NPS) Inventory and Monitoring Program. The Geologic Resources Division of the NPS Natural Resource Stewardship and Science Directorate administers the GRI. This report synthesizes discussions from a scoping meeting for Great Basin National Park (Nevada) on 17–19 September 2003 and a follow-up conference call on 15 December 2011, which were held by the Geologic Resources Division to determine geologic resources, the status of geologic mapping, and geologic resource management issues and needs. It is a companion document to previously completed GRI digital geologic map data.

Great Basin National Park was established in 1986 to preserve a representative segment of the Great Basin. The park's 31,234 ha (77,180 ac) form part of the arid Great Basin, a physiographic region within the unique Basin and Range province, and contain a myriad of geologic features that document a geologic history spanning over 500 million years. Included in this history are several mountain–building events (orogenies), the formation of the supercontinent Pangaea, multiple incursions of shallow seas onto the North American continent, extension and thinning of Earth's crust, and the rare exposure of a metamorphic core complex. The park also expanded the protection provided by Lehman Caves National Monument (established in 1922) and includes the spectacular cave formations (speleothems) and fragile cave ecosystems of 46 known caves in eastern Nevada's Southern Snake Range.

The geologic features and associated processes in the park that were identified by participants at a 2003 scoping meeting and during a follow-up conference call in 2011 include the following:

- **Cave systems.** Forty-six known caves within the park form four distinct cave systems: (1) Lehman Hills Caves, (2) Baker Creek Caves, (3) Snake Creek Caves, and (4) Alpine Caves. The caves began forming approximately 1 million years ago during the wet, late Pleistocene climate.
- **Cave development.** In general, cave formation has been driven by one or both of two, quite contrasting processes. Some caves are clearly the result of the epigenic process, which involves dissolution of limestone due to slightly acidic meteoric groundwater. In contrast, some caves contain evidence of the hypogenic process in which caves form in a confined environment, hydrologically isolated from any connection with the surface. In this system, dissolution is driven by a deep source of water that enters the formation due to hydrostatic pressure and spreads due to such controls as fractures, permeability variations, and porosity barriers. Park staff are actively working to determine the relative role each process played in cave formation.
- **Speleothems.** In the Lehman Hills Cave system, Lehman Caves are renowned for their exceptional variety of speleothems, which range from curtains and thick columns of calcium carbonate extending from cave floor to ceiling to delicate, tubular-shaped soda straws the diameter of a drop of water. Today, the 3.2 km (2 mi) of cave passageways make Lehman Caves the longest known cave system in Nevada.
- **Metamorphic core complex and the Snake Range décollement.** The metamorphic core complex and the associated low-angle detachment fault known as the Southern Snake Range décollement, a relatively horizontal fault with large displacement (kilometers to tens of kilometers), are the primary geologic structures in the park. Great Basin National Park preserves geologic features associated with the formation of the décollement as well as the deformation of the rocks above and below the fault. Rock units in the metamorphic core complex are the oldest units in the park and form the higher-elevation ridges and peaks, such as the 3,982-m (13,063-ft) summit of Wheeler Peak, the second tallest mountain in Nevada.
- **Basin and Range boundary faults**. During the Miocene, extension began to stretch and pull apart Earth's crust, generating today's Basin and Range topography. High-angle faults separate the north–south-trending ranges and basins. One of these faults separates the Snake Range from the adjacent Spring Valley.
- **Sedimentary and metasedimentary rocks.** Sedimentary features and fossils in the park's strata document episodic incursions of shallow marine environments that inundated the western margin of North America throughout the Paleozoic Era.
- **Igneous rocks**. Great Basin National Park contains remnants of the extensive magmatic events that affected the southwest during the Mesozoic Era.
- **Rock glaciers**. Forming approximately 1,200 years ago during the Little Ice Age, rock glaciers are the only modern glaciers in the interior Great Basin. Rock glaciers may be "ice-cored" (rock burying ice) or "ice-cemented" (ice present in cracks between rocks). Seven rock glaciers have been identified in the park.
- **Glacial features**. Glacial features, such as cirques, arêtes, tarns, moraines, and horns, preserve a history of ice age alpine glaciation that carved the higher elevations in Great Basin National Park.

- **Periglacial features**. The park includes features that formed adjacent to glaciers due to freeze-thaw processes or erosion, such as solifluction lobes, stone polygons, stone garlands, and protalus ramparts.
- **Lexington Arch**. This feature rises about 23 m (75 ft) above Lexington Canyon in the southeast area of the park. It may be the only limestone arch in the Southwest.
- **Geomorphic features**. Today's arid Great Basin climate produced geomorphic features typical of desert regions, such as alluvial fans, playa lakes, and ephemeral stream channels.
- **Paleontological Resources.** Limestones in the park include a variety of marine fossils, such as algae (*Girvinella* and *Receptaculites oweni*), trilobites, brachiopods, corals (*Eofletcheria* and *Foerstephyllum*), crinoids, gastropods, stromatoporoids, and foraminifera.
- **Geology and Cultural Features**. Humans have been using the rocks in Great Basin National Park as a canvas for their painting and designs for approximately 11,000 years. Seven styles of pictographs and petroglyphs have been identified in the Southern Snake Range.

Participants also identified the following geologic issues that are of particular significance for resource management at Great Basin National Park.

- **Cave preservation and protection**. In 2004, a Cave and Karst Management Plan was drafted that identified preferred methods of cave preservation and protection. Ongoing threats to Lehman Caves include visitor use, cave lighting, air and water quality, invasive species, and climate change.
- **Lehman Cave restoration project**. Park staff continue to restore Lehman Caves to as natural a state as possible by removing lint and algae from speleothems and by restoring previous cave development.
- **Groundwater withdrawal**. Increased groundwater pumping for expanding population centers may decrease the limited water resources available in Great Basin National Park, which may negatively impact stream morphology and cave development.
- **Documenting glacial features**. A baseline inventory and map are needed to document and monitor changes to the park's glacial features.
- **Geohazards.** Landslides, avalanches, floods, and debris flows primarily occur in the backcountry, but may impact campgrounds and trails.
- **Paleontological resource inventory, monitoring, and protection**. The park is in the process of documenting fossil localities of Paleozoic marine invertebrates. These fossils help unravel the complex depositional and deformational history of the Basin and Range.
- **Seismic activity (earthquakes).** Although Nevada is a seismically-active state, the potential for earthquakes in Great Basin National Park is minor.
- **Reclamation of abandoned mineral lands**. Disturbed lands and degraded water quality from past mining activities are issues for the park.
- **Preservation of rock art**. The park preserves and protects a variety of pictographs and petroglyphs from prehistoric cultures.

This Geologic Resources Inventory report was written for resource managers to support science-informed decision making, but it may also be useful for interpretation. The report was prepared using available geologic information and the NPS Geologic Resources Division did not conduct any new fieldwork in association with this report. Sections of the report discuss distinctive geologic features and processes within Great Basin National Park, highlight geologic issues facing resource managers, describe the geologic history leading to the present-day landscape, and provide information about the GRI geologic map data. A Geologic Map Graphic (in pocket) illustrates these data. The Map Unit Properties Table (in pocket) summarizes report content for each geologic map unit.

Acknowledgements

The NPS Geologic Resources Division partners with institutions such as Colorado State University, the US Geological Survey, state geological surveys, local museums, and universities to develop Geologic Resources Inventory products. This section acknowledges contributors to this report.

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Introduction

This section briefly describes the National Park Service Geologic Resources Inventory Program and the regional geologic and historic setting of Great Basin National Park.

Geologic Resources Inventory Program

The objective of the Geologic Resources Inventory is to provide geologic map data and pertinent geologic information to support resource management and science-informed decision making in more than 270 natural resource parks throughout the National Park System. To realize this objective, the GRI team undertakes three tasks for each natural resource park: (1) conduct a scoping meeting and provide a summary document, (2) provide digital geologic map data in a geographic information system (GIS) format, and (3) provide a GRI report (this document). These products are designed and written for nongeoscientists.

Scoping meetings bring together park staff and geologic experts to review and assess available geologic maps, develop a geologic mapping plan, and discuss geologic features, processes, and resource management issues that should be addressed in the GRI report. Following the scoping meeting, the GRI map team converts the geologic maps identified in the mapping plan to digital geologic map data in accordance with the GRI data model. After the map is completed, the GRI report team uses these data, as well as the scoping summary and additional research, to prepare the GRI report.

The compilation and use of natural resource information by park managers is called for in the 1998 National Parks Omnibus Management Act (section 204), 2006 National Park Service Management Policies, and the Natural Resources Inventory and Monitoring Guideline (NPS-75). The "Additional References" section and Appendix B provide links to these and other resource management documents and information.

Additional information regarding the GRI, including contact information, is available at: http://www.nature.nps.gov/geology/inventory/. The current status and projected completion dates of products are at: http://www.nature.nps.gov/geology/GRI_DB/Scoping/Quick_Status.aspx.

Park Setting

Great Basin National Park in eastern Nevada's Southern Snake Range preserves 31,234 ha (77,180 ac) of majestic mountains, alpine ecosystems, cave systems, and desert landscapes (plate 1, in pocket). The park is a relatively new addition to the National Park System, being established as the 49th national park in 1986. However, the region's popularity extends back to 1885 when rancher Absalom Lehman discovered and commercialized the cave that bears his name.

Figure 1. The view to the south from the Wheeler Peak summit. Prospect Mountain Quartzite (geologic map unit CZpm) forms the ridges and slopes. National Park Service photograph by Loren Reinhold.

Figure 2. Speleothems in Lehman Cave. A trail leads through some of the outstanding cave formations (speleothems) in Lehman Cave. National Park Service Photograph by Rick Bowersox, available online: http://www.nps.gov/grba/photosmultimedia/photogallery.htm (accessed 30 January 2014).

In 1922, Congress established Lehman Caves National Monument under the direction of the U.S. Forest Service. The national monument was transferred to the National Park Service in 1933. Attempts to establish a national park stalled until 1986. According to Darwin Lambert (1992), support for national park status expanded after a researcher cut down a bristlecone pine (*Pinus longaeva*) growing at timberline on Wheeler Peak, counted its tree rings, and discovered that he had cut down the oldest known living tree in the world.

From the stately peaks and ridges of the Southern Snake Range to the broad alluvial fans spreading into Spring and Snake valleys, Great Basin National Park preserves a diverse array of alpine glacial landforms, igneous intrusions, sedimentary rocks, geomorphic features, and desert topography. At 3,982 m (13,063 ft), Wheeler Peak stands as the highest point in the park and the second tallest mountain in Nevada (fig. 1). Rock glaciers flow from glacially-carved depressions (cirques) at the bases of mountain peaks. In the rugged southern part of the park, the Lexington Arch rises about 23 m (75 ft) from the floor of Lexington Canyon and may be the only limestone arch in the Southwest.

Great Basin National Park preserves and protects spectacular cave formations (speleothems) and fragile ecosystems in 46 known caves (fig. 2). Formed in Cambrian-age limestone deposited over 500 million years ago, Lehman Caves contain 3.2 km (2 mi) of passageways, making it the longest known cave in Nevada.

The park also contains historic cultural remains such as late 19th century mining relics and stone hut foundations on Wheeler Peak. Installed by the U.S. Coast and Geodetic Survey in the 1880s, these huts were heliograph stations, which sent messages (usually in Morse code) by flashing sunlight off a mirror.

Geologic Setting

The Great Basin forms the northern part of the Basin and Range physiographic province, a unique landscape that extends from Mexico to southern Oregon and Idaho (fig. 3). The Basin and Range Province is noted for its arid conditions and its characteristic topography of long, north–south trending, fault-bounded mountain ranges (horsts) separated by equally long, relatively flat basins (grabens). Pioneer geologist Clarence Dutton aptly described the short, abrupt ranges as looking on a map like "an army of caterpillars crawling northward" (Dutton 1886, p. 116).

The Great Basin is considered a "cold" desert, receiving less than 25 cm (10 in) of precipitation per year, nearly all as snow. The other three deserts in the United States (Mohave, Chihuahuan, and Sonoran), also located in the Southwest, are regarded as "hot" deserts and receive most of their precipitation as rainfall.

Figure 3. Topographic map of the Basin and Range Province. Great Basin National Park (yellow star) is within the Great Basin portion of the Basin and Range Province. Compiled by Philip Reiker (NPS Geologic Resources Division) from ESRI Arc Image Service, National Geographic Society TOPO Imagery.

The Sierra Nevada mountain range borders the Great Basin to the west and is primarily responsible for its arid conditions. Blocked by the Sierra Nevada, air masses flowing into California from the Pacific rise, cool, and release most of their moisture before crossing into the Great Basin. This "rain shadow" effect results in a dry, arid landscape except for isolated mountainous areas that rise high enough to intercept short-duration rain or snowfall events.

The Colorado River flows along the southern border of the Great Basin, but no rivers flow out of the Great Basin. The region is internally drained with streams flowing from mountain ranges into local interior basins, forming temporary playa lakes.

The park contains all three major rock types: metamorphic, sedimentary, and igneous. Metamorphic rocks are the oldest rocks in the park (fig. 4). Exposed to intense heat and pressure, Late Proterozoic and Lower Cambrian sandstone and shale were metamorphosed to quartzite and argillite. Approximately 1,200 m (3,900 ft) of Late Proterozoic-to-Lower Cambrian Prospect Mountain Quartzite (geologic map unit CZpm) covers the northern portion of Great Basin National Park (fig. 4; see Geologic Map Graphic [in pocket]). The quartzite caps the summits of Wheeler, Jeff Davis, Baker, and Pyramid peaks, Bald and Buck mountains, and many other ridges.

Sedimentary rocks dominate the Paleozoic Era (figs. 4 and 5). In Great Basin National Park, Cambrian-to-Devonian limestone, dolomite, sandstone, and shale ("C", "O", and "D" map units) lie above the thick section of Prospect Mountain Quartzite (CZpm) and are exposed along the eastern border of the park and south of Snake Creek (Hose and Blake 1976; Miller et al. 2007). Limestone exposed in humid environments dissolves and tends to form hummocky, rolling hills or slopes, but in the arid Great Basin, limestone, like sandstone, forms erosion-resistant cliffs and ledges. The sedimentary rock layers represent a variety of relatively shallow and nearshore marine environments that inundated western North America during the Paleozoic.

During the Mesozoic and early Tertiary (fig. 5), igneous activity resulted in the Jurassic, Cretaceous, and Tertiary granitic plutons (Jg, Kgr, Tgr) and extrusive lava flows (Tlf, Trdi) exposed in the park. The plutonic bodies primarily intrude Prospect Mountain Quartzite in the northern part of Great Basin National Park and Pole Canyon Limestone (Cpc) in the southern part of the park.

Late Proterozoic (fig. 5) metamorphic rocks may be the oldest rocks in the park, but they were not exposed at the surface until the Paleogene, about 35 million years ago. The metamorphic rocks constitute a 'metamorphic core complex' based on their regional and stratigraphic similarities. Twenty-five metamorphic core complexes have been identified in the Basin and Range province, and national parks such as Great Basin National Park and Arizona's Saguaro National Park (see GRI report by Graham 2010) provide rare opportunities to study their geologic characteristics and deformation history (Davis 1987).

The metamorphic core complex is separated from younger Paleozoic strata by the Southern Snake Range décollement, a low-angle detachment fault (Miller et al. 1987). The metamorphic core complex and associated Southern Snake Range décollement are the prominent geologic structures in the park, but they represent only a part of the complex tectonic history preserved in Great Basin National Park. In addition to the metamorphic core complex, Tertiary extension produced the Snake Range, bordering valleys, and the fault-bounded blocks of strata in the southern section of the park. Plate tectonic collisions during the Paleozoic and Mesozoic, briefly summarized below and addressed in more detail in the Geologic History section, generated compressive forces that built mountains and sutured land masses onto the western margin of North America. Great Basin National Park preserves over 500 million years of dynamic processes that folded, faulted, tilted, and uplifted entire sections of the western seaboard of North America.

Overview of the Geologic History Preserved in Great Basin National Park

Early in the Paleozoic, the west coast of the North American craton was a passive tectonic margin, similar to today's Atlantic seaboard. During the Ordovician (fig. 5), a subduction zone developed off the western margin of North America as the North American plate collided with the Pacific plate. Regionally extensive reverse and thrust faults (fig. 6) in mountain ranges west of Great Basin National Park attest to a major mountain-building event (Antler Orogeny) in the Devonian (fig. 5).

Tectonic activity and periods of glaciation caused relative sea level to fluctuate so that western North America, especially the Great Basin National Park region,

Era	Period	Geologic Map Unit (map symbol)	General Description
Cenozoic	Quaternary	Talus (Qt*), Alluvium (Qa*), Lacustrine gravels (Qlg), Landslide deposits (Ql*), Glacial deposits (Qg*), Older alluvium (Qoa*)	Unconsolidated clay, silt, sand, and pebbles.
	Quaternary and Tertiary	Conglomerate (QTc)	Clasts of Paleozoic units.
	Tertiary: Neogene, Paleogene	Conglomerate (Tc*), Needles Range Formation (Tnr), Lacustrine deposits (Tl), Latite flows (Tlf), Rhyodacite flows and intrusive rocks (Trdi*), Older conglomerate (Toc), Muscovite-bearing rhyolite dikes and sills (Tmp*), Granite (Tgr*)	Tc, Toc: conglomerate Tnr: conglomerate and tuff Tl: lake deposits Tlf: feldspar-rich volcanic rock Trdi: volcanic flows Tmp: rhyolite dikes and sills Tgr: biotite-rich granite
Mesozoic	Cretaceous	Granite (Kgr*)	Biotite and muscovite granite.
	Jurassic	Granite (Jg*)	Granitic pluton with a variety of minerals.
	Triassic	No rock units of this interval mapped within the vicinity of Great Basin National Park	
Paleozoic	Permian		
	Pennsyl-vanian	Ely Limestone (PNe)	Fossiliferous limestone forming ledges and slopes.
	Mississippian	Chainman Shale (Mc)	Shale and siltstone. Forms slopes.
		Joana Limestone (Mj)	Massive, cliff-forming limestone.
		Pilot Shale (MDp)	Calcareous shale with thin interbeds of limestone.
	Devonian	Guilmette Formation (Dg*)	Slope- to cliff-forming limestone.
		Simonson Dolomite (Ds*)	Fossiliferous dolomite.
		Sevy Dolomite (Dse*)	Dolomite. Fossils rare.
	Silurian	Fish Haven and Laketown Dolomites (OSfl*)	Dark brown to light grey, ledge- and cliff-forming dolomites.
	Ordovician	Eureka Quartzite (Oe*)	Cliff-forming quartzite.
		Pogonip Group (Op*): Lehman Formation (Opl*)	Limestone and silty limestone.
		Kanosh Shale (Opk*)	Shale and fossiliferous limestone.
		Juab Limestone (Opj*)	Fossiliferous, ledge-forming limestone.
		Wahwah Limestone (Opw*)	Limestone and silty limestone.
		Fillmore Limestone (Opf*)	Limestone and shaley limestone.
		House Limestone (Oph*)	Limestone.
		Notch Peak Limestone (OCn*)	Cherty, cliff-forming, fossiliferous limestone.
	Cambrian	Corset Spring Shale (Ccs*)	Slope-forming shale.
		Johns Wash Limestone (Cjw*)	Cross-bedded, oolitic limestone.
		Lincoln Peak Formation (Clp*)	Slope-forming limestone and shale.
		Pole Canyon Limestone (Cpc*)	Members a-e consist of slope- and ledge-forming to massive limestone.
		Pioche Shale (Cpi*)	Shale, siltstone, and quartzite.
		Prospect Mountain Quartzite (CZpm*)	Cliff-forming quartzite.
Neoproterozoic	Late Proterozoic	McCoy Creek Group (Zm*): Osceola Argillite (Zmoa*)	Laminated slates and siltstone with various degrees of metamorphism.
		Shingle Creek Shale (Zmsc*)	Shale.
		McCoy Group quartzite (Zmq*)	Well-bedded quartzite and conglomerate beds of variable thickness. Ledge- and slope-former.

Figure 4. General stratigraphic column for the Great Basin National Park area. * indicates a unit mapped within the park. Colors are standard colors approved by the U.S. Geological Survey to indicate different time periods on geologic maps; they also correspond to the colors on the Map Unit Properties Table. See the Map Unit Properties Table for more detail.

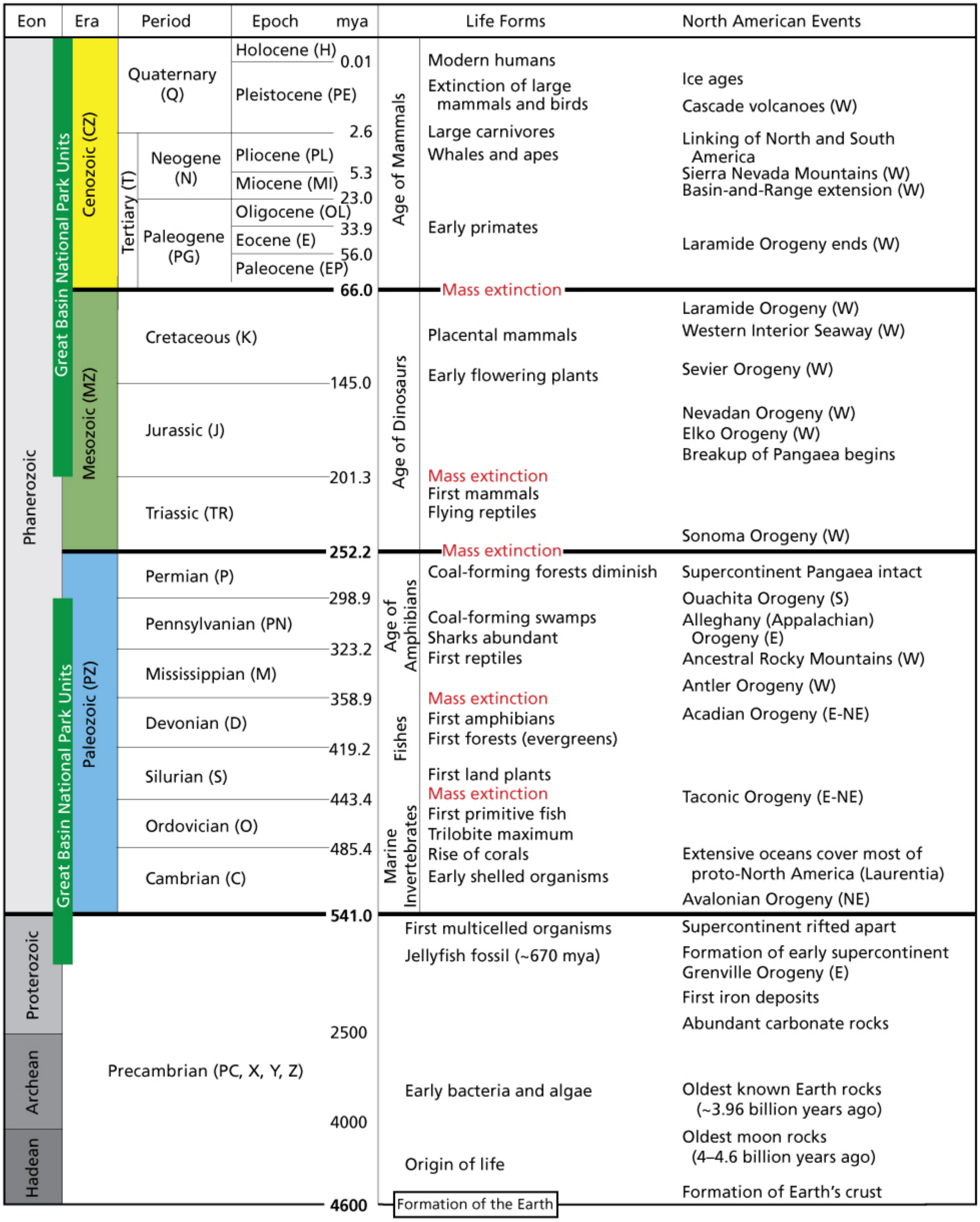


Figure 5. Geologic time scale. The divisions of the geologic time scale are organized stratigraphically, with the oldest at the bottom and youngest at the top. The green bars indicate the ages of geologic units that are mapped within Great Basin National Park. GRI map abbreviations for each time division are in parentheses. Compass directions in parentheses indicate the regional locations of events. Boundary ages are millions of years ago (MYA). National Park Service graphic using dates from the International Commission on Stratigraphy (http://www.stratigraphy.org/index.php/ics-chart-timescale; accessed 10 January 2014)

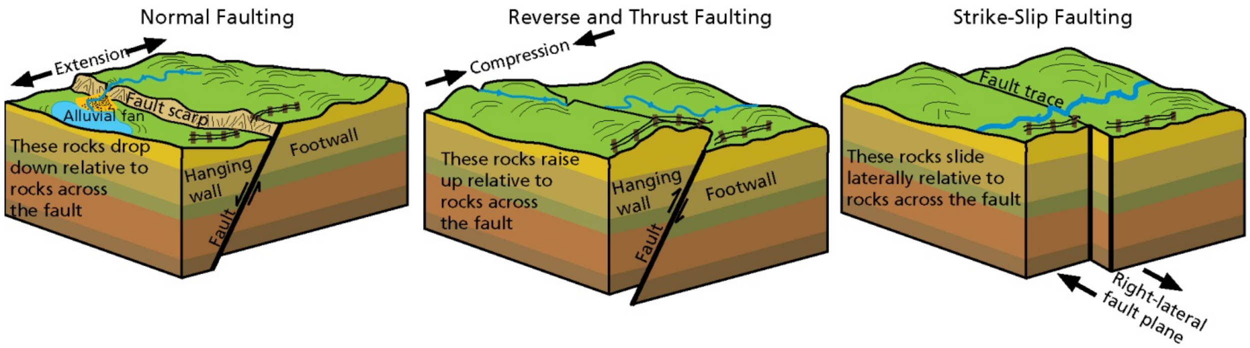


Figure 6. Schematic illustrations of fault types. Footwalls are below the fault plane and hanging walls are above. In a normal fault, crustal extension (pulling apart) moves the hanging wall down relative to the footwall. In a reverse fault, crustal compression moves the hanging wall up relative to the footwall. A thrust fault is similar to a reverse fault, but has a dip angle of less than 45°. In a strike-slip fault, the relative direction of movement of the opposing plate is lateral. When movement across the fault is to the right, it is a right-lateral (dextral) fault, as illustrated above. When movement is to the left, it is a left-lateral (sinistral) fault. A strike-slip fault between two plate boundaries is called a transform fault. Graphic by Trista Thornberry-Ehrlich (Colorado State University).

was frequently inundated by shallow, epicontinental seas throughout the Paleozoic. Calcium carbonate precipitated directly from seawater, as well as from the remains of marine organisms, accumulated to form thick sequences of limestone, such as the 760 m- (2,500 ft) thick Devonian Guilmette Formation (geologic map unit Dg), Ordovician Pogonip Group (Op) with an estimated thickness of over 3,000 m (10,000 ft), and the 557 m- (1,840 ft) thick Cambrian Pole Canyon Limestone (Cpc).

Compression continued into the Mesozoic and Tertiary, generating several additional orogenies. Subduction caused rocks to melt, and magma rose through Earth's crust, solidifying into the park's intrusive granitic plutons (Jg, Kgr, Tgr). Approximately 140 million years ago (Early Cretaceous), rocks from Canada to northern Mexico were compressed, folded, and thrust eastward as if a giant accordion was being squeezed. Known as the Sevier Orogeny, this mountain-building event thrust older Paleozoic rocks over younger strata, thickening the crust until the sedimentary layers at the bottom of these thrust stacks were metamorphosed. The easternmost extent of the thrusting produced Utah's Wasatch Range. Evidence for this kilometer-scale thrusting may be found in exposures north of the park on the western edge of the Snake Range (Hose and Blake 1976). However, evidence of the Sevier Orogeny has been eroded from the Great Basin National Park area (Miller et al. 2007).

Approximately 35 million years ago, west-to-east extension (stretching) began to pull apart the Earth's crust beneath the Great Basin. At depth, the Snake Range décollement separated metamorphosed Cambrian and Precambrian rocks from younger, unmetamorphosed Paleozoic strata. As stretching continued, rocks above the Southern Snake Range décollement were fractured by high-angle normal faults (fig. 6). The blocks detached, tilted, rotated and slid to the southeast. Once the weight of these overlying rocks was removed, the metamorphic core complex domed upward and now forms the northern portion of Great Basin National Park (Miller et al. 1987).

Continued thinning and stretching caused the crust to break into a series of north–south-trending, normal fault-bounded blocks that were several kilometers wide, tens of kilometers long, and thousands of meters thick (fig. 7). These linear blocks form the ranges (horsts) and basins (grabens) of today's Basin and Range landscape. The Snake Range is one of these horsts, and it is separated from the Spring Valley graben by a range-bounding fault.

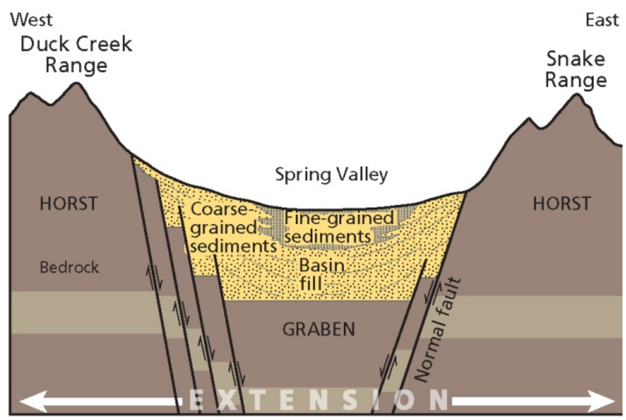


Figure 7. Schematic cross-section of fault-bounded basin and ranges. Crustal extension caused the Great Basin region to rift, or pull-apart, creating normal fault-bounded ranges (horsts), such as the Snake Range, and down-dropped basins (grabens), such as Spring Valley. The grabens filled with sediment eroded from the adjacent horsts. Original graphic by the US Geological Survey, available online: http://pubs.usgs.gov/ha/ha730/ch_c/C-text3.html (accessed 13 October 2012), modified by Trista Thornberry-Ehrlich (Colorado State University).

During the Pleistocene (fig. 5), alpine glaciers carved a landscape of rocky ridges, peaks, and cirque basins in the park's higher elevations. The movement of glacial ice above 2,800 m (9,200 ft) is marked by terminal and lateral moraines, the jumbled piles of unconsolidated debris left behind by melting glaciers.

Caves in Great Basin National Park also began forming during the Pleistocene. Two processes have been proposed to explain cave development in the park. The more common process involves downward movement of meteoric water (epigenic cave development). In this explanation, during the wet Pleistocene, abundant groundwater flowed through fractured limestone, slowly dissolving calcium carbonate and opening vertical shafts and horizontal solution caves along fracture planes.

Cave and karst research over the last two decades has recognized another cave development process, termed 'hypogenic,' that involves a deep source of acidity or a confined flow system that does not have a hydrologic connection to the surface (Klimchouk 2007). Hypogenic karst systems may be more common than previously thought, and Great Basin National Park may provide critical support for hypogenic karst formation.

Lehman Caves formed in the Middle Cambrian, cliff-forming Pole Canyon Limestone (Cpc). When the water table lowered, the caves became decorated with impressive speleothems such as folia, bulbous stalactites, anthodites, and shields composed of calcium carbonate precipitated from dripping groundwater (fig. 2). Currently, 46 known caves are protected in Great Basin National Park.

A cooling period in the Holocene produced another episode of glaciation in the Snake Range that resulted in the seven identified rock glaciers in the park. Rock glaciers form lobes of angular boulders and cobbles in which ice fills the spaces or forms lenses between the blocks. These rock glaciers are the only identified modern glaciers in the interior Great Basin. All but one of the rock glaciers originate from the base of a steep-walled mountain peak. They vary in length and character. For example, the Wheeler Peak rock glacier begins at the base of Wheeler Peak approximately 3,667 m (12,030 ft) above sea level and forms three distinct lobes over a distance of 900 m (3,000 ft), ending at an elevation of 3,272 m (10,730 ft) above sea level (Van Hoesen and Orndorff 2011). The clean-ice part of the glacier that was documented in 1988 has since melted (Osborn 1988).

Today's landforms that rim Great Basin National Park are typical of those found in arid regions and include such features as alluvial fans, bajadas (coalescing alluvial fans), pediments, bolsons (interior basins), and playas. Water is the primary erosional process in the Great Basin. Streams in the northern half of the park, including Snake Creek, flow year round, while those in the southern half of the park are ephemeral streams. With little or no vegetation to retard surface runoff, intense storms produce flash floods that have a tremendous capacity to erode and transport sediment and debris.

Great Basin National Park is a diverse region that offers the solitude of the desert, the beauty of Lehman Caves, and pristine panoramic views from mountain peaks that rise over 4,000 m (13,000 ft). Prickly pear cactus and sagebrush in desert valleys transition to alpine wildflowers and 5,000 year old bristlecone pines growing on rocky glacial moraines (fig. 8). In Lehman Caves, magnificent cave formations record the natural beauty created through the persistent march of geologic time. At Great Basin National Park, resource managers strive to maintain and restore these diverse ecosystems, conserving the natural resources for the enjoyment of future generations.

Figure 8. Bristlecone pines. These trees are among the oldest living organisms on Earth and grow from fractures in the Paleozoic bedrock within Great Basin National Park. Bristlecone pines may grow to be almost 5,000 years old. National Park Service photograph by Loren Reinhold, available online: http://www.nps.gov/grba/photosmultimedia/Trees-Gallery.htm (accessed 3 October 2012).

Geologic Features and Processes

Geologic resources underlie park ecosystems and geologic processes shape the landscape of every park. This section describes the most prominent and distinctive geologic features and processes in Great Basin National Park.

During the 2003 scoping meeting and 2011 conference call, participants (see Appendix A) identified the following geologic features and processes:

- Cave systems
- Cave development
- Speleothems
- Metamorphic core complex and the Snake Range décollement
- Basin and Range boundary faults
- Sedimentary and metasedimentary rocks
- Igneous rocks
- Rock glaciers
- Glacial features
- Periglacial features
- Lexington Arch
- Geomorphic features
- Geology and cultural features
- Paleontological resources

Cave Systems

At least 1 million years ago, stalagmites began forming in caves in Great Basin National Park (McGee 2011). The caves formed primarily in the Pole Canyon Limestone (geologic map unit Cpc), Lincoln Peak Formation (Clp), Notch Peak Limestone (OCn), and Guilmette Formation (Dg; fig. 4). The 46 known caves in the park form four distinctive groups: Lehman Hill Caves, Baker Creek Caves, Snake Creek Caves, and Alpine Caves (table 1). Refer to the Cave Development section for more discussion on the geologic processes surrounding cave and karst formation.

Lehman Hills Caves

The Lehman Hills Cave system includes Lehman Caves, Little Muddy Cave, Lehman Annex Cave, and Root Cave. The caves are found in Pole Canyon Limestone (Cpc) and are located near the Lehman Caves Visitor Center. Lehman Annex Cave, at an elevation of 2,200 m (7,300 ft) above sea level, may have been the first cave to form in the system. Lehman Cave and Root Cave are similar in elevation and may have formed at the same time. Little Muddy Cave has a spring-like appearance and may have previously been a spring for the cave system (National Park Service 2012a).

Lehman Caves holds the distinction of the longest cave in Great Basin National Park, if not all of Nevada (figs. 9 and 10), and its Talus Room contains the most surface area. The room measures 27 m (90 ft) wide, 115 m (376 ft) long, and covers 1,998.4 m^2 (21,511 ft^2), or about 0.2 ha (0.5 ac). For comparison, a football field is about 0.5 ha (1.3 ac). Extending 34 m (113 ft) from floor to ceiling, the Talus Room is also the tallest room. Compared to other caverns in Great Basin National Park, the Talus Room is enormous. Sunken Gardens, the second tallest room, is only 9.8 m (32 ft) from floor to ceiling (National Park Service 2012a).

Baker Creek Caves

Discovered in 1958, the Baker Creek caves include Ice, Crevasse, Wheelers Deep, Model, Systems Key, and Dynamite caves, which also formed in the Pole Canyon Limestone (Cpc). Cave explorers documented the physical connection among Ice, Crevasse, and Wheelers Deep caves. Further studies showed that Model, Systems Key, and Dynamite caves were hydrologically connected to the Ice-Crevasse-Wheelers Deep system.

Snake Creek Caves

Squirrel Springs, Fox Skull Cave, and Snake Creek Cave comprise the Snake Creek caves. Snake Creek Cave, formed in the Notch Peak Limestone (OCn), contains spectacular aragonitic anthodite and frostwork speleothems (table 2), the cave is 513 m (1,682 ft) long and 17 m (57 ft) deep (Jasper et al. 1999). In 1886, cave explorers Morrison and Roland left their signatures in the cave, documenting a long history of visitation to Snake Creek Cave.

Alpine Caves

Although some alpine caves formed by dissolution of bedrock, such as High Pit Cave, most alpine caves are fracture caves that formed along fracture planes (National Park Service 2012a). During the summer of 2004, the park completed its Wild Cave Inventory and Management Project, concentrating on alpine caves above 2,700 m (9,000 ft; Reece 2004). Prior to 2004, the park had documented 14 alpine caves, of which 3 had been surveyed. During a survey, park staff found that in two instances a single cave had been given two names and counted twice. In addition, three small unknown caves were discovered. Eleven caves were surveyed in 2004, including High Pit Cave and Long Cold Cave.

High Pit Cave is the highest solution cave in the park and the highest solution cave in Nevada. In addition to its elevation, High Pit Cave is known for the compacted, old snow that plugs the bottom of the cave.

Table 1. Cave systems in Great Basin National Park

Cave System	Caves	Distinguishing Characteristics
Lehman Hill Caves	Lehman Caves	Lehman Cave is 3.2 km (2 mi) long and is the longest cave in Nevada.
	Little Muddy Cave	
	Lehman Annex Cave	
	Root Cave	
Baker Creek Caves	Ice Cave	All of the caves are hydrologically connected.
	Crevasse Cave	
	Wheelers Deep Cave	
	Model Cave	
	Systems Key Cave	
	Dynamite Cave	
Snake Creek Caves	Snake Creek Cave Fox Skull Cave	Snake Creek Cave is 513 m (1,682 ft) long and 17 m (57 ft) deep, contains spectacular anthodite and frostwork speleothems, and has signatures from cave explorers Morrison and Roland from 1886.
Alpine Caves	High Pit Cave	Highest solution cave in the park and possibly in Nevada.
	Long Cold Cave	Deepest cave in the park. Extends to a depth of 150 m (480 ft).
	Roaring Wind Cave	Two caves in the Lincoln Peak cirque are extremely difficult to access.
	Pine Cone Pit	
	11 other caves	

The deepest cave in Great Basin National Park is Long Cold Cave. The cave extends to a depth of 150 m (480 ft) below the cave entrance (National Park Service 2012a).

Cave Development

When the Paleozoic limestones in which the caves would form in Great Basin National Park were deposited, approximately 500–360 million years ago, most of Nevada and western Utah were covered by a warm, shallow, inland sea. Thick layers of limestone developed from the accumulation of carbonate tests (shells) from minute marine organisms. With burial and compaction, increased pressure and temperature caused some of the limestone to metamorphose into a low-grade marble. Subsequent west-to-east compression of the region from subduction along the western margin of North America caused the layers to buckle, crack, and fracture. These fractures would eventually serve as additional conduits for groundwater flow.

Both epigenic and hypogenic processes, or a combination of the two, have been proposed for the formation of park's caves. In the epigenic process, slightly acidic (carbonic acid) groundwater flows downward through the unsaturated zone to the zone of saturation, the area where all the small openings and spaces in the rock are completely filled with water. The contact of the zone of saturation with the overlying unsaturated zone is known as the water table. In this unconfined system (hydrologically connected to the surface), caves form just below the water table because acidic groundwater, moving more slowly than groundwater percolating through the unsaturated zone, stays in contact with the bedrock for a longer period of time (National Park Service 2012e). Limestone dissolution also increases when water of two different chemistries or temperatures mix, as it does at the water table.

In contrast to the epigenic process, water in the hypogenic process enters the soluble formations from below in a confined system that is isolated from water percolating downward from the surface (Klimchouk 2007). Hypogenic caves, therefore, are not the result of solution by near-surface acidic water. Rather, water driven by hydrostatic pressure or other sources of energy flows upward and enters soluble formations, such as the Pole Canyon Limestone (Cpc). This deep-seated water may be hydrothermal or may contain hydrogen sulfide, which would aggressively dissolve calcium carbonate.

The cave systems in Great Basin National Park may represent a subsurface karst system that developed in limestone units without any exposure to the overlying surface. If this is the case, the deep-seated karst would be different from buried karst, or paleokarst, which originated due to meteoric groundwater and was subsequently buried (Klimchouk 2007). Hypogenic systems develop intricate hydraulic connections that cross formation boundaries. Fractures, porosity barriers, and variations in permeability control the spatial organization of the cave systems. Distribution of the cave systems in Great Basin National Park may be an example of hypogenic karst. With uplift and/or expansion, a hypogenic karst system may lose its confinement and become connected with the overlying surface.

Passageways that connect underground voids become conduits for groundwater flow. Groundwater will flow at various rates through these newly created underground passageways and further enhance the openings, as illustrated by the Lost River Passage in Lehman Caves. When the water table lowers, the caves fill with air and new caves begin to form just below the new, stabilized water table.

The time it took to develop Lehman Caves is not known, but the extreme climate fluctuations during the Pleistocene were probably connected to the formation of

Figure 9. Map of Lehman Caves system. The map shows the many rooms and 3.2 km (2 mi) of passageways that make Lehman Cave the longest known cave in Nevada. National Park Service map, available online: http://www.nps.gov/grba/naturescience/lehman-caves-dimensions.htm (accessed 15 October 2012).

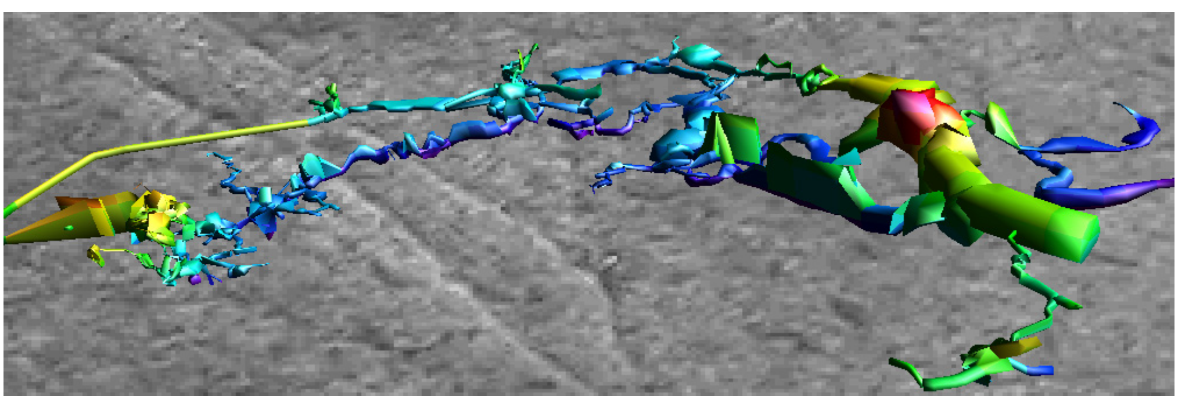


Figure 10. Three-dimensional map of Lehman Caves. This computer generated model shows the passages of Lehman Caves that formed from the dissolution of Pole Canyon Limestone (Cpc) by groundwater. National Park Service graphic available online: http://www.nps.gov/grba/naturescience/the-formation-of-lehman-caves.htm (accessed 9 January 2013).

these underground passageways. To form the caves in Great Basin National Park, the water table must have remained relatively constant for a long time. Although the bedrock is inclined at a steep angle, a constant water table resulted in a relatively horizontal distribution of caves and passageways in Lehman Caves (Kiver and Harris 1999; National Park Service 2012e).

Speleothems

Water also forms the many speleothems that decorate the caves (table 2). Speleothems are mineral deposits that grow inside already formed cave passages, which are now above the water table. These cave deposits may be called by different names such as travertine or dripstone, a generic term that includes any decoration caused by dripping, splashing, or seeping groundwater. Speleogens are features such as smooth scalloped surfaces that are carved in the bedrock as the cave is forming (National Park Service 2012a).

Lehman Caves is renowned for its exceptional variety of speleothems, some of which are extremely rare (fig. 11). While the shapes of the speleothems differ, they all formed from groundwater saturated with dissolved calcium.

Two main processes cause calcium to precipitate from groundwater: degassing and evaporation. Degassing occurs because surface water passing through soil absorbs carbon dioxide, which transforms the groundwater into a weak carbonic acid. The acid dissolves a small amount of calcium from the limestone through which it passes. When groundwater enters a cave passage, it may contain about 250 times more carbon dioxide than the air-filled cavity. Similar to what happens when a soda pop is opened, the groundwater degasses and releases carbon dioxide. With the loss of carbon dioxide, the water cannot hold as much dissolved calcium. The excess calcium comes out of solution and precipitates on cave walls and ceilings, forming speleothems.

Evaporation is the other main process by which calcium precipitates. Fresh water evaporates, leaving a solution supersaturated with calcium. In both processes, calcium is deposited primarily in the form of the mineral calcite (calcium carbonate). Some speleothems, such as anthodites and frostwork, are composed of aragonite, a more dense, often fibrous form of calcium carbonate.

The growth rate of the speleothems in Lehman Caves is unknown. Growth varies depending on the amount of calcite in solution and the drop rate, conditions that change with time. Current rates, therefore, may be quite different from growth rates of the past. Cave conditions may also be localized so that areas that are now dry may be wetter in the future.

Size is also not a good indicator of growth rate. A 5–cm (2–in) soda straw, for example, may be older than the largest column in the cave. As an indication of how fast stalactites grow, soda straws growing on formations that were broken roughly a century ago are less than 2.5 cm (1 in) long. And being hollow, soda straws grow longer and at a faster rate than most other speleothems (National Park Service 2012a).

Table 2. Some speleothem types in Great Basin National Park.

Speleothem	Description
drapery	Curtain-like sheet of travertine formed by water flowing down an inclined cave ceiling (fig. 11).
folia	Downward-sloping, shelf-like tiers of calcite.
stalactite	Bulbous, conical or cylindrical feature hanging from the ceiling (fig. 11).
stalagmite	Conical or cylindrical feature rising from the floor of the cave.
column	Forms when a stalactite and a stalagmite unite (fig. 11).
anthodite	Pencil-shaped. In clusters radiating from a common base and fed through a small central canal.
frostwork	Bristly feature with intricately branched aragonite crystals.
shield	Shield-shaped. Two parallel, semicircular plates separated by a thin, planar crack. Growth occurs radially along the rim of the feature, where water issues under pressure from the crack.
soda straw	Tubular stalactite the diameter of a drop of water. Resembles a drinking straw (fig. 11).
helictite	Curved twig-like deposit. Grows from water emerging from a nearly microscopic central canal (fig. 11).
rimstone	Deposit that forms around the rim of a cave pool.
popcorn	Lumpy, nodular forms.
flowstone	General term for any deposit formed by flowing water on the walls or floor of a cave.

Because they grow slowly, drip by drip, stalagmites can be used to precisely date past climatic conditions by using oxygen isotopes in the speleothem’s carbonate minerals. For example, isotopes can pinpoint the end of an ice-age to within a few centuries. Analysis of radioactive isotopes in unbroken Lehman Cave stalagmites (previously unbroken) suggests that they started forming at least 1 million years ago, and oxygen-18 isotopic content in one Lehman Cave stalagmite places the end of the second-to-last ice age at 130,000 years before present, as suggested by models of Earth’s orbital characteristics (fig. 12; McGee 2011; Shakun 2011). However, oxygen-18 data from Devils Hole, Nevada, suggests the ice age ended 140,000 years ago (McGee 2011). This difference in 10,000 years is a source of debate and highlights the need for additional research. If additional Lehman Cave stalagmites are found that are 130,000 to 140,000 years old, they might not only help solve this puzzle but also provide a better understanding of Nevada’s paleoclimate.

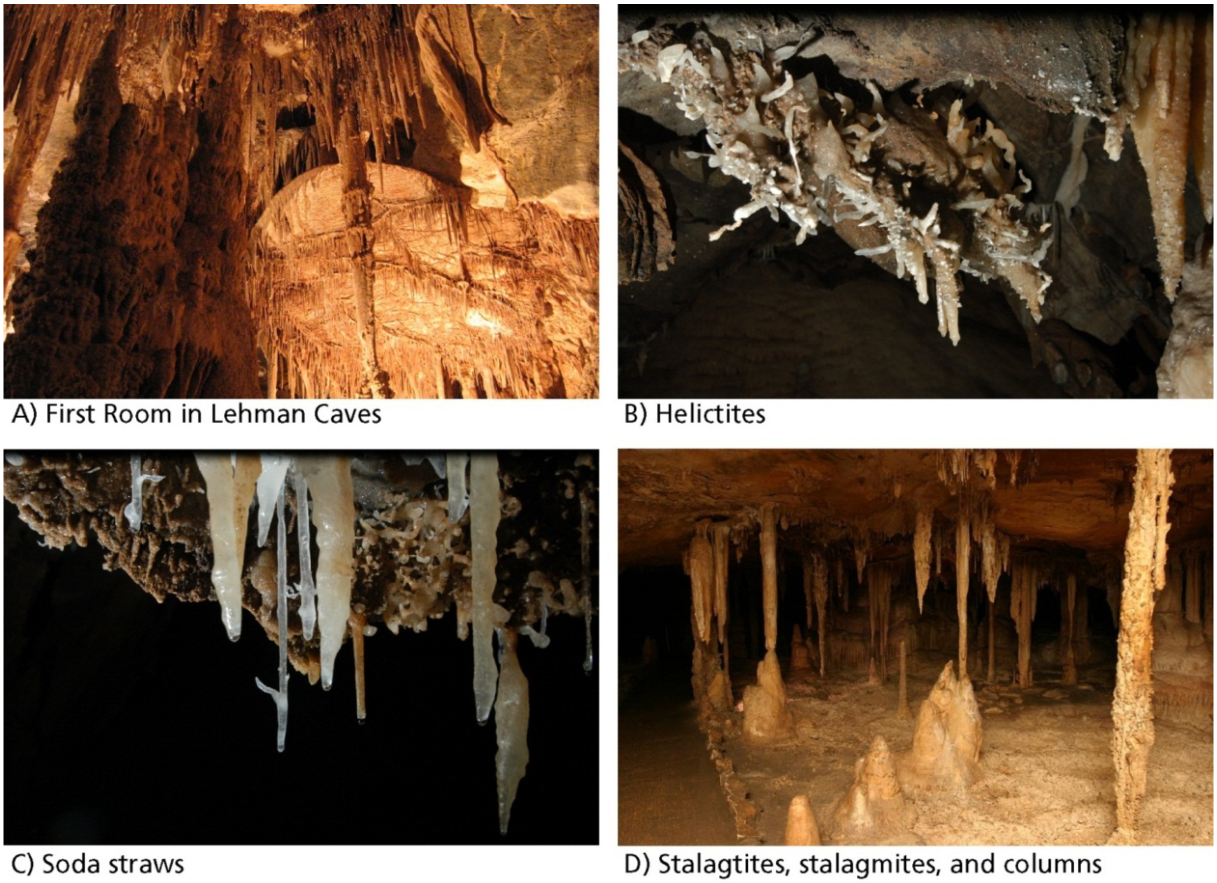


Figure 11. Examples of speleothems in Lehman Caves. A) Stalactites, soda straws, and draperies in the first room in Lehman Caves. National Park Service photograph by Alana Dimmick. B) Twig-like helictites on the ceiling of Lehman Caves form from water emerging from a very small central canal. National Park Service photograph. C) Delicate soda straws are the diameter of a drop of water. National Park Service photograph. D) Stalactites, stalagmites, and columns form in the Cypress Swamp room. National Park Service photograph by Bill and John DeHeide. Photographs available online: http://www.nps.gov/grba/photosmultimedia/photogallery.htm, accessed 30 January 2014.

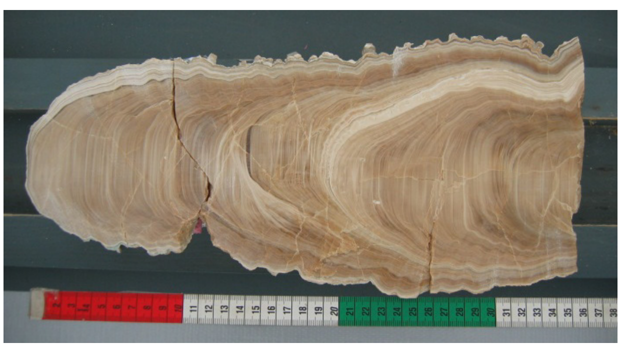


Figure 12. Stalagmite cross section. This stalagmite from Lehman Caves has been sectioned and polished to show the layers of calcite that form lines, like tree rings. Oxygen isotope data from different sections of the stalagmites provides evidence of long-term climate patterns. NPS photograph courtesy of Ben Roberts (Great Basin NP).

Metamorphic Core Complex and the Southern Snake Range Décollement

Extensional forces during the Oligocene and Miocene epochs stretched, thinned, and broke the crust along low-angle faults (detachment faults) in the Great Basin, exhuming masses of metamorphosed sedimentary and plutonic rocks known as metamorphic core complexes (figs. 13 and 14). Great Basin National Park contains one of the more than twenty-five distinctive, isolated, domed metamorphic core complexes that extend in a narrow sinuous belt from southern Canada to northwestern Mexico (Coney 1979; Nations et al. 1985; Miller et al. 1983, 1987; Davis 1987; McGrew 1993).

In general, metamorphic core complexes include (Anderson 1988; Davis 1987):

- a low-angle detachment fault—called a "décollement"—separating rock units above the fault surface (upper plate, or hanging wall) from rock units below the fault surface (lower plate, or footwall),
- an upper-plate and lower-plate with fundamentally contrasting styles of deformation,
- a lower-plate ("core") of metamorphosed crystalline rocks, displaying a shallow-dipping zone of intense shearing (mylonitic foliation) and a uniform trending (usually northeast-southwest) lineation truncated by the overlying detachment fault and associated breccias containing abundant chlorite,
- an upper plate of crystalline, sedimentary, and volcanic rocks that lack the mylonitic deformation and metamorphism of the lower plate, and
- an assemblage of normal faults in the upper-plate that have a sense of motion consistent with movement of the detachment fault.

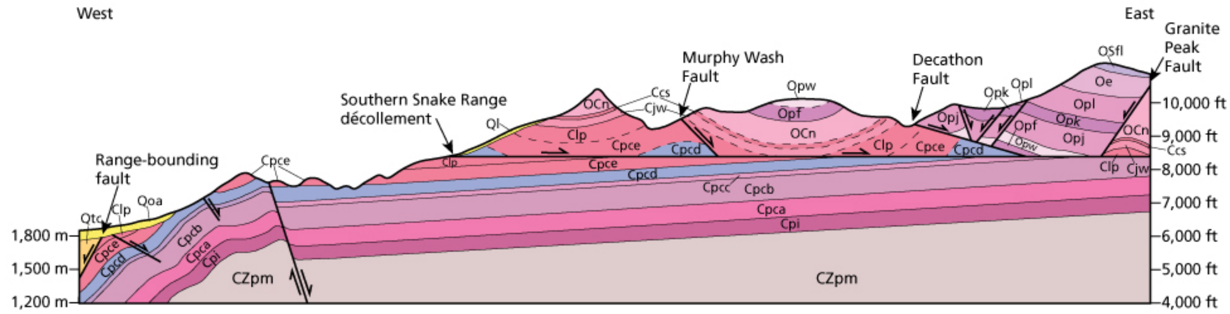


Figure 13. Geologic cross-section C-C' from Miller et al. (2007). This cross section shows the Southern Snake Range décollement and subsurface geology in Great Basin National Park. The west-to-east cross-section is located on the GRI GIS data. Note the relatively undisturbed stratigraphic units in the lower plate below the Snake Range décollement and the high-angle normal faults in the upper plate above the décollement. In the northern part of the park, the upper plate units have been removed, exposing the core of the metamorphic core complex. The range bounding fault resulted from crustal extension during the Miocene that formed the Basin and Range Province. Original graphic from Miller et al. (2007) modified by Trista Thornberry-Ehrlich (Colorado State University).

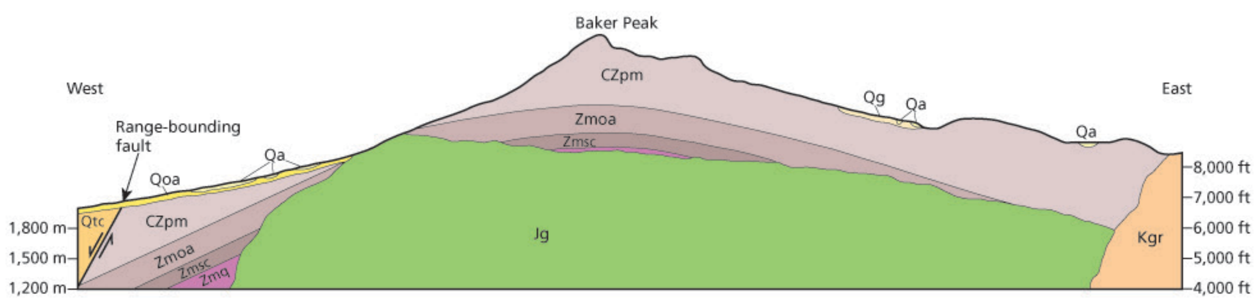


Figure 14. Geologic cross-section B-B' from Miller et al. (2007). This cross section shows the domed metamorphic core complex and subsurface geology beneath Baker Peak, Great Basin National Park. The west-to-east cross-section is located on the GRI GIS data. Note that the Mesozoic plutons (Jg and Kg) have intruded into older, Paleozoic units. The range bounding fault resulted from crustal extension during the Miocene that formed the Basin and Range Province. Original graphic from Miller et al (2007) modified by Trista Thornberry-Ehrlich (Colorado State University).

The dominant geologic structure in Great Basin National Park is the low-angle, Southern Snake Range décollement (fig. 13). The metamorphic core complex forms the exhumed footwall (lower plate) beneath the Southern Snake Range décollement and exposes deformed metasedimentary rocks and three granitic plutons (fig. 14). Stretching lineations in the metasedimentary rocks indicate that they were deformed during the early phases of regional extension. The Jurassic, Cretaceous, and Tertiary plutons, however, were emplaced prior to the onset of extensional deformation. Emplacement of the plutons occurred approximately 160 million years ago (Jg), 79 million years ago (Kgr), and 36 million years ago (Tgr) (Miller et al. 1983; McGrew 1993). The Map Unit Properties Table identifies units associated with both the upper and lower plates.

The degree of metamorphism suggests that the décollement developed approximately 6–7 km (3–4 mi) below the ground surface. The fault formed near the contact of the weaker layers of Lower Cambrian Pioche shale (Cpi) and the overlying Middle Cambrian Pole Canyon Limestone (Cpc). Locally, the fault cuts through the Pole Canyon Limestone (Miller et al. 1983).

Two generations of northeast–trending normal faults cut the hanging wall (upper plate). Both sets of faults originated as high-angle faults with fault surfaces that dipped (inclined) about 60° and flattened abruptly into the Snake Range décollement (fig. 14; Miller et al. 1983). The earlier faults tilt in the opposite direction of the east-dipping Snake Range décollement while the latter faults dip in the same direction as the décollement. In the Southern Snake Range, reconstruction of the bedding planes to their original position suggests that the two generations of normal faults rotated the bedding about 80° to 90° (Miller et al. 1983).

Because the normal faults displace 35-million-year-old volcanic rocks deposited during the Eocene, the extension that caused the faulting must have occurred in the Oligocene or Miocene (Miller et al. 1983). Total extension dislocated the upper plate rocks in the Southern Snake Range between 8 km (5 mi) and 24 km (15 mi) to the southeast (McGrew 1993).

Packages of fault-bounded Paleozoic strata are exposed in the southern portion of Great Basin National Park (see geologic map graphic in pocket). A long, north-south trending normal fault forms the eastern border of Granite Peak, for example, and separates the Fish Haven and Laketown dolomites (OSfl) of Granite Peak from the older Notch Peak Limestone (OCn). The faults trend in two general directions within the park, north-south and northeast-southwest. In general, displacement on these upper plate faults juxtaposes formations within the Ordovician Pogonip Group or the Ordovician/Silurian strata against Devonian strata.

Wheeler Peak stands at the top of a large, broad anticlinal fold ("A"-shaped, convex-upward fold) that resulted from isostatic rebound. When the detachment fault removed the weight of the upper plate rocks, the lower plate responded to this "unroofing" by bending upward. The greatest amount of extension and unroofing in the park occurred in the Wheeler Peak area. The Wheeler Peak anticline may be viewed from the Wheeler Peak overlook .

Lower Plate Sedimentary and Metasedimentary Rocks

In the northwest corner of Great Basin National Park, weakly metamorphosed Precambrian sandstone and mudstone form the Osceola Argillite (Zmoa) and the McCoy Creek Group Quartzite (Zmq), the upper two formations of the McCoy Creek Group (Zm). Consisting of approximately 200 m (700 ft) of laminated slates and siltstone, the Osceola Argillite forms the slopes north of Hub Mine and in the Pine Creek drainage. The contact between the argillite and the overlying Prospect Mountain Quartzite (CZpm) occurs over a 10–15 m (33–49 ft) interval in which predominantly argillaceous layers gradually give way to predominantly cross-bedded quartzite beds.

The degree of metamorphism varies in the Osceola Argillite. Near Stella Lake on the trail to Wheeler Peak, the unit shows very little metamorphism, but adjacent to Jurassic plutons (Jg) in the western part of the park, the unit contains the metamorphic minerals staurolite, garnet, andalusite, sillimanite, biotite, and muscovite, which commonly form as a result of more intense heat and pressure. These minerals form in pressures ranging from 2 to 4 kilobars (29,000–58,000 psi) and temperatures ranging from 500° C to 750° C (930° F to 1,400° F).

North of Bald Mountain and in the Wheeler Creek area, the McCoy Creek Group Quartzite occurs as incomplete sections of well-bedded quartzite and conglomeratic quartzite. Pebble conglomerates in the unit distinguish it from the overlying Prospect Mountain Quartzite. Resistant to erosion in the arid Great Basin climate, the unit forms ledges and cliffs that range from 30 to 112 m (100 to 367 ft) thick.

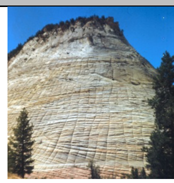
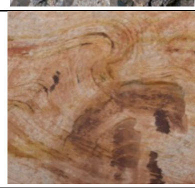
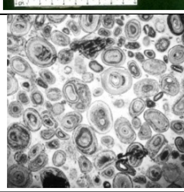
The Prospect Mountain Quartzite (CZpm) dominates the metamorphic core complex and northern portion of Great Basin National Park. Forming a landscape of peaks, ridges, steep glacial cirques, cirque walls, and cliffs, the Prospect Mountain Quartzite is over 1,200 m (3,900 ft) thick (fig. 15). The cliffs of quartzite and talus slopes weather rust-brown, tan, or purple. At the upper contact with the overlying Pioche Shale (Cpi), thick layers of slope-forming dark siltstone and silty shale give the unit a terraced appearance. A rigorous hike to the ridge between Box and Dry canyons, north of Mt. Wheeler Mine, accesses the best exposures of this upper contact while the cirque walls north of Wheeler Peak display the thick beds [0.3–1 m (1–3 ft)] of the lighter colored, well-sorted, medium- to coarse-grained quartzite in the main part of the unit.

Figure 15. Wheeler and Jeff Davis peaks. Prospect Mountain Quartzite (CZpm) forms the summits and slopes of Wheeler and Jeff Davis peaks in Great Basin National Park. The Prospect Mountain Quartzite (CZpm) is part of the lower plate of the Snake Range décollement. Photograph by Loren Reinhold (CC BY-ND 2.0), available at the National Parks Conservation Association Flickr page: http://flic.kr/p/6avsjB (accessed 30 January 2014).

Except in the vicinity of the Jurassic granitic intrusion (Jg) in the Snake Creek drainage and on the ridgeline between Pyramid Peak and Mt. Washington, the Lower Cambrian Pioche Shale (Cpi) remains largely unmetamorphosed in Great Basin National Park (Hose and Blake 1976). On the ridgeline and near Jurassic plutons, the shale and calcareous sandstones in the unit have been metamorphosed to schist and calc-silicate rocks and contain characteristic metamorphic minerals, such as garnet, epidote, diopside, and andalusite, that represent mid-crustal depths of 6–7 km (3–4 mi) (Miller et al. 1983).

The Pioche Shale (Cpi) forms a transition from clastic rocks (sandstone, siltstone, and shale) common in the Lower Cambrian to carbonate units that dominate the rest of the Paleozoic. The Snake Range décollement developed within the Pioche Shale, and the unit is considered to be the youngest unit below the décollement (Miller et al. 1983). However, in Great Basin National Park, good exposures in snow avalanche chutes on the northeastern face of Mount Washington demonstrate a gradual transition between the Pioche Shale (Cpi) and the Middle Cambrian Pole Canyon Limestone (Cpc). At this location, interbedded layers of orange weathering siltstone (Pioche Shale) and grey limestone (Pole Canyon Limestone) mark the transition between the two units. This gradual contact suggests that the youngest formation below the Snake Range décollement is the Pole Canyon Limestone, at least in Great Basin National Park.

Table 3. Sedimentary structure descriptions.

Structure	General Description	
Cross-bedding (cross-stratification)		Strata inclined at an angle to the main stratification. Primarily produced by the migration of sand-sized particles moving along the surface. Commonly form ripples (small-scale cross-beds) and dunes (medium to large cross-beds). USGS photograph of Checkerboard Mesa in Zion National Park, available online: http://libraryphoto.cr.usgs.gov/htmllib/btch205/btch205j/btch205z/gjr00939.jpg (accessed 24 January 2013).
Ripple marks		Shape captures the form of small-scale ripples. Develop due to the interaction of a moving fluid (air or water) with loose sediment (most commonly sand-size sediment). USGS photograph of the Carmel Formation, Capitol Reef National Park, available online: http://libraryphoto.cr.usgs.gov/htmllib/btch195/btch195j/btch195z/ghe01291.jpg (accessed 24 January 2013).
Fluid escape (dewatering) structures		A sedimentary feature produced when fluid, such as water, is pressed out of a bed of sediment after deposition. Photograph of fluid escape structure in the Cretaceous Dakota Sandstone by the author.
Rip-up clasts		Mud clasts (usually flat shaped) that have been "ripped-up" by currents from a semi-consolidated mud deposit and transported to a new depositional site. Photograph of the Cretaceous Winthrop Sandstone by Marli Miller (University of Oregon), available online: http://serc.carleton.edu/details/images/32295.html (accessed 24 January 2013).
Soft sediment folds and slumps		Deformation in semi-consolidated sediment. Commonly caused by gravity. Photograph of soft sediment deformation in the Navajo Sandstone at Capitol Reef National Park by the University of Utah, available online: http://sed.utah.edu/Stop2_4.htm (accessed 24 January 2013).
Fenestral (birdseye) fabric		An open space in a rock or fossil (particularly invertebrate fossils). Sediment or mineral cement may partly fill the opening after it forms. Commonly found in bryozoans. Photograph by Peter A. Scholle.
Oolite		Usually formed in shallow, wave-agitated water when calcium carbonate precipitates in concentric layers around a shell fragment, algal pellet, sand grain or other object. USGS 1923 photograph of oolite grains in a thin-section cut through the Laney Shale Member of the Green River Formation, available online: http://libraryphoto.cr.usgs.gov/htmllib/btch274/btch274j/btch274z/bwh00253.jpg (accessed 24 January 2013).
Bioturbation		Reworking of sediment by organisms. Includes burrows, trails, tracks, and other traces of organisms. Photograph of bioturbation of the Cretaceous Dakota Sandstone courtesy of the author.
Flat pebble conglomerate		A conglomerate formed by rounded, pebble-sized clasts arranged in a sub-horizontal fashion. The imbrication of the pebbles indicates the direction of the current. Photograph of edge-wise-oriented flat pebble conglomerate in the Upper Cambrian Hwajeol Formation, central eastern Korea courtesy of Dr. J. I. Lee (Korea Polar Research Institute).

Note: These photos are of features outside of the park, but are representative of those within Great Basin National Park.

Sedimentary structures in these Late Proterozoic and Lower Cambrian units include small-scale cross-beds with a maximum height of 6 cm (2 in), ripple marks, fluid-escape structures, rip-up clasts, soft sediment folds and slumps, and thin layers of limestone (table 3). Today, features such as these form in shallow marine, nearshore environments, suggesting that similar environments existed in the Great Basin National Park region over 500 million years ago.

Upper Plate Sedimentary Rocks

Slope- to cliff-forming limestone and dolomite dominate the Paleozoic strata above the décollement surface, and are mapped primarily in the southern portion of the park. Unlike the units in the lower plate, most of these sedimentary rocks have not been metamorphosed. Because they have not been subjected to the heat of metamorphism invertebrate marine fossils in many of the formations have not been destroyed. These fossils characterize and help determine the age, stratigraphic order, and depositional environment of a specific unit (see the Map Unit Properties Table and the Paleontological Resources section).

Fossiliferous Cambrian and Ordovician units are sharply overlain by the non-fossiliferous Eureka Quartzite (Oe; fig. 4). Composed almost entirely of quartz sand grains, the white, cliff-forming quartzite forms a conspicuous stratigraphic marker, approximately 100 m (300 ft) thick, throughout the Great Basin (fig. 16). It is the only thick, erosion-resistant, non-carbonate Paleozoic unit above the Snake Range décollement in Great Basin National Park. Although distinctively lacking in fossils, the quartzite contains vertical burrows indicative of organisms that once lived in nearshore depositional environments.

Rather than being a metamorphic quartzite, the Eureka Quartzite contains quartz grains that have been tightly cemented together by silica into a sedimentary quartzite known as an “orthoquartzite.” Orthoquartzite is more similar to a metamorphic quartzite than to a sandstone based on the way the rocks shatter when struck by a rock hammer. In an orthoquartzite, the rock breaks through the grains, while in a sandstone, the rock breaks around the grains.

Figure 16. Examples of Paleozoic units and fossils in the upper plate of the Snake Range décollement. A) Ordovician Eureka Quartzite forms a conspicuous marker bed throughout the Great Basin. National Park Service photograph. B) The Upper Devonian Guilmette Formation limestone overlies Lower Devonian dolomite and represents a relative sea level rise and subsequent marine transgression into the area. The unit contains abundant marine invertebrates such as brachiopods, crinoids, and stromatoporoids (shown here). National Park Service photograph. C) Fossilized stems of crinoids and brachiopods from the Mississippian Chainman Shale, collected from east-central Nevada, document a marine depositional environment for the unit. Penny for scale. Photograph by the author. D) Fossil fusilinids (foraminifera) litter the surface of this sample of Pennsylvanian Ely Limestone, collected west of the park in east-central Nevada. Penny for scale. Photograph by the author.

Paleozoic carbonate formations that overlie the Eureka Quartzite include the Simonson Dolomite (Ds), Guilmette Formation (Dg; fig. 16), Joana Limestone (Mj), and Ely Limestone (PNe). These formations contain fossil brachiopods, crinoids, gastropods, corals, stromatoporids, and fusulinids (fig. 16).

Interspersed with the carbonate units are slope-forming shale formations such as the poorly exposed Mississippian Chainman Shale (Mc), the rarely exposed Mississippian Pilot Shale (MDp), and the fossiliferous Ordovician Kanosh Shale (Opk). While fossils are rarely found in the Chainman or Pilot shales, crinoids and brachiopods have been discovered in local exposures of Chainman Shale west of the Snake Range (fig. 16). The Ordovician Kanosh Shale contains abundant ostracods, trilobite spines, turitella (coiled, cone-shaped marine gastropods), and brachiopods with shells consisting of calcium-phosphate.

Although more easily eroded than the surrounding carbonate and sandstone units, these inconspicuous shale units of the Great Basin contain a wealth of information. Dark, black shales represent deep marine, anoxic environments or shallow marine, restricted lagoon environments. The Pilot and Chainman shales, for example, document the advance of the Antler Orogeny into eastern Nevada and the deep trough that formed in front of the Roberts Mountains Thrust. Black shales contain high amounts of organic matter. In the subsurface, this organic material transformed into hydrocarbons, which has been of interest to the petroleum industry since the last half of the 20^{th} century.

Tertiary conglomerates overlie the Paleozoic rocks in the upper plate of the Snake Range décollement in the Southern Snake Range. Older Tertiary conglomerate (Toc) occurs in the hillside east of the upper Johns Wash road spring, between the roads in Johns Wash and Murphy Wash south of the park. The poorly sorted unit contains occasional cobbles, a few sandstone beds up to 5 cm (2 in) thick, and a few granitic clasts about 3 cm (1 in) in diameter. Conglomerates of the Oligocene Needles Range Formation (Tnr) conformably overlie the older Tertiary conglomerates in the southern part of Johns Wash. A conglomeratic marker bed (Tcmb) within Tertiary conglomerate (Tc) is mapped east of the southern half of the park, and a conglomerate of uncertain age (QTc) is exposed in the hills leading into Decathon Canyon, east of the park. This conglomerate contains clasts of Paleozoic units and the Needles Range Formation. The most notable clasts are the car-sized boulders of Eureka Quartzite.

Basin and Range Boundary Faults

Throughout the Paleozoic, Mesozoic, and early Cenozoic, the western margin of North America compressed, folded, and buckled as converging tectonic plates collided. In the Miocene, a dramatic shift in the tectonic regime and high heat flow from the mantle began to reverse this trend and create crustal extension. As the crust was pulled apart, north-south-trending, high-angle, regional normal faults broke the surface into the basins and ranges that define today's Basin and Range topography (figs. 3 and 7). Displacement on these basin- and range-bounding faults may exceed 400 m (8,000 ft; Hose and Blake 1976). A major range-bounding fault uplifted the Great Basin National Park region and separates the Southern Snake Range from Spring Valley (fig. 14; Hose and Blake 1976). Continued movement on these faults in Nevada generates earthquakes, as discussed in the Geologic Issues section.

Igneous Rocks

Subduction of the oceanic Pacific Plate beneath the western margin of North American Plate during the Mesozoic and early Cenozoic transformed the landscape through regional thrust faulting, folding, pluton development, and widespread volcanic activity. In Great Basin National Park, remnants of these dynamic processes remain in the Jurassic, Cretaceous, and Tertiary granitic intrusions that have been exposed beneath the Southern Snake Range décollement.

Plutonic (intrusive) igneous rocks form when magma (molten rock) cools and solidifies within Earth's crust. Because they cool slowly, the igneous rocks contain individual crystals and primary minerals that are often large enough to be visible to the unaided eye. Primary minerals in granitic intrusions, such as those in Great Basin National Park, include quartz, potassium feldspar (orthoclase), and plagioclase feldspar (fig. 17). Quartz crystals, which lack well-defined borders, are typically clear, white, or smoky, and are harder than the other minerals. Orthoclase feldspar is white or pink, and plagioclase feldspar is white or gray. Unlike quartz, both feldspars have nearly perpendicular surfaces, so at least one well-defined edge of a feldspar crystal can be recognized in a granitic rock. Granitic rocks are classified by the relative proportions of quartz, potassium feldspar, and plagioclase. The granitic rocks in Great Basin National Park fall into the classification of granite (mostly quartz and orthoclase feldspar), granodiorite (more feldspar, less quartz), and tonalite (mostly quartz and plagioclase feldspar).

Biotite and hornblende form common accessory minerals in the park's granitic rocks. Black, opaque biotite has a shiny luster and breaks along only one plane of weakness, which allows it to flake into thin sheets like the pages of a book. Abundant biotite and hornblende crystals among the light-colored quartz and feldspar crystals may impart a "salt-and-pepper" appearance to the granitic rock (fig. 17).

Jurassic Snake Creek/Williams Canyon Pluton

The Snake Creek/Williams Canyon pluton (Jg) intruded Precambrian and Paleozoic rocks approximately 160 million years ago and covers an area of approximately 35 km^2 (14 mi^2) in the central part of Great Basin National Park, aptly termed "Granite Basin" (plate 1). From east to west, the granitic intrusion gradually changes in composition from a biotite-rich tonalite with 63% quartz to a biotite-rich granite with 76% quartz.

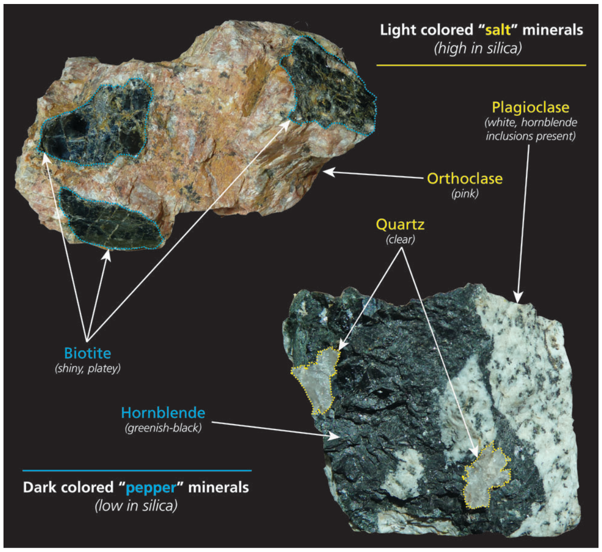


Figure 17. Minerals in granite. The Jurassic granite (Jg), one of the granitic plutons in Great Basin National Park, contains an abundance of quartz and feldspar. Graphic by Rebecca Port (NPS Geologic Resources Division).

The eastern portion of the pluton contains accessory amounts of the minerals epidote, titanite, magnetite, and allanite, as well as biotite. Garnet, ilmenite, and monazite occur in the central and western portions of the intrusion. Apatite and zircon may be found throughout the pluton. Veins of quartz, some as much as 5 m (16 ft) thick, contain the mineral assemblage muscovite-galena-wolframite. Hornblende-bearing granodiorite dikes lie east of Pyramid Peak.

Heat generated from the pluton metamorphosed the adjacent Precambrian and Paleozoic rocks in a process known as contact metamorphism. Muscovite, chlorite, biotite, and staurolite minerals grew in argillaceous layers (shale and siltstone) while epidote, garnet, diopside, and actinolite formed in silty limestone or dolomite.

Cretaceous Pole Canyon Pluton

Emplaced approximately 80 million years ago, the Pole Canyon pluton (Kgr) is part of a north-trending band of Cretaceous granites in eastern Nevada. The granite is characterized by phenocrysts (large crystals) of muscovite that are up to 2 mm (0.1 in) in diameter. East-west trending dikes intrude into the pluton exposed in Pole Canyon, but these igneous dikes may be derived from the Tertiary Young Canyon–Kious Basin pluton to the east rather than be contemporary with the Cretaceous Pole Canyon pluton.

Tertiary Granite

Tertiary biotite-rich granite (Tgr) is exposed west of Lehman Caves and along the eastern boundary of the park between Young Canyon and Clay Spring. North of North Fork Big Wash, muscovite-bearing rhyolite dikes and sills (Tmp) form exposures of limited extent. A sliver of rhyodacite flows and subvolcanic intrusive rocks (Trdi) form a linear feature mapped in the southwestern portion of the park.

Other Tertiary Igneous Rocks

Other Tertiary igneous units have been mapped outside the boundaries of the park. Volcanic tuff interlayered with conglomerate occurs in the Needles Range Formation (Tnr), which is exposed southwest of the park. The tuff contains phenocrysts (larger crystals) of plagioclase feldspar, hornblende, and biotite. The Needles Range Formation was deposited about 33 million to 27 million years ago, and is part of the Indian Peak caldera complex, which distributed volcanic ashflows over an area of about 55,000 km^2 (21,000 mi^2) in the southeastern Great Basin (Best et al. 1989). Latite flows (Tlf) have been mapped northeast of the park.

Rock Glaciers

Rock glaciers are jumbled masses of boulders and smaller rock material that may bury an ice glacier ("ice-cored") or have ice filling much of the space between the rocks ("ice-cemented"). As of December, 2011, park staff had identified seven rock glaciers in the park. Six of the seven rock glaciers originate from glacially-carved, bowl-shaped depressions, called cirques, at the bases of mountain peaks (fig. 18). Prospect Mountain Quartzite (CZpm) forms the steep walls surrounding the cirques and rock glaciers in Great Basin National Park. The following five rock glaciers have been described in detail by Van Hoesen and Orndorff (2011): (1) Wheeler Peak (also known as Lehman Cirque rock glacier), (2) North Fork Baker Cirque, (3) Teresa Cirque, (4) Big Canyon, and (5) Jeff Davis rock glacier (fig. 19). All the rock glaciers in Great Basin National Park are composed of blocky clasts of Prospect Mountain Quartzite.

Figure 18. Wheeler Peak rock glacier. This rock glacier is one of seven in Great Basin National Park and one of five that have been described in detail. National Park Service photograph courtesy of Ben Roberts (Great Basin NP).

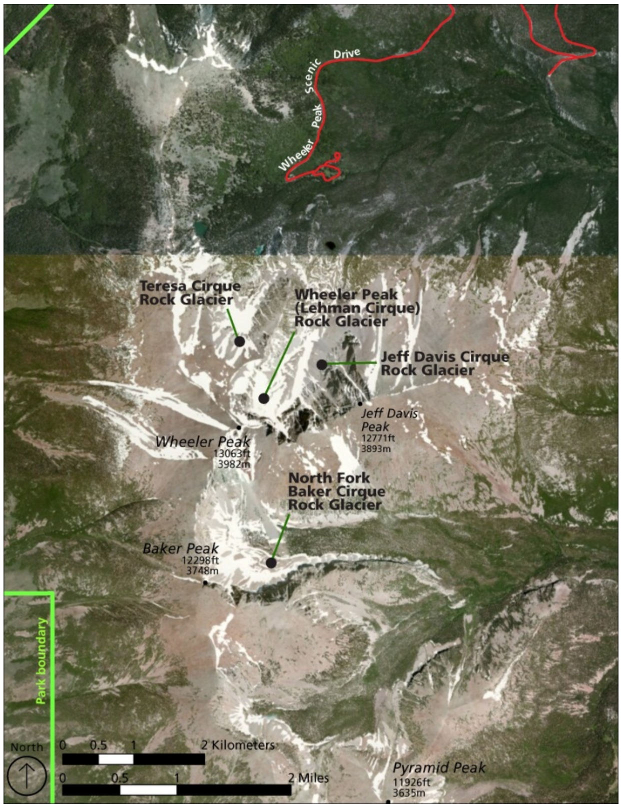


Figure 19. Locations of the rock glaciers identified in Great Basin National Park. Graphic by Rebecca Port (NPS Geologic Resources Division) using data from Hoesen and Orndorff (2011). Aerial imagery from ESRI World Imagery Basemap layer.

Wheeler Peak (Lehman Cirque) Rock Glacier

Prior to the park's inventory in 2001, the Wheeler Peak rock glacier (fig. 18) was believed to be the only surviving alpine glacier in Nevada (Van Hoesen 2001; National Park Service 2012b). Overall, the glacier measures 900 m (3,000 ft) long and 120 m (400 ft) wide. Ground-penetrating radar suggests that the rock glacier contains distinct lenses of ice rather than being ice-cored (Van Hoesen 2001, 2003; Van Hoesen and Orndorff 2011).

At Wheeler Peak, the quartzite forms three distinct lobes of the glacier. The 434 m (1,420 ft) long by 206 m (676 ft) wide upper lobe is a convex landform with sparse vegetation and well-developed furrows and ridges with amplitudes ranging from 0.5 to 3 m (2 to 10 ft). The moderately convex middle lobe is approximately 265 m (869 ft) long and 178 m (584 ft) wide and contains significantly more vegetation than the upper lobe. Abundant vegetation characterizes the lower lobe, a weakly convex landform about 195 m (640 ft) long and 100 m (330 ft) wide. All three lobes contain steep frontal slopes ranging from 30° to 36° (Van Hoesen and Orndorff 2011).

North Fork Baker Cirque Rock Glacier

The North Fork Baker Creek rock glacier consists of multiple lobes that have evolved into a tongue-shaped landform. Located below a steep, north-facing ridge, the glacier is approximately 673 m (2,210 ft) long and 88 m (290 ft) wide. The surrounding cirque walls contribute abundant talus and shade during summer months. Prominent furrows and ridges on the glacier are bordered by steep frontal and lateral margins, boulder aprons, and sparse vegetation (Van Hoesen and Orndorff 2011).

Teresa Cirque Rock Glacier

Located in a small east-to-northeast facing cirque, the smaller Teresa Cirque rock glacier is 147 m (482 ft) long and 225 m (738 ft) wide. The rock glacier is detached from the headwall, has a steep frontal snout, and contains moderately developed furrows and ridges up to 1.5 m (4.9 ft) deep. Well-developed boulder aprons spread out from the vegetated front of the rock glacier (Van Hoesen and Orndorff 2011).

Big Canyon Rock Glacier

Although not in the park, the weakly convex, lobate-shaped Big Canyon rock glacier is approximately 172 m (564 ft) long and 119 m (390 ft) wide. Located below Mt. Moriah's west-facing slope, the landform contains a steep frontal snout, weakly developed furrows and ridges that are 0.5–1.0 m (2–3.3 ft) deep, moderately developed boulder aprons at the base of the frontal slope, and sparse vegetation (Van Hoesen and Orndorff 2011).

Jeff Davis Cirque Rock Glacier

The Jeff Davis rock glacier is also a weakly convex, tongue-shaped landform. It is the only identifiable rock glacier that is not located in a cirque or below a steeply sloping ridge. Measuring approximately 230 m (750 ft) long and 119 m (390 ft) wide, the rock glacier is found on the north-facing slope of Jeff Davis Peak. Similar to the Big Canyon rock glacier, this rock glacier has weakly-developed furrows and ridges, a steep frontal snout, moderately developed boulder aprons, and sparse vegetation (Van Hoesen and Orndorff 2011).

Glacial Features

Glacial features fall into two general categories, erosional and depositional, and include cirques, bergschrund, moraines, tarns (glacial lakes), kettles, and rocky ridges that formed at the ice's edge as it flowed downslope (table 4; fig. 20). Two cirques and lateral and terminal moraines are visible from the Wheeler Peak overlook, and lateral moraines on Lehman Creek can be viewed from the Mather overlook.

Table 4. Glacial features in Great Basin National Park

Erosional Features	Depositional Features
cirques	terminal moraines
bergschrund	lateral moraines
arêtes, horns	kettles
tarns	

Erosional Features

Alpine glaciers are extremely effective agents of erosion. Rocks, sand, and other grit embedded in the glacial ice

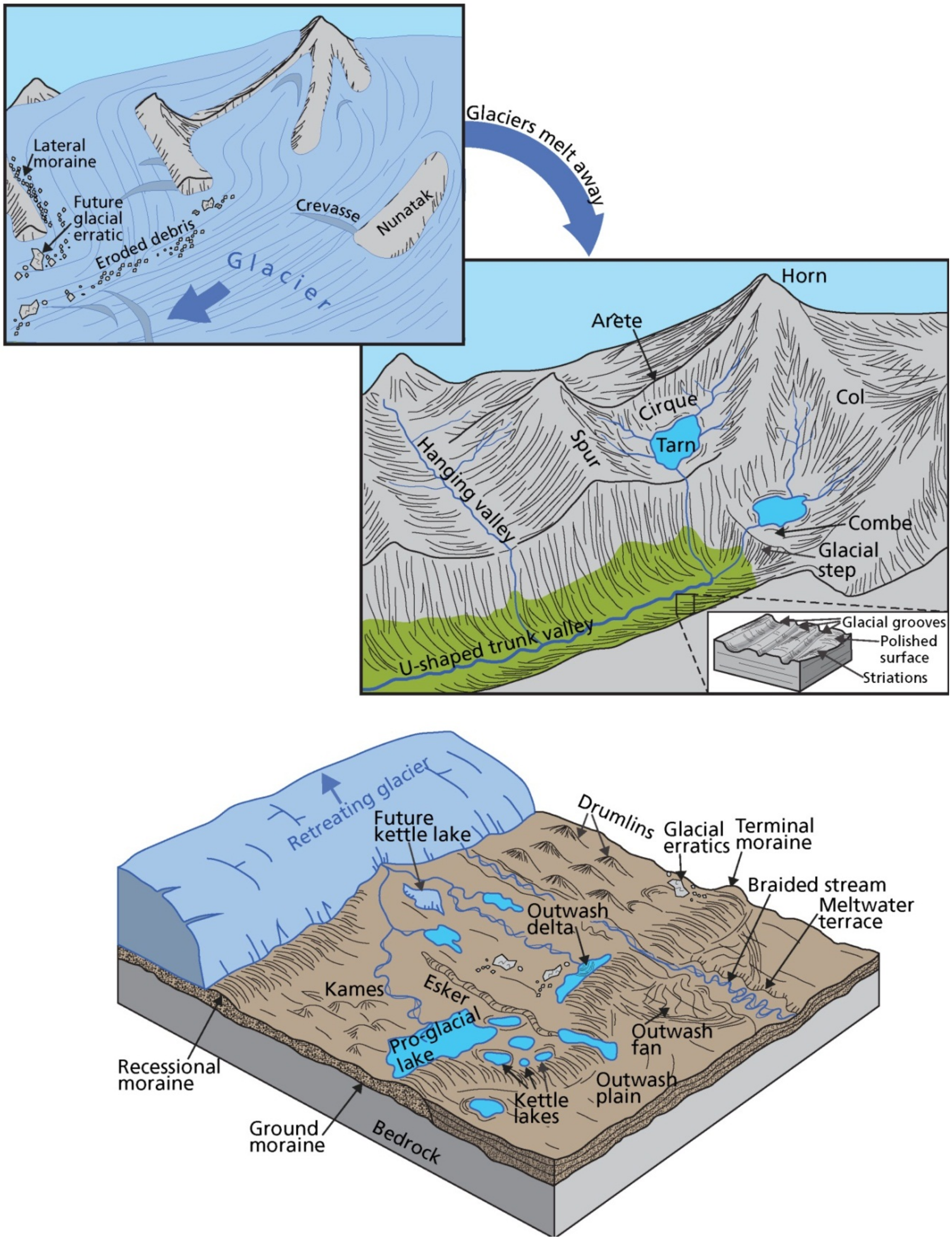


Figure 20. Schematic illustrations of glacial features. Great Basin National Park contains terminal and lateral moraines and kettle lakes. Other glacial features in the park include cirques, bergschrund, arêtes, horns, and tarns. Graphic by Trista Thornberry-Ehrlich (Colorado State University).

abrade, pluck, and polish bedrock. Water aids the process when it flows through cracks in the ice, enters fractures in the bedrock, freezes and expands, thereby shattering the rock. The glacier then carries away the broken fragments. This process may eventually form jagged ridgelines known as arêtes, such as the ridgeline between Bald Mountain and Wheeler Peak, and horns, sharp peaks that form where jagged arêtes branch (fig. 21). Wheeler Peak, Bald Mountain, Baker Peak, and Pyramid Peak are examples of glacially-carved horns in Great Basin National Park.

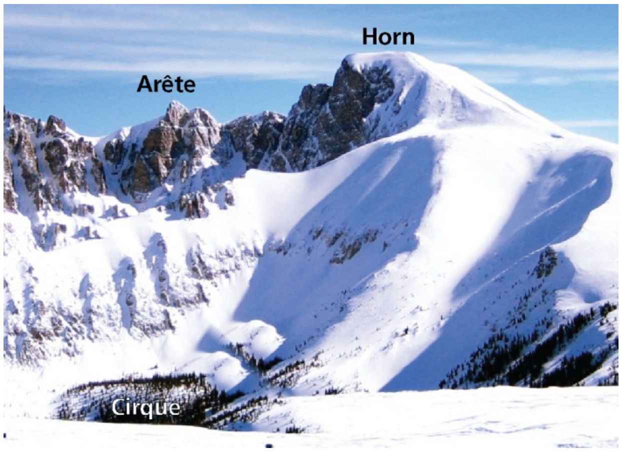


Figure 21. Glacial features associated with Wheeler Peak. A cirque basin, outlined by snow, lies at the base of Wheeler Peak (a glacier-carved horn). The jagged ridgeline, formed by glacial erosion, is called an arête. National Park Service photograph available online: http://www.nps.gov/grba/photosmultimedia/Winter-Landscapes-Gallery.htm (accessed 8 October 2012).

Glaciers gouged a steep cirque at the base of the impressive vertical cliff at Wheeler Peak (fig. 21). As late as 1988, this bowl-shaped depression below the steep headwall of Prospect Mountain Quartzite (CZpm) contained an ice glacier that passed downstream into an ice-cored rock glacier (Osborn 1988). In 1988, the glacier was still active, and the head of the glacier had pulled away from the cliff, creating a crevice known as a bergschrund.

Many cirques in Great Basin National Park contain tarns, small lakes that fill ice-carved depressions (fig. 22). Stella, Teresa, Brown, Baker, Johnson, and Dead lakes are tarns, and their distribution helps define the extent of past glacial coverage. These glacial lakes are significant to the park's ecosystem and their water quality is monitored on an annual basis. In addition, sediment cored from the lakes provides data used to monitor climate change.

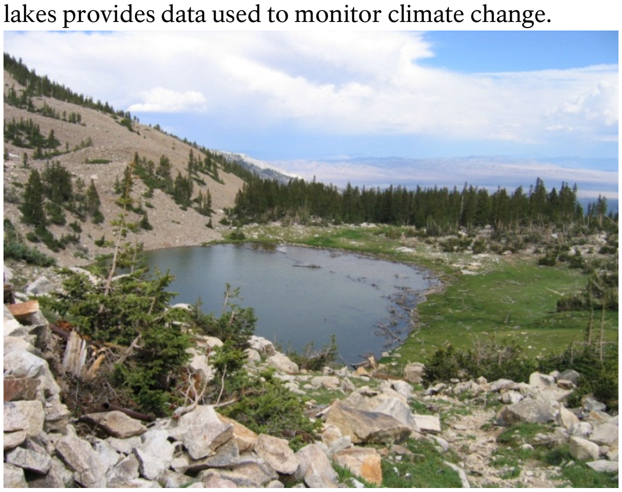


Figure 22. Johnson Lake (tarn). The lake has filled a glacier-carved depression, forming a tarn. Tarns are important water sources for the wildlife in the park. Sediment cores taken from tarns in the park can help define climate change since the Pleistocene. National Park Service photograph by Chris Wonderly, available online: http://www.nps.gov/grba/photosmultimedia/Water-It-means-everything-Gallery.htm (accessed 8 October 2012).

Depositional Features

Glaciers transport all sizes of unconsolidated debris, from fine silt termed "rock flour" to boulders, depositing it along the sides and at the farthest extents of the glaciers in unsorted piles of fine- to coarse-grained rock debris. These piles of debris are called glacial moraines. In Great Basin National Park, glacial deposits (Qg) form lateral and terminal moraines. Lateral moraines consist of till deposited along glacial margins. Terminal moraines mark the farthest advance of a glacier. Wheeler Peak and Mather overlooks offer views of moraines left behind after the glaciers melted.

When the glaciers receded, they left behind blocks of ice buried by sediment. When the ice melted, water filled the depressions in the sediment, forming small kettle-shaped ponds. Kettles are typically found in high alpine meadows.

Periglacial Features

Periglacial features form adjacent to glaciers. Lithology, clast size, precipitation, moisture conditions, and slope influence the spatial distribution of the periglacial landforms in the Snake Range. The most common periglacial landforms in Great Basin National Park include stone-banked solifluction lobes, stone polygons and circles, stone garlands, and protalus ramparts (fig. 23; Van Hoesen and Orndorff 2011).

The east to southeast-facing slope of Jeff Davis Peak contains the most extensive preservation of stone-banked solifluction lobes (fig. 23). Solifluction is the process of slow viscous downslope flow of water-logged soil and other unsaturated and saturated surficial material. Solifluction lobes are tongue-shaped features that form by rapid solifluction. Developed on slopes ranging from 21° to 33°, the solifluction lobes in Great Basin National Park range in length from 3.0 to 7.0 m (10 to 23 ft). They are also present on northern slopes of Bald Mountain, Mt. Moriah, Johnson Pass, and Baker Ridge (Van Hoesen and Orndorff 2011).

Freeze-thaw processes produced polygons and small stone circles on Lincoln Peak, Johnson Pass, Baker Ridge, and on the lower lobe of the Wheeler Peak rock glacier (fig. 23; Van Hoesen and Orndorff 2011). Stone polygons and circles are generally composed of quartzite, but stone circles on Lincoln Peak are composed of limestone and those in Johnson Pass are composed of granite. Freeze-thaw processes on the eastern flank of Mt. Moriah, which is north of the park, produced a surface called "The Table," which contains an extensive area of larger polygons and stone circles. The polygons are composed of quartzite and range from 4.0 to 5.2 m (13 to 17 ft) in diameter, while the stone circles range from 1.3 to 1.8 m (4.3 to 5.9 ft) in diameter.

Stone garlands are rare in the Snake Range, but they have been identified on south–to–southeast-facing slopes on Jeff Davis Peak and Baker Ridge (Van Hoesen and Orndorff 2011). Stone garlands consist of fine material enclosed on the downslope side by a crescent-shaped

A) Solifluction lobes (Antarctica)

B) Stone polygons (Antarctica)

C) Protalus rampart (Mount Rainier NP)

Figure 23. Periglacial features. These features are all outside of the park, but examples of these features are present in Great Basin National Park. A and B are from the Ulu peninsula in Antarctica. Photographs by Bethan Davies (CC BY-NC-SA 3.0), available online: http://www.antarcticglaciers.org/antarctic-periglacial-environments/ (accessed 15 July 2013). The protalus rampart (C) formed on the Sunrise Ridge in Mount Rainier National Park. A 1.6–1.8 m (5–6 ft) deep and 6–9 m (20–30 ft) wide depression separates the rampart from the partly vegetated talus on the left side of the photograph. When the rampart formed, a wedge-shaped snowbank covered the talus and the depression. U.S. Geological Survey photograph available online: http://www.cr.nps.gov/history/online_books/geology/publications/bul/1288/sec5c.htm (accessed 15 July 2013).

stony embankment. The three sites developed on slopes ranging from 29° to 33° at an elevation range of 3,500 to 3,700 m (11,600 to 12,200 ft) above sea level. They range in size from 1.0 to 4.0 m (3.3 to 13 ft) long and from 8.0 to 15 m (26 to 50 ft) wide.

A protalus rampart forms when angular blocks of rock fall from a cliff and roll or slide across a snowbank (fig. 23). When the snowbank melts, the angular blocks form a rampart or ridge some distance beyond the base of the cliff. Protalus ramparts occur in two locations in Great Basin National Park. Two occur at the head of North Fork Baker Cirque and form east to northeast–trending lobate landforms. Another rampart is located below a north-facing cliff in Teresa Cirque and forms a northwest–trending complex landform (Van Hoesen and Orndorff 2011). The landforms range in size from 3.0 to 4.0 m (10 to 13 ft) high and 15 to 30 m (50 to 100 ft) long.

Geomorphic Features

Alluvial fans, bajadas, playas, bolsons, and pediments are geomorphic landforms typical of dry regions, such as the Great Basin. Wind and running water serve as primary agents of both erosion and deposition in forming these features in arid regions.

When a steep mountain stream emerges into a relatively flat basin, its gradient decreases and its sediment load of silt, sand and gravel gets deposited. With its channel choked with sediment, the stream migrates away from its old channel and erodes a new path into the basin. Successive deposits of unconsolidated alluvium follow the stream as it migrates back and forth, creating a fan-shaped feature that slopes gently into the basin. Construction of alluvial fans was more active during glacial periods when stream flow and sediment load were higher. Currently, fans are being incised by intermittent, ephemeral streams.

Alluvial fans composed of older and younger alluvium (Qoa and Qa) spread into Snake and Spring valleys from the borders of Great Basin National Park (fig. 24; Geologic Map Graphic; Hose and Blake 1976). The highway from Baker to the park entrance crosses a gently sloping alluvial fan (Qa). Alluvial fans in the Great Basin commonly coalesce to form a bajada, a broad, continuous alluvial slope extending from the base of a mountain range into an inland basin.

Playas and bolsons in Spring and Snake valleys may be viewed from various overlooks and mountain peaks in Great Basin National Park. The vegetation-free playas are underlain by stratified clay, silt, sand, and soluble salts. Playas (Spanish for "beach") are flat-bottomed depressions that in Nevada are often temporarily covered by water due to spring runoff. Bolsons (Spanish for "large purse") are also flat-bottomed, alluvium-floored desert valleys or depressions that are centered on a playa (fig. 24). The term is generally restricted to the southwestern United States and Mexico. Bolsons collect the drainage from the surrounding ranges. Dry for most of the year, playas may become lakes during spring

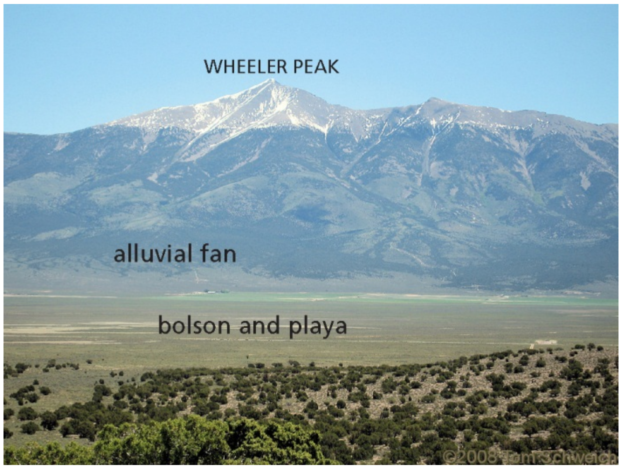


Figure 24. View of Wheeler Peak from Spring Valley, Nevada. Alluvial fans, formed by sediment emerging from the mouth of canyons cut into the mountain front, spread into the valley. The relatively flat valley floor forms a bolson. During wet years, the playa within the bolson may fill with water. Glacial features in the photograph include the horn of Wheeler Peak and the arêtes that branch from the peak to form the ridgeline. Photograph courtesy of Tom Schweich and available online: http://www.schweich.com/imagehtml/IMG00989sm.html (accessed 8 October 2012). Used with permission.

runoff, and in exceptionally wet springs, they may fill the entire bolson.

At the base of mountains in arid regions of the southwest, water and wind erosion bevels the bedrock into broad gently sloping surfaces of low relief, called pediments. The enclosed map suggests that pediments are forming in the McCoy Group (Zmoa, Zmq) and the Prospect Mountain Quartzite (CZpm) along the western border of Great Basin National Park and on the surfaces of igneous intrusions (Tgr, Kgr, Jg) on the eastern border of the park.

In addition to wind and water erosion, landslides also modify the modern landscape. Chaotic blocks of various sizes of rocks (Ql) travel down avalanche chutes to be deposited as talus (Qt) at the base of steep slopes throughout Great Basin National Park. It is a good idea for hikers to avoid avalanche-prone areas. These areas can be recognized by their lack of vegetation.

Lexington Arch

Lexington Arch rises approximately 23 m (75 ft) from the floor of Lexington Canyon in the rugged southeastern part of Great Basin National Park (fig. 25). Most of the natural arches in the western United States, such as those in Arches National Park (see GRI report by Graham 2004), consist of sandstone, but Lexington Arch is carved in the Notch Peak Limestone (OCn). It may be the only limestone arch in the southwest. The origin of the natural arch is unknown, but because it is made of limestone, the arch may be the remnants of a passage that was once a part of a cave system. Smooth, glossy flowstone, similar to flowstone that forms in caves, has been found at the base of the opening and supports the cave hypothesis.

Figure 25. Lexington Arch. Formed in Notch Peak Limestone (OCn), the arch is approximately 23 m (75 ft) tall. National Park Service photograph available online: http://www.nps.gov/grba/photosmultimedia/Mountain-Views-Gallery.htm (accessed 8 October 2012).

It is also possible that Lexington Arch may be a natural bridge, rather than an arch. Natural arches form from weathering processes, such as ice, wind, or chemical breakdown of the rock. Natural bridges, on the other hand, form from flowing water in a stream. Perhaps when Lexington Canyon was shallower than today, water flowed through a cave in the wall of the canyon. Over time, the stream may have enlarged the tunnel that would become Lexington Arch. If this was the case, Lexington Arch would be a natural bridge.

Regardless of how it formed, Lexington Arch continues to change, albeit slowly. Limestone is particularly vulnerable to dissolving in rainwater. Rain, ice, and changing temperatures will continue to shape the Arch.

Paleontological Resources

During the Paleozoic, episodes of rising sea level periodically inundated the Great Basin with relatively shallow seas. Trilobites, brachiopods, crinoids, coral, fusulinids, and other marine organisms lived in well-circulated, oxygenated seawater while gastropods and ostracods inhabited more restricted, nearshore marine environments. Stromatolites, which form when microorganisms (commonly blue-green algae) trap and bind sediment, grew in shallow, coastal environments. Today, some of the more famous stromatolites form in Shark Bay, Western Australia, and provide an example of how these accretionary structures formed millions of years ago.

Prior to 2011, descriptions of Paleozoic units mapped in Great Basin National Park only included general information about fossils. Fossilized shells of gastropods, inarticulate brachiopods, and trilobites were noted in the Notch Peak Limestone (OCn) and represented the oldest marine invertebrates found in the park. The abundance of *Girvinella*, a type of algae that is only 1.2–2.5 cm (0.49–1.0 in) in diameter, was recognized as a diagnostic feature of the Pole Canyon Limestone A Member (Cpca). Fossils of ostracods, trilobites, gastropods, and brachiopods were distinguishing features associated with the Ordovician Juab Limestone (Opj) and Kanosh Shale

Figure 26. *Receptaculites oweni*. This Ordovician fossil algae was found in the park in 2010. Because the fossil spans a relatively short geological time interval, it is useful in dating the rocks in which it is found. National Park Service photograph courtesy Gorden Bell (Great Basin NP).

(Opk). Descriptions of Fish Haven and Laketown Dolomites (OSfl) noted the presence of large brachiopods, which were 10–13 cm (4–5 in) in diameter.

Since 2011, park staff have made great strides in documenting the paleontological resources in Great Basin National Park. In August 2011, two fossils were discovered in stream pebbles from the southern part of the park (Bell 2011). The first fossil was an excellent example of *Receptaculites oweni*, fossil algae (fig. 26). Because this species occurs in many places over a short geological interval, it allows paleontologists to confidently date the rocks in which it is found. Such a fossil is known as an index fossil. Returning to the site, staff found part of *Orthoceras*, a cephalopod that is another Middle Ordovician index fossil. Unlike today's octopi and squids, *Orthoceras* had a long, tapering, conical shell that protected its soft body. The specific unit could not be identified, but Middle Ordovician rocks in the southern part of the park include the Juab Limestone (Opj), Kanosh Shale (Opk), and Lehman Formation (Opl).

Extensive 12-week surveys of 600 ha (1,500 ac) during the summer of 2012 and 200 ha (500 ac) during the summer of 2013 significantly bolstered the park's paleontological record (fig. 27). The more than 1,000 specimens inventoried during the survey included trilobites, brachiopods, cephalopods (including one coiled nautiloid), bryozoans, crinoids, a single plate from a chiton, and corals (Bell 2012). Middle Ordovician rocks yielded the ice cream cone-shaped *Calathium*, an algae that commonly formed mounded colonies in the Pogonip group (Op) of southern Nevada, in addition to *Receptaculites oweni* (Donovan 1990). Straight-shelled nautiloid cephalopods, bryozoans (*Hadrocystis*?), and an undescribed trilobite species of *Cybelopsis*, were discovered in the Lehman Formation (Opl; fig. 27). The tabulate corals, *Eofletcheria* and *Foerstephyllum*, two of the three earliest coral forms known in the fossil record, were discovered north of Granite Peak (fig. 27). The

Figure 27. Selected fossils identified during the 2012 inventory. The trilobite *Cybelopsis* (upper photo) and the nautiloid cephalopod (middle photo) are from the Lehman Formation (Opl). The coral *Eofletcheria* (lower photo), indicates a reef-type habitat and was discovered north of Granite Peak, possibly in the Lehman Formation. The quarters and dime are for scale. National Park Service photographs courtesy Gorden Bell (Great Basin NP).

discovery of *Foerstephyllum* is only the second on record from Nevada (Bell 2012).

The discovery of *Eofletcheria* and *Foerstephyllum* is especially exciting because they may have formed some of the earliest reef-like structures called "biostromes" about 470 million years ago (Bell 2012). In contrast to the massive reefs that exist today, however, the Ordovician biostromes in Great Basin National Park formed a patchwork topography that only stood 1–2 m (3–6 ft) above the sea floor, but they would have functioned as a reef-like habitat. The outcrop that contained this coral bed in the park was removed by erosion or faulting, but outcrops of the same age and biostromal accumulations occur from Crystal Peak, in Utah, to west of the park in the White Pine Range at the western edge of White Pine County. Compensating for the amount of extension and faulting that has occurred in the Great Basin, this biostrome habitat would have extended east-to-west for a distance of about 100 km (60 mi). Eofletcheria has also been observed at about the same stratigraphic level near Big Springs on the southern end of the Snake Range, suggesting that the coral habitat grew over an area that was 100 km (60 mi) long and 16 km (10 mi) wide (Bell 2012).

Extensive carbonate banks and intertidal shoals and bays are represented in the undifferentiated dolostones of the Fish Haven and Laketown Dolomites of Late Ordovician and Silurian age. Characteristic deposits commonly found in these paleoenvironments are depositional structures called "stromatolites" which are thinly layered algal accumulations. A second extensive locality of stromatolites was discovered in 2013 (fig. 28). The park has now documented a total of six stromatolite localities in the Fish Haven–Laketown and Sevy dolomites.

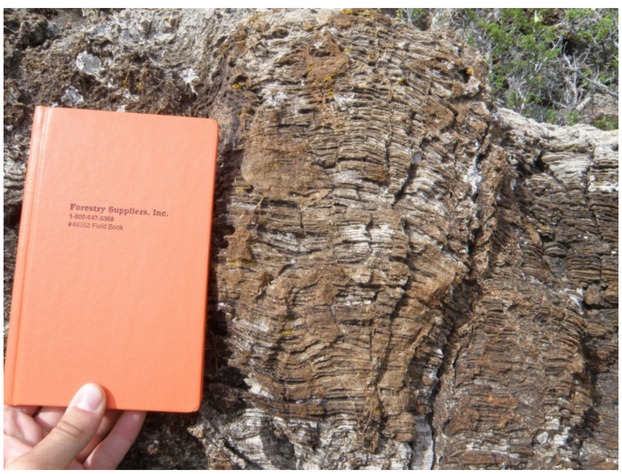


Figure 28. Stromatolite fossils. This specimen was discovered in 2013 in the Upper Ordovician Silurain Fish Haven-Laketown Dolomite. Stromatolites are characteristic deposits of carbonate banks and intertidal shoals and bays. National Park Service photograph courtesy of Gorden Bell (Great Basin NP).

Also discovered in 2012 was the first vertebrate fossil from Great Basin National Park (fig. 29). Only 13 mm (0.5 in) long, the fossil is a fragmentary fin spine of an acanthodian fish (Bell 2012). The fish was discovered in the Sevy Dolomite (Dse), which ranges from about 405–400 million years ago, and has been tentatively identified by Dr. David Elliot of Northern Arizona University as *Nodocosta denisoni*. Appropriately, the Devonian Period is known as the Age of Fishes (fig. 5).

The fossil discoveries in 2012 suggest that Great Basin National Park contains paleontological resources that have been previously overlooked. Map descriptions of the Paleozoic units in the Snake Range record fossiliferous units that might also outcrop within the park's boundaries. For example, brachiopods, crinoids,

Figure 29. *Nodocosta denisoni?*. This partial fin spine of an acanthodian fish is from the Devonian Sevy Dolomite (Dse). National Park Service photograph courtesy of Gorden Bell (Great Basin NP).

gastropods, and stromatoporoids occur in the Devonian Simonson Dolomite (Ds) and Guilmette Formation (Dg). Corals are present in the Joana Limestone (Mj), and foraminifera are prevalent in the Pennsylvanian Ely Limestone (PNe; fig. 16).

In addition to identifying depositional environments, fossils play a critical role in unraveling the chronology of geologic events in the Basin and Range Province, a complex region that has experienced several episodes of deformation as well as transgressions and regressions of the shoreline due to rises and falls of sea level. For example, the evolution and distribution of brachiopods and conodonts in the Devonian and Mississippian proved useful in determining the geographic position of ancestral North America relative to the Equator as well as the initiation and development of the Antler Orogeny (Johnson 1970; Johnson et al. 1985; Johnson and Sandberg 1989; Johnson et al. 1991).

On a more recent note, Pleistocene vertebrate fossils were discovered in Snake Creek Cave in the park during late 2012 and 2013. This marks the first Pleistocene remains documented from inside Great Basin National Park. A variety of reptiles and mammals, and a few birds and fish, are present in the fauna. Most of the mammals are small- to medium-sized rodents and rabbits. Pikas, now extirpated within the Snake and surrounding mountain ranges, are represented within the fauna, as is an extinct rabbit, *Aztlanolagus agilis* (Baker and Bell 2013).

The paleontological inventory at Great Basin National Park is in its initial stage. Additional field work may compare discoveries of Cambrian-age trilobite specimens with those collected by Drewes and Palmer in 1957 (Drewes and Palmer 1957). Units within the park may contain fossil species that expand the current knowledge of the tectonic and depositional development of the Great Basin throughout the Paleozoic Era. See also Blodgett et al. (2007) and Zhang et al. (2008). Refer to the Paleontological Resource Inventory, Monitoring, and Protection section for additional information.

Geology and Cultural Features

For approximately 11,000 years, human cultures have been scratching and painting symbols and designs on the rocks in the Great Basin (fig. 30). Seven styles of pictographs and petroglyphs have been identified in the Southern Snake Range (table 5; Lohman 2011). The Parowan Fremont pictographs and petroglyphs are very distinct and recognizable. As discussed in the Geologic Issues section, their art work is displayed at Upper Pictograph Cave in Great Basin National Park (fig. 30).

Figure 30. Parowan Fremont style pictograph from Upper Pictograph Cave. The natural image on the left has been digitally enhanced in the image on the right. National Park Service photograph from *The Midden* (Lohman 2011).

Table 5. Rock art in Great Basin National Park

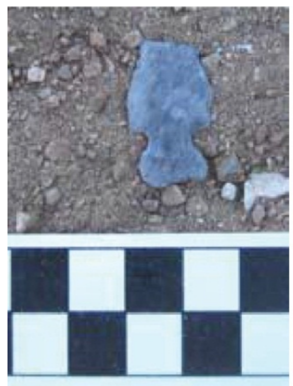
Style	Description
Archaic Period (9,000 B.C. to 500 C.E.)	
Pit and Grove	Shallow pits connected by grooved lines or enclosed by a grooved circle.
Cupule	Pecked depressions 3 mm (0.1 in) to 30 mm (1 in) deep.
Great Basin Curvilinear Abstract and Representational	Meandering lines, circles, sun disks, wavy lines, serpentine forms. Human-like and animal-like figures are common.
Great Basin Rectilinear Abstract	Dots, rectangular grids, rakes, crosshatching.
Great Basin Scratched	Stone scratched or carved by a harder, sharper stone. Common at the end of the Archaic period.
Great Basin Painted	Red and black pictographs of circles, sun disks, dots, zigzags, parallel lines, short vertical lines, and blobs.
Post-Archaic Period (500 C.E. to 1,300 C. E.)	
Parowan Fremont	Petroglyphs or red pictographs. Human-like with stylized triangular bodies, occasionally black charcoal tally lines and meanders.

Source: Lohman (2011).

After the Fremont Culture, Southern Paiute and Western Shoshone occupied the region around Great Basin National Park. While no specific rock art style has been attributed to these people, they may have added to the existing rock art in the area. Unfortunately, the hacks and scratches of today's vandals obscure the preexisting rock art.

In addition to rock art, past cultures used a variety of different rock material to craft projectile points (often called arrowheads) of various forms and sizes (Jensen 2011). The most recent and smallest stone points, which are the only true 'arrowheads,' were attached to the shaft of arrows and used with a bow. Other projectile points tipped the end of spears or atlatl darts.

Projectile points found in the park cover a span of about 6,000 years. Larger projectile points used on spears and darts come from the Archaic period and include Elko series projectile points that range from approximately 2,000 to 6,000 years ago (fig. 31). Smaller points adapted to bow and arrow technology date from the Late Archaic period about 1,600 years ago. The Fremont and later Paiute and Shoshone people fashioned Parowan, Cottonwood triangular, and Desert side-notched style projectile points for hunting both large and small game (Jensen 2011).



A) Archaic projectile point

B) Obsidian arrow point

Figure 31. Projectile points found in Great Basin National Park. A) Found in an isolated drainage in the Southern Snake Range, this projectile point is typical of an Elko type point from the Archaic period that ranged from 2,000 to 6,000 years ago. B) Obsidian arrow points had to be transported into the area since no obsidian exists in the park. National Park Service photographs from Jensen (2011).

While some points found in Great Basin National Park were fashioned from chalcedony and chert, both of which consist of microcrystalline quartz, others were crafted from obsidian (fig. 31). The chert used to make projectile points may have come from Great Basin National Park. Nodules and layers of chert are found in many of the Paleozoic limestone formations, including the Pennsylvanian Ely Limestone (PNe), Mississippian Joana Limestone (Mj), and the Ordovician–Cambrian Notch Peak Limestone (OCn). The Ordovician and Silurian Fish Haven and Laketown Dolomites (OSfl) contain local layers of chert that may be 1–2 m (3.3–6.6 ft) thick. However, obsidian, which is volcanic glass, is not found in the park, suggesting that some of the earliest projectile points were carried hundreds of miles by early occupants in the Great Basin (Jensen 2011).

Geologic Issues

This section describes geologic features, processes, or human activities that may require management for visitor safety, protection of infrastructure, and preservation of natural and cultural resources in Great Basin National Park. The NPS Geologic Resources Division provides technical and policy assistance for these issues.

During the 2003 scoping meeting and 2011 conference call, participants (see Appendix A) identified the following geologic resource management issues:

- Cave preservation and protection
- Lehman Cave restoration project
- Groundwater withdrawal
- Documenting glacial features
- Geohazards
- Paleontological resource inventory, monitoring, and protection
- Seismic activity (earthquakes)
- Reclamation of abandoned mineral lands
- Preservation of rock art

Resource managers may find *Geological Monitoring* (Young and Norby 2009; http://go.nps.gov/geomonitoring) useful for addressing these geologic resource management issues. The manual provides guidance for monitoring vital signs—measurable parameters of the overall condition of natural resources. Each chapter covers a different geologic resource and includes detailed recommendations for resource managers and suggested methods of monitoring.

Cave Preservation and Protection

The 1988 Federal Cave Resources Protection Act mandates inventorying of significant caves on federal land, science-based management of those caves, and appropriate dissemination of cave resource information.

During the scoping meeting in 2003, a variety of cave resource management issues were facing the park, including lack of cave inventories, understanding of biological associations and cultural significance of the caves, and public safety. Air quality issues, impacts from visitor use, and monitoring needs were also identified during the scoping meeting. Since the 2003 meeting, progress has been made towards addressing some of these issues. As of 2012, most of the 46 wild caves have been surveyed and mapped. A physical inventory, which identifies resources in each cave, has been completed for approximately 40 of the caves, and in 2004 a cave management plan was drafted. Public safety was an issue in 2003, but 2011 conference call participants did not perceive current visitor use to be a problem. Unsafe levels of carbon dioxide in the caves were identified as a potential issue in 2003. However, air quality detectors in use in the caves today do not indicate dangerous carbon dioxide levels (Gorden Bell, Environmental Protection Specialist and Paleontologist, Great Basin National Park, 15 December 2011).

In the *Geological Monitoring* chapter about caves and associated landscapes, Toomey (2009) described methods for inventorying and monitoring cave-related vital signs, including the following: (1) cave meteorology, such as microclimate and air composition; (2) airborne sedimentation, including dust and lint; (3) direct visitor impacts, such as breakage of cave formations, trail use in caves, graffiti, and artificial cave lighting; (4) permanent or seasonal ice; (5) cave drip and pool water, including drip locations, rate, volume, and water chemistry, pool microbiology, and temperature; (6) cave microbiology; (7) stability issues associated with breakdown, rockfall, and partings; (8) mineral growth of speleothems, such as stalagmites and stalactites; (9) surface expressions and processes that link the surface and the cave environment, including springs, sinkholes, and cracks; (10) regional groundwater levels and quantity; and (11) fluvial processes, including underground streams and rivers.

Great Basin National Park's 2004 Cave and Karst Management Plan utilized many of Toomey's (2009) suggested methods to monitor cave and karst landscapes. The plan adopted a Cave Classification System following National Park Service Reference Manual 77 (National Park Service 2004) that classifies each cave according to six management classes, four resource classes, and five hazard classes (table 6). Different classification ratings may be assigned to different portions of each cave and may vary with seasons. Regardless of the classification, all of the caves in the park are closed due to white-nose syndrome, except for Little Muddy cave (Ben Roberts, Chief of Natural Resources, Great Basin National Park, written communication, 14 March 2013). See also the NPS white-nose syndrome website for additional information: http://nature.nps.gov/biology/WNS/index.cfm.

The plan's inventory and monitoring program included photo-monitoring, biological assessment for bats and cave invertebrates, microclimate monitoring, vegetation management, and water quality assessment.

Management plan safety protocols included monitoring for radon, carbon dioxide, and oxygen levels, which are currently non-issues, as well as plans for search and rescue. The plan's safety protocols also recommended that the Talus Room, a fault-controlled cavern that had been closed in 1981 due to abundant fragmented and broken rock debris, remain closed. Since 2011, the entire section of the Talus Room has been restored (Ben

Table 6. Cave classification system, Great Basin National Park.

Management Classes		
Class	Description	Management Objectives
Class 1	Highly developed and minimally developed caves. Highly developed caves provide a visitor maximum convenience. Minimally developed caves have easy access with minimal modification to cave resources.	To provide educational opportunities for visitors to gain knowledge and appreciation of park natural resources while minimizing impact to the cave, and to protect, maintain, and conserve natural and cultural cave resources.
Class 2	Undeveloped caves that can be visited with a NPS trip leader.	To preserve and protect cave resources while providing an opportunity for a small number of park visitors to experience the undeveloped cave environment.
Class 3	Undeveloped caves that can be visited by permit.	To preserve and protect cave resources while allowing technically experienced and cave conservation-minded visitors to experience wild caves in the park.
Class 4	Closed to general use pending further evaluation for designation.	To further explore newly discovered caves, or to provide baseline inventories and resource impact studies for known caves.
Class 5	Closed to general use because they contain resources of scientific value that are easily impacted.	To protect and preserve sensitive cave resources, and provide opportunities for scientific studies that apply directly to the management and conservation of park caves.
Class 6	Closed to all use except the minimum entry required for administrative purposes. Caves have a Class V hazard rating, are difficult to enter without causing irreparable damage to fragile cave resources, or contain threatened species that could be damaged by visitor use.	Managed exclusively for the purposes of protecting, preserving, and perpetuating natural and cultural cave and karst resources in the park, and ensuring human safety.

Resource Classes	
Class	Description
Class A	Few features of scientific value. Resources that are present are of the type not easily impacted by human use.
Class B	Caves contain significant physical or biological cave resources that are not easily subject to vandalism or disruption by visitor use based on their location or size.
Class C	Caves contain speleothems that are unusually susceptible to breakage, and/or other biological or physical resources of scientific value that could be seriously disturbed or destroyed by cavers. Examples of Class C speleothems include gypsum flowers or hair, anthodites, delicate frostwork, and helictites.
Class D	Caves contain resources (biological and physical) of scientific value that would be damaged by any use of the cave.

Hazard Classes	
Class	Description
Class I	Caves offer the least hazard to the caver with the following general characteristics: 1. single, well-defined main passageway with no lateral passages 2. no passageways less than 60 cm (24 in) in diameter 3. no step-type drops over 1 m (3 ft) 4. no known loose ceiling rocks and few loose rocks on the floor.
Class II	Caves contain moderate hazards and are mostly horizontal in structure. General characteristics include: 1. well-defined main passageways with minimal side passages 2. no step-type drops over 3 m (10 ft) 3. no known loose ceiling rocks or hazardous floor material.
Class III	Caves contain structural hazards not found in Class I and II caves. Any of the following qualify a cave as Class III: 1. multiple passageways with various connections 2. vertical drops up to 15 m (50 ft) 3. extensive crawling and tight restrictions
Class IV	Caves are the most hazardous from a structural standpoint. Each caver needs to have a complete set of vertical gear. General characteristics include: 1. maze-type passageways 2. extremely difficult access 3. vertical drops over 15 m (50 ft) 4. loose ceiling rocks on crawlways under 2 m (6 ft) high.
Class V	Extremely hazardous caves due to such characteristics as human health hazards, dangerous gases, flooding, hazardous access, and unstable rock. Entered only by qualified cavers with special equipment, and only if the need for information is greater than the risk involved. Extra safety precautions should be taken, and special communications should be available.

Note: table data extracted from the 2004 draft Cave and Karst Management Plan for Great Basin National Park.

Roberts, Chief of Natural Resources, Great Basin National Park, written communication, 14 March 2013).

The management plan identified three preferred means of cave protection: (1) confidentiality of cave locations, (2) ranger patrols, and (3) cooperating with the Interpretation Division to educate visitors. Interpretation was, and is today, considered vital to preserving and protecting sensitive cave resources because it encourages voluntary compliance and cooperation. In addition, criteria were outlined for the use of cave gates as well as policies regarding any future developments associated with the caves.

Cave restoration practices (see below) in the plan focused on lamp flora, lint, formation restoration, and physical restoration. Management protocols also addressed the restoration of broken speleothems as well as the removal of unused and/or deteriorating structures that have been built in Lehman Cave since its discovery in the late 19th century.

Tour sizes, disabled access, and cave registers are addressed by the management plan as are permit policies regarding research, wild caves, and special use. Cave records and files, electronic data, and data ownership are summarized under a Data Management section and the responsibilities of each department branch in the park are outlined in the Cave Management Responsibilities.

Lehman Cave Restoration Project

Lehman Cave became a well-known tourist attraction soon after its discovery in 1885. By 2007, more than one million visitors had explored the cave. Over a century of exploration has led to intentional and unintentional damage to the fragile cave ecosystem. Early explorers broke open passageways; souvenir hunters removed cave formations; and early park rangers built staircases, wooden seats, and metal cables as an aid to visitors. An asphalt and concrete trail system made the caves more accessible, and electric lighting was installed in 1941.

With each visit, visitors leave behind thousands of skin cells, lint, and hair. The deterioration and decomposition of foreign materials has had harmful effects on cave life, water quality, mineral growth, and other natural processes (National Park Service 2012a).

Funded by the Southern Nevada Public Lands Management Act, Great Basin National Park staff restored 440 m^2 (4,700 ft^2) of cave floor to its natural, pre-disturbance condition. Deteriorating staircases, corroded metal conduits, and construction debris have been removed.

In addition, a LED lighting system has been installed to minimize heat and reduce algae growth within Lehman Cave. Crews also clean the cave to reduce the everyday wear and tear on the cave. Ongoing cleaning includes both lint and algae removal from cave formations.

Talus Room and West Room Restoration

In 1981, the trails into Talus Room and West Room were permanently closed due to safety concerns. Since that time, the approximately 34 m^3 (1,200 ft^3) of trail material and 460 m (1,500 ft) of electrical conduit have been deteriorating and negatively impacting natural resources and water quality in the cave (National Park Service 2008; Roberts 2009).

Restoration of the Talus Room began on April 1, 2008, and field work was completed May 1, 2011 (fig. 32). Removal of over 240 m (800 ft) of abandoned tour trail and over 460 m (1,500 ft) of electrical lines restored natural hydrologic function to 440 m^2 (4,700 ft^2) of the cave. Over 52 metric tons (57 tons) of debris was removed from the cave in over 2,200 5-gallon buckets. The park developed a variety of interpretive media to explain the project and to inform the public about its progress. Media included a site bulletin, newspaper articles, articles in the Resource Management newsletter, and a poster in the Lehman Cave Visitor Center (Roberts 2011).

Figure 32. Lehman Cave restoration. Park staff remove material from the old trail in the Talus Room. National Park Service photograph available online: http://www.nps.gov/grba/naturescience/talus-room-restoration.htm (accessed 4 October 2012).

Lint Removal

Lint not only visually degrades the cave environment but also provides an unnatural nutrient source that can alter cave ecosystem dynamics. Composed of fibers, hairs, skin cells, dust, and other foreign particles, lint discolors cave formations and may even dissolve natural cave surfaces (fig. 33). Removing lint is a labor-intensive, tedious process, accomplished using tweezers and paint brushes.

Great Basin National Park conducts lint and restoration camps where volunteers remove accumulations of lint along with other introduced material such as dirt and mud. In 2008, ten volunteers worked over a weekend to remove lint from tour routes in the Grand Palace, Inscription Room, Music Room, Tom Tom Room, Rose Trellis Room, Gothic Palace, Exit Tunnel, and the Natural Entrance area. Over 50 hours of in-cave volunteer time resulted in the removal of over 4

Figure 33. Lint buildup on speleothems. These speleothems are along tour routes in Lehman Caves. National Park Service photograph available online: http://www.nps.gov/grba/naturescience/lint-removal.htm (accessed 4 October 2012).

kilograms (8 pounds) of material (National Park Service 2012a). Near the Exit Tunnel, volunteers also cleaned bits of hardened mud and sand off the ceiling. The sediments had been there since the early 1970s when the passage was created via blasting.

Air currents had deposited some of the most concentrated lint accumulations in the entire cave on the ceiling of Gothic Palace. During the 2008 "lint camp", a ladder was used to reach ceiling areas 6–9 m (20–30 ft) off the ground and remove lint that had shrouded soda straws, stalactites, and other cave formations. In some areas, the lint had become cemented to the cave formations so that removal was impossible (National Park Service 2012a).

In 2010, nineteen volunteers removed 45 kg (100 lb) of sand, rocks, concrete, trash, and lint from the Inscription Room and the Grand Palace. In the 1930s, passages were enlarged with explosives, and sandbags were used to contain the blasts. Sand still coats ceilings and walls of many passages. The volunteers also removed 107 buckets filled with cement, asphalt, sand, and gravel from a section of a trail in the Sunken Gardens area. This was not an easy task. Each filled bucket averaged 25 kg (55 lb), resulting in the removal of approximately 2,700 kg (5,900 lb) of material (Roberts 2010).

In 2012, several members of the Southern Nevada Grotto spent their Thanksgiving vacation surveying and cleaning cave passages (Baker 2012). They spent over 120 hours in the cave and removed 16.6 kg (36.5 lb) of dirt, lint, hair, and debris from the Entrance and Exit tunnels and from the Music and Lodge rooms.

Algae Reduction

Artificial lights, which were installed for visitor access and safety, disrupt the cave ecosystem, which exists naturally in total darkness. "Lamp flora" includes non-native cyanobacteria (blue-green algae), mosses, and other non-native plants. The yellow-tinted light from incandescent bulbs, the light fixture of choice in the past, hides the true color of cave formations and encourages algae growth. For example, the orange color in the caves in figure 2 is a result of incandescent lighting and algae growth. In addition, incandescent bulbs only last an average of 200 hours and are fragile, operate at high temperatures, and consume an average of 11,200 watts of power in the cave (National Park Service 2012a).

Figure 34. Cleaning algae growth with a diluted bleach solution. This photo was taken prior to the installation of LED lights. National Park Service photograph available online: http://www.nps.gov/grba/naturescience/algae-reduction.htm (accessed 4 October 2012).

Algae deposits also introduce an invasive food source that greatly affects the natural balance of cave life. Algae can permanently change the color of the cave and waterproof formations so that further growth is impossible.

In 2006, Great Basin National Park staff replaced the incandescent bulbs with Light Emitting Diodes (LEDs). In contrast to incandescent bulbs, LEDs last an average of 50,000 hours and are shock resistant, operate at low temperatures, and consume one third the amount of electricity. They allow visitors to view the wide range of cave colors and reduce algae growth.

LEDs, however, do not eliminate algae growth. The park determined which type of bulb, wattage, and wavelength of light best reduces algae growth while still allowing visitors to enjoy the cave, but park crews continue to regularly remove algae growth with a spray bottle filled with a diluted bleach solution (fig. 34). Mammoth Cave National Park in Kentucky (see GRI report by Thornberry-Ehrlich 2011) and Oregon Caves National Monument (see GRI report by KellerLynn 2011) are also addressing issues associated with lamp flora.

Groundwater Withdrawal

Groundwater's role in meeting the water demands of desert metropolitan areas, like Las Vegas, has been increasing. Extensive groundwater pumping may limit the water resources available in Great Basin National Park, significantly impacting groundwater discharge into springs, surface streamflow, and cave resources. In 2002, when groundwater applications increased in areas around the park, the National Park Service asked the U.S. Geological Survey (USGS) to conduct a study on the impact to Great Basin National Park from groundwater withdrawal.

Table 7. Surface-water resources susceptible to groundwater withdrawals in adjacent valleys.

Areas likely susceptible to groundwater withdrawals	
Areas within Great Basin National Park	1. Lehman Creek from the lower Lehman Creek campground to the terminus of the stream in Snake Valley, including Rowland and Cave springs, which emerge from Quaternary alluvium (map unit **Qa**). 2. Baker Creek upstream of the confluence with Pole Canyon tributary to the terminus of the stream in Snake Valley. 3. Snake Creek from just upstream of the park boundary to the terminus of the stream, including Spring Creek.
Areas adjacent to the park	1. The lower half of Strawberry Creek downstream of the fault contact of the intrusive rocks (Jg) and Tertiary rocks (**Tc**), including the springs and seeps. 2. Shingle Creek downstream of the intrusive rocks (**Jg**) and upstream of the pipeline. 3. Williams Canyon upstream of the pipeline. 4. Weaver Creek along the alluvial slope on the northeast end of the Southern Snake Range. 5. Pine and Ridge creeks on the west side of the Southern Snake Range between the mountain front and where streams are diverted into pipelines. 6. The numerous springs at the change in slope between the valley floor of Spring Valley and the alluvial slope on the west side of the Southern Snake Range 7. Big Springs, Big Springs Creek, Lake Creek, Big Wash near Hidden Canyon Ranch, and Pruess Lake in Southern Snake Valley.
Areas potentially susceptible to groundwater withdrawals	
Areas within Great Basin National Park	1. That part of Snake Creek that crosses over the Cambrian and Ordovician limestones on the upper plate of the Southern Snake Range décollement. 2. The upper part of Snake Creek that crosses over undifferentiated Pole Canyon Limestone (map unit **Cpc**), Pioche Shale (map unit **Cpi**), and Prospect Mountain Quartzite (map unit **CZpm**) on the lower plate of the Southern Snake Range décollement.
Areas not susceptible to groundwater withdrawals	
Areas within Great Basin National Park	1. Big Wash, Lexington Creek, and Big Spring Wash. 2. Decathon and Lincoln canyons.
Areas adjacent to the park	1. Johns Wash and Murphy Wash

Compiled from Elliott et al. (2006).

During 2003 and 2004, the USGS measured discharge from eight drainage basins and one spring within the Great Basin National Park area. The data indicated that surface-water resources in several areas in and adjacent to the park would be impacted by groundwater pumping in Snake and Spring valleys. The study suggested that the streams most susceptible to changes in groundwater flow were those in contact with permeable rocks, such as fractured limestone, and areas where streams receive either spring discharge or groundwater inflow (table 7; Elliott et al. 2006).

The USGS further evaluated the susceptibility of water levels to groundwater pumping in 2011 (Halford and Plume 2011). Numerical groundwater-flow models were used to assess the hydrologic effects of developing groundwater supplies in Snake and Spring valleys.

As climate continues to change, water is projected to become scarcer. Much of the Southwest has been in a drought since 1999, and the region is expected to become even drier (Karl et al. 2009). Average annual precipitation is expected to decrease in the Southwest, although El Niño events will increase precipitation in the Great Basin (Christensen et al. 2007; Meehl et al. 2007). The combination of drought and increased potential flooding (see the Geohazards section) may exacerbate potential water shortages as reservoirs cannot be filled to capacity. In addition, sediment from increased flooding will fill reservoirs at a faster rate (Karl et al. 2009).

The Water Resources Division of the National Park Service in Fort Collins, Colorado, can provide further information regarding the hydrology and water resources of Great Basin National Park.

Documenting Glacial Features

Glacial features in Great Basin National Park include rock glaciers, glacial lakes (tarns), cirques, kettles, terminal moraines, and lateral moraines (see the Geologic Features and Processes section). They represent a time during the Pleistocene when the climate of the Great Basin was much wetter than today's desert climate. As of 2011, the park does not yet have a map of the glacial features in the park (Natural Resource Staff, Great Basin National Park, conference call, 15 December 2011). A baseline inventory of the features is needed not only to document the evidence of the Pleistocene Ice Ages but also to monitor the changes to the park's rock glaciers due to global climate change. For example, the rock glaciers in the park, including the Wheeler Peak rock glacier, may disappear in the next 20 years as the global climate continues to warm (National Park Service 2012b). Recent warming has increased the average temperature in the southwestern United States by approximately 0.85°C (1.5°F) compared to a 1960-1979 baseline period (Christensen et al. 2007; Field et al. 2007; Karl et al. 2009). By the end of the century, average annual temperatures are expected to increase by roughly 2°–6°C (4°–10°F) above the historical baseline. Some regional estimates are as high as 7°C (12.6°F) of warming (Cubashi et al. 2001). Large differences in Great Basin topography will influence the increase in carbon dioxide by 2100 and thus, the degree of change, but losses in snowpack are expected to continue.

Geohazards

Landslides, Avalanches, and Rockfalls

Large landslides (geologic map unit Ql) are mapped within and outside the park. Avalanches are common and occur primarily in the backcountry and pose little threat to park infrastructure or visitor safety. For example, between 2006 and 2011, two large avalanches slid into Johnson Lake at the base of Pyramid Peak. Park staff have mapped some of the avalanche chutes, which impact some of the backcountry trails. In addition, rockfalls may occur along fractures in the cave systems. Rockfalls are discussed in the Cave Preservation and Protection section.

In the *Geological Monitoring* chapter about slope movements, Wieczorek and Snyder (2009) described five vital signs for understanding and monitoring slope movements: (1) types of landslide, (2) landslide causes and triggers, (3) geologic materials in landslides, (4) measurement of landslide movement, and (5) assessment of landslide hazards and risks. Highland and Bobrowsky (2008), the US Geological Survey landslides website (http://landslides.usgs.gov/), and the NPS Geologic Resources Division Geohazards (http://www.nature.nps.gov/geology/hazards/index.cfm) and Slope Movement Monitoring (http://www.nature.nps.gov/geology/monitoring/slopes.cfm) websites provide detailed information regarding slope movements, monitoring, and mitigation options.

Floods and Debris Flows

Floods and debris flows have occurred in Great Basin National Park, but they do not present a significant resource management issue at this time due to limited infrastructure in flood-prone areas (Natural Resource Staff, Great Basin National Park, conference call, 15 December 2011). Major floods in the Great Basin generally result from snowmelt, frontal-storm rainfall, and localized convective rainfall (Water Resources Division 1991). Snowmelt floods typically occur during April–June; frontal rain and frontal rain-on-snow flooding occur during November–March; and convective-type rainfall flooding occurs during localized summer thunderstorms (Burkham 1988). Because of the relatively steep canyons in the park, flash flooding is a potential hazard, but one which is difficult to predict or manage. Great Basin National Park monitors nine active weather and climate stations within its boundaries (Davey et al. 2007). One of the stations near the visitor center has been recording data since 1937. Most of the stations in the park are located near the Lehman Caves or the Baker Creek drainage, and monitoring efforts could be improved by installing a remote near-real-time station in the Snake Creek drainage (Davey et al. 2007).

As climate continues to change and temperatures warm, flooding is also expected to increase as snow cover decreases on lower mountain slopes and more precipitation falls as rain than snow. Streamflow is expected to increase in winter, peak earlier in the spring, and decrease in the summer and fall (Chambers 2008). Spring snowmelt-driven streamflow now arrives 10–15 days earlier than in the mid-1900s (Baldwin et al. 2003; Stewart et al. 2004). Increased rain on snow events will result in rapid runoff and increased sediment in floods and debris flows. Fire frequency is projected to increase, especially with the invasion of highly flammable cheatgrass. Surface runoff may increase from burned areas, increasing sediment into streams.

Granites produce very erosive, unconsolidated debris called “grus.” Grus becomes highly mobile during heavy rainstorms, especially following fires (Gorden Bell, Environmental Protection Specialist and Paleontologist, Great Basin National Park, written communication, 27 September 2013). Intense rainfall events commonly occur at the end of summer and the beginning of autumn, and these events move large amounts of grus. Any of the granite units listed in the Map Unit Properties Table weather to produce significant quantities of grus, which may impact the roads and trails in the park.

Many of the campgrounds in Great Basin National Park, such as Upper and Lower Lehman Creek, Wheeler Peak, Baker Creek, Shoshone Creek, and Snake Creek campgrounds, are located near well-defined and high gradient stream channels common in the mountainous areas of the park. A flood hazard map, which would include the base (100–year) and critical action (500–year) floodplains, would provide useful information for resource managers and help avoid development in flood-prone areas.

Paleontological Resource Inventory, Monitoring, and Protection

All paleontological resources are non-renewable and subject to science-informed inventory, monitoring, protection, and interpretation as outlined by the 2009 Paleontological Resources Preservation Act (see Appendix B). As of January 2014, regulations associated with the Act were being developed.

An overview of paleontological resources for Great Basin National Park and the rest of the Mojave Desert Network was completed in 2004 (Santucci et al. 2004). The report documented how little was known about the paleontological resources within the park boundaries prior to the summer of 2012. During a 12-week field season, Gorden Bell, paleontologist at Great Basin National Park, and two Geoscientists-in-the-Parks

Figure 35. 2012 paleontological survey discoveries. More than 1,000 fossil specimens were discovered during the 2012 field season. This piece of Ordovician Kanosh Shale (Opk) contains an abundant assortment of trilobites and brachiopods (*Orthambonites michaelis*). Quarter, 2.5 cm (1 in) in diameter, is for scale. National Park Service photograph courtesy of Gorden Bell (Great Basin NP).

interns (GIPs), Linda Sue Lassiter and Spencer Holmes, surveyed approximately 600 ha (1,500 ac) of the park for fossils (Bell 2012). They added 38 new paleontology localities to the park's database, documenting the sites using GPS and photographs. The new sites represent 476 GPS positions and more than 1,000 fossil specimens (fig. 35). The fossils represent organisms that lived in a marine environment during the Paleozoic (see the Geologic Features and Processes section).

Prior to the summer of 2012, only 11 paleontological localities had been identified in the park (Gorden Bell, Environmental Protection Specialist and Paleontologist, Great Basin National Park, conference call, 15 December 2011). One of these sites contained Quaternary fossils. The other sites consisted of Paleozoic marine invertebrate fossils.

Currently the park is developing a paleontological resource-potential map that will be translated into GIS coverage to assist resource management and field surveys. Illegal collecting of paleontological resources is not a significant issue at Great Basin National Park, perhaps due to limited information regarding the park's paleontological resources. Future interpretation and outreach should include an NPS resource stewardship message. Additional information about fossils within the park is summarized in the Geologic Features and Processes section.

In the *Geological Monitoring* chapter about paleontological resources, Santucci et al. (2009) described five methods and vital signs for monitoring in situ paleontological resources: (1) erosion (geologic factors), (2) erosion (climatic factors), (3) catastrophic geohazards, (4) hydrology/bathymetry, and (5) human access/public use.

Seismic Activity (Earthquakes)

Extension of Earth's crust promotes normal-fault movement along basin-bounding faults, which results in

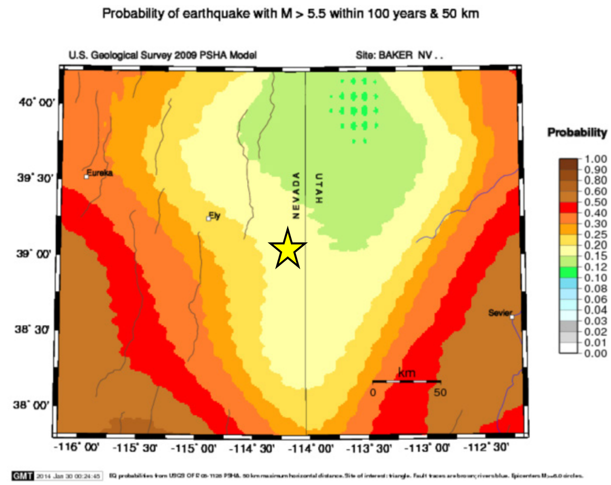


Figure 36. Earthquake probability map. The park (star indicates the location of Baker, Nevada) has a 15%-20% probability of a magnitude 5.5 earthquake in the next 100 years. Map generated by the U.S. Geological Survey 2009 Earthquake Probability Mapping application, available online: https://geohazards.usgs.gov/eqprob/2009/index.php (accessed 30 January 2014).

earthquakes. Although Nevada ranks as one of the most seismically active states in the country, Nevada's earthquake activity is primarily concentrated along its western and southwestern borders. The potential for an earthquake that would sustain significant damage to Great Basin National Park is minor. According to the U.S. Geological Survey 2009 earthquake probability mapping application (https://geohazards.usgs.gov/eqprob/2009/index.php, accessed 29 January 2014), the park has a 15% to 20% probability of experiencing a magnitude 5.5 (moderate) earthquake in the next 100 years (fig. 36). Probabilities are much higher to the southeast and southwest. The park may experience ground shaking from earthquakes originating elsewhere in the state.

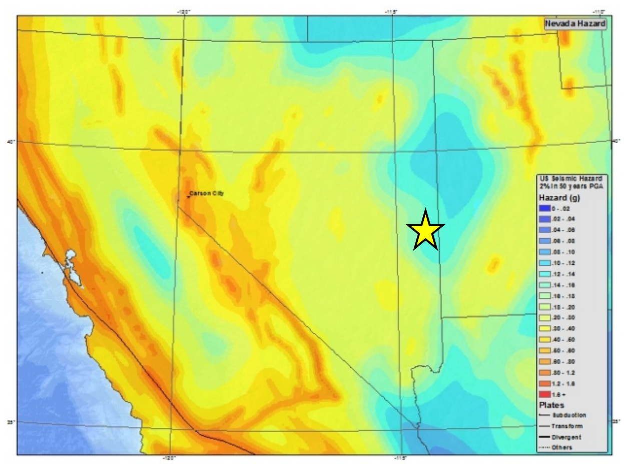


Figure 37. Seismic hazard map of the Great Basin. The most intensive areas of seismic activity (red) in the Great Basin occur in three general areas: 1) Utah's Wasatch Mountain front, 2) west-central Nevada, and 3) eastern California. Eastern Nevada is notably quiet. The yellow star approximates the location of Great Basin National Park. Modified from the U.S. Geological Survey map available online: http://earthquake.usgs.gov/earthquakes/states/nevada/hazards.php (accessed 5 October 2012).

Between the Sierra Nevada Mountains in eastern California and the Wasatch Mountains in central Utah, the Great Basin continues to expand in an east–southeast to west–northwest direction at a rate of approximately 13 mm/year (0.51 in/year). Extension is concentrated in three north-south trending belts: (1) along Utah's Wasatch Mountain front, (2) in west-central Nevada, and (3) along extreme eastern California (fig. 37; Machette et al. 2012). Little evidence for contemporary extension is available for eastern Nevada and western Utah (dePolo and Price 2012; Machette et al. 2012).

Real-time data for Nevada earthquakes are available on the U.S. Geological Survey Earthquake Hazards Program website (http://earthquake.usgs.gov/earthquakes/states/?regionID=28, accessed 17 July 2012) and the Nevada Bureau of Mines and Geology Geohazards website (http://www.nbmg.unr.edu/Geohazards/index.html, accessed 17 July 2012).

Reclamation of Abandoned Mineral Lands (AML)

Mining activities, primarily for tungsten and gold, occurred in the Southern Snake Range in the 19th and 20th century, but no existing mining claims remain in Great Basin National Park (table 8; Smith 1976; Natural Resource Staff, Great Basin National Park, conference call, 15 December 2011). White Pine County contains only two significant active mines. The Robinson Mine near Ely, Nevada, in central White Pine County produces copper, gold, silver, and molybdenite, and the Bald Mountain Mine in the northwestern corner of the county produces gold and silver (Driesner and Coyner 2011; Visher and Coyner 2012).

In general, mining activities result in disturbed lands and water quality issues, but most mines in Great Basin National Park have been reclaimed and acid mine drainage does not exist in any known mine (Natural Resource Staff, Great Basin National Park, conference call, 15 December 2011). Overall, Great Basin National Park has restored more than 66.8 ha (165 ac) and over 26 km (16 mi) of roads. Because of significant safety hazards and critical bat habitat, a bat compatible gate was installed on the Lincoln Canyon Mine adit in 2010 using American Recovery and Reinvestment Act of 2009 funding (fig. 38; Ben Roberts, Chief of Natural Resources, Great Basin National Park, written communication, 20 December 2011).

The NPS Geologic Resources Division AML database (accessed 31 January 2014) lists 281 AML features, such as prospects, trenches, adits, and surface structures, at 15 sites within Great Basin National Park. Many features and sites have been reclaimed although 69 features at five sites were classified as high priority for mitigation by Burghardt et al. (2013).

In 2009, archeologists visited the historic Chapman-Taylor tungsten mine and formally documented the

Table 8. Mining activity in the Great Basin National Park area during the 20th Century.

Mining District	Location	Ore-bearing Geologic Unit (geologic map symbol)	Ore Deposits
Osceola	West flank of the Snake Range, west of the park.	McCoy Group quartzite (Zmq) Prospect Mt. Quartzite (CZpm) Alluvium (Qa, Qoa)	Gold ore (Zmq, CZpm) Tungsten (CZpm) Placer gold (Qa, Qoa)
Tungsten	South of the Osceola district. Wheeler Peak area.	Jurassic granite (Jg)	Tungsten (Jg)
Mount Washington	West slope of the Snake Range south of Tungsten district from Williams Canyon nearly to Shoshone. Includes Mount Washington and Lincoln Peak.	Pioche Shale (Cpi) Pole Canyon Limestone (Cpc)	Tungsten-beryllium (Wheeler Limestone Member of Cpi) Lead-silver (Cpc)
Shoshone (Minerva)	South of the Mount Washington district to Silver Chief Canyon.	Pole Canyon Limestone (Cpc)	Tungsten (Cpc)
Snake	Southern part of the park, south of Lehman Caves, on the east slope of the Snake Range. Includes Baker and Snake creeks and Pyramid Peak.	Jurassic granite (Jg)	Tungsten (Jg) Secondary production of gold, silver, lead (Jg)
Lexington	South of the Snake district on the east slope of the Snake Range and the area of Granite Peak. The only productive mine was located near the head of Lexington Creek.	Notch Peak Limestone (OCn) or Fish Haven/Laketown dolomites (OSfl). The ore is in a limestone but both of the two shafts are caved.	Tungsten (OCn or OSfl)

Data from Smith (1976) and the Nevada Bureau of Mines and Geology webpage, http://www.nbmg.unr.edu/Mining/index.html (accessed 19 March 2013).

Figure 38. Bat-friendly gate. This gate was installed on the Lincoln Canyon Mine adit. National Park Service photograph courtesy of Ben Roberts (Great Basin NP).

remaining material of the mine for the first time. The mine operated from 1915-1916, and the site currently contains a relatively intact cabin, an adit, mining prospects, and open cuts (Lohman 2009). The park also contains the abandoned ruins of the Johnson Lake Mine Historic District, an early 20th century tungsten mining operation. The ruins are accessible by a strenuous hike with an 820 m (2,700-ft) elevation gain (National Parks Conservation Association 2009).

Preservation of Rock Art

Since 2002, when the cultural resources program was initiated at Great Basin National Park, park archeologists have discovered, mapped, and inventoried cultural resources that display an intimate association between prehistoric cultures and geology (see the Features and Processes section). As of 2010, only about 5% of the park's acreage had been surveyed, yet almost 200 sites had been documented and recorded (Jageman 2010).

The Parowan Fremont Culture, which occupied the region from approximately 500 C.E. to 1300 C.E., left enigmatic and distinct pictographs (art painted on rock) and petroglyphs (art carved into rock) throughout the Snake Range and Great Basin. Pictographs and petroglyphs are especially prevalent at Upper Pictograph Cave at Grey Cliffs where the rock walls include 76 different symbols on 23 panels of Pole Canyon Limestone (Cpc; National Parks Conservation Association 2009). At Great Basin National Park, park archeologists are using digital image enhancement to recognize pigments and carvings that may have faded over time, discovering new pictographs and petroglyphs at old sites (fig. 30; Lohman 2011).

Rock art is susceptible to degradation by both natural and anthropomorphic causes. Surface deposits build up on paintings, which fade upon cleaning, and the rock substrate is subject to gradual erosion. Rock art is a fragile resource and may be damaged by being touched, chalked, or rubbed.

Vandals have etched new symbols, written over, and destroyed some of the rock art in Pictograph and Baker Creek caves (Lohman 2009; National Parks Conservation Association 2009; National Park Service 2012d). Unauthorized entrance also occurs in other rock shelter sites in the park (Lohman 2009; National Parks Conservation Association 2009). Currently, funding is needed to help protect and preserve these cultural sites.

Geologic History

This section describes the chronology of geologic events that formed the present landscape of Great Basin National Park.

The geologic history of Great Basin National Park captures the dynamic evolution of western North America. Paleozoic strata record millions of years of marine inundation, as well as several major mountain-building events (orogenies). Granitic plutons in the park document plate tectonic subduction along the western margin of North America and the subsequent volcanic and plutonic turmoil of the Mesozoic. The metamorphic core complex in the Snake Range records Tertiary extension that pulled apart the Earth's crust, generating today's Great Basin landscape of north-south trending, block-faulted basins and ranges. During the Quaternary, alpine glaciers left their mark on the higher elevations in the park. In the wetter Pleistocene climate, groundwater dissolved passages in limestone that widened and developed into the spectacular caves that are currently preserved in Great Basin National Park.

A Passive Margin and Paleokarst: Late Proterozoic–Middle Ordovician (550–461 million years ago)

From the Late Proterozoic into the Middle Ordovician, western North America was bordered by a passive tectonic margin, similar to the East Coast of North America today, in which a ramp-like continental shelf sloped gradually to the west (Stewart 1991). Because vegetation did not exist, sediment was easily eroded from the initial North American craton and deposited in near-shore, relatively shallow marine environments. Sand, silt, and clay lithified into the thick sections of Proterozoic McCoy Creek Group Osceola Argillite and quartzite (geologic map units Zmoa and Zmq) and the Lower Cambrian Prospect Mountain Quartzite (CZpm) and Pioche Shale (Cpi; fig. 39).

Oolitic limestone and voids in the rock (fenestral fabric) in various members of the Middle Cambrian Pole Canyon Limestone (Cpc) suggest that the ramp-like continental shelf transformed into a carbonate platform during the Middle Cambrian (fig. 39; Stewart 1991). Sea level rose in the latest Cambrian, leaving only a strip of land (or perhaps just a series of islands) exposed along what is known as the Transcontinental Arch, an upland that stretched from northern Minnesota southwestward across Nebraska, Colorado and northwestern New Mexico (fig. 39; Speed 1983; Sloss 1988).

The abundant trilobite debris, brachiopods, and stromatolites in the Cambrian–Ordovician Notch Peak Limestone (OCn) indicate that this well-oxygenated, warm, Equatorial marine environment persisted into the Lower Ordovician when a carbonate shelf developed in western Utah, Nevada, and southern California (fig. 39; Ross et al. 1991; Poole et al. 1992). Algae and sponges grew in low, stacked, overlapping mounds on the carbonate shelf and may have formed the first barriers to the ocean, behind which the fossiliferous black mud of the Kanosh Shale (Opk) collected (Poole et al. 1992). These mounds are now exposed in the northern and southern Egan Ranges of east-central Nevada, west of Great Basin National Park.

As sea level rose, the carbonate shelf expanded into western Utah, depositing the fossiliferous limestones of the Early-Middle Ordovician Pogonip Group (Op). Biostromes, some of the earliest reef-like structures in the stratigraphic record, formed a network of patchwork buildups in eastern Nevada, including the area of Great Basin National Park (fig. 39). The warm, shallow seas produced an incredible amount of limestone, including the approximately 530–730 m (1,700–2,400 ft) of Pogonip Group exposed in the Snake Range.

Regional tectonic movements caused relative sea level to rise and fall several times during the deposition of the Pogonip Group (Op) in southern Nevada (Keller and Lehnert 2010). When relative sea level fell, a paleokarst topography developed on the exposed Pogonip surface (Cooper and Keller 2001). Dolomite breccias and karst features in eastern California and southern Nevada record a maximum sea-level fall of as much as 180 m (590 ft) in the upper part of the Pogonip Group (Cooper and Keller 2001; Kosmidis et al. 2008; Keller and Lehnert 2010).

Accelerated formation of karst topography and features of the Pogonip surface may have been triggered by intense, worldwide Ordovician volcanism. During the Ordovician, major volcanic eruptions ejected tremendous amounts of sulfur dioxide and hydrogen sulfide into the atmosphere. Combined with water vapor, these compounds form sulfuric acid, or acid rain. Extreme volcanic activity caused rapid global warming and a strongly acidic atmosphere in the Ordovician (Sigurdsson 1990; Huff 2008; Keller and Lehnert 2010). Positioned near the Equator, limestones in the Pogonip Group would have been subjected to tropical and subtropical climates. When relative sea level fell in the Late Ordovician, the low-relief, non-vegetated Pogonip limestones would have been exposed to high temperatures and abundant (acid) rainfall, conditions which would have dramatically increased carbonate dissolution and formed an ancient karst landscape. Dramatic evidence of this karst landscape can be found in the Cottonwood Mountains and Nopah Range in southern Nevada where karst dissolution extends down to a depth of almost 180 m (590 ft), recording the exceptional fall in sea level (Keller and Lehnert 2010).

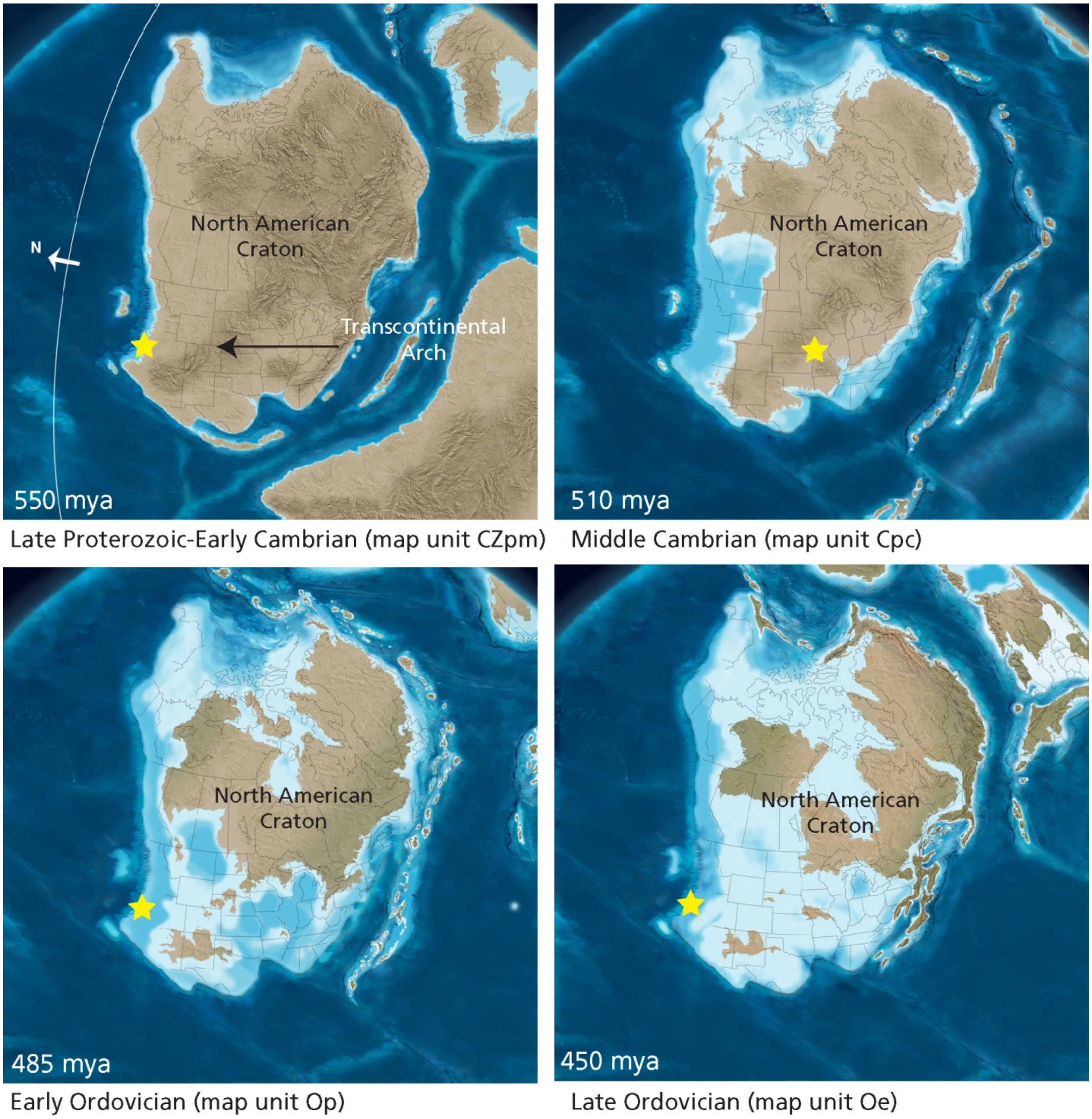


Figure 39. Late Precambrian (Proterozoic) and Paleozoic paleogeographic maps of North America. The age of each time frame is in million years ago (mya). For most of the Paleozoic, the Great Basin National Park region (yellow star) was inundated by shallow marine environments (light blue color). The Transcontinental Arch bisected the ancestral North American craton. By the Ordovician, shallow epicontinental seas cover most of the arch in the southwestern United States. The white line across the Late Proterozoic-Early Cambrian graphic represents the approximate location of the equator. Base paleogeographic maps by Ron Blakey (Colorado Plateau Geosystems, Inc.), available online: http://cpgeosystems.com/index.html (accessed 8 October 2012). Annotation by the author.

From Global Warming to Global Glaciation: Late Ordovician–Early Devonian (461–398 million years ago)

The Middle-Late Ordovician Eureka Quartzite (Oe) forms a prominent interruption in the predominantly carbonate Middle Cambrian to Mississippian stratigraphic sequence. The cliff-forming, roughly 100–m- (300–ft-) thick unit forms a distinct marker bed of tan orthoquartzite throughout the Great Basin. Deposited above the karst surface of the Pogonip Group, the Eureka Quartzite documents a major sea-level rise, or transgression, perhaps triggered by Early–Middle Ordovician global warming (Saltzman et al. 2003; Pope et al. 2008; Keller and Lehnert 2010). The well-sorted, quartz-rich, rounded, cross-bedded sandstone represents deposition in a high energy, upper shoreface environment (fig. 39; Druschke et al. 2009).

Quartz sand from the north and northeast periodically prograded over the Middle Ordovician carbonate platform until it eventually smothered carbonate production (Ross 1977; Ross et al. 1991). Questions still remain, however, about the origin of the Eureka Quartzite. The dominant source area for the sand was

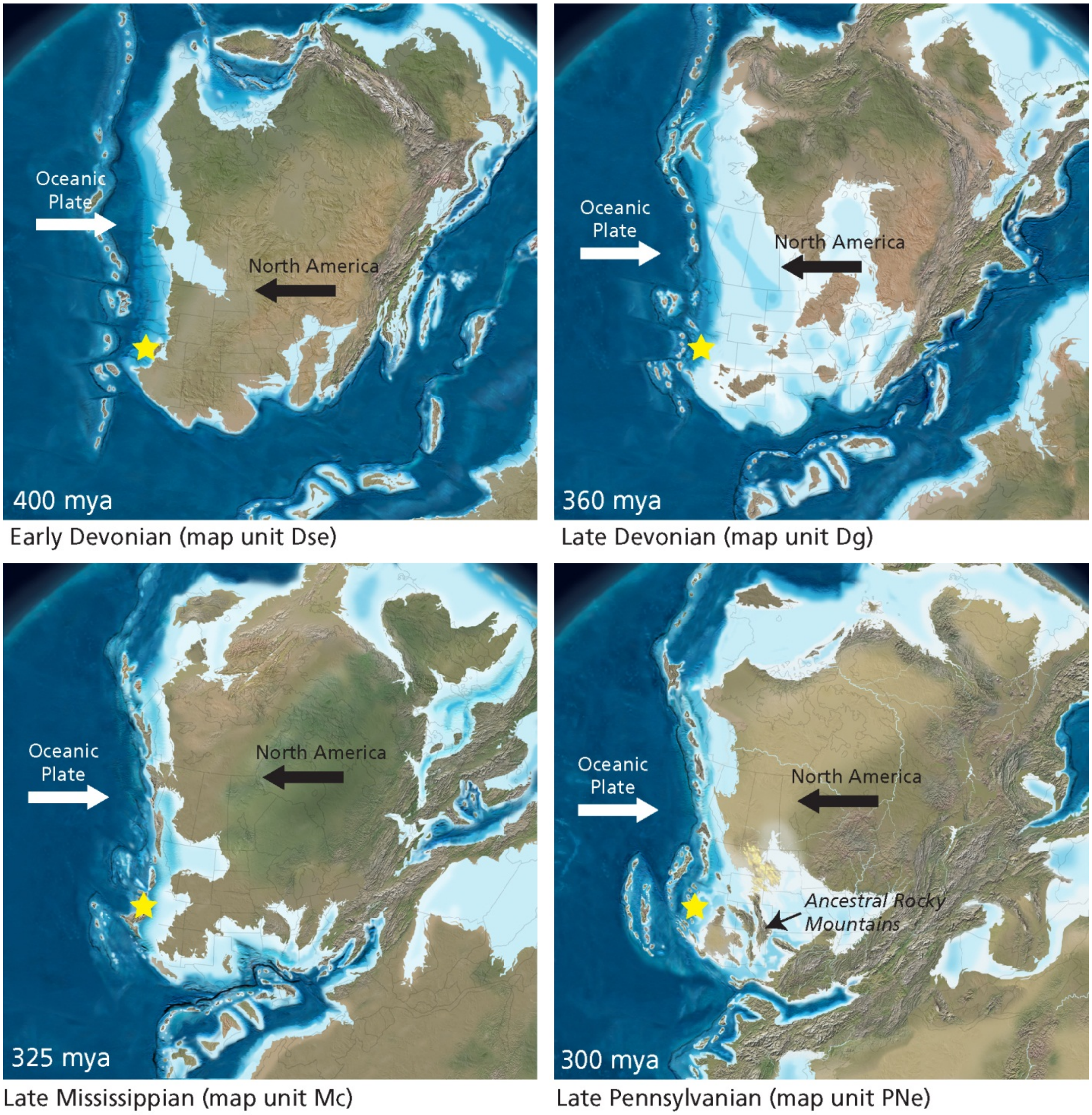


Figure 40. Paleozoic paleogeographic maps of North America. Beginning in the Devonian, a subduction zone developed off the coast of western North American, generating the Antler Orogeny in Nevada. By the end of the Paleozoic, subduction zones along the western, southern, and eastern margins of North America sutured together North America, South America, and Africa. Base paleogeographic maps by Ron Blakey (Colorado Plateau Geosystems, Inc.), available online: http://cpgeosystems.com/index.html (accessed 8 October 2012). Annotation by the author.

originally thought to be the exposed Transcontinental Arch, east of the passive margin. Recycled Precambrian or Cambrian siliciclastics may have supplied some of the sediment. However, recent studies of detrital zircon, grain size, and sediment sorting suggest that the Eureka Quartzite came from the Peace River Arch in British Columbia (Pope et al. 2008). In this model, longshore currents transported sand over 2,000 km (1,200 mi) along the passive margin to the Great Basin region. Another hypothesis suggests that intensive volcanism and acid rain dissolved exposed limestone and left large amounts of residual quartz sand that may have spread over the area (Keller and Lehnert 2010).

The Eureka Quartzite is bounded by major unconformities that record significant changes in sea level. The base of the unit rests on the eroded, karst surface of the Pogonip Group and represents the transgression of the shoreline into the area following a sea level fall. Following deposition of the Eureka Quartzite, a Late Ordovician glacial episode resulted in a lowering of sea level. River channels, some about 20 m (65 ft) deep, incised into the upper Eureka surface (Keller and Lehnert 2010).

With the end of glaciation, sea level rose again, inundating the quartz sand source area and reestablishing a new carbonate platform upon which the dark-colored Late Ordovician–Early Silurian Fish Haven and Laketown Dolomites (OSfl) were deposited. Following glaciation, the continent became submerged to a greater extent than in any previous Paleozoic time (fig. 39; Poole et al. 1992). Far to the west, island-arc systems formed that would eventually collide with the North American continent (Oldow et al. 1989).

From Late Silurian to mid-Early Devonian, relative sea level fell and the shoreline regressed to the west once again. Shallow marine, subtidal to peritidal dolomites of the Early Devonian Sevy Dolomite (Dse) were deposited on a carbonate platform that deepened gradually to the west (fig. 40; Johnson et al. 1991). Regression reached a climax in the Early Devonian when the entire cratonic interior emerged above sea level and marine environments were confined to the edges of the continent (Sloss, 1988).

The Antler Orogeny and an Active Tectonic Margin: Middle Devonian–Late Mississippian (398–318 million years ago)

The transition from a passive tectonic margin to an active subduction zone along the western margin of North America began in the Arctic in the Early Silurian, but its impact on Nevada was not felt until the Devonian. The Middle Devonian Simonson Dolomite (Ds) marks the initial influence of the Antler Orogeny in east-central Nevada (Johnson et al. 1991). The tectonic collision between the North American plate and the Pacific plate caused a rapid sea level rise across the carbonate platform in Nevada and resulted in marine environments conducive to the crinoids and brachiopods found in the Simonson Dolomite. As the passive margin along the western United States changed to an active tectonic margin, a correlative orogeny (Acadian Orogeny) was deforming the east coast of North America (fig. 40). Sea level rose in episodic pulses and transgressed far inland, eventually extending throughout most of the Western Hemisphere (Johnson 1970; Johnson et al. 1985; Johnson and Sandberg 1989; Johnson et al. 1991).

As the Antler Orogeny continued to encroach on the western margin in the Middle Devonian, the offshore carbonate ramp transformed into a carbonate platform consisting of shallow, subtidal carbonate rocks and bioherms (reef-like buildups) in east-central Nevada (Johnson et al. 1991). In the region of Great Basin National Park, the Upper Devonian Guilmette Formation (Dg) contains marine limestones constructed primarily from the remains of brachiopods, crinoids, and stromatoporoids (fig. 40).

The Antler Orogeny produced the northeast–southwest trending Roberts Mountains Thrust, a thrust sheet composed of intricately stacked Paleozoic strata that is exposed from Idaho through central Nevada and into southeastern California (Johnson et al. 1991). In the Upper Devonian, the Pilot Shale (MDp) was deposited in a basin that formed in front of this west-to-east advancing thrust. In Great Basin National Park, the poorly exposed calcareous shale is estimated to be approximately 90 m (300 ft) thick, but the Pilot Shale thickens to the west and contains black carbonaceous shale indicative of anoxic (lacking oxygen) depositional environments (Hose and Blake 1976; Johnson et al. 1991).

The final emplacement of the Roberts Mountains Thrust and the end of the Antler Orogeny occurred in the Mississippian. In the Early Mississippian, a relatively deep trough formed in front of the advancing thrust sheet, and a carbonate platform formed landward of the trough and emerging Antler Orogenic Highlands (Poole and Sandberg 1977, 1991). The crinoids, corals, and brachiopods of the Lower Mississippian Joana Limestone (Mj) inhabited the western border of the carbonate platform and the eastern edge of the trough in the Great Basin National Park area.

Once the Roberts Mountains Thrust was emplaced and the orogeny shut down in the Middle Mississippian, relative sea level fell and the trough filled with sediments shed from the eroding western highlands (Goebel 1991; Poole and Sandberg 1991). The sandstones, siltstones, and shale of the Chainman Shale (Mc) were deposited in deltaic systems, alluvial fans, and fluvial systems as the basin filled and sea level regressed off the craton at the end of the Mississippian (fig. 40).

Compared with other orogenies, the Antler Orogeny in Nevada was fairly rapid. In all, active thrusting lasted only about 25 million years, but the Antler Orogeny established a compressional tectonic regime on the western margin of the United States. Collisions between the North American and Pacific plates would continue for hundreds of millions of years, and still occur today.

The End of an Era and the Emergence of Pangaea: Pennsylvanian–Permian (318–251 million years ago)

During the Pennsylvanian, more land was accreted to the western margin of the United States by the Sonoma Orogeny. The orogeny compressed and attached continental shelf and slope rocks to the continental margin and caused episodic marine transgressions onto the continental interior. The fossiliferous Ely Limestone (PNe) records an Early–Middle Pennsylvanian marine incursion onto the continent (fig. 40).

Permian-age rocks are not mapped in Great Basin National Park, but in Arches National Park and Capitol Reef National Park (see GRI reports by Graham 2004, 2006), stratigraphic sequences record episodic sea level fluctuations and the development of large dune fields throughout the arid west–central United States at the close of the Paleozoic.

As the supercontinent Pangaea formed at the end of the Paleozoic, Africa collided with the east coast and South America sutured onto the southern margin of North America. The Appalachian mountain chain, the Ouachita Mountains in Arkansas and Oklahoma, and the northwest–southeast trending Ancestral Rocky Mountains in Colorado formed as a result of these continent-continent collisions (fig. 40).

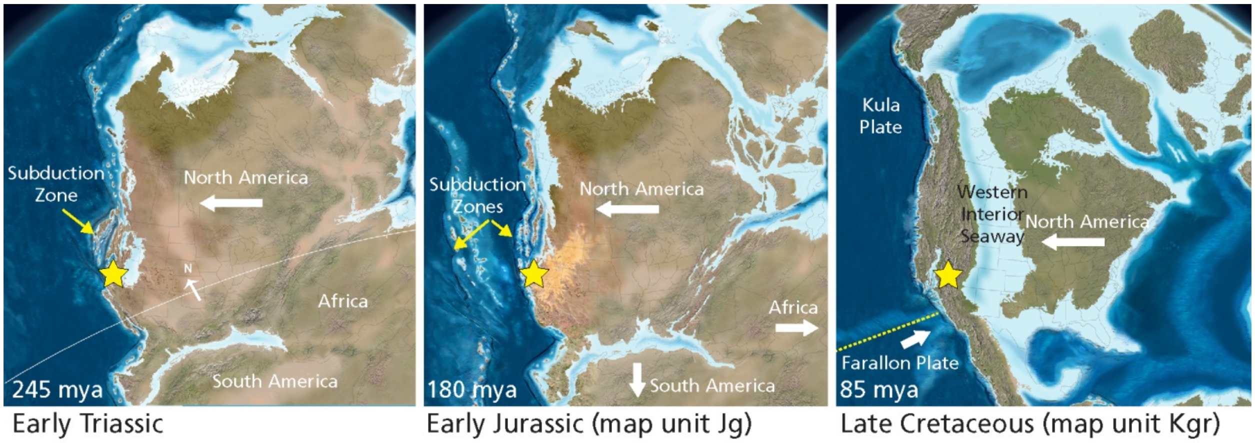


Figure 41. Mesozoic paleogeographic maps of North America. The age of each time frame is in million years ago (mya). In the Early Triassic, all the major land masses came together to form the supercontinent Pangaea. The Sevier Orogeny produced pluton emplacement in the Jurassic (map unit Jg) and Cretaceous (map unit Kgr). Vast dune fields (ergs) covered developed in the Jurassic, also (light brown area). The Western Interior Seaway bisected the North American continent in the Cretaceous. The yellow star approximates the location of Great Basin National Park. The white line across the Early Triassic graphic represents the approximate location of the equator. White arrows represent the direction of plate movement. Base paleogeographic maps by Ron Blakey (Colorado Plateau Geosystems, Inc.), available online: http://cpgeosystems.com/index.html (accessed 8 October 2012). Annotation by the author.

Volcanoes and an Ancient Seaway: The Mesozoic (251–66 million years ago)

In Great Basin National Park, only Jurassic and Cretaceous granitic plutons (Jg and Kgr) remain from the turbulent Mesozoic. Plate subduction along the active tectonic margin of western North America continued throughout the Mesozoic and continues today. Subduction generated magma fed volcanoes on the overriding North American Plate in a process similar to the process that formed Mount St. Helens and other volcanoes in the Cascade Range. This chain of volcanoes stretched nearly the entire length of the western margin of North America (Oldow et al. 1989; Lawton 1994). Magma chambers developed, and igneous intrusions solidified to form the granitic plutons exposed in Great Basin National Park (fig. 41), as well as the iconic features of Yosemite National Park (see GRI report by Graham 2012). Mesozoic strata exposed in many of the national parks and monuments in the southwestern United States document a dynamic history of mountain-building, catastrophic volcanism, vast dune fields (ergs) and complex fluvial systems.

In the Early Triassic, the supercontinent Pangaea reached its greatest areal extent (fig. 41). All the continents converged to form a single landmass that was located symmetrically about the Equator (Dubiel 1994). As the last Paleozoic epicontinental sea withdrew, fluvial, mudflat, sabkha, and shallow marine environments developed in what is now the Great Basin region (Stewart et al. 1972; Morales 2003). Fossilized plants and animals from the Triassic document a warm tropical setting that included both monsoon and drought conditions (Stewart et al. 1972; Dubiel 1994).

Catastrophic volcanic eruptions occurred in the Jurassic as the Farallon Plate collided with North America. Volcanic activity along the western margin of North America extended from Mexico to Canada. Some of the magma that fed the volcanoes solidified to form the Jurassic plutons (Jg) in Great Basin National Park. The collision caused west-to-east thrusting in Nevada and additional land was accreted to the continent. Inland, extensive dune fields developed in western Utah and northern Arizona (fig. 41).

In the Cretaceous, continued subduction produced the Sevier Orogeny, which may have deformed the western margin of North America from approximately 140 million to 50 million years ago (fig. 42). The north–south-trending belt of folds and thrusts (called the Rocky Mountain fold-and-thrust belt) extends from the Brooks Range in Alaska to the Sierra Madre Oriental in Mexico and documents approximately 90 million years of subduction along the entire western margin of North America (Lageson and Schmitt 1994; DeCelles 2004). The Sevier Orogeny is responsible for the voluminous magma that formed the Sierra Nevada Batholith and emplaced continental-margin plutons from Mexico to the Alaskan peninsula, including the Cretaceous granitic pluton (Kgr) in Great Basin National Park (fig. 41; Oldow et al. 1989; Lawton 1994).

As thrust sheets stacked atop one another, the crust parallel to the fold-and-thrust belt began to subside, creating the Western Interior Basin (fig. 41). With subsidence, sea water began to fill the basin from the Arctic region and the Gulf of Mexico. Episodic fluctuations in sea level occurred throughout the Cretaceous, culminating in the formation of the most extensive interior seaway ever to bisect the North American continent (fig. 41). The Western Interior Seaway extended from today's Gulf of Mexico to the Arctic Ocean, a distance of about 4,800 km (3,000 mi; Kauffman 1977; Steidtmann 1993). During periods of maximum sea-level rise, the width of the basin reached 1,600 km (1,000 mi). The Great Basin National Park region was located on the western border of this interior seaway.

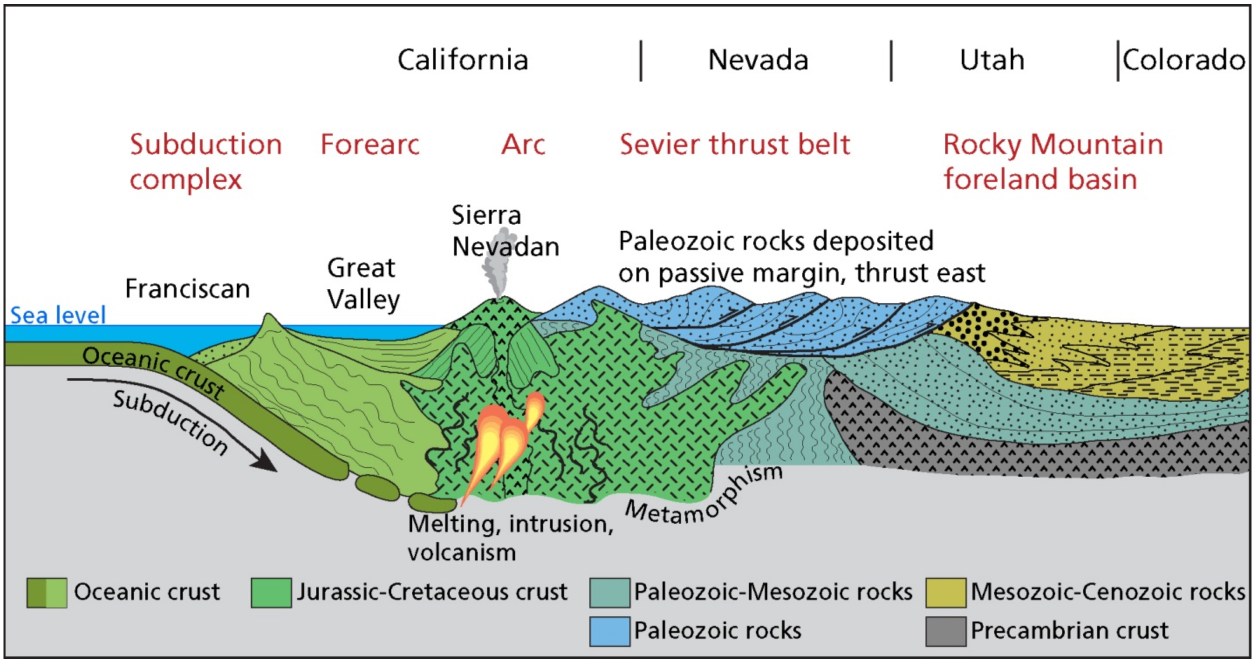


Figure 42. West-east schematic cross-section of the Sevier Orogenic Belt. Original graphic by Ron Blakey (Colorado Plateau Geosystems, Inc.), available online http://cpgeosystems.com/index.html (accessed 8 October 2012). Redrafted by Trista Thornberry-Ehrlich (Colorado State University).

The seaway receded from the continental interior with the onset of the Laramide Orogeny, which occurred about 70–35 million years ago. This orogeny marked a pronounced eastward shift in tectonic activity as the angle of the subducting plate flattened and compressive forces were felt far inland, east of the Great Basin region. Rather than generating volcanic mountain ranges on the west coast as in previous orogenies, the Laramide Orogeny displaced deeply buried Precambrian plutonic and metamorphic rocks that form the core of the Rocky Mountains.

Extensional Tectonics and the Metamorphic Core Complex: The Tertiary (66–2.6 million years ago)

Early in the Tertiary, the angle of the subducting Farallon Plate increased, and as it did, the Laramide Orogeny came to a close and volcanism returned to the western margin of North America (fig. 43). Volcanic calderas, voluminous volcanic deposits, and igneous intrusions that occurred during the Paleogene (65–23 million years ago) can be found throughout the southern Basin and Range Province, including various national parks and monuments, such as Saguaro National Park, Chiricahua National Monument, and Coronado National Memorial (see GRI reports by Graham 2009, 2010, 2011).

In Great Basin National Park, volcanic tuff in the Needles Range Formation (Tnr), exposed southwest of the park in Murphy Wash and Johns Wash, was deposited between 33 million and 27 million years ago by an eruption of the Indian Peak caldera complex. The rhyolitic tuff in the Needles Range Formation is similar in composition to the Tertiary granitic pluton (Tgr) that was emplaced about 36 million years ago during the Eocene (McGrew 1993).

Approximately 35 million years ago, tectonic rifting began to pull apart the Earth's crust beneath the Great Basin, and at depth, the low-angle Snake Range décollement separated metamorphosed Cambrian and Precambrian rocks from younger, unmetamorphosed Paleozoic strata. At least two episodes of normal-fault deformation displaced the hanging wall rocks above the décollement between 8 km (5 mi) and 24 km (15 mi) to the southeast (McGrew 1993). Initial normal fault movement dipped in the opposite direction of the décollement. Later, faults formed that tilted in the same direction as the Southern Snake Range décollement.

As faulting displaced the mass of overlying rock, the part of Earth's crust that was being uncovered (unroofed) began to rise. The rocks that slowly rose to the surface were composed primarily of metamorphic mineral assemblages that formed under unusually high temperatures and pressures. In Great Basin National Park, these consisted of older Precambrian and Lower Cambrian metamorphic rocks. More than 25 of these distinctive, isolated, domed-shaped metamorphic core complexes form a narrow sinuous belt from southern Canada to northwestern Mexico (Coney 1979; Davis 1987; Spencer and Reynolds 1989; Dickinson 1991). In addition to the metamorphic core complex exposed in Great Basin National Park, Saguaro National Park in Arizona preserves a metamorphic core complex that includes the Tortilita, Santa Catalina, and Rincon mountains (Graham 2010).

About 20 million years ago, during the Miocene, subduction off the southwestern coast of North America ceased and volcanism waned in southeastern Arizona (Oldow et al. 1989; Pallister et al. 1997). Plate motion shifted to strike-slip faulting, initiating the San Andreas

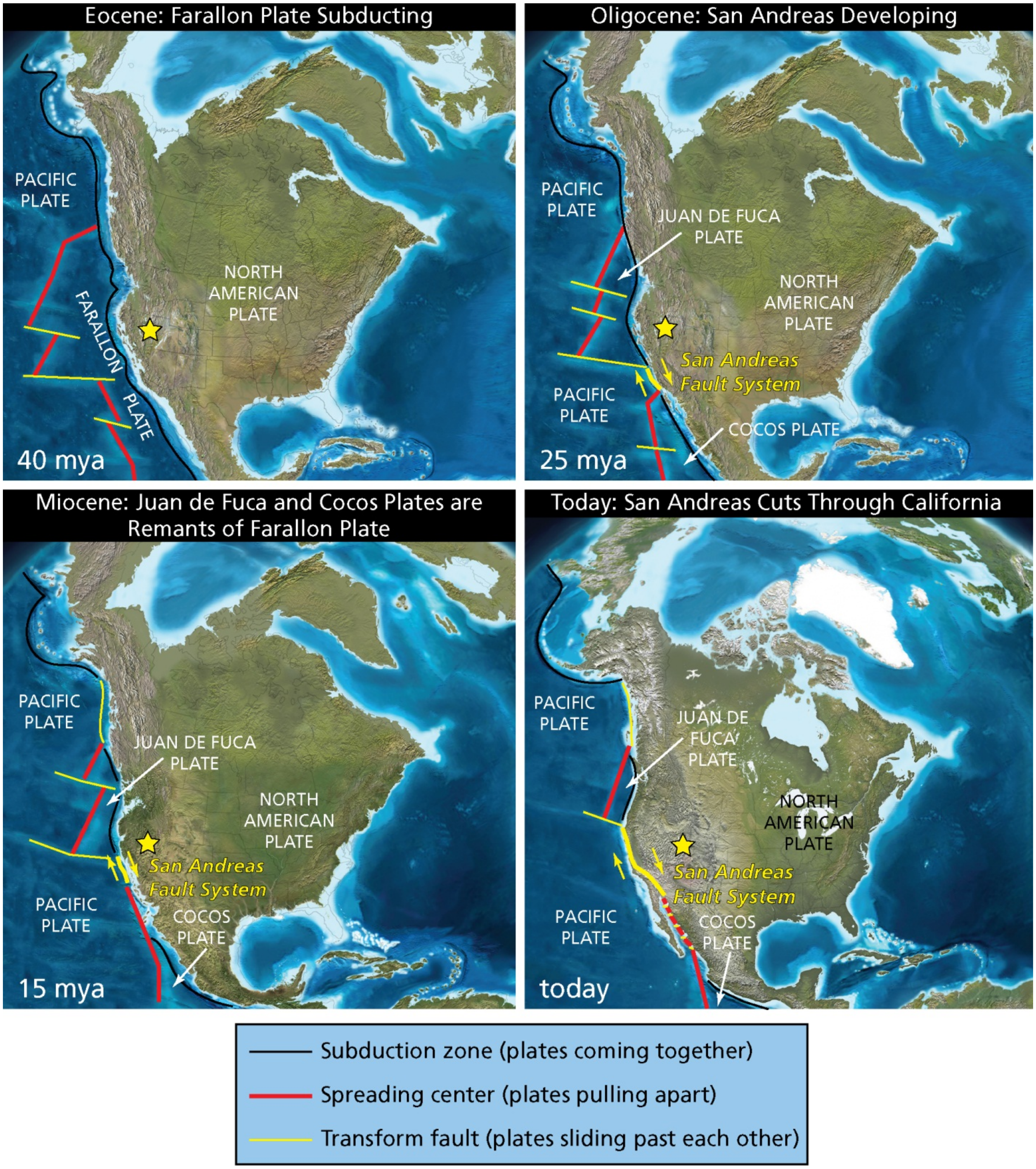


Figure 43. Cenozoic paleogeographic maps of North America illustrating the growth of the San Andreas Fault System. When the spreading center between the Pacific and Farallon plates intersected the North American Plate, a transform fault formed (San Andreas Fault zone), causing strike-slip (transpressional) movement. The Farallon Plate has been subdivided into the Juan de Fuca Plate, to the north, and the Cocos Plate, to the south. Strike-slip faulting and high heat flow caused crustal extension beneath the Great Basin and the subsequent development of Basin and Range horsts and grabens. Base paleogeographic maps by Ron Blakey (Colorado Plateau Geosystems, Inc.), available online: http://cpgeosystems.com/index.html (accessed 8 October 2012). Annotation by Jason Kenworthy (NPS Geologic Resources Division).

Fault system of California (fig. 43). Strike-slip faulting and high heat flow beneath the southwestern United States thinned and stretched the crust beneath the Basin and Range. Large crustal blocks were downdropped along high-angle normal faults to create grabens, such as Spring Valley, while other blocks were uplifted into horsts, such as the Snake Range. This type of regional faulting produced today's Basin and Range topography (figs. 3 and 7).

The Colorado River began eroding the Grand Canyon approximately 5 million years ago (Spencer et al. 2001; Lucchitta 2003). By 3.8 million years ago (Pliocene), the Colorado River had established its current course in the upper Lake Mead area, and by 1 million years ago (middle Pleistocene), it had carved its present path in the western Grand Canyon and formed the southern border of the Great Basin (Lucchitta and Jeanne 2001; Hamblin 2003; Lucchitta 2003).

Ice Sculpture and Cave Carving: The Quaternary (2.6 million years ago to the Present)

When the great Laurentide Ice Sheet covered the northern portion of North America during the Pleistocene ice ages (about 2.5 million to 11,000 years ago), alpine glaciers carved the mountainous landscape of today's Sierra Nevada and many Nevada ranges, including the Snake Range (fig. 44). The wet Pleistocene climate also initiated the growth of cave systems in Great Basin National Park. Studies of radioactive isotopes from Lehman Cave stalagmites suggest that the stalagmites are at least 1 million years old, and possibly much older (McGee 2011). Detailed analysis of one Lehman Cave stalagmite records the end of the second-to-last ice age at 130,000 years before present (Shakun 2011). In contrast, data from Devils Hole, Nevada, suggests that the second-to-last ice age ended 140,000 years before present. Further research on the Lehman Cave stalagmites in Great Basin National Park may help resolve this discrepancy.

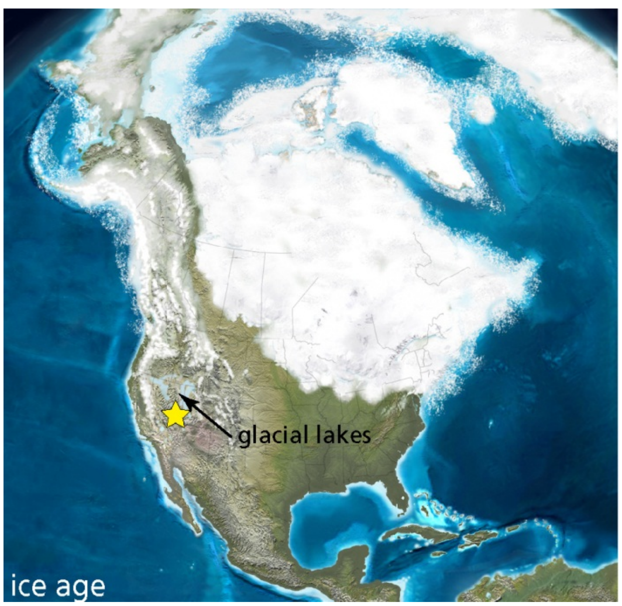


Figure 44. Pleistocene paleogeographic map of North America. Continental ice sheets advanced from the northern latitudes and alpine glaciers formed in the mountains, including the Snake Range (yellow star). Lake Bonneville, which had an area about the size of today's Lake Michigan but was significantly deeper, formed northeast of the Snake Range. Base paleogeographic map created by Ron Blakey (Colorado Plateau Geosystems, Inc.), available online http://cpgeosystems.com/index.html (accessed 8 October 2012). Annotation by the author.

Great Basin National Park contains evidence of two glacial advances in the Southern Snake Range. The younger glacial advance correlates to the Angel Lake Glaciation, named for a tarn lake in the East Humboldt Range of northeastern Nevada. This glaciation occurred approximately 19,300 years ago during the Last Glacial Maximum and formed the hummocky, bulky, lobate Dead Lake moraine, east–southeast of Johnson Lake (Osborn and Bevis 2001; Laabs et al. 2011). Glaciers descended to elevations between 2,650 m (8,690 ft) and 2,850 m (9,350 ft) in the major drainages (Osborn and Bevis 2001).

Moraines in the Dead Lake, South Fork Baker Creek, and Upper Lehman Creek Campground areas formed during the older glaciation (Qg; see the Geologic Features and Processes section). More extensive than the younger glaciers, the pre-Angel Lake glaciers were about 6 km (4 mi) long and descended to elevations between 2,440 m (8,000 ft) and 2,530 m (8,300 ft; Osborn and Bevis 2001). Age data for pre-Angel Lake deposits are rare, but one radiocarbon age from the Wasatch Front in Utah documents an approximate age of 26,000 years before present for the older glacial deposits (Osborn and Bevis 2001).

During the Pleistocene, Lake Bonneville formed in the lowlands northeast of the Snake Range (fig. 44). The lake was more than 300 m (1,000 ft) deep and covered an area of more than 51,000 km^2 (20,000 mi^2). Today's Great Salt Lake, Utah Lake, Sevier Lake, Rush Lake, and Little Salt Lake are remnants of Lake Bonneville.

Sediment cores from Stella and Bake lakes, sub-alpine lakes in Great Basin National Park, provide evidence of paleoclimate during the past 11,000 years (Mark et al. 2006; Porinchu et al. 2008). Analysis of the Stella Lake core indicated that the climate was warm and arid from about 5,400 to 5,000 calendar years before present and then became cool and moist during the "Neoglacial" interval of the late Holocene. Warm conditions returned to the Great Basin approximately 2,000 years ago (Reinemann et al. 2009). Cores from both Stella and Baker lakes indicate consistently above average temperature during the late-20th century (Porinchu et al. 2010).

The current glaciers in Great Basin National Park, which are the only modern glaciers in the interior Great Basin, are not a product of the Pleistocene ice ages. The upper, clean-ice part of the Wheeler Peak glacier formed during the "Little Ice Age", approximately 1,200 years before present. The hummocky surface of the lower segment formed before the clean-ice part of the glacier but after the end of the Pleistocene (Osborn 1988; Osborn and Bevis 2001).

Landslide deposits (Ql) and alluvium (Qa) in the park resulted from erosion and weathering processes that continue to wear down the Snake Range. With each rockfall, talus debris (Qt) accumulates at the base of sheer, glacially-carved cliffs. Tarns slowly fill with sediment in the higher elevations. Ephemeral streams continue to periodically transport unconsolidated sediment to the Spring and Snake valleys. In the subsurface, limestone continues to dissolve near the water table, creating new passageways.

Geologic Map Data

This section summarizes the geologic map data available for Great Basin National Park. The Geologic Map Graphic (in pocket) displays the map data draped over imagery of the park and surrounding area. The Map Unit Properties Table (in pocket) summarizes this report's content for each geologic map unit. Complete GIS data are included on the accompanying CD and are also available at the GRI publications website: http://go.nps.gov/gripubs.

Geologic Maps

Geologic maps facilitate an understanding of an area's geologic framework and the evolution of its present landscape. Using designated colors and symbols, geologic maps portray the spatial distribution and relationships of rocks and unconsolidated deposits. Geologic maps also may show geomorphic features, structural interpretations, and locations of past geologic hazards that may be prone to future activity. Additionally, anthropogenic features such as mines and quarries may be indicated on geologic maps. The American Geosciences Institute website, http://www.agiweb.org/environment/publications/mapping/index.html, provides more information about geologic maps and their uses.

Source Maps

The GRI team digitizes paper maps and converts digital data to conform to the GRI GIS data model. The GRI digital geologic map product includes essential elements of the source maps such as map unit descriptions, a correlation chart of units, a map legend, map notes, references, and figures. The GRI team used the following sources to produce the digital geologic data set for Great Basin National Park. These sources also provided information for this report.

Digital map reference

Miller, E. L, and the Stanford Geological Survey. 2007. Geologic map of Great Basin National Park and environs, Southern Snake Range, Nevada. Stanford Geological Survey (scale 1:24,000).

Reference for unit descriptions

Miller, E. L., and Gans, P. B. 1993. Geologic map of the Wheeler Peak and Minerva Canyon 7.5' quadrangle, White Pine County, Nevada. Department of Geology, Stanford University, unpublished, OF93.

GRI GIS Data

The GRI team implements a GIS data model that standardizes map deliverables. The data model is included on the enclosed CD and is also available at http://science.nature.nps.gov/im/inventory/geology/GeologyGISDataModel.cfm. This data model dictates GIS data structure, including layer architecture, feature attribution, and relationships within ESRI ArcGIS software. The GRI team digitized the data for Great Basin National Park using data model version 2.1. The GRI Geologic Maps website, http://www.nature.nps.gov/geology/inventory/geo_maps.cfm, provides more information about GRI map products.

GRI digital geologic data are included on the attached CD and are available through the NPS Integrated Resource Management Applications (IRMA) portal (https://irma.nps.gov/App/Reference/Search?SearchType=Q). Enter "GRI" as the search text and select a park from the unit list.

The following components are part of the data set:

- A GIS readme file (PDF) that describes the GRI data formats, naming conventions, extraction instructions, use constraints, and contact information.
- Data in ESRI geodatabase GIS format
- Layer files with feature symbology (table 9)
- Federal Geographic Data Committee (FGDC)–compliant metadata
- An ancillary map information document (PDF) that contains information captured from source maps such as map unit descriptions, geologic unit correlation tables, legends, cross-sections, and figures.
- An ESRI map document (.mxd) that displays the digital geologic data
- A KML/KMZ version of the data viewable in Google Earth™ (table 9).

Table 9. Geology data layers in the Great Basin National Park GIS data.

Data Layer	Data Layer Code	On Map Graphic?	On Google Earth?
Geologic Attitude and Observation Points	ATD	No	No
Linear Dikes	DKE	Yes	Yes
Faults	FLT	Yes	Yes
Linear Marker Beds	GLN	Yes	Yes
Geologic Cross Section Lines	SEC	No	Yes
Geologic Contacts	GLGA	Yes	Yes
Geologic Units	GLG	Yes	Yes

Geologic Map Graphic

The Geologic Map Graphic displays the GRI digital geologic data draped over a shaded relief image of the park and surrounding area. Not all GIS feature classes may be included on the graphic (table 9). The graphic's extent was limited to the park and vicinity (fig. 45). Geographic information and selected park features have been added to the graphic. Digital elevation data and added geographic information are not included in the GRI GIS data set, but are available online from a variety of sources. Contact GRI for assistance locating these data.

Map Unit Properties Table

The Map Unit Properties Table lists the geologic time division, symbol, and a simplified description for each of the geologic map units in the GRI GIS data. Following the structure of the report, the table summarizes the geologic features, processes, resource management issues, and history associated with each map unit.

Use Constraints

Graphic and written information provided in this report is not a substitute for site-specific investigations. Ground-disturbing activities should neither be permitted nor denied based upon the information provided here. Please contact GRI with any questions.

Minor inaccuracies may exist regarding the locations of geologic features relative to other geologic or geographic features on the Geologic Map Graphic. Based on the source map scale (1:24,000) and US National Map Accuracy Standards, geologic features represented in the geologic map data are horizontally within 12 m (40 ft) of their true locations.

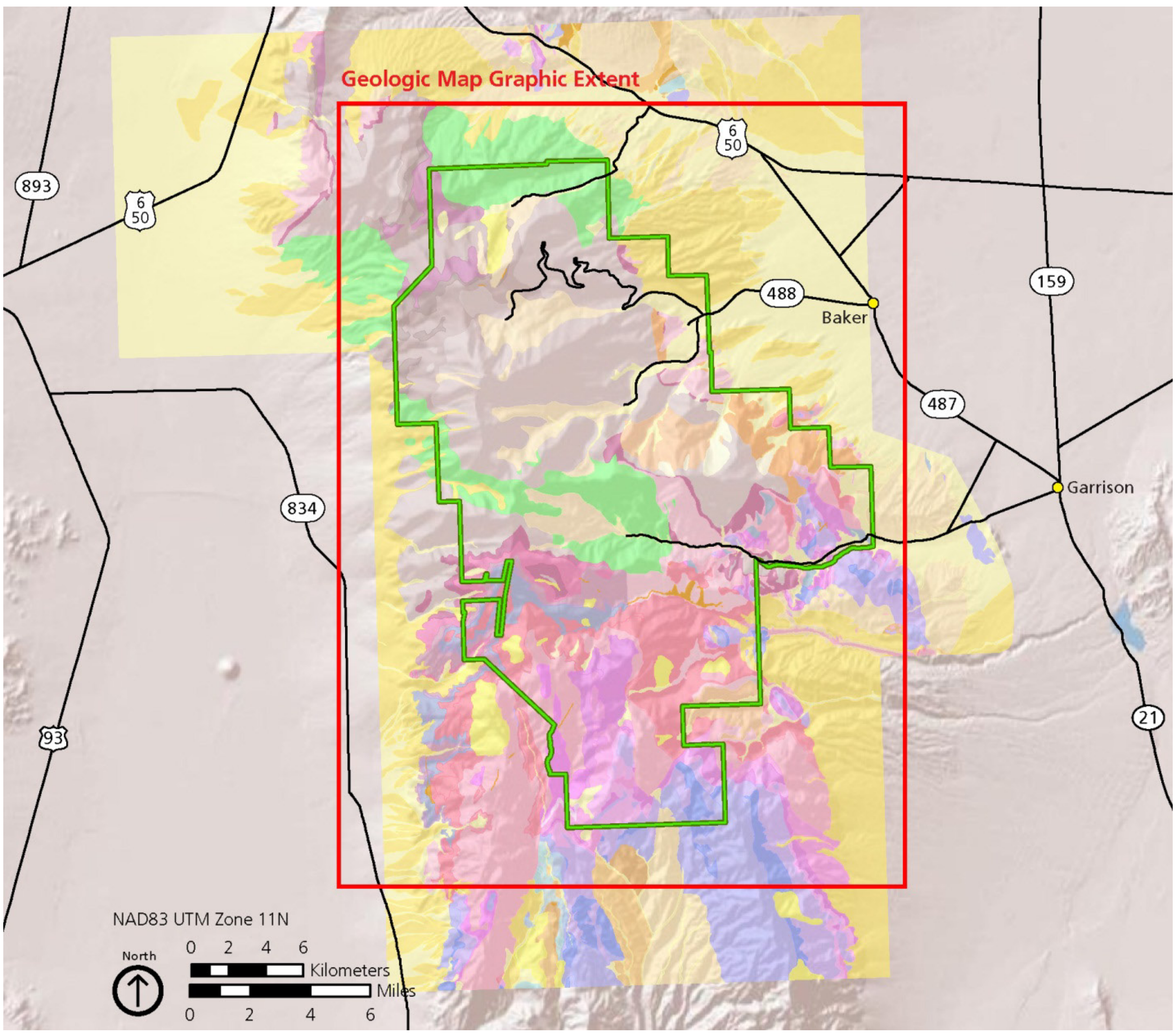


Figure 45. Full extent of GRI GIS data for Great Basin National Park. The Geologic Map Graphic (in pocket) includes the park and surrounding area (red box), the full extent of GRI GIS data is beyond what is depicted on the Geologic Map Graphic. Source maps by Miller and the Stanford Geological Survey (2007). Graphic by Derek Witt (Colorado State University) and Georgia Hybels (NPS Geologic Resources Division).

Glossary

This section contains brief definitions of selected geologic terms relevant to this report. Definitions are based on those in the American Geosciences Institute Glossary of Geology *(5th edition; 2005). Additional terms are defined at http://geomaps.wr.usgs.gov/parks/misc/glossarya.html.*

absolute age. The geologic age of a fossil, rock, feature, or event in years; commonly refers to radiometrically determined ages.
accessory mineral. A mineral whose presence in a rock is not essential to the proper classification of the rock.
accretion. The gradual addition of new land to old by the deposition of sediment or emplacement of landmasses onto the edge of a continent at a convergent margin.
active margin. A tectonically active margin where lithospheric plates come together (convergent boundary), pull apart (divergent boundary) or slide past one another (transform boundary). Typically associated with earthquakes and, in the case of convergent and divergent boundaries, volcanism. Compare to "passive margin."
adit. A horizontal passage from the surface into a mine.
alluvial fan. A fan-shaped deposit of sediment that accumulates where a hydraulically confined stream flows to a hydraulically unconfined area. Commonly out of a mountainous area into an area such as a valley or plain.
alluvium. Stream-deposited sediment.
alpine glacier. A glacier occurring in a mountainous region; also called a valley glacier.
angular unconformity. An unconformity where the rock layers above and below are oriented differently. Also see "unconformity."
anthodite. A pencil-like speleothem, fed through a small central canal, usually composed of aragonite, typically in clusters radiating out from a common base.
anticline. A convex-upward ("A" shaped) fold. Older rocks are found in the center.
aplite. A light-colored intrusive igneous rock characterized by a fine-grained texture. Emplaced at a relatively shallow depth beneath Earth's surface.
arête. A rocky sharp-edged ridge or spur, commonly present above the snowline in rugged mountains sculptured by glaciers. The feature results from the continued backward growth of the walls of adjoining cirques.
argillaceous. Describes a sedimentary rock composed of a substantial amount of clay.
argillite. A compact rock, derived either from mudstone (claystone or siltstone) or shale, that has undergone a somewhat higher degree of induration than mudstone or shale but is less clearly laminated than shale and without its fissility, and that lacks the cleavage distinctive of slate.
ash (volcanic). Fine material ejected from a volcano (also see "tuff").
asthenosphere. Earth's relatively weak layer or shell below the rigid lithosphere.
avalanche. A large mass of snow, ice, soil, or rock, or mixtures of these materials, falling, sliding, or flowing very rapidly under the force of gravity. Velocities may sometimes exceed 500 km/hr (300 mi/hr).
axis (fold). A straight line approximation of the trend of a fold which divides the two limbs of the fold. "Hinge line" is a preferred term.
bajada. Geomorphic feature formed from the coalescence of alluvial fans along a basin margin.
basalt. A dark-colored, often low-viscosity, extrusive igneous rock.
basin (structural). A doubly plunging syncline in which rocks dip inward from all sides.
basin (sedimentary). Any depression, from continental to local scales, into which sediments are deposited.
batholith. A massive, discordant pluton, larger than 100 km^2 (40 mi^2), and often formed from multiple intrusions of magma.
bed. The smallest sedimentary strata unit, commonly ranging in thickness from one centimeter to a meter or two and distinguishable from beds above and below.
bedding. Depositional layering or stratification of sediments.
bedrock. A general term for the rock that underlies soil or other unconsolidated, surficial material.
bentonite. A soft clay or greasy claystone composed largely of smectite. Formed by the chemical alteration of glassy volcanic ash in contact with water.
bergschrund. The crevasse occurring at the head of an alpine glacier that separates the moving snow and ice of the glacier from the relatively immobile snow and ice adhering to the headwall of a cirque.
block (fault). A crustal unit bounded by faults, either completely or in part.
bioherm. A mound-like, dome-like, lens-like, or reef-like mass of rock built up by sedentary organisms, composed almost exclusively of their calcareous remains, and enclosed or surrounded by rock of different lithology.
bioturbation. The reworking of sediment by organisms.
bolson. A term applied in the desert regions of the southwest U.S. to an extensive, flat, alluvium-floored basin or depression, into which drainage from the surrounding mountains flows centripetally, with gentle gradients toward a playa or central depression. An internally drained basin.
breccia. A coarse-grained, generally unsorted sedimentary rock consisting of cemented angular clasts greater than 2 mm (0.08 in).
calcareous. Describes rock or sediment that contains the mineral calcium carbonate ($CaCO_3$).

calc-silicate rock. A metamorphic rock consisting mainly of calcium-bearing silicates and formed by metamorphism of impure limestone or dolomite.

calcite. A common rock-forming mineral: $CaCO_3$ (calcium carbonate).

carbonaceous. Describes a rock or sediment with considerable carbon content, especially organics, hydrocarbons, or coal.

carbonate. A mineral that has CO_3^{-2} as its essential component (e.g., calcite and aragonite).

carbonate rock. A rock consisting chiefly of carbonate minerals (e.g., limestone, dolomite, or carbonatite).

cementation. Chemical precipitation of material into pores between grains that bind the grains into rock.

chalcedony. A variety of quartz that is commonly fibrous on a microscopic level, may be translucent or semitransparent, and has a nearly wax-like luster.

chemical sediment. A sediment precipitated directly from solution (also called nonclastic).

chemical weathering. Chemical breakdown of minerals at Earth's surface via reaction with water, air, or dissolved substances; commonly results in a change in chemical composition more stable in the current environment.

chert. A extremely hard sedimentary rock with conchoidal (smooth curved surface) fracturing. It consists chiefly of interlocking crystals of quartz Also called "flint."

cirque. A deep, steep-walled, half-bowl-like recess or hollow located high on the side of a mountain and commonly at the head of a glacial valley. Produced by the erosive activity of a mountain glacier.

clast. An individual grain or rock fragment in a sedimentary rock, produced by the physical disintegration of a larger rock mass.

clastic. Describes rock or sediment made of fragments of pre-existing rocks (clasts).

clay. Can be used to refer to clay minerals or as a sedimentary fragment size classification (less than 1/256 mm [0.00015 in]).

claystone. Lithified clay having the texture and composition of shale but lacking shale's fine layering and fissility (characteristic splitting into thin layers).

conglomerate. A coarse-grained, generally unsorted, sedimentary rock consisting of cemented, rounded clasts larger than 2 mm (0.08 in).

conodont. One of a large number of small, disjunct fossil elements assigned to the order Conodontophorida, phosphatic in composition and commonly tooth-like in form but not necessarily in function.

contact metamorphism. Changes in rock as a result of contact with an igneous body.

convergent boundary. A plate boundary where two tectonic plates are colliding.

coprolite. Fossil dung (a trace fossil).

cordillera. A Spanish term for an extensive mountain range; used in North America to refer to all of the western mountain ranges of the continent.

country rock. The rock surrounding an igneous intrusion or pluton. Also, the rock enclosing or traversed by a mineral deposit.

craton. The relatively old and geologically stable interior of a continent (also see "continental shield").

crinoid. A marine invertebrate (echinoderm) that uses a stalk to attach itself to a substrate. "Arms" are used to capture food. Rare today, they were very common in the Paleozoic. Crinoids are also called "sea lilies."

cross-bedding. Uniform to highly varied sets of inclined sedimentary beds deposited by wind or water that indicate flow conditions such as water flow direction and depth.

cross section. A graphical interpretation of geology, structure, and/or stratigraphy in the third (vertical) dimension based on mapped and measured geological extents and attitudes depicted in a vertically oriented plane.

crust. Earth's outermost compositional shell, 10 to 40 km (6 to 25 mi) thick, consisting predominantly of relatively low-density silicate minerals (also see "oceanic crust" and "continental crust").

cryptocrystalline. Describes a rock texture where individual crystals are too small to be recognized and separately distinguished with an ordinary microscope.

crystalline. Describes a regular, orderly, repeating geometric structural arrangement of atoms.

crystal structure. The orderly and repeated arrangement of atoms in a crystal.

debris flow. A moving mass of rock fragments, soil, and mud, in which more than half the particles of which are larger than sand size.

décollement. A large-displacement (kilometers to tens of kilometers), shallowly-dipping to sub-horizontal fault or shear zone.

deformation. A general term for the processes of faulting, folding, and shearing of rocks as a result of various Earth forces such as compression (pushing together) and extension (pulling apart).

detachment fault. Synonym for décollement. Widely used for a regionally extensive, gently dipping normal fault that is commonly associated with extension in a metamorphic core complex.

detritus. A collective term for lose rock and mineral material that is worn off or removed by mechanical means.

differential erosion. Erosion that occurs at irregular or varying rates, caused by differences in the resistance and hardness of surface material.

dike. A narrow igneous intrusion that cuts across bedding planes or other geologic structures.

dip. The angle between a bed or other geologic surface and horizontal.

divergent boundary. An active boundary where tectonic plates are moving apart (e.g., a spreading ridge or continental rift zone).

dolomite. A carbonate sedimentary rock of which more than 50% by weight or by areal percentages under the microscope consists of the mineral dolomite (calcium-magnesium carbonate).

dolomitic. Describes a dolomite-bearing rock, or a rock containing dolomite.

dome. General term for any smoothly rounded landform or rock mass. More specifically refers to an elliptical uplift in which rocks dip gently away in all directions.

downcutting. Stream erosion process in which the cutting is directed in primarily downward, as opposed to lateral erosion.

dripstone. A general term for a mineral deposit formed in caves by dripping water.

ductile. Describes a rock that is able to sustain deformation (folding, bending, or shearing) before fracturing.

dune. A low mound or ridge of sediment, usually sand, deposited by wind. Common dune types include "barchan," "longitudinal," "parabolic," and "transverse" (see respective listings).

eolian. Describes materials formed, eroded, or deposited by or related to the action of the wind. Also spelled "Aeolian."

ephemeral stream. A stream that flows briefly only in direct response to precipitation in the immediate locality and whose channel is at all times above the water table.

epicontinental. Describes a geologic feature situated on the continental shelf or on the continental interior. An "epicontinental sea" is one example.

epigenic. Said of a geologic process, or of its resultant features, occurring at or near the Earth's surface.

erg. An regionally extensive tract of sandy desert; a "sand sea."

euhedral. A grain bounded by perfect crystal faces; well-formed.

extension. A type of strain resulting from forces "pulling apart." Opposite of compression.

extrusive. Describes molten (igneous) material that has erupted onto Earth's surface.

fault. A break in rock along which relative movement has occurred between the two sides.

feldspar. A group of abundant (more than 60% of Earth's crust), light-colored to translucent silicate minerals found in all types of rocks. Usually white and gray to pink. May contain potassium, sodium, calcium, barium, rubidium, and strontium along with aluminum, silica, and oxygen.

fenestral. Having openings or transparent areas in a rock; perforated or reticulated.

floodplain. The surface or strip of relatively smooth land adjacent to a river channel and formed by the river. Covered with water when the river overflows its banks.

flowstone. Coatings of calcium carbonate (limestone) that cover many cave surfaces.

folia. Speleothems that are downward-sloping, shelf-like, interveaved tiers, commonly of calcite.

fold. A curve or bend of an originally flat or planar structure such as rock strata, bedding planes, or foliation that is usually a product of deformation.

footwall. The mass of rock beneath a fault surface (also see "hanging wall").

formation. Fundamental rock-stratigraphic unit that is mappable, lithologically distinct from adjoining strata, and has definable upper and lower contacts.

fracture. Irregular breakage of a mineral. Any break in a rock (e.g., crack, joint, fault).

geology. The study of Earth including its origin, history, physical processes, components, and morphology.

graben. A down-dropped structural block bounded by steeply dipping, normal faults (also see "horst").

granite. An intrusive igneous (plutonic) rock composed primarily of quartz and feldspar. Mica and amphibole minerals are also common. Intrusive equivalent of rhyolite.

granodiorite. A group of intrusive igneous (plutonic) rocks containing quartz, plagioclase, and potassium feldspar minerals with biotite, hornblende, or, more rarely, pyroxene, as the mafic components.

groundmass. The material between the large crystals in a porphyritic igneous rock. Can also refer to the matrix of a sedimentary rock.

grus. A silica-rich sand that is the product of weathering and granular disintegration of rocks, typically granite. Rhymes with "goose."

hanging wall. The mass of rock above a fault surface (also see "footwall").

helictites. Delicate speleothems that grow in all directions.

horn. A high pyramidal peak with steep sides formed by the intersection walls of three or more cirques.

horst. Areas of relative "up" between grabens, representing the geologic surface left behind as grabens drop. The best example is the Basin and Range province of Nevada. The basins are grabens and the ranges are weathered horsts. Grabens become a locus for sedimentary deposition (also see "graben").

igneous. Refers to a rock or mineral that originated from molten material; one of the three main classes of rocks—igneous, metamorphic, and sedimentary.

incision. The process whereby a downward-eroding stream deepens its channel or produces a narrow, steep-walled valley.

intrusion. A body of igneous rock that invades (pushes into) older rock. The invading rock may be a plastic solid or magma.

isostacy. The condition of equilibrium, comparable to floating, of the units of the lithosphere above the asthenosphere. Crustal loading (commonly by large ice sheets) leads to isostatic depression or downwarping; removal of the load leads to isostatic uplift or upwarping.

isotopic age. An age expressed in years and calculated from the quantitative determination of radioactive elements and their decay products; "absolute age" and "radiometric age" are often used in place of isotopic age but are less precise terms.

karst topography. Topography characterized by abundant sinkholes and caverns formed by the dissolution of calcareous rocks.

lacustrine. Pertaining to, produced by, or inhabiting a lake or lakes.

lamination. Very thin, parallel layers.

landslide. Any process or landform resulting from rapid, gravity-driven mass movement.

latite. A porphyritic extrusive rock having phenocrysts of plagioclase and potassium feldspar in nearly equal amounts, little or no quartz, and a finely crystalline to glassy groundmass. Extrusive equivalent to monzonite.

lava. Still-molten or solidified magma that has been extruded onto Earth's surface though a volcano or fissure.

left lateral fault. A strike slip fault on which the side opposite the observer has been displaced to the left Synonymous with "sinistral fault."

limestone. A sedimentary rock consisting chiefly of calcium carbonate, primarily in the form of the mineral calcite.

lineament. Any relatively straight surface feature that can be identified via observation, mapping, or remote sensing, often reflects crustal structure.

lithification. The conversion of sediment into solid rock.

lithify. To change to stone or to petrify; especially to consolidate from a loose sediment to a solid rock through compaction and cementation.

lithosphere. The relatively rigid outmost shell of Earth's structure, 50 to 100 km (31 to 62 miles) thick, that encompasses the crust and uppermost mantle.

longshore current. A current parallel to a coastline caused by waves approaching the shore at an oblique angle.

lowstand. The interval of time during one or more cycles of relative change of sea level when sea level is below the shelf edge.

magma. Molten rock beneath Earth's surface capable of intrusion and extrusion.

mass wasting. A general term for the downslope movement of soil and rock material under the direct influence of gravity.

mechanical weathering. The physical breakup of rocks without change in composition. Synonymous with "physical weathering."

megabreccia. A term for a coarse breccia containing individual blocks as much as 400 m (1,300 ft) long.

member. A lithostratigraphic unit with definable contacts; a member subdivides a formation.

meta–. A prefix used with the name of a sedimentary or igneous rock, indicating that the rock has been metamorphosed.

metamorphic. Describes the process of metamorphism or its results. One of the three main classes of rocks—igneous, metamorphic, and sedimentary.

metamorphic core complex. A generally domal or arch-like uplift of deformed metamorphic and plutonic rocks overlain by tectonically detached and distended relatively unmetamorphosed cover rocks.

metamorphism. Literally, a change in form. Metamorphism occurs in rocks through mineral alteration, formation, and/or recrystallization from increased heat and/or pressure.

mineral. A naturally occurring, inorganic crystalline solid with a definite chemical composition or compositional range.

moraine. A mound, ridge, or other distinct accumulation of unsorted, unstratified glacial drift, predominantly till, deposited by glacial ice movement.

mud cracks. Cracks formed in clay, silt, or mud by shrinkage during dehydration at Earth's surface.

normal fault. A dip-slip fault in which the hanging wall moves down relative to the footwall.

obsidian. A black or dark-colored volcanic glass, usually of rhyolite composition with conchoidal fracture. Can be used as a raw material for arrowheads, jewelry, and art objects.

oceanic crust. Earth's crust formed at spreading ridges that underlies the ocean basins. Oceanic crust is 6 to 7 km (3 to 4 miles) thick and generally of basaltic composition.

oolite. A sedimentary rock, usually limestone, made of ooliths—round or oval grains formed by accretion around a nucleus of shell fragment, algal pellet, or sand grain. These laminated grains can reach diameters of 2 mm (0.08 in), but 0.5–1 mm (0.02–0.04 in) is common.

orogeny. A mountain-building event.

orthoquartzite. A clastic sedimentary rock that is made up almost exclusively of quartz sand.

ostracode. Any aquatic crustacean belonging to the subclass Ostracoda, characterized by a two-valved (shelled), generally calcified carapace with a hinge along the dorsal margin. Most ostracodes are of microscopic size.

outcrop. Any part of a rock mass or formation that is exposed or "crops out" at Earth's surface.

paleogeography. The study, description, and reconstruction of the physical landscape from past geologic periods.

paleontology. The study of the life and chronology of Earth's geologic past based on the fossil record.

Pangaea. A theoretical, single supercontinent that existed during the Permian and Triassic periods.

parent material. The unconsolidated organic and mineral material in which soil forms.

parent rock. Rock from which soil, sediments, or other rocks are derived.

passive margin. A margin where no plate-scale tectonism is taking place; plates are not converging, diverging, or sliding past one another. An example is the east coast of North America (compare to "active margin").

pebble. Generally, small rounded rock particles from 4 to 64 mm (0.16 to 2.52 in) in diameter.

pediment. A broad gently sloping rock-floored erosion surface or plain of low relief, typically developed by subaerial agents (including running water) in an arid or semiarid region at the base of an abrupt and receding mountain front or plateau escarpment, and underlain by bedrock.

periglacial. Processes, conditions, areas, climates, and topographic features at the immediate margins of former and existing glaciers and ice sheets.

petroglyph. Literally, a rock carving; it usually excludes writing and therefore is of prehistoric or protohistoric age.

phenocryst. A coarse (large) crystal in a porphyritic igneous rock.

phosphatic. Pertaining to or containing phosphates; commonly refers to a sedimentary rock containing phosphate minerals.

pictograph. A picture painted on a rock by primitive peoples and used as a sign.

plagioclase. An important rock-forming group of feldspar minerals.

plate tectonics. The concept that the lithosphere is broken up into a series of rigid plates that move over Earth's surface above a more fluid asthenosphere.

playa. A dry, vegetation-free, flat area at the lowest part of an undrained desert basin.

playa lake. A shallow, intermittent lake in an arid region, covering up or occupying a playa in the wet season but subsequently drying up.

pluton (plutonic). A body of intrusive igneous rock that crystallized at some depth beneath Earth's surface.

pluvial. Describes geologic processes or features resulting from rain.

porphyry. An igneous rock consisting of abundant coarse crystals in a fine-grained matrix.

porphyritic. Describes an igneous rock wherein the rock contains conspicuously large crystals in a fine-grained groundmass.

potassium feldspar. A feldspar mineral rich in potassium (e.g., orthoclase, microcline, sanidine, adularia).

protalus rampart. An arcuate ridge of coarse, angular blocks of rock derived by single rockfalls from a cliff or steep rocky slope above, marking the downslope edge of an existing or melted snowbank.

pull-apart basin. A topographic depression created by an extensional bend or extensional overstep along a strike-slip fault.

quartzite. Metamorphosed quartz sandstone.

radioactivity. The spontaneous decay or breakdown of unstable atomic nuclei.

radiometric age. An age expressed in years and calculated from the quantitative determination of radioactive elements and their decay products.

regression. A long-term seaward retreat of the shoreline or relative fall of sea level.

relative dating. Determining the chronological placement of rocks, events, or fossils with respect to the geologic time scale and without reference to their numerical age.

reverse fault. A contractional high-angle (greater than 45°) dip-slip fault in which the hanging wall moves up relative to the footwall (also see "thrust fault").

rhyodacite. A volcanic rock intermediate between rhyolite and dacite. Extrusive equivalent to quartz monzonite.

rhyolite. A group of extrusive volcanic rocks, typically porphyritic and commonly exhibiting flow texture, with phenocrysts of quartz and alkali feldspar in a glassy to cryptocrystalline groundmass. The fine-grained extrusive equivalent of granite.

rift. A region of crust where extension results in formation of many related normal faults, often associated with volcanic activity.

ripple marks. The undulating, approximately parallel and usually small-scale ridge pattern formed on sediment by the flow of wind or water.

rip-up clast. A mud clast (usually of flat shape) that has been "ripped up" by currents from a semiconsolidated mud deposit, transported, and deposited elsewhere. Often associated with storms or other high-energy events.

rock. A solid, cohesive aggregate of one or more minerals.

rock fall. Mass wasting process where rocks are dislodged and move downslope rapidly; it is the fastest mass wasting process.

rock glacier. A mass of poorly sorted angular boulders and fine material, with interstitial ice a meter or so below the surface (ice-cemented) or containing a buried ice glacier (ice-cored).

roundness. The relative amount of curvature of the "corners" of a sediment grain.

sand. A clastic particle smaller than a granule and larger than a silt grain, having a diameter in the range of 1/16 mm (0.0025 in) to 2 mm (0.08 in).

sandstone. Clastic sedimentary rock of predominantly sand-sized grains.

seafloor spreading. The process by which tectonic plates pull apart and new lithosphere is created at oceanic ridges.

sediment. An eroded and deposited, unconsolidated accumulation of rock and mineral fragments.

sedimentary rock. A consolidated and lithified rock consisting of clastic and/or chemical sediment(s). One of the three main classes of rocks—igneous, metamorphic, and sedimentary.

shale. A clastic sedimentary rock made of clay-sized particles that exhibit parallel splitting properties.

shield. A speleothem composed of two parallel hemicircular plates separated by a thin, planar crack. Growth occurs radially along the rim, where water issues under pressure from the crack.

silicate. A compound whose crystal structure contains the SiO_4 tetrahedra.

silicic. Describes a silica-rich igneous rock or magma.

sill. An igneous intrusion that is of the same orientation as the surrounding rock.

silt. Clastic sedimentary material intermediate in size between fine-grained sand and coarse clay (1/256 to 1/16 mm [0.00015 to 0.002 in]).

siltstone. A variably lithified sedimentary rock composed of silt-sized grains.

slump. A generally large, coherent mass movement with a concave-up failure surface and subsequent backward rotation relative to the slope.

solifluction. The slow viscous downslope flow of water-logged soil and other unsorted and saturated surficial material, normally at 0.5–5.0 cm/year (0.2–2.0 in/year).

solifluction lobe. An isolated, tongue-shaped feature formed by more rapid solifluction on certain sections of a slope showing variations in gradient.

speleothem. Any secondary mineral deposit that forms in a cave.

spreading center. A divergent boundary where two lithospheric plates are spreading apart. It is a source of new crustal material.

spring. A site where water issues from the surface due to the intersection of the water table with the ground surface.

stalactites. Calcite deposits that form as water drips from the roof of a cave.

stalagmites. Mounds of calcite that commonly form beneath stalactites from dripping water in a cave.

stone garland. A sorted step consisting of a tongue-shaped mass of fine material enclosed n the downslope side by a crescentic stone embankment.
strata. Tabular or sheet-like masses or distinct layers of rock.
stratification. The accumulation, or layering of sedimentary rocks in strata. Tabular, or planar, stratification refers to essentially parallel surfaces. Cross-stratification refers to strata inclined at an angle to the main stratification.
stratigraphy. The geologic study of the origin, occurrence, distribution, classification, correlation, and age of rock layers, especially sedimentary rocks.
stream. Any body of water moving under gravity flow in a clearly confined channel.
stream channel. A long, narrow depression shaped by the concentrated flow of a stream and covered continuously or periodically by water.
stream terrace. Step-like benches surrounding the present floodplain of a stream due to dissection of previous flood plain(s), stream bed(s), and/or valley floor(s).
structural geology. The branch of geology that deals with the description, representation, and analysis of structures, chiefly on a moderate to small scale. The subject is similar to tectonics, but the latter is generally used for the broader regional or historical phases.
structure. The attitude and relative positions of the rock masses of an area resulting from such processes as faulting, folding, and igneous intrusions.
subduction zone. A convergent plate boundary where oceanic lithosphere descends beneath a continental or oceanic plate and is carried down into the mantle.
subsidence. The gradual sinking or depression of part of Earth's surface.
suture. The linear zone where two continental landmasses become joined via obduction.
talus. Rock fragments, usually coarse and angular, lying at the base of a cliff or steep slope from which they have been derived.
tectonic. Relating to large-scale movement and deformation of Earth's crust.
tectonics. The geologic study of the broad structural architecture and deformational processes of the lithosphere and asthenosphere.
terrace. A relatively level bench or step-like surface breaking the continuity of a slope (also see "stream terrace").
terrane. A large region or group of rocks with similar geology, age, or structural style.
terrestrial. Relating to land, Earth, or its inhabitants.
terrigenous. Derived from the land or a continent.
thrust fault. A contractional dip-slip fault with a shallowly dipping fault surface (less than 45°) where the hanging wall moves up and over relative to the footwall.
till. Unstratified drift, deposited directly by a glacier without reworking by meltwater, and consisting of a mixture of clay, silt, sand, gravel, and boulders ranging widely in size and shape.
tonolite. In the IUGS classification, a plutonic rock with quartz between 20% and 60%, and the ration of plagioclase to (albite+plagioclase) is greater than 90%.
topography. The general morphology of Earth's surface, including relief and locations of natural and anthropogenic features.
trace (fault). The exposed intersection of a fault with Earth's surface.
trace fossil. Tracks, trails, burrows, coprolites (dung), etc., that preserve evidence of organisms' life activities, rather than the organisms themselves.
transcurrent fault. A term for a continental strike-slip fault that does not terminate at lithospheric plate boundaries.
transform fault. A strike-slip fault that links two other faults or two other plate boundaries (e.g. two segments of a mid-ocean ridge). A type of plate boundary at which lithosphere is neither created nor destroyed, and plates slide past each other on a strike-slip fault.
transgression. Landward migration of the sea as a result of a relative rise in sea level.
tuff. Generally fine-grained, igneous rock formed of consolidated volcanic ash.
tuffaceous. A non-volcanic, clastic sedimentary rock that contains mixtures of ash-size pyroclasts.
type locality. The geographic location where a stratigraphic unit (or fossil) is well displayed, formally defined, and derives its name. The place of original description.
unconformity. An erosional or non-depositional surface bounded on one or both sides by sedimentary strata. An unconformity marks a period of missing time.
uplift. A structurally high area in the crust, produced by movement that raises the rocks.
volcanic. Describes anything related to volcanoes. Can refer to igneous rock crystallized at or near Earth's surface (e.g., lava).
water table. The upper surface of the saturated zone; the zone of rock in an aquifer saturated with water.
weathering. The physical, chemical, and biological processes by which rock is broken down.

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Additional References

This section lists additional references, resources, and websites that may be of use to resource managers. Web addresses are valid as of January 2014. Refer to Appendix B for laws, regulations, and policies that apply to NPS geologic resources.

Geology of National Park Service Areas

NPS Geologic Resources Division (Lakewood, Colorado): http://nature.nps.gov/geology/

NPS Geologic Resources Inventory: http://www.nature.nps.gov/geology/inventory/index.cfm.

NPS Geoscientist-In-the-Parks (GIP) internship and guest scientist program: http://www.nature.nps.gov/geology/gip/index.cfm

NPS Views program (geology-themed modules are available for Geologic Time, Paleontology, Glaciers, Caves and Karst, Coastal Geology, Volcanoes, and a variety of geologic parks): http://www.nature.nps.gov/views/

NPS Resource Management Guidance and Documents

1998 National parks omnibus management act: http://www.gpo.gov/fdsys/pkg/PLAW-105publ391/pdf/PLAW-105publ391.pdf

Management Policies 2006 (Chapter 4: Natural resource management): http://www.nps.gov/policy/mp/policies.html

NPS-75: Natural resource inventory and monitoring guideline: http://www.nature.nps.gov/nps75/nps75.pdf

NPS Natural resource management reference manual #77: http://www.nature.nps.gov/Rm77/

Geologic monitoring manual (Young, R., and L. Norby, editors. 2009. Geological monitoring. Geological Society of America, Boulder, Colorado): http://nature.nps.gov/geology/monitoring/index.cfm

NPS Technical Information Center (TIC) (Denver, Colorado; repository for technical documents): http://www.nps.gov/dsc/technicalinfocenter.htm

Climate Change Resources

NPS Climate Change Response Program Resources: http://www.nps.gov/subjects/climatechange/resources.htm

US Global Change Research Program: http://globalchange.gov/home

Intergovernmental Panel on Climate Change: http://www.ipcc.ch/

Geological Surveys and Societies

Nevada Bureau of Mines and Geology: http://www.nbmg.unr.edu/

US Geological Survey: http://www.usgs.gov/

Geological Society of America: http://www.geosociety.org/

American Geophysical Union: http://sites.agu.org/

American Geosciences Institute: http://www.agiweb.org/

Association of American State Geologists: http://www.stategeologists.org/

US Geological Survey Reference Tools

National geologic map database (NGMDB): http://ngmdb.usgs.gov/

Geologic names lexicon (GEOLEX; geologic unit nomenclature and summary): http://ngmdb.usgs.gov/Geolex/geolex_home.html

Geographic names information system (GNIS; official listing of place names and geographic features): http://gnis.usgs.gov/

GeoPDFs (download searchable PDFs of any topographic map in the United States): http://store.usgs.gov (click on “Map Locator”)

Publications warehouse (many publications available online): http://pubs.er.usgs.gov

Tapestry of time and terrain (descriptions of physiographic provinces): http://tapestry.usgs.gov/Default.html

Appendix A: Scoping Participants

The following people attended the GRI scoping meeting for Great Basin National Park, held on 12 September 2003, or the follow-up report writing conference call, held on 13 December 2011. Discussions during these meetings supplied a foundation for this GRI report. The scoping summary document is available on the GRI publications website: http://go.nps.gov/gripubs.

2003 Scoping Meeting Participants

Name	Affiliation	Position
Beck, Dave	USGS – Las Vegas	Hydrologist
Billings, Kathy	NPS Great Basin National Park	Superintendent
Darby, Neal	NPS Great Basin National Park	Biologist, GIS
Faulds, Jim	NV Bureau of Mines and Geology/University of Nevada, Reno	Research Geologist, Graduate Faculty
Heise, Bruce	NPS Geologic Resources Division	Geologist, GRE Program Coordinator
Heister, Kris	NPS Mojave Network	Network Coordinator
Johnson, Shylo	NPS Great Basin National Park	Physical Science Technician
Norby, Lisa	NPS Geologic Resources Division	Geologist
O'Meara, Stephanie	Colorado State University	Geologist, GIS
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2011 Conference Call Participants

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Appendix B: Geologic Resource Laws, Regulations, and Policies

The NPS Geologic Resources Division developed this table to summarize laws, regulations, and policies that specifically apply to National Park Service minerals and geologic resources. The table does not include laws of general application (e.g., Endangered Species Act, Clean Water Act, Wilderness Act, National Environmental Policy Act, or National Historic Preservation Act). The table does include the NPS Organic Act when it serves as the main authority for protection of a particular resource or when other, more specific laws are not available. Information is current as of January 2014. Contact the NPS Geologic Resources Division for detailed guidance.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Caves and Karst Systems	**Federal Cave Resources Protection Act of 1988, 16 USC. §§ 4301 – 4309** requires Interior/Agriculture to identify "significant caves" on Federal lands, regulate/restrict use of those caves as appropriate, and include significant caves in land management planning efforts. Imposes civil and criminal penalties for harming a cave or cave resources. Authorizes Secretaries to withhold information about specific location of a significant cave from a FOIA requester. **National Parks Omnibus Management Act of 1998, 16 USC. § 5937** protects the confidentiality of the nature and specific location of cave and karst resources. **Lechuguilla Cave Protection Act of 1993, Public Law 103-169** created a cave protection zone (CPZ) around Lechuguilla Cave in Carlsbad Caverns National Park. Within the CPZ, access and the removal of cave resources may be limited or prohibited; existing leases may be cancelled with appropriate compensation; and lands are withdrawn from mineral entry.	**36 C.F.R. § 2.1** prohibits possessing/ destroying/disturbing…cave resources…in park units. **43 C.F.R Part 37** states that all NPS caves are "significant" and set forth procedures for determining/releasing confidential information about specific cave locations to a FOIA requester.	**Section 4.8.1.2** requires NPS to maintain karst integrity, minimize impacts. **Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. **Section 4.8.2.2** requires NPS to protect caves, allow new development in or on caves if it will not impact cave environment, and to remove existing developments if they impair caves. **Section 6.3.11.2** explains how to manage caves in/adjacent to wilderness.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Paleontology	**National Parks Omnibus Management Act of 1998, 16 USC. § 5937** protects the confidentiality of the nature and specific location of paleontological resources and objects. **Paleontological Resources Preservation Act of 2009**, **16 USC. § 470aaa *et seq.*** provides for the management and protection of paleontological resources on federal lands.	**36 C.F.R. § 2.1(a)(1)(iii)** prohibits destroying, injuring, defacing, removing, digging or disturbing paleontological specimens or parts thereof. **36 C.F.R. § 13.35** prohibition applies even in Alaska parks where the surface collection of other geologic resources is permitted. Regulations in association with 2009 PRPA are being finalized (December 2013).	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity. **Section 4.8.2.1** emphasizes Inventory and Monitoring, encourages scientific research, directs parks to maintain confidentiality of paleontological information, and allows parks to buy fossils only in accordance with certain criteria.
Rocks and Minerals	**NPS Organic Act**, **16 USC. § 1 *et seq.*** directs the NPS to conserve all resources in parks (which includes rock and mineral resources) unless otherwise authorized by law. **Exception: 16 USC. § 445c (c) – Pipestone National Monument enabling statute**. Authorizes American Indian collection of catlinite (red pipestone).	**36 C.F.R. § 2.1** prohibits possessing, destroying, disturbing mineral resources…in park units. **Exception: 36 C.F.R. § 7.91** allows limited gold panning in Whiskeytown. **Exception: 36 C.F.R. § 13.35** allows some surface collection of rocks and minerals in some Alaska parks (not Klondike Gold Rush, Sitka, Denali, Glacier Bay, and Katmai) by non-disturbing methods (e.g., no pickaxes), which can be stopped by superintendent if collection causes significant adverse effects on park resources and visitor enjoyment.	**Section 4.8.2** requires NPS to protect geologic features from adverse effects of human activity.
Mining Claims	**Mining in the Parks Act of 1976, 16 USC. § 1901 *et seq.*** authorizes NPS to regulate all activities resulting from exercise of mineral rights, on patented and unpatented mining claims in all areas of the System, in order to preserve and manage those areas. **General Mining Law of 1872, 30 USC. § 21 *et seq.*** allows US citizens to locate mining claims on Federal lands. Imposes administrative and economic validity requirements for "unpatented" claims (the right to extract Federally-owned locatable minerals). Imposes additional requirements for the processing of "patenting" claims (claimant owns surface and subsurface). Use of patented mining claims may be limited in Wild and Scenic Rivers and OLYM, GLBA, CORO, ORPI, DEVA. **Surface Uses Resources Act of 1955, 30 USC § 612** restricts surface use of unpatented mining claims to mineral activities.	**36 C.F.R. § 5.14** prohibits prospecting, mining, and the location of mining claims under the general mining laws in park areas except as authorized by law. **36 C.F.R. Part 6** regulates solid waste disposal sites in park units. **36 C.F.R. Part 9, Subpart A** requires the owners/operators of mining claims to demonstrate bona fide title to mining claim; submit a plan of operations to NPS describing where, when, and how; prepare/submit a reclamation plan; and submit a bond to cover reclamation and potential liability. **43 C.F.R. Part 36** governs access to mining claims located in, or adjacent to, National Park System units in Alaska.	**Section 6.4.9** requires NPS to seek to remove or extinguish valid mining claims in wilderness through authorized processes, including purchasing valid rights. Where rights are left outstanding, NPS policy is to manage mineral-related activities in NPS wilderness in accordance with the regulations at 36 C.F.R. Parts 6 and 9A. **Section 8.7.1** prohibits location of new mining claims in parks; requires validity examination prior to operations on unpatented claims; and confines operations to claim boundaries.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Nonfederal minerals other than oil and gas	**NPS Organic Act, 16 USC. §§ 1 and 3** **Surface Mining Control and Reclamation Act of 1977, 30 USC § 1201 *et. seq.*** prohibits surface coal mining operations on any lands within the boundaries of a NPS unit, subject to valid existing rights.	**NPS regulations at 36 C.F.R. Parts 1, 5, and 6** require the owners/operators of other types of mineral rights to obtain a special use permit from the NPS as a § 5.3 business operation, and § 5.7 – Construction of buildings or other facilities, and to comply with the solid waste regulations at Part 6. **SMCRA Regulations at 30 C.F.R. Chapter VII** govern surface mining operations on Federal lands and Indian lands by requiring permits, bonding, insurance, reclamation , and employee protection. Part 7 of the regulations states that National Park System lands are unsuitable for surface mining.	**Section 8.7.3** states that operators exercising rights in a park unit must comply with 36 CFR Parts 1 and 5.
Park Use of Sand and Gravel	**Materials Act of 1947, 30 USC. § 601** does not authorize the NPS to dispose of mineral materials outside of park units. **Exception:** 16 USC. §90c 1(b) the non-wilderness portion of Lake Chelan National Recreation Area, where sand, rock and gravel may be made available for sale to the residents of Stehekin for local use as long as such sale and disposal does not have significant adverse effects on the administration of the National Recreation Area.	None applicable.	**Section 9.1.3.3** clarifies that only the NPS or its agent can extract park-owned common variety minerals (e.g., sand and gravel), and -Only for park administrative uses. -After compliance with NEPA and other federal, state, and local laws, and a finding of non-impairment. -After finding the use is park's most reasonable alternative based on environment and economics. -Parks should use existing pits and create new pits only in accordance with park-wide borrow management plan. -Spoil areas must comply with Part 6 standards -NPS must evaluate use of external quarries. Any deviations from this policy require written waiver from the Secretary, Assistant Secretary, or Director.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Upland and Fluvial Processes	**Rivers and Harbors Appropriation Act of 1899, 33 USC. § 403** prohibits the construction of any obstruction, on the waters of the united states, not authorized by congress or approved by the USACE. **Clean Water Act 33USC. § 1342** requires a permit from the USACE prior to any discharge of dredged or fill material into navigable waters (waters of the US (including streams)). **Executive Order 11988** requires federal agencies to avoid adverse impacts to floodplains. (see also D.O. 77-2) **Executive Order 11990** requires plans for potentially affected wetlands (including riparian wetlands). (see also D.O. 77-1)	None Applicable.	**Section 4.1** requires NPS to manage natural resources to preserve fundamental physical and biological processes, as well as individual species, features, and plant and animal communities; maintain all components and processes of naturally evolving park ecosystems. **Section 4.1.5** directs the NPS to re-establish natural functions and processes in human-disturbed components of natural systems in parks unless directed otherwise by Congress. **Section 4.4.2.4** directs the NPS to allow natural recovery of landscapes disturbed by natural phenomena, unless manipulation of the landscape is necessary to protect park development or human safety. **Section 4.6.4** directs the NPS to (1) manage for the preservation of floodplain values; [and] (2) minimize potentially hazardous conditions associated with flooding **Section 4.6.6** directs the NPS to manage watersheds as complete hydrologic systems and minimize human-caused disturbance to the natural upland processes that deliver water, sediment, and woody debris to streams **Section 4.8.1** directs the NPS to allow natural geologic processes to proceed unimpeded. Geologic processes…include…erosion and sedimentation…processes. **Section 4.8.2** directs the NPS to protect geologic features from the unacceptable impacts of human activity while allowing natural processes to continue.

Resource	Resource-specific Laws	Resource-specific Regulations	2006 Management Policies
Soils	**Soil and Water Resources Conservation Act, 16 USC. §§ 2011 – 2009** provides for the collection and analysis of soil and related resource data and the appraisal of the status, condition, and trends for these resources. **Farmland Protection Policy Act, 7 USC. § 4201 *et. seq.*** requires NPS to identify and take into account the adverse effects of Federal programs on the preservation of farmland; consider alternative actions, and assure that such Federal programs are compatible with State, unit of local government, and private programs and policies to protect farmland. NPS actions are subject to the FPPA if they may irreversibly convert farmland (directly or indirectly) to nonagricultural use and are completed by a Federal agency or with assistance from a Federal agency. Applicable projects require coordination with the Department of Agriculture's Natural Resources Conservation Service (NRCS).	**7 C.F.R. Parts 610 and 611** are the US Department of Agriculture regulations for the Natural Resources Conservation Service. Part 610 governs the NRCS technical assistance program, soil erosion predictions, and the conservation of private grazing land. Part 611 governs soil surveys and cartographic operations. The NRCS works with the NPS through cooperative arrangements.	**Section 4.8.2.4** requires NPS to -Prevent unnatural erosion, removal, and contamination. -Conduct soil surveys. -Minimize unavoidable excavation. -Develop/follow written prescriptions (instructions).

The Department of the Interior protects and manages the nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors its special responsibilities to American Indians, Alaska Natives, and affiliated Island Communities.

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