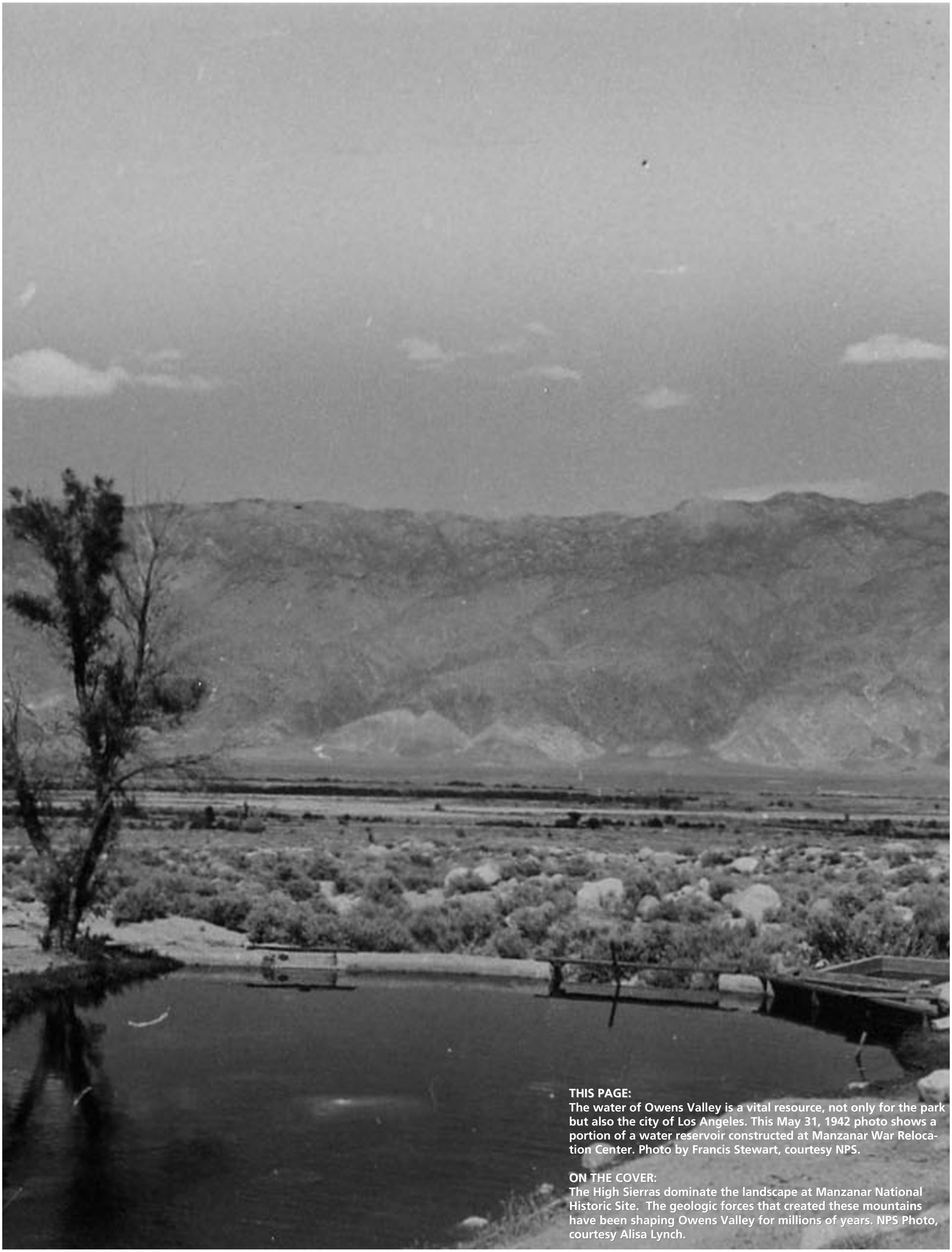
National Park Service
U.S. Department of the Interior

Natural Resource Program Center

Manzanar National Historic Site
Geologic Resources Inventory Report

Natural Resource Report NPS/NRPC/GRD/NRR—2009/130



THIS PAGE:
The water of Owens Valley is a vital resource, not only for the park but also the city of Los Angeles. This May 31, 1942 photo shows a portion of a water reservoir constructed at Manzanar War Relocation Center. Photo by Francis Stewart, courtesy NPS.

ON THE COVER:
The High Sierras dominate the landscape at Manzanar National Historic Site. The geologic forces that created these mountains have been shaping Owens Valley for millions of years. NPS Photo, courtesy Alisa Lynch.

Manzanar National Historic Site

Geologic Resources Inventory Report

Natural Resource Report NPS/NRPC/GRD/NRR—2009/130

Geologic Resources Division
Natural Resource Program Center
P.O. Box 25287
Denver, Colorado 80225

September 2009

U.S. Department of the Interior
National Park Service
Natural Resource Program Center
Denver, Colorado

The Natural Resource Publication series addresses natural resource topics that are of interest and applicability to a broad readership in the National Park Service and to others in the management of natural resources, including the scientific community, the public, and the NPS conservation and environmental constituencies. Manuscripts are peer-reviewed to ensure that the information is scientifically credible, technically accurate, appropriately written for the intended audience, and is designed and published in a professional manner.

Natural Resource Reports are the designated medium for disseminating 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. Examples of the diverse array of reports published in this series include vital signs monitoring plans; "how to" resource management papers; proceedings of resource management workshops or conferences; annual reports of resource programs or divisions of the Natural Resource Program Center; resource action plans; fact sheets; and regularly-published newsletters.

Views, statements, findings, conclusions, recommendations and data in this report are solely those of the author(s) and do not necessarily reflect views and policies of the U.S. Department of the Interior, National Park Service. Mention of trade names or commercial products does not constitute endorsement or recommendation for use by the National Park Service.

Printed copies of reports in these series may be produced in a limited quantity and they are only available as long as the supply lasts. This report is also available online from the Geologic Resources Inventory website (http://www.nature.nps.gov/geology/inventory/gre_publications) and the Natural Resource Publication Management website (http://www.nature.nps.gov/publications/NRPM/index.cfm) or by sending a request to the address on the back cover.

Please cite this publication as:

Thornberry-Ehrlich, T. 2009. Manzanar National Historic Site Geologic Resources Inventory Report. Natural Resource Report NPS/NRPC/GRD/NRR—2009/130. National Park Service, Denver, Colorado.

NPS 359/100134, September 2009

Contents

Figures

Executive Summary

This report accompanies the digital geologic map for Manzanar National Historic Site in California, which the Geologic Resources Division produced in collaboration with its partners. It contains information relevant to resource management and scientific research. This document incorporates preexisting geologic information and does not include new data or additional fieldwork.

Manzanar National Historic Site contains cultural resources that reflect a long history of recurring human settlement and ultimately displacement. This landscape was the home of Owens Valley Paiute Indians, an apple farming center, a cattle ranch, and a War Relocation Center. Manzanar preserves more than human history, as this historic site sits atop a geologically active area of eastern California. The site's location against the backdrop of the Sierra Nevada Mountains attests to the dynamic nature of the features and processes responsible for the development of the current landscape.

The site is located on the western side of Owens Valley, a closed graben basin formed by crustal extension as part of the Great Basin section of the Basin and Range physiographic province. The active tectonic processes of eastern California continue to uplift the surrounding mountains relative to the valley floor primarily along three transform-normal fault systems: the Sierra Nevada Frontal, Owens Valley, and Inyo-White Mountains fault zones. These faults have lowered Owens Valley several kilometers (miles) relative to the surrounding mountain ranges. Factors countering uplift include weathering and erosion of the highlands by glaciers, wind and water, and the deposition of vast amounts of sediment in Owens Valley.

Sediments entrained by glaciers, wind, and water are transported down catchment basins to the range front. Today, Owens Valley is mantled by large coalesced alluvial fans called bajadas. These deposits are mixed with volcanogenic and lacustrine layers from Owens Lake, now a desiccated playa southeast of Manzanar National Historic Site. The historic site sits on a large, uninterrupted bajada northwest of the Alabama Hills, a large bedrock half-horst in the center of Owens Valley.

Geology and geological processes have been particularly prominent in the development of the Owens Valley ecosystem. Understanding the geology of this part of eastern California enhances one's connection to the environment at Manzanar. Geologic processes initiate complex responses that give rise to the rock formations, topographic expression, surface and subsurface fluid movement, and soils in Owens Valley. Because of these correlations, flora and fauna distribution patterns vary with underlying geologic units and structure.

Geologic units hold clues to the geologic history of the area. Geologic resources and the natural history of the Manzanar area merit emphasis and interpretation to enhance the visitor's experience. Human land-use disturbances are easily observed at the park. Surface water diversions and groundwater pumping into the Los Angeles aqueduct have had lasting impacts on the vegetation pattern and water budget of the Owens Valley area. These effects increase the material available for erosion and contribute to dust storms.

The following geologic issues have a high level of management significance at the historic site:

- Flooding and Erosional Processes.
  Erosion is very prevalent as sheet runoff and streams are carving channels and gullies into the landscape. Two perennial streams, Shepherd Creek and Bairs Creek, cause significant erosional channeling into the unconsolidated alluvial fan deposits. During peak stages of natural seasonal floods, both creeks overflow their primary channels into subsidiary channels. These flooding processes have caused channeling and erosion on the western side of the unit and sediment deposition on the eastern side. Overflow from these creeks carries floodwaters threatening cultural and historical resources.

- Active Seismicity.
  Faults are prevalent features of the park's landscape. The large-scale Sierra Nevada Frontal fault system runs west of the site, parallel to the range front. Fault processes are active, displaying evidence of recent movement. This evidence consists of many fresh fault scarps cutting the alluvial fans, offsetting stream channels, and forming local depressions. Most seismic events are small in scale, but can still damage historic site infrastructure such as buildings and roads and undermine slope stability throughout the site. On March 26, 1872, one of the largest recorded earthquakes in California, more than 7.5 M_w (moment magnitude scale), shook the Lone Pine area. Areas of visible displacement were noted along a 32-km (20-mi) transect along the base of the Alabama Hills, southeast of Manzanar National Historic Site. The measurement and study of seismic activity increases knowledge of the tectonic setting and geologic structure throughout the area.

Mineral resources, volcanic activity potential, hydrogeology, and Owens Lake dust are other geologic issues of resource management significance at Manzanar. Understanding the geology of the area is paramount to understanding the environment, how it changes, and the effects of anthropogenic alterations.

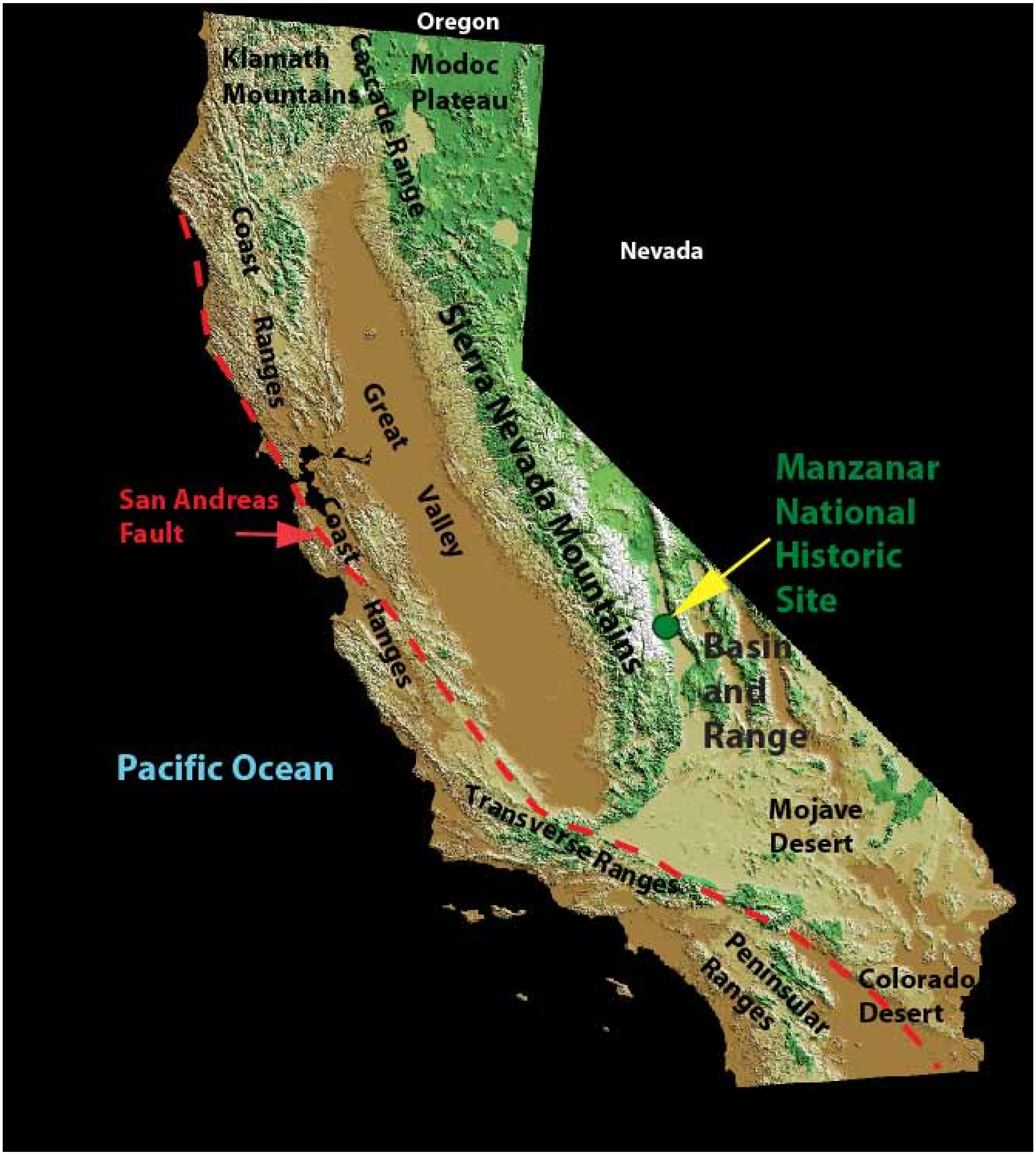


Figure 1. Location of Manzanar National Historic Site on a landform map of California. Dashed red line indicates the rough trace of the San Andreas fault. Note the location of the site on the border between the Basin and Range Province and the Sierra Nevada. Adapted by Trista L. Thornberry-Ehrlich (Colorado State University) from a U.S. Geological Survey graphic.

Introduction

The following section briefly describes the National Park Service Geologic Resources Inventory and the regional geologic setting of Manzanar National Historic Site.

Purpose of the Geologic Resources Inventory

The Geologic Resources Inventory (GRI) is one of 12 inventories funded under the National Park Service (NPS) Natural Resource Challenge designed to enhance baseline information available to park managers. The program carries out the geologic component of the inventory effort. The Geologic Resources Division of the Natural Resource Program Center administers this program. The GRI team relies heavily on partnerships with the U.S. Geological Survey, Colorado State University, state surveys, and others in developing GRI products.

The goal of the GRI is to increase understanding of the geologic processes at work in parks and provide sound geologic information for use in park decision making. Sound park stewardship relies on understanding natural resources and their role in the ecosystem. Geology is the foundation of park ecosystems. The compilation and use of natural resource information by park managers is called for in section 204 of the National Parks Omnibus Management Act of 1998 and in NPS-75, Natural Resources Inventory and Monitoring Guideline.

To realize this goal, the GRI team is systematically conducting a scoping meeting for each of the identified 270 natural area parks and providing a park-specific digital geologic map and geologic report. These products support the stewardship of park resources and are designed for nongeoscientists. Scoping meetings bring together park staff and geologic experts to review available geologic maps and discuss specific geologic issues, features, and processes.

The GRI mapping team converts the geologic maps identified for park use at the scoping meeting into digital geologic data in accordance with their Geographic Information Systems (GIS) Data Model. These digital data sets bring an interactive dimension to traditional paper maps by providing geologic data for use in park GIS and facilitating the incorporation of geologic considerations into a wide range of resource management applications. The newest maps come complete with interactive help files. This geologic report aids in the use of the map and provides park managers with an overview of park geology and geologic resource management issues.

For additional information regarding the content of this report and current GRI contact information please refer to the Geologic Resources Inventory Web site (http://www.nature.nps.gov/geology/inventory/).

Establishment and Geologic Setting

Manzanar National Historic Site was authorized on March 3, 1992. The site protects natural, cultural, and historical resources on 329 ha (814 ac) in the Owens Valley of California, including those related to the relocation and internment of approximately 120,000 Japanese Americans during World War II. Owens Valley is a closed basin in the rain shadow of the Sierra Nevada in eastern California (figs. 1 and 2). This long narrow valley extends approximately 240 km (150 mi) from Haiwee Reservoir north to Lake Crowley. The low point constituting the southern end of Owens Valley contains a small part of Owens Lake, a dry playa at 1,085 m (3,560 ft) of elevation.

Manzanar is situated on an easterly sloping alluvial fan (part of the bajada described below) that slopes 6.5% where they emerge from the mountain front to a more level 2.5% in the vicinity of the internment camp. The location is approximately 8 km (5 mi) east of the sharp Sierra Nevada Front escarpment and 1.6 km (1 mi) west of the Owens River. The site sits between two perennial streams, Shepherd Creek to the north and Bairs Creek to the south, both of which flow east from the Sierra Nevada.

Owens Valley is the westernmost graben basin of the Basin and Range physiographic province (figs. 2 and 3). Two nearly vertical normal faults bound this graben: the Sierra Nevada Frontal and Inyo-White Mountains fault zones. The Sierra Nevada Mountains form the upthrown side of the fault zone immediately to the west of the valley. This mountain range contains the highest peaks of the conterminous United States. The Inyo-White Mountain Range, one of many long, linear, north-south trending parallel ranges of the Basin and Range Province, borders Owens Valley to the east. The Alabama Hills lie near the center of Owens Valley, south of Manzanar, bound on the east by the Owens Valley fault zone (fig. 4).

Sierra Nevada peaks in the Manzanar region include Mount Langley, with an elevation of 4,275 m (14,494 ft), and Mount Williamson, the second-highest peak in the Sierra Nevada at 4,382 m (14,375 ft). Elevations in the Inyo-White Mountains reach 2,960 m (9,700 ft) in the Manzanar area. The site is located at an elevation of approximately 1,200 m (3,900 ft), where bajadas (shallow sloping areas at the base of rocky hills, where materials eroded from the highlands accumulate) or merged alluvial fans from the Sierra Nevada Front meet the Owens Valley floor. The valley formed as a result of crustal extension starting in the Miocene Epoch. Sediments deposited in the graben valley since approximately 3 million years ago are now nearly 3,050 m (10,000 ft) deep at Lone Pine, California.

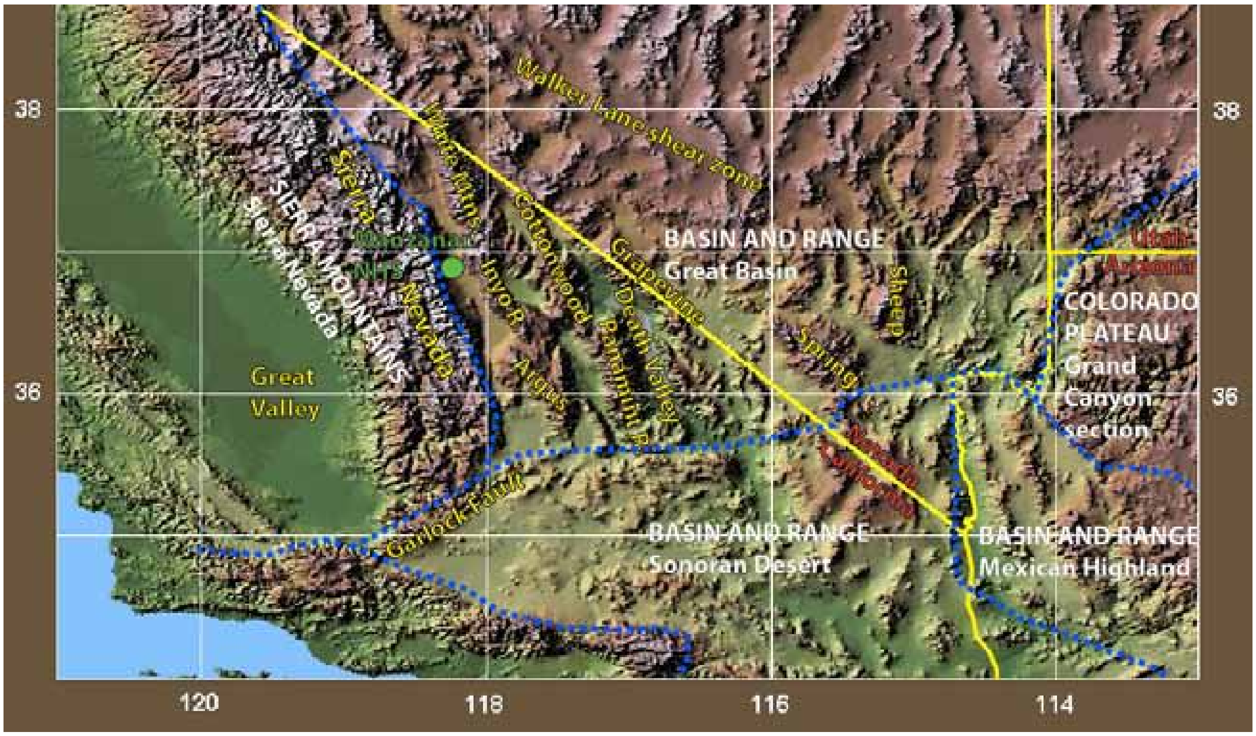


Figure 2. Location of Manzanar National Historic Site (green circle) on a physiographic map of the area. Dashed blue lines indicate approximate boundaries between physiographic provinces and sections. Adapted by Trista L. Thornberry-Ehrlich (Colorado State University) from a NASA image (http://rst.gsfc.nasa.gov/Sect6/Sect6_8.html, accessed March 2, 2009).

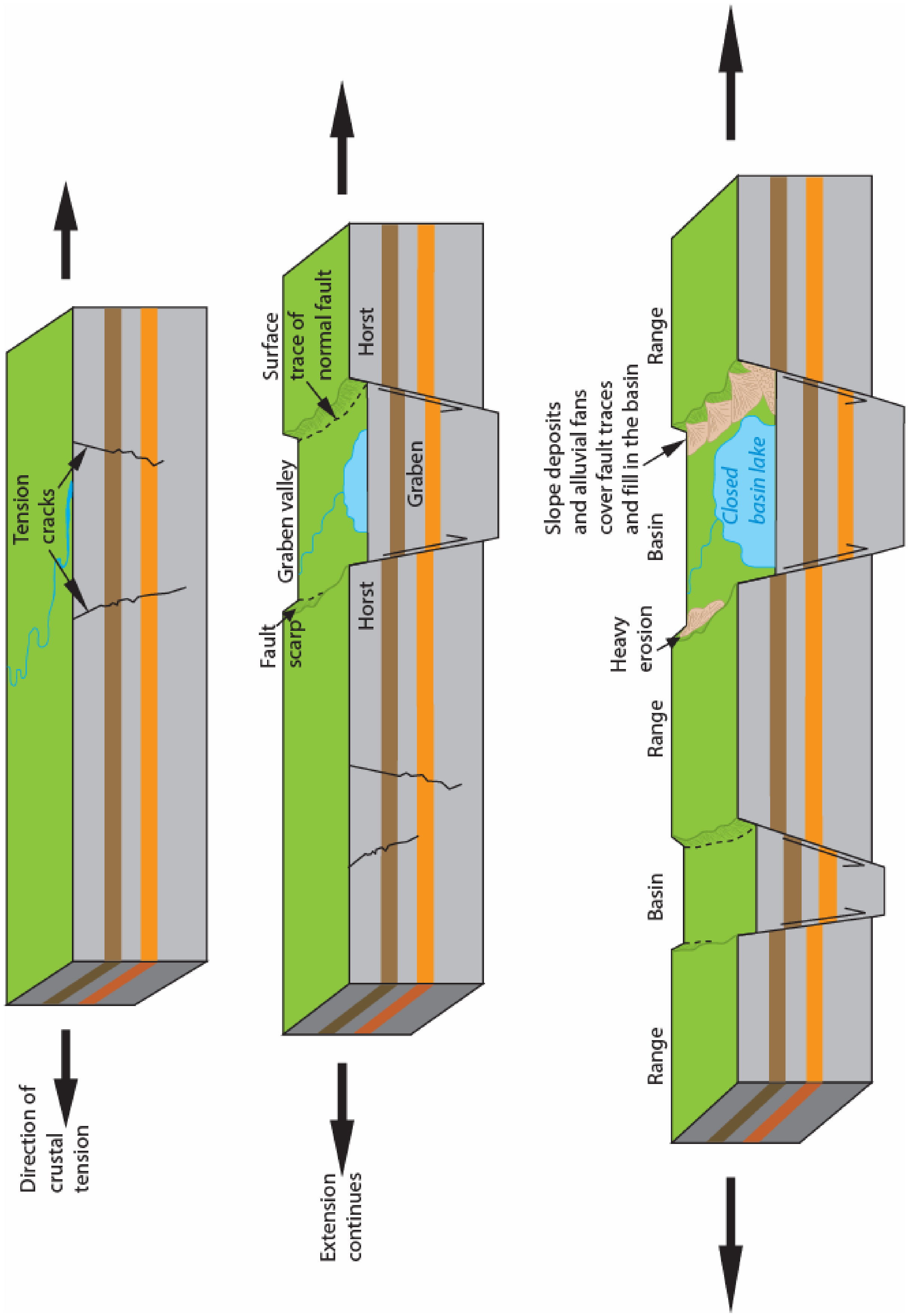


Figure 3: Diagram illustrating the formation of basin and range topography during extension of the Earth's crust along a system of normal faults. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University).

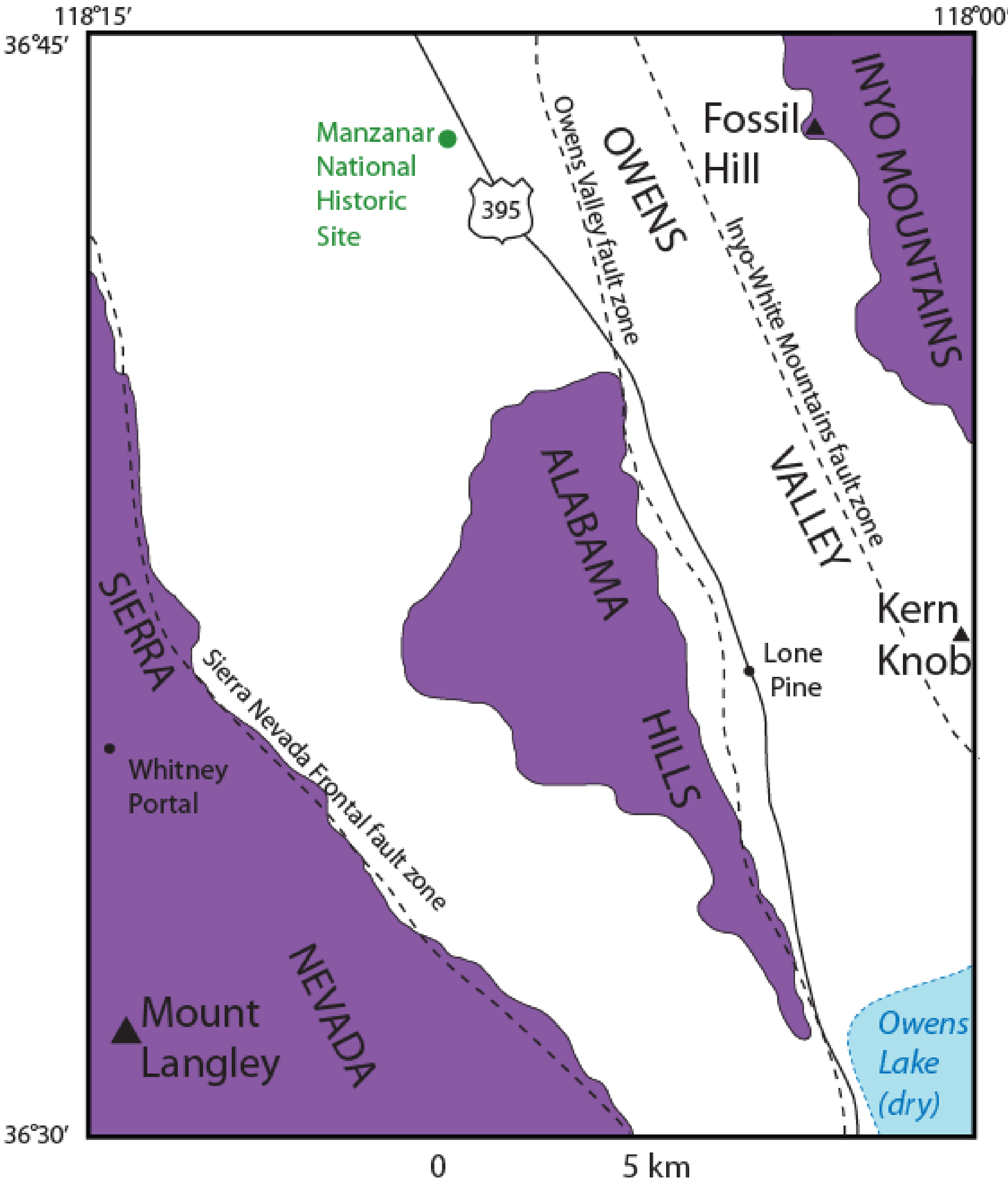


Figure 4. Map of the Manzanar National Historic Site area showing major mountain ranges and approximate fault zone traces. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University), adapted from figure 1 of Stone et al. (2000).

Geologic Issues

The Geologic Resources Division held a Geologic Resources Inventory scoping session for Manzanar National Historic Site on April 28 – May 1, 2003, to discuss geologic resources, address the status of geologic mapping, and assess resource management issues and needs. This section synthesizes the scoping results, in particular those issues that may require attention from resource managers.

Issues in this section are identified in relative order of resource management significance, with the most critical listed first. Potential research projects and topics of scientific interest are presented at the end of each section. Contact the Geologic Resources Division for technical assistance regarding the suggested projects.

Flooding and Erosional Processes

Manzanar National Historic Site sits on alluvial fans that stretch across the Owens Valley from the foothills of the Sierra Nevada. The slope of the fans varies from 6.5% to 2.5%. The fans are comprised of a mixture of bedded gravels and moderately rounded clasts (< 0.5 m [1.6 ft] diameter), in a matrix of finer-grained material. Intermixed with these alluvial fan deposits are layers of debris-flow gravels and poorly bedded clast-supported boulder flows, with angular blocks as large as 1–2 m (3–6 ft) in diameter (Stone et al. 2000). These deposits were shed from the upthrown highlands west of the Sierra Nevada Frontal normal fault zone. Exposure of these unconsolidated deposits makes them extremely susceptible to erosion, especially during seasonal flash flood events.

The geologic processes of erosion are very prevalent at Manzanar. Sheet runoff and streams are carving channels and gulleys into the landscape. At the site, two perennial streams, Shepherd Creek to the north and Bairs Creek to the south, cause significant erosional channeling into the unconsolidated fan deposits. This channeling poses a significant resource management issue at the site. During natural seasonal floods, both creeks overflow their primary channels into subsidiary channels during peak stages (GRI scoping notes 2003).

These flooding processes have resulted in channeling and erosion on the western side of the unit and sediment deposition on the eastern side. Channels eroded into the alluvial fan are parallel to the primary channels of the creeks, and peak-flood-stage events send water flowing south from Shepherd Creek and north from Bairs Creek (National Park Service 2002). Overflow from these creeks carries floodwaters toward, and occasionally through, Manzanar National Historic Site. This impact threatens cultural and historical resources.

Owens Valley sits in the rain shadow formed by the Sierra Nevada Mountains and has a low mean annual precipitation of 12.7–15.2 cm (5–6 in). Much of this rain comes in sporadic and unpredictable, seasonal localized storms that cause flash-flooding and severe gullying into the unconsolidated and sparsely vegetated sediments of the alluvial fans (Jayko et al. 2003). The area is relatively well watered by runoff streams flowing from the heights of the Sierra Nevada. The Los Angeles Department of Water and Power (LADWP), however, collects a considerable quantity of the surface water from the eastern flank of the Sierra Nevada via the Los Angeles aqueduct. This water previously flowed southward to join Owens Creek near Owens Lake, now a dry playa (Hollett et al. 1991). The LADWP owns the water rights from both of the site's creeks; the flow is captured by the Los Angeles aqueduct, about 0.8 km (0.5 mi) east of Manzanar National Historic Site (National Park Service 2002).

The operations of the LADWP are a major factor affecting the hydrologic system of the valley and consequent erosion during floods. The department controls flow at the mountain front and diverts flow to aquifer recharge; thus, the LADWP can cause or mitigate flood damage to the historic site (Hughson written communication 2009). The actions of the LADWP are discussed in more detail under the following "Hydrogeology and Owens Lake Dust" heading.

The geologic framework—the interrelation of rocks and structures such as faults and folds—determines and controls many hydrologic characteristics of the surface and groundwater systems. Because of this relationship, it is vital to understand geologic parameters such as elevation, surface area, and mountain slope, as well as the aerial extent, thickness, and type of rocks forming aquifers. It is also necessary to recognize features within the rock that define its ability to transmit water, including fractures, faults, pore space, and permeability (Hollett et al. 1991). Knowledge of the geologic parameters influencing the hydrologic system would be a great benefit to resource managers at Manzanar National Historic Site.

Although the Manzanar area is generally arid, rocks and soil are prone to slide down the slope in slumps of lobe-shaped masses called solifluction lobes when the ground is water-saturated and heavy. These lobes form a landscape of hummocky topography.

Inventory, Monitoring, and Research Suggestions for Flooding and Erosion Processes

- Actively control flooding by diversion of the Shepherd and Bairs creeks away from park resources. Construct a flood control berm upgradient to deflect flow to the north and south (refer to National Park Service 2002).

- Identify areas susceptible to debris flow processes and incorporate spatial information into the site's GIS.
- Investigate the long-term implications of allowing floodwaters to flow through the site in maintained channels and relocate any impacted cultural resources (refer to National Park Service 2002).
- Perform slope vulnerability studies to identify reaches within the site susceptible to landslides and slumps in the event of an earthquake. Target gullied and/or undercut unconsolidated deposits.
- Determine what effects, if any, historic events and social trail use have had on erosion and seasonal runoff in the site.
- Incorporate spatial slope data into the site's GIS to correlate with underlying geologic units and structure, vegetation patterns, and hydrologic information. Use these data to determine areas vulnerable to extreme erosion and mass wasting.
- Evaluate areas along site roads and trails that have been subject to repeated slide and/or flood events for reinforcement engineering needs.

Active Seismicity

The faults in the Manzanar region are seismically active and major fault systems (the Sierra Nevada Frontal, Owens Valley, and Inyo-White Mountains fault zones) extend the length of Owens Valley (fig. 5). The region is on the extreme western edge of the tectonically active Basin and Range physiographic province. Estimates of the Holocene slip rate vary locally from 1.5 mm/year to 7 mm/year (0.06 in/year to 0.3 in/year) and the local seismic recurrence interval is probably between 3,000 and 4,000 years (Jessey and Wall 2006). Continued extension in this area promotes downdropping of the valley and relative uplift of the surrounding mountains. The setting of Owens Valley on the eastern side of California is significant because it experiences both Basin and Range extension and right-lateral fault movement associated with the San Andreas Fault (forming the boundary between the North American and Pacific plates). This combined activity results in major regional earthquake activity.

On March 26, 1872, a Richter scale magnitude 8 (7.5+ M_w, moment magnitude scale) or greater earthquake shook the Lone Pine area. This was one of the largest quakes to occur in California in recorded time. Twenty-seven people died in the Lone Pine earthquake and most buildings in the area suffered severe damage. Slip from the 1872 event was approximately 1.2 m (4 ft) vertically and 6 m (18 ft) horizontally (Jessey and Wall 2006). Mass wasting (rockslide) events, triggered by the shaking, occurred as far north as Yosemite Valley, 177 km (110 mi) from the earthquake's epicenter (Sharp and Glazer 1997). In 1986, a 6.3 M_w earthquake occurred near the town of Chalfant, California. The epicenter for this event was located north of Manzanar National Historic Site, but local residents felt the earthquake and many aftershocks throughout the area. The faults of the Lone Pine area pose a significant seismic hazard (Martel 1989). Areas of visible displacement from the 1872 earthquake are exposed along a 32-km (20-mi) transect near the town of Lone Pine, along the base of the Alabama Hills (Norris and Webb 1976; Jessey and Wall 2006). Relative ground movement along the so-called Lone Pine fault was locally as much as 5 m (15 ft) vertically and 15 m (45 ft) horizontally.

The threat of future large-scale seismic activity throughout the Owens Valley region is high. Many measured seismic events occur in the Manzanar area each year. Most earthquakes at Manzanar are relatively small, and seldom detected by humans; even minor shaking, however, can pose hazards of mass wasting (slumps, landslides, and debris flows) that affect undercut, weakened or unconsolidated geologic units exposed on moderate slopes. Ground shaking related to a single large earthquake event can produce widespread effects that may include an increase in intensity and quantity of smaller-scale seismic events preceding and following the earthquake. Even if earthquakes are not focused within the boundaries of Manzanar, regional seismic episodes have far-reaching effects that may impact the site's natural and cultural resources. Vulnerable areas are identifiable by factors such as the composition of the surface and bedrock material, degree of slope, and proximity to known active faults. Resource managers need to consider the earthquake-related hazards of liquefaction, lateral spreading, rockfalls, landslides, and fault ruptures in planning future site development.

Inventory, Monitoring, and Research Suggestions for Active Seismicity

- Promote regional seismic activity studies by local universities and the U.S. Geological Survey.
- Perform detailed mapping of the fault traces across the area to better understand and constrain conditions of deformation through time.
- Work to increase the number of seismometers in Owens Valley.
- Study the most recent paleoseismic events along sections of the area's faults using samples of fault gouge and radiocarbon dating of any offset organic material.
- Perform vulnerability index assessment of areas likely to impact visitor health and safety in the event of a large earthquake.
- Incorporate spatial earthquake data, such as epicenters, into a GIS. Include geologic, slope, and trail data to determine areas susceptible to failure during a moderate earthquake.

Volcanic Activity Potential

Recent volcanic activity is widespread throughout the southwestern United States in Arizona, New Mexico, Nevada, and California. In the Basin and Range province, active tectonic extension thins the crust, allowing hot, upwelling magmatic material to reach the surface through shorter conduits. When subduction of the former Farallon tectonic plate beneath North America ceased (described in the "Geologic History" section), a portion of the East Pacific Rise was trapped beneath continental North America. This mid-ocean ridge is the feeder system for Cenozoic volcanism in eastern California (Jessey and Wall 2006). Owens Valley volcanic activity began around 7 million years ago (Fridrich et al. 2000).

The Long Valley-Mono Lake volcanic area lies north of Manzanar National Historic Site in the upper reaches of the Owens River. This center is associated with frequent explosive rhyolitic eruptions, some as recently as 600 years ago. These eruptions emanated from the Glass Creek, Obsidian, and South Deadman vents of the Inyo Craters chain. Volcanic deposits from this center include ash falls, pyroclastic flows, and lava flows covering more than 9,000 square km (3,500 square mi) (Miller 1985). The Bishop Tuff, a unit of welded volcanic ash and pumice, was deposited approximately 710,000 years ago by a major eruption of the Long Valley Caldera. Estimates of the volume of material extruded by this event range from 125 to 165 cubic km (30 to 40 cubic mi).

The Coso volcanic field lies east of the Sierra Nevada Range and south of Manzanar National Historic Site. This field contains rhyolite domes and basaltic cinder cones of Pliocene to Quaternary age. These volcanic deposits cover an area of approximately 390 square km (150 square mi) with younger, bimodal eruptions of basaltic lava flows intruded by rhyolite domes and flows. Volcanism, and the threat of a major eruption, continue in this area into the Holocene (Jessey and Wall 2006). Other regional volcanic fields include the basalts of the Big Pine field.

Inventory, Monitoring, and Research Suggestions for Volcanic Activity Potential

- Perform engineering studies using a strain meter to evaluate the potential for new volcanism.
- Use high resolution Global Positioning System (GPS) to detect moving, swelling, and collapse in areas of the historic site.
- Prepare an action plan in the event of active regional volcanism.
- Prepare interpretive exhibits focusing on the history of volcanism in the area and highlighting the potential for future events.

Mineral Resource Issues

The deep deposits of the alluvial fans in the Manzanar National Historic Site area contain vast amounts of valuable sand, gravel, and cobbles, which are attractive to local developers in search of fill material for construction projects. In 2003, a private company proposed developing a sand and gravel pit for the area to the west and upslope of the historic site to provide fill material (GRI scoping notes 2003). However, given the sloped nature of the landscape as well as the presence of vast deposits of unconsolidated material, any disturbance of surface material uphill from Manzanar could result in alterations to the hydrologic system and increased erosion and sedimentation in the site. The NPS worked with the Inyo County Planning Department and Board of Supervisors and the permit application for the gravel pit was denied (F. Hays, written communication, 2009). At that time, the NPS suggested to the Inyo County Planning Department to change the zoning around the park to reflect the need to prevent such proposals in the future (F. Hays, written communication, 2009).

Negative effects from mining activities are far-reaching and long lasting. Impacts include disturbed floodplain areas resulting from extensive quarrying. Sand and gravel mining may remove riparian zone vegetation and excavate topsoil and gravel from the stream channel and active floodplain. It may also change the slope of alluvial fan and debris flow deposits. If these deposits are undercut by a mining operation, severe erosion and mass wasting potential could increase. Park resource management is concerned that sand and gravel mining activity could result in changes in channel and floodplain morphology, streamflow, and streambed composition facilitated by erosion and/or deposition. These changes could profoundly affect cultural resources at Manzanar National Historic Site (GRI scoping notes 2003).

Inventory, Monitoring, and Research Suggestions for Mineral Resource Issues

- Monitor suspended sediment concentrations and fine bed material in local streams to help determine ecological effects of potential mining.
- Cooperate with local developers to determine areas available for mining that do not threaten the site’s natural and cultural resources.
- Collect continuous records of streamflow that relate changes in channel configuration and bed elevation to sediment transport, erosion and deposition in local stream reaches to help determine potential effects of upslope mining.

Hydrogeology and Owens Lake Dust

One major stream, Owens River, incises Owens Valley, flowing southward from its headwaters in Long Valley. It flows along the eastern side of Owens Valley toward its southern terminus, Owens Lake, dammed by the Coso volcanic complex. The volcanic complex also blocks significant groundwater outflow from the southern end of the valley (Hollett et al. 1991). Additionally, active fault zones form hydraulic barriers and generate perched discharge areas. In these, groundwater flows along a barrier to the surface in the midst of otherwise gently sloping fans and pediments (Jayko et al. 2003).

Prior to anthropogenic interference, Owens Lake was a large body of water filling much of Owens Valley, with depths reaching 6 m (20 ft) and an area covering more than 285 square km (110 square mi) (McCarley Holder et al. 1991). Diversion of water for local agriculture began in the early 1900s and the river aqueduct system was established in 1913 (Hollett et al. 1991). Today, evaporation exceeds inflow and the lake is a dry playa.

The Los Angeles Department of Water and Power (LADWP) owns much of the land and water rights of Owens Valley and performs extensive pumping and surface water diversion there. The water is transported over 320 km (200 mi) in the Los Angeles aqueduct. The large volumes of water pumped by the LADWP are a source of concern regarding the amount and sustainability of valley aquifer recharge. Surface subsidence may also occur as a result of the absence of buoying groundwater in pore space (hydraulic head declines, reducing pore pressure and draining pore space). Pumping has also reduced the water available to native grasses, riparian habitats, and wetlands. Groundwater pumping in Owens Valley has greatly reduced phreatophytic shrubs and grasses. Soil erodability increases as vegetation decreases due to increased aridity and range fires, adding to an already significant problem at Manzanar National Historic Site (Bierman and Gillespie 1990; Zekster et al. 2005).

Owens Lake is currently a dry playa that contains vast layers of evaporites and brines, including alkali dust covering 164 sq km (63.5 sq mi) and 120 sq km (46.5 sq mi) of lake bed composed of lacustrine sediments (clay, silt, sand, and gravel) (McCarley Holder et al. 1991). Park management has expressed concern for air quality and visitor safety regarding the presence of windblown alkali dust from the desiccated Owens Lake, southeast of the site. The mineral dusts from this playa also contain elevated concentrations of sulfates and heavy metals including arsenic, chromium, copper, nickel, lead, thorium, uranium, molybdenum, and antimony. These metals are soluble and bioavailable in the lakebed evaporites (Reheis et al. 2001).

The playa surface is susceptible to wind erosion, the degree of which is controlled by crust strength and continuity. Dust generation stems from soil erosion caused by saltation, fine soil particle entrainment, and salt efflorescence. Saltating sand and chunks of crust damage and destroy evaporative crusts during heavy winds. Fine particles become wind-entrained from the damaged crusts and underlying loose dry soils, and become part of the dust plume. During colder periods, efflorescent white salt powder forms on the surface of the salt crust and is prone to erosion by high winds. Wind speeds above 32 km/hr (20 mi/hr) trigger dust storms from Owens Lake, with plumes from large storms rising vertically more than 2,740 m (9,000 vertical ft) and transporting dust more than 240 km (150 mi) downwind. This dust impacts air quality and contains salts and contaminants trapped in lake sediments (McCarley Holder et al. 1991).

After years of agreements, court hearings, and appeals, the LADWP is now under court order to release canal water into Owens Lake for dust control (Klingler 2008; D. Hughson, written communication, 2009). This began in late 2006, with base flow targets achieved in Owens River by mid-2007 (Klingler 2008). The ongoing drought in California, however, may shift water rights priorities. For more detailed information on the history of this situation, visit the Inyo County Water Department's website (http://www.inyowater.org). This remains a topic for resource managers to monitor at Manzanar National Historic Site.

Inventory, Monitoring, and Research Suggestions for Hydrogeology and Owens Lake Dust

- Research potential for artificial recharge of groundwater aquifers, focusing on areas with noticeable subsidence.
- Cooperate with local, state, and federal agencies to increase the water budget for Owens Lake in an attempt to keep dust levels low.
- Research means to reduce the amount of erosion of the Owens Lake playa.
- Monitor air quality, including dust composition, at the historic site to determine the effects and sources of dust storms.
- Correlate air quality changes with surface water quality monitoring and soil composition.

Other Geologic Issues and Suggestions

- Perform detailed geologic and soils mapping, preferably in a digital format for incorporation in the park's GIS.
- Cooperate with state, federal, and local agencies and universities on geologic mapping and field studies efforts.
- Develop more geologic themed interpretive programs to increase visitor awareness of the role geology plays in the landscape evolution and ecosystem at the park.

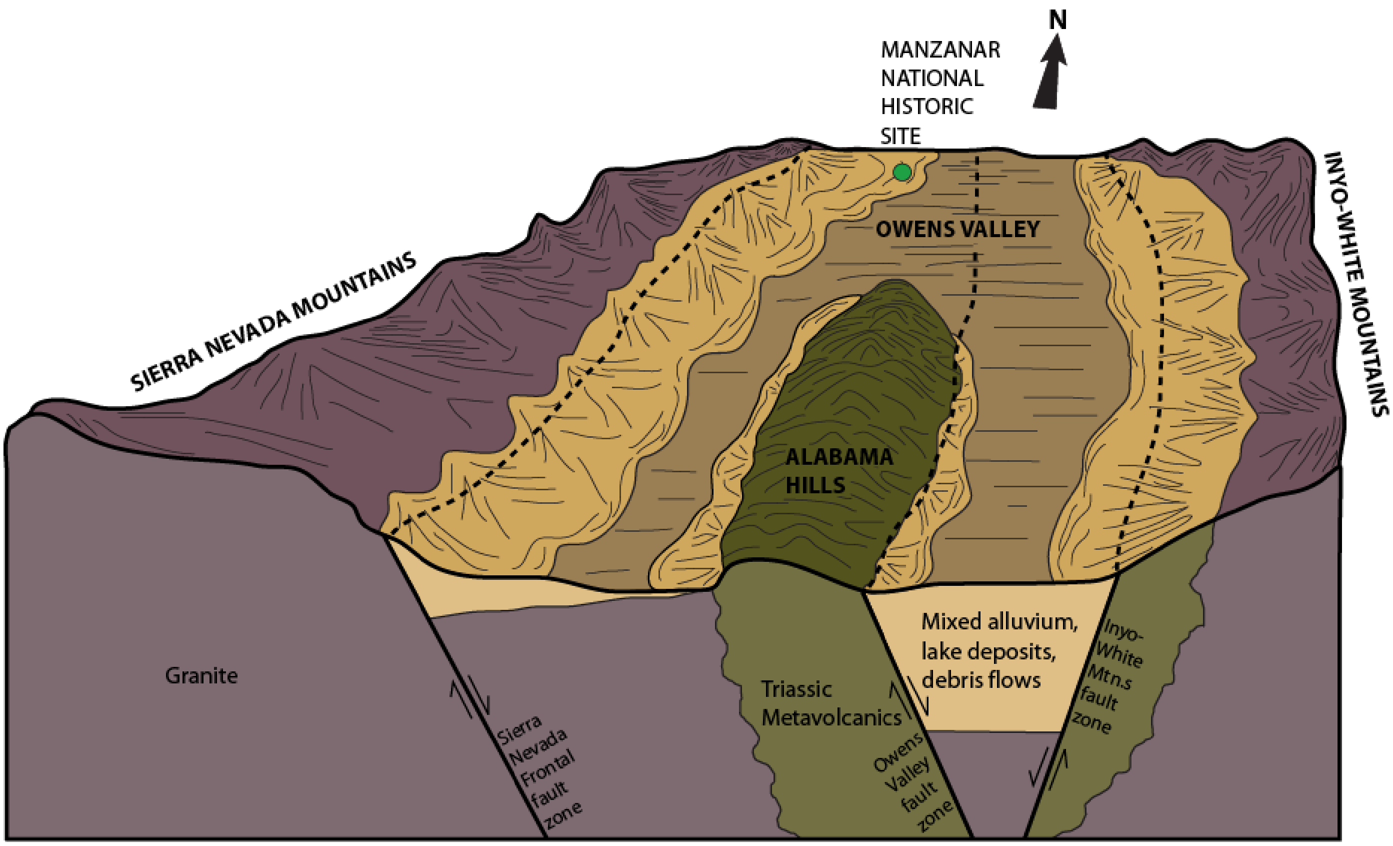


Figure 5. Diagrammatic cross section of Owens Valley in the vicinity of Manzanar National Historic Site (green circle). Note dashed lines indicating the approximate surface trends of major fault zones and arrows indicating the direction of movement across faults. Diagram is not to scale. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University), based on a graphic by Jessey and Wall (2006).

Figure 6. Ansel Adams photograph of Manzanar War Relocation Center, looking west from a guard tower in 1943. Note added text indicating the location of the range front and alluvial fan source points. Modified from reproduction number LC-DIG-ppprs-00200 DLC, Library of Congress, Prints & Photographs Division, Ansel Adams, photographer (http://memory.loc.gov/ammem/collections/anseladams/index.html, accessed September 2009).

Geologic Features and Processes

This section describes the most prominent and distinctive geologic features and processes in Manzanar National Historic Site.

Sierra Nevada Front

Dominating the viewshed west of Manzanar National Historic Site, the Sierra Nevada is the most prominent topographic feature in California. It reaches the highest elevation in the conterminous United States at Mount Whitney (4,421 m [14,505 ft]) and stretches some 640 km (400 mi) from northern California below the Cascade Range south to the Mojave Desert. Crustal compression from the collision of the North American and Farallon plates throughout the Mesozoic and into the Cenozoic (described in the "Geologic History" section) caused extensive shortening, manifested as folds and thrust faults that uplifted the Sierra Nevada. Most of the uplift occurred during the Nevadan and Laramide orogenic (mountain-building) events and culminated in the Jurassic and Late Cretaceous-Early Tertiary, respectively. This tectonic activity was also related to the emplacement of vast amounts of igneous intrusive material. The Sierra Nevada Batholith contains granitic to granodioritic plutons in a linear trend comprising the core of the range.

Compressional tectonics subsided by the Eocene Epoch. By the Miocene, extensional basin-and-range-style deformation was the dominant structural regime throughout the southwest. This regime involves movement along high-angle normal faults that separate downdropped grabens from horsts, which appear uplifted relative to the valleys. In addition to normal movement, many areas in the Basin and Range physiographic province underwent en echelon faulting and extensive right-lateral strike-slip movement, forming the topographic features visible today in the Manzanar area. En echelon faulting creates parallel or subparallel, closely-spaced, overlapping or step-like structures such as fractures or uplifted blocks, that are oblique to the overall structural trend. Right-lateral strike-slip movement refers to movement on a near vertical fault surface where the rocks on one side of the fault move laterally to the right relative to the rocks on the other side with very little vertical motion.

High Angle Normal and Strike-Slip Faults and Fault Processes

The development of the horst and graben structure of Owens Valley is controlled by three major north-south trending fault zones: the Sierra Nevada Frontal, Owens Valley, and Inyo-White Mountains faults. The Sierra Nevada Frontal fault zone has accommodated up to 3 km (1.8 mi) of vertical displacement and bounds the Owens Valley on the west (Stone et al. 2000).

The Inyo-White Mountains fault zone bounds Owens Valley on the east. It is a more or less continuous range-front fault system. Estimates of total dip-slip displacement in the Manzanar area are as much as 8 km (5 mi) (Stockli et al. 2003). Activity along the length of this fault zone throughout the late Quaternary Period has been discontinuous.

The most active period along the Inyo-White Mountains Fault was 13,310–10,590 years before present (ybp) (Vandal and Pinter 2003; Bacon et al. 2005). Numerous separated fault scarps (0.5–3 m, 1.6–10 ft in height) have developed in younger alluvium, indicating the most recent Quaternary activity. Other areas show dextral (to the right) offset across well-developed drainages that indicates long-term activity. An approximate oblique slip rate of 0.1-0.3 m/1,000 years (0.3 to 1 ft/1,000 years) is recorded by this offset (Bacon et al. 2005).

The Owens Valley fault zone, bisecting the valley, accommodates both strike-slip and normal fault movement. The estimated slip rate is 0.8 ± 0.5 m/1,000 years (2.6 ± 1.6 ft/1,000 years) (Lee et al. 2001; Bacon et al. 2002; Kylander-Clark et al. 2005). The Owens Valley fault zone bounds the eastern edge of the Alabama Hills, south of Manzanar National Historic Site. This is among the most recently active faults in the area. Two earthquakes are recorded in the stratigraphic record north of the town of Lone Pine, approximately 4 and 7 km (2.5 and 4.3 mi) from the site. These indicate that movements along the fault started as early as 10,210 ybp (Lee et al. 2001; Bacon et al. 2002; Kylander-Clark 2005). The most recent event is the historic 1872 earthquake (described in the "Geologic Issues" section).

A series of linear dikes appear on both sides of Owens Valley. These include the Golden Bear dike in the Sierra Nevada, the Independence dike swarm, and the Coso dikes in the Coso volcanic complex. The map traces of these dikes, however, are offset by approximately 65 km (40 mi) (Glazner et al. 2003; Kylander-Clark et al. 2005). Compiled evidence, such as similarities in: 1) age—about 83 million years old; 2) petrology and mineralogy; 3) bulk chemical compositions; and 4) strontium (Sr) and neodymium (Nd) isotope data, suggest that the dikes were probably once continuous. The amount of dike offset was used to estimate the dextral slip across Owens Valley since 83 million years ago (Kylander-Clark et al. 2005).

This strike-slip motion is probably related to the overall relative plate motion between the North American and Pacific plates, accommodated in large part by the San Andreas fault system. Much of this dextral shear (approximately 20-25%), however, is within the Eastern California Shear Zone, of which the Owens Valley and Inyo-White Mountains faults are a significant component. Some of the regional transform stress (approximately 1.4–4.1 mm/year; 0.06–0.2 in/year) is accommodated by both the Owens Valley and Inyo-White Mountains fault zones (Schroeder et al. 2003).

Based on recent offsets, it appears significant regional right-lateral shear (oblique rifting followed by transpressional uplift) might transfer from the dip-slip Fish Springs fault strand of the Owens Valley fault zone to the Inyo-White Mountains fault zone in the vicinity of Poverty Hills , northeast of Manzanar (Martel 1989; Angerman 2002; Bishop 2005). Offset paleo-shorelines of Pleistocene Owens Lake (that once filled the valley) indicate the possible presence of a transfer zone of extensional stress between the east-dipping Sierra Nevada Frontal fault zone and the west-dipping Inyo-White Mountains fault zone across Owens Valley (Willis 2004).

Thick mantles of slope deposits and alluvial fans cover the traces of these faults; however, small-scale recent fault scarps, depressions, stream diversions and offset features, pressure ridges, and other linear features trace the faults (Stone et al. 2000). These new features attest to the relative youth of Owens Valley among the valleys of the Basin and Range province (Hollett et al. 1991).

Owens Valley

Owens Valley is the westernmost closed graben basin in the tectonically active Great Basin section of the Basin and Range physiographic province (figs. 2 and 3; Hollett et al. 1991). The valley floor is approximately 1,200 m (3,937 ft) above sea level. It is flanked by 3,200 m (10,500 ft) of vertical relief to the west of the Sierra Nevada and 2,200 m (7,220 ft) of relief to the east of the Inyo-White Mountains. Recent volcanic complexes, including the Long Valley complex to the north and the Coso complex to the south, enclose the valley. The valley is 15–25 km (9–15 mi) wide and extends along a N25W trend for more than 150 km (93 mi).

Owens Valley runs parallel to a series of normal and transform faults. The Sierra Nevada Frontal fault zone delineates the western boundary of the valley. This major structural feature records more than 3,500 m (11,483 ft) of throw on a high-angle fault plane. The eastern side of the valley is marked by an equally prominent high-angle normal fault system—the Inyo-White Mountains fault zone. The Owens Valley fault runs the length of the valley. This normal-dextral strike-slip fault cuts through the eastern side of the valley and forms the eastern boundary of the bedrock outlier called the Alabama Hills. This lower relief structure is a half-horst about 18.5 km (11.5 mi) long and is exposed west of the town of Lone Pine, southeast of Manzanar National Historic Site (Blair 2002).

The Owens Valley area is undergoing crustal extension that began during the Tertiary period and continues today. Small-scale scarps, 1–5 m (3–15 ft) high, are traceable in the series of alluvial fans (that overlap to form a bajada; see below) near the valley margins (Blair 2002).

In 1872 a significant earthquake (described in the "Geologic Issues" section) caused fault offset, surface tilting, and subsidence throughout the Owens Valley. This earthquake resulted in the formation of Diaz Lake, the westward avulsion of Owens River, and locally offset fan deposits.

Given the large amount of offset recorded on the normal faults bounding Owens Valley, significant amounts of sedimentary and volcanic material have filled the down-dropped graben basin. Thousands of meters (yards) of thick, heterogeneous alluvial fan deposits shed from the Sierra Nevada and Inyo-White ranges apron both sides of the valley. Owens River, flowing approximately 100 km (62 mi) towards Owens Lake in the southeastern corner of the valley, has deposited mantles of alluvium. Lacustrine deposits from Owens Lake also form much of the valley fill.

Manzanar National Historic Site sits on the continuous bajada (see below; figs. 6–8) along the Sierra Nevada foothills that stretch uninterrupted between the towns of Independence and Lone Pine. Local drainages, including Shepherd Creek, extend 5–8km (3–5 mi) from the heads of individual fans to the range crest. The associated relief changes from more than 30° at the headwaters to approximately 6° at the front. The bajada extends 10 to 12 km (6 to 7 mi) from the range front. This particular site is important for alluvial fan studies because of the lack of bedrock constrictions, volcanic activity or complex foothill tectonics, as well as its high degree of development and well-known Quaternary history (Whipple and Dunne 1992).

Bajada Development

Relatively rapid extensional faulting in the Manzanar area caused extreme slope development followed by weathering and erosion that continues to lower the highlands and fill in Owens Valley. Glacial events in the highlands significantly increased the amount of erosion and the amount of unconsolidated material available. The oldest surficial deposits in the area are late Tertiary landslide deposits. Large masses of material plummeted down the newly formed normal fault scarps (Stone et al. 2000). Locally, mega-rock avalanche deposits contain masses of rock, several square km (square mi) in size. Hummocky (rounded) and hackled (jagged) surfaces and lower average gradients characterize these deposits, which are often confused with bedrock outcrops (Bishop 1998).

Landslide deposits covered the young normal fault scarps, decreasing the slope angle. As the basin filled with coarse sediments, the relative difference in elevation led to the deposition of finer-grained material in interbedded alluvial fan and intermittent debris flow deposits (Stone et al. 2000). The morphology of debris-flow deposits differs along the length of a fan. Debris-flow spatial deposition depends on the variations in bulk sediment concentration and flow deformation, as well as the pattern of preexisting channels (Whipple and Dunne 1992). Along the steep (6–26°) upper-fan (proximal) segment, levee and boulder-lined channel deposits show flow-parallel clast orientations and linear structures. Deposits in the less steep (3–6°) lower-fan (distal) areas are finer-grained and lobe-shaped with smooth surfaces (Whipple and Dunne 1992; Kim and Lowe 2004).

A bajada forms where a series of alluvial fans overlap, resulting in a continuous mass along the base of a mountain front (fig. 7). In contrast to more extensive and linear bajadas, alluvial fans have semi-circular belts and a wedge-shaped area in which active streams are located. Unlike fans, bajadas lack mechanisms such as channel migration or channel diversion that produce heterogeneous sequences of sediments; bajadas display homogeneous distributions of sedimentary processes along strike (Milana 2000). Manzanar National Historic Site is located at approximately 1,200 m (3,900 ft) of elevation, where bajadas derived from material shed from the Sierra Nevada meet the Owens Valley floor (figs. 6 and 8).

Sedimentologists categorize alluvial fans using sedimentary facies that are differentiated by characteristics such as texture, grain size, degree of sorting, layering, composition, degree of weathering, thickness, and slope. Alluvial fan development is broadly lumped into two categories: meteorological flooding and outburst hyperconcentrated flooding (Milana 2000; Blair 2002). Interbedded alluvial and debris-flow gravels, boulders, sands, and mixed sediments form the broad gentle slopes between the eastern base of the Sierra Nevada and the flat floor of Owens Valley (Stone et al. 2000). For the bajada-alluvial fan complex underlying Manzanar National Historic Site, hyperconcentrated flash floods with occasional glacial-outburst flooding from certain individual upland catchments formed the fans (Milana 2000; Blair 2002).

Glacial moraines typically mark the furthest extent of glacial advance. When a glacier begins to melt and retreat, the sediment it carries remain in a characteristic pile of unconsolidated, poorly sorted, angular debris. Glaciers extending from the Sierra Nevada almost reached the mountain front during the Pleistocene ice ages (Stone et al. 2000). Some of the discernable fans of the Sierra Nevada Front bajada contain thickly bedded, poorly sorted, stratified beds of angular cobbles and fine boulders. Based on sedimentary facies, clast size and orientations, and fan slope, these fans likely formed by outburst floods of moraine-dammed glacial lakes located in the upland catchments of the Sierra Nevada (Blair 2002). For fans that do not show evidence of glacial outburst flooding and are not supported by a glacially carved catchment, a combination of processes influenced fan accumulation. These include periodic water flow in shifting distributary channels and sporadic aggradation of debris-flow levees and lobes.

Regardless of the individual alluvial fan accumulation mechanism, the size of the fans along the Sierra Nevada Front in Owens Valley is immense. For each mountain valley catchment, a fan is present. These Pliocene and Pleistocene deposits along the range fronts record sedimentary and tectonic events from the onset of normal fault movement to the present (Lueddecke et al. 1998).

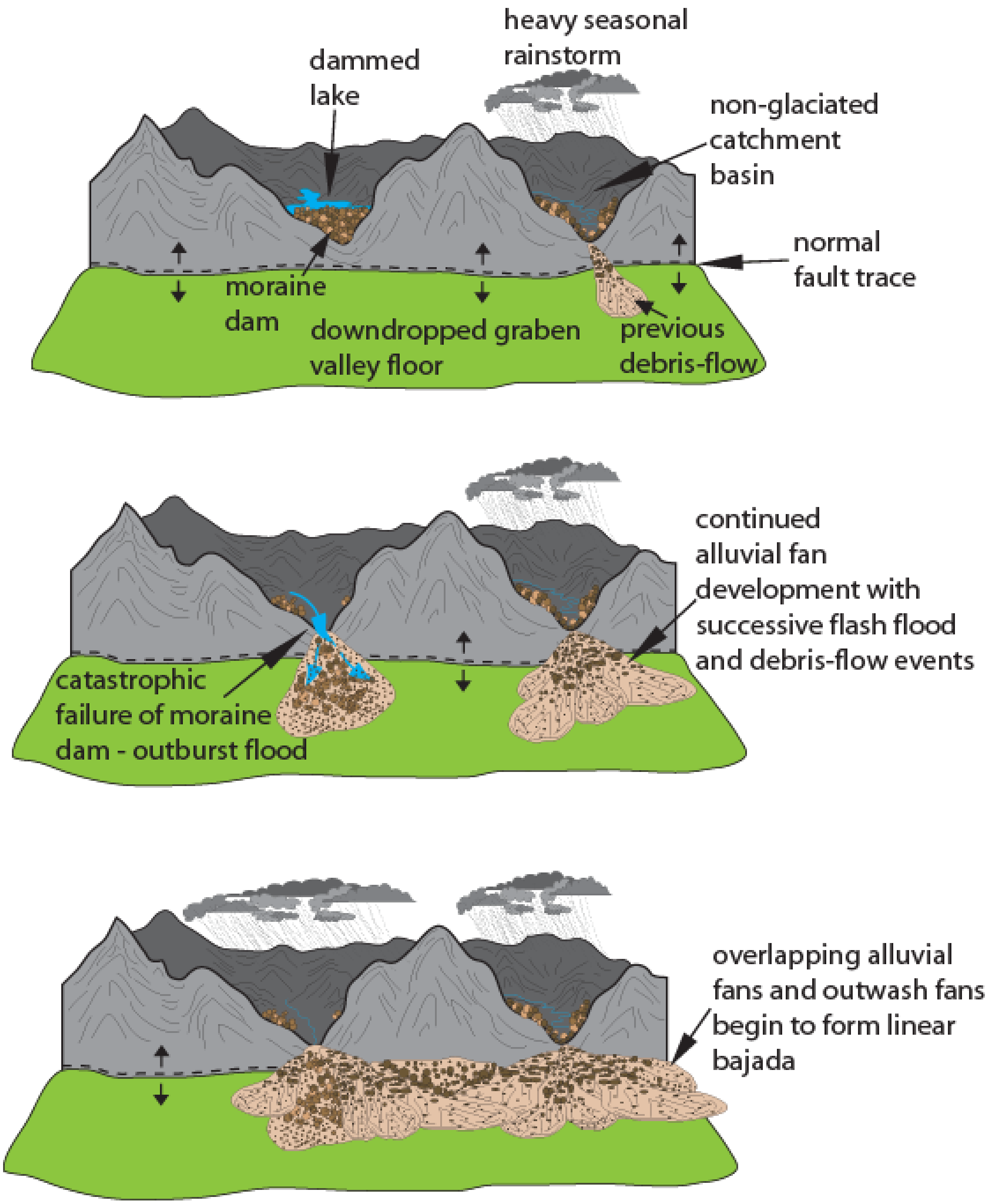


Figure 7. Diagram illustrating the formation of a bajada from the overlapping of alluvial fans, debris-flow deposits, and outwash flood deposits along the Sierra Nevada Front in the vicinity of Manzanar National Historic Site. Diagram is not to scale. Graphic by Trista L. Thornberry-Ehrlich (Colorado State University).

Figure 8. Aerial view of Owens Valley in the vicinity of Manzanar National Historic Site. Note the size and extent of the bajada west of the park. Individual alluvial fans are visible on the west flanks of the Inyo Mountains. Compiled by Jason Kenworthy (NPS Geologic Resources Division) from ESRI Arc Image Service, USA Prime Imagery.

Map Unit Properties

This section identifies characteristics of map units that appear on the Geologic Resources Inventory digital geologic map of Manzanar National Historic Site. The accompanying table is highly generalized and for background purposes only. Ground-disturbing activities should not be permitted or denied on the basis of information in this table.

Geologic Units

The oldest rock units in the Manzanar area are metamorphosed sediments and less common volcanic deposits that accumulated along the western margin of the North American continent, beginning in the late Precambrian through the early Mesozoic eras. The rocks underwent metamorphism and deformation, and then uplift, during the formation of the Inyo Mountains. Units such as Keeler Canyon and the lower beds of the Lone Pine Formations contain turbidites (from submarine mass movements) and fine-grained sediments deposited in a deepwater marine basin setting throughout the Pennsylvanian and Early Permian periods (Stone et al. 2000).

The upper beds of the Lone Pine Formation record an abrupt change to a shallow-water, nonmarine setting with the deposition of coarse-grained, conglomeratic beds. This change may have resulted from uplift of the continental margin during the Permian. The deposits of the overlying Conglomerate Mesa Formation formed in the Late Permian and Early Triassic . The limestone beds within this unit contain fossils (exposed on Fossil Hill, see fig. 4) and sedimentary features that indicate a shallow marine setting, whereas the conglomeratic and sandstone-rich layers indicate subaerial deposition. Renewed subsidence led to the open-marine deposition of the Union Wash Formation atop the conglomerates. This unit is comprised of fine-grained calcareous rocks (Stone et al. 2000).

The Mesozoic Era saw the emplacement of numerous igneous plutons, as well as widespread volcanic activity in the Manzanar region. Volcanic flows and sediments of Middle to Late Jurassic age crop out in the Alabama Hills and Inyo Mountains. Most of the volcanic rocks are present as silica-rich ash falls, and less common intermediate composition flows. These are exposed with intermixed sediments from fluvial and debris-flow settings, as well as evaporative lakes and a few eolian dunes (Stone et al. 2000).

During the Middle Jurassic, the Pat Keyes Pluton intruded in the Inyo Mountains area. This was followed by later magmatic activity, represented by granitic plutons emplaced during the Early and Late Cretaceous.

These intrusive masses include the Kern Knob Pluton, the Alabama Hills Granite, the granodioritic plutons of the Mount Whitney Intrusive Suite and Lone Pine Creek, the Dragon and Independence plutons, and the Granite of Carroll Creek. The massive volume of the Mount Whitney Intrusive Suite intruded the pre-Jurassic rocks near the end of the Late Cretaceous episode of igneous activity in the Sierra Nevada (part of the Sierra Nevada Batholith). The suite becomes more silica-rich inward and trends northwest (Norris and Webb 1976; Stone et al. 2000).

Numerous dikes of compositions, with varying mafic (low silica), intermediate, and felsic (high silica) contents, cut most of the older rocks of the Alabama Hills and Inyo-White Mountains. The largest grouping of these dikes is the Independence dike swarm, dated to the Late Jurassic (148 million years ago). Other local dikes are Early Cretaceous in age (about 140 million years ago) (Dunne and Walker 1993; Stone et al. 2000).

Surficial deposits of Quaternary age cover much of the landscape in Owens Valley and Manzanar National Historic Site. The oldest of these unconsolidated deposits are large landslide masses dating to the late Tertiary and early Quaternary. These jumbled masses have hummocky surfaces located downhill from steep outcrops. The most abundant surficial units are the Pleistocene-age, coarse-grained alluvial and debris-flow deposits derived from erosion of the surrounding highlands. Rock glaciers, regolith, talus, and colluvium in the Manzanar area are the products of gravity and weathering acting on steep slopes. Other recent units include eolian sands, active and inactive alluvium, terrace gravels, late Pleistocene and Holocene lake deposits, and less common glacial moraine deposits in the Sierra Nevada, west of Manzanar (Stone et al. 2000).

Digital Geologic Map

Geologic maps facilitate an understanding of Earth, its processes, and the geologic history responsible for its formation. Hence, the geologic map for Manzanar National Historic Site informed the “Geologic History,” “Geologic Features and Processes,” and “Geologic Issues” sections of this report. Geologic maps are essentially two-dimensional representations of complex three-dimensional relationships. The various colors on geologic maps illustrate the distribution of rocks and unconsolidated deposits. Bold lines that cross or separate the color patterns mark structures such as faults and folds. Point symbols indicate features such as dipping strata, sample localities, mines, wells, and cave openings.

Incorporation of geologic data into a Geographic Information System (GIS) increases the usefulness of geologic maps by revealing the spatial relationships to other natural resources and anthropogenic features. Geologic maps are indicators of water resources because they show which rock units are potential aquifers and are useful for finding seeps and springs. Geologic maps do not show soil types and are not soil maps, but they do show parent material, a key factor in soil formation. Furthermore, resource managers have used geologic maps to make connections between geology and biology; for instance, geologic maps have served as tools for locating sensitive, threatened, and endangered plant species, which may prefer a particular rock unit.

Although geologic maps do not show where earthquakes will occur, the presence of a fault indicates past movement and possible future seismic activity. Geologic maps do not show where the next landslide, rockfall, or volcanic eruption will occur, but mapped deposits show areas that have been susceptible to such geologic hazards. Geologic maps do not show archaeological or cultural resources, but past peoples may have inhabited or been influenced by various geomorphic features that are shown on geologic maps. For example, alluvial terraces may preserve artifacts, and formerly inhabited alcoves may occur at the contact between two rock units.

The geologic units listed in the following table correspond to the accompanying digital geologic data. Map units are listed in the table from youngest to oldest. Please refer to the geologic timescale (fig. 9) for the age associated with each time period. This table highlights characteristics of map units such as susceptibility to hazards; the occurrence of fossils, cultural resources, mineral resources, and caves; and the suitability as habitat or for recreational use. Some conclusions are conjectural and are meant to serve as suggestions for further investigation.

The GRI digital geologic maps reproduce essential elements of the source maps including the unit descriptions, legend, map notes, graphics, and report. The following reference is source data for the GRI digital geologic map for Manzanar National Historic Site:

Stone, P., G. C. Dunne, J. G. Moore, and G. I. Smith. 2000. *Geologic Map of the Lone Pine 15" Quadrangle, Inyo County, California*. Scale 1:62,500. Geologic Investigation Series I-2617. Reston, VA: U.S. Geological Survey.

The GRI team implements a geology-GIS data model that standardizes map deliverables. This data model dictates GIS data structure including data layer architecture, feature attribution, and data relationships within ESRI ArcGIS software, increasing the overall quality and utility of the data. GRI digital geologic map products include data in ESRI personal geodatabase, shapefile, and coverage GIS formats, layer files with feature symbology, Federal Geographic Data Committee (FGDC)-compliant metadata, a Windows help file that contains all of the ancillary map information and graphics, and an ESRI ArcMap map document file that easily displays the map. GRI digital geologic data are included on the attached CD and are available through the NPS Data Store (http://science.nature.nps.gov/nrdata/).

Map Unit Properties Table

Colored rows indicate map units within Manzanar National Historic Site.

Age	Unit Name (Symbol)	Features and Description	Erosion Resistance	Suitability for Development	Hazards	Paleontological Resources	Cultural Resources	Karst	Mineral Occurrence	Habitat	Recreation	Geologic Significance
QUATERNARY	Active alluvium (Qal) Eolian sand (Qes) Younger lake deposits (Qly) Rock glaciers (Qrg) Talus, regolith, and colluviums (Qt) Inactive alluvium (Qai)	*Qal* forms floors of active channels, washes and fan surfaces comprised of sand and fine to coarse gravel. *Qes* contains sand sheets locally thicker than 2 m (7 ft)with some dunes. *Qly* contains bar and beach gravels, sand, clay, and silt with some cemented ooliths, and some local salt accumulations in the upper 1–2 m (3–7 ft). *Qrg* forms lobate masses of poorly sorted angular boulders and finer-grained material with some interstitial ice cores. *Qt* is composed of broken and weathered rock debris with some local buried soil horizons. *Qai* contains fine to coarse gravels atop inactive fan surfaces with some local fine sand to pebble grus and angular, poorly sorted gravel.	Very low	Suitable for light development unless exposed and/or undercut on a slope. Avoid for septic systems due to high permeability.	Units are prone to slumping and sliding when exposed on slopes. Especially when water-saturated, seismic activity may loosen thick masses of deposits, rendering them susceptible to mass wasting.	Modern remains; Pleistocene soil horizons may contain fossils and root traces; ice cores may contain paleoclimate information (oxygen isotopes, pollen, etc).	Modern artifacts	None	Sand, gravel, silt, clay, pebbles	Units provide burrow habitat and support some riparian habitat along streams.	Relatively sorted units are suitable for most recreation; jumbled units are unstable and unsafe for trail bases.	Units record Holocene conditions throughout the area. *Qly* records the presence of Owens Lake at larger size than today since diversion of Owens River into L.A. aqueduct in 1913. *Qrg* records local glaciation in Sierra Nevada cirques.
QUATERNARY	Very large boulder gravels (Qgvl) Debris-flow deposits (Qdf) Older lake deposits (Qlo) Younger alluvial and debris-flow gravels (Qgy)	*Qgvl* forms gravel terraces 2–5 m (7–16 ft) above modern stream channel alluvium, boulders are locally 2–15 m (7–49 ft) in diameter. *Qdf* contains unsorted 2–4 m (7–13 ft) thick layers of angular clasts and little matrix. Clasts are as large as 0.5 m (1.6 ft) in diameter. *Qlo* contains massive to well-bedded deposits of light tan silt and sand with a few gravel layers near paleoshorelines, may be as much as 2,500 m (8,200 ft) thick. *Qgy* contains abundant subangular to subrounded cobbles and boulders derived from plutonic rocks in a sandy-gravely matrix. Boulders of two different ages (differentiated by degree of weathering and oxide staining) may approach 2 m (7 ft) in diameter and display igneous porphyritic textures and mafic inclusions.	Very low	Avoid most large boulder areas and debris flow deposits for heavy development due to instability of slopes, likelihood of future movement, and high permeability.	Units are associated with stream-edge slopes, and mass movements deposited by gravity, water, and debris-flow processes.	Lake fossils (fish, plant fragments, algae) are possible in this unit.	There is a slight chance units may contain modern artifacts.	None	Boulders (some with mafic igneous mineral inclusions), sand, gravel	Unit may support small mammal burrow habitat.	Unit may be attractive to climbers, but should be avoided for most recreation as unstable surfaces are an unsuitable trail base.	Exposed boulders date to 2,000–1,200 years ago. *Qlo* may contain Tertiary age deposits and record deposition in a structural depression between Owens Valley and Inyo-White Mountains fault zones.
QUATERNARY	Glacial moraines (Qm) Older alluvial and debris-flow gravels (Qgo)	*Qm* contains poorly sorted massive gravel and boulder deposits as well as till deposits and ridge crests. *Qgo* contains coarse sand and fine gravel with occasional cobbles and boulders derived from felsic plutonic rocks. Beds are stained by iron oxide, yielding orange to greenish-gray tones.	Very low	Unit acts as an aquitard to groundwater percolation. Due to heterogeneity of units, avoid for most development including wastewater treatment facilities.	Poorly sorted nature of units render them unstable on slopes, *Qgo* is associated with mass wasting due to movement by water and gravity.	Pleistocene macrofauna remains are possible in this unit.	Oxides may have provided paint material for American Indians.	None	Sand, gravel, igneous rock boulders. Unit contains large subhedral feldspar crystals up to 6 cm (2 in) long.	Unit supports thick stands of vegetation where windblown soils have accumulated due to aquitard habit.	Units may be suitable for mountain bike course, avoid areas associated with mass movements.	Unit records Tahoe and Tioga glacial events.
TERTIARY – QUATERNARY	Landslide deposits (QTls)	*QTls* forms dissected lobate hummocky masses of unsorted rock debris. Larger blocks are typically plutonic (gneissic or mafic) boulders.	Very low	Unsorted, jumbled mass of rock debris should be avoided for development.	Unit is associated with mass wasting processes facilitated by water and gravity, jumbled masses are unsafe to traverse on foot.	Fossil remains possible	None documented	None	Gravel and igneous rock boulders including fine-grained granitic boulders from the granite of French Spring	Unit may support small mammal burrow habitat.	Unit may be attractive to climbers, but should be avoided for most recreation.	Unit records slope processes of Pleistocene age and thus local tectonic activity.
CRETACEOUS	Whitney Granodiorite (Kwg) Paradise Granodiorite (Kpg) Granodiorite of Lone Pine Creek (Klp)	*Kwg* contains porphyritic granodiorite and granite with an average of 71% quartz. *Kpg* is porphyritic granodiorite and granite at 70% quartz with abundant zonally arranged inclusions of biotite and hornblende. *Klp* contains dark granodiorite with locally finer-grained areas and abundant mafic inclusions with 64% quartz.	Very high	Unit may contain radon-emitting minerals, avoid for basements, suitable for most development unless highly fractured.	Unit is susceptible to sheet-like exfoliation weathering and may pose a blockfall hazard on slopes.	None	None documented	None	Fine-grained igneous rocks may be useful as building material. Potassium feldspar phenocrysts up to 8 cm (3 in) long and mafic inclusions also present.	None documented	Suitable for most recreation; plutonic rocks may attract climbers.	K-Ar date of 83 million years ago (Ma), Pb-U date of 83 Ma for *Kw*. Biotite K-Ar date of 78 Ma, Pb-U age of 86 to 83 Ma, and hornblende K-Ar date of 84 Ma for *Kpg*. *Klp* has a Pb-U age of 87 Ma.

Age	Unit Name (Symbol)	Features and Description	Erosion Resistance	Suitability for Development	Hazards	Paleontological Resources	Cultural Resources	Karst	Mineral Occurrence	Habitat	Recreation	Geologic Significance
CRETACEOUS	Dragon Pluton (Kd) Independence Pluton (Kip) Granite of Carroll Creek (Kcc) Alabama Hills Granite (Kah) Kern Knob Granite (Kkg)	*Kd* is quartz monzodiorite and quartz monzonite with average quartz content of 69%. *Kip* is light colored granite with approximately 74% quartz. *Kcc* contains 72% quartz in coarse-grained granite, cross cut by *Klp*. *Kah* contains biotite monzogranite with hypidiomorphic seriate to faintly porphyritic textures that appears pale orange to pinkish-gray in outcrop. Some prominent pegmatite dikes present locally. *Kkg* contains medium-grained biotite monzogranite exposed on Kern Knob	High	Possibility of radon emission from alteration and decay of potassium, avoid for basements	Unit is susceptible to sheet-like exfoliation weathering and may pose a blockfall hazard on slopes, pegmatite may pose rockfall hazard if more resistant than surrounding rocks.	None	Large crystals may have provided trade material for American Indians	None	Fine-grained igneous rocks may be useful as building material. Potassium feldspar phenocrysts up to 1 cm (0.4 in) long, fluorite, garnet, hematite, amazonite, aplite, pegmatite dike minerals present.	None documented	Suitable for most recreation; plutonic rocks may attract climbers.	*Kd* has Pb-U date of 103 Ma. *Kip* has Pb-U age of 112 Ma. *Kah* has biotite K-Ar age of 82 Ma and Pb-U age of 85 Ma. Mixed country rocks on margins of *Kah* record conditions of emplacement and *Kkg* has an Ar/Ar age of 91 Ma.
JURASSIC – CRETACEOUS	Felsic dike (KJf) Mafic, intermediate-composition, and minor felsic dikes (KJd)	*KJf* is a light gray dike, aphanitic in texture and felsic in composition, approximately 4 m (13 ft) thick. *KJd* contains aphanitic to fine-grained porphyritic dikes of compositions ranging from diorite to granite. Some mafic areas locally present. Most dikes are vertical to subvertical and strike northwest. Swarms may constitute up to 90% of a local rock volume.	Moderately high	Avoid highly altered and/or fractured areas, heterogeneity of dike localities and morphologies may render units unstable for heavy foundations.	Unit may pose rockfall hazard if undercut or exposed on a slope.	None	Aphanitic rock may have been used by American Indians for tool material	None	None documented	Unit may form ledges attractive to birds if exposed on slopes.	Suitable for most recreation unless unit is resistant relative to surrounding rocks.	*KJf* may correlate with 140 Ma felsic dikes or a 148 Ma French Spring granite. *KJd* may be associated with *Javl*, has Pb-U age of 148 Ma.
JURASSIC	Volcanic complex of the Alabama Hills, upper part (Javu) lower part (Javl)	*Javu* has upper layers of light to medium gray, massive slightly welded tuff at least 450 m (1,500 ft) thick with 18–28% phenocrysts in an aphanitic matrix. Lower layers of unit consist of muscovite schist, quartzite, and rare volcanogenic conglomerate with a thickness of about 10 m (33 ft). *Javl* contains an upper volcanogenic sedimentary sequence with volcanic rocks atop a lower subunit of rhyolite tuff beds. Sedimentary layers include weakly bedded to massive pebble to cobble conglomerate, siltstone, sandstone, and pebbly sandstone. Lower subunit is grayish-pink to yellowish-gray, massive and slightly welded with some phenocrysts.	Moderate	Unit may contain radon-emitting materials and shrink-and-swell clays if altered. Heterogeneous nature of unit may be undesirable for development on slopes.	Shrink-and-swell clays may buckle trail bases and be slippery when water-saturated; rockfall hazard associated with resistant units (massive conglomerate) underlain by weaker units.	Fossils possible, but unlikely in sedimentary units	Aphanitic rock may have been used by American Indians for tool material	None	Flattened pumice lapilli, lithic lapilli, quartz, potassium feldspar, plagioclase, and biotite phenocrysts, vesicles	Vesicles and vugs may provide burrow habitat and nesting areas if exposed on cliffs.	More resistant layers—conglomerate—may attract climbers, avoid thinly bedded areas	*Javu* has a Pb-U age of 170 Ma, *Javl* has a Pb-U age of 167 Ma for tuff layers.
JURASSIC	Inyo Mountains Volcanic Complex of Dunne and others (1998) upper part (Jivu) middle part (Jivm) lower part (Jivl)	*Jivu* is 900–2,200 m (3,000–7,200 ft) thick unit of massive to faintly bedded, matrix-supported volcanogenic conglomerate, with some parallel-bedded to crossbedded sandstone and siltstone that comprises about 30% of the unit and some lenses of felsic to intermediate silica composition tuff. *Jivm* is comprised of andesite and rhyolite lava flows with some bedded to massive volcanogenic sandstone and conglomerate beds and rarer rhyolite tuff layers (about 20% of the unit). Total thickness is around 750 m (2,500 ft). *Jivl* contains predominantly matrix-supported, volcanogenic, massive pebble, cobble, and boulder conglomerate with some parallel-bedded to crossbedded volcanogenic sandstone and pebbly sandstone interbeds comprising close to 20% of the unit. Unit also contains sparse lenticular lava flows of basalt and andesite. Total thickness about 300 m (980 ft).	Moderate	Heterogeneous nature of unit may render it unstable in areas of thin bedding, pervasive alteration, heavy fracture density, and high degree of foliation and/or deformation.	Where altered, unit may contain shrink-and-swell clays.	Freshwater pelecypods, gastropods	None documented	None	Abrasives; Vesicles in basalt and andesite flows may contain secondary minerals.	Units support a wide variety of habitats; boulder conglomerate may weather out forming vugs for nests.	Units may attract climbers and scramblers; avoid relatively heterogeneous areas for development of recreational facilities.	*Jivu* has Pb-U ages of 173, 148, and 150 Ma. *Jivm* has Pb-U age dates of 168 and 169 Ma

Age	Unit Name (Symbol)	Features and Description	Erosion Resistance	Suitability for Development	Hazards	Paleontological Resources	Cultural Resources	Karst	Mineral Occurrence	Habitat	Recreation	Geologic Significance
JURASSIC	Pat Keyes Pluton (Jpk) Intrusive rocks marginal to Pat Keyes Pluton (Jir)	*Jpk* contains plutonic rocks of varying compositions and textures from medium-grained, hypidiomorphic granular to seriate. Unit appears medium to light gray in outcrop and has monzogranite to granitic composition that grades irregularly into a mafic border facies of monzodiorite, quartz diorite, and diorite. *Jir* contains dark gray fine-grained, altered and recrystallized diorite and tonalite. These appear reddish-brown in outcrop and are saussneritized and sericitized in irregular masses. Some metasedimentary rocks and irregular light-colored intrusions locally present.	High to moderately high for altered areas	Unit may contain radon-emitting minerals, avoid for basements, (especially altered areas); suitable for most development unless highly fractured.	Unit is susceptible to sheet-like exfoliation weathering and may pose a blockfall hazard on slopes; saussneritized and sericitized areas are friable and prone to slides.	Fossils possible, but unlikely in locally present metasedimentary units	None documented	Not enough carbonate present	Igneous rocks may make attractive building stones. Minerals include clinopyroxene, biotite, hornblende, quartz, plagioclase, epidote, clinozoisite, calcite, sericite	Units support wide range of habitats	Units are suitable for most recreation; may attract climbers; avoid heavily altered areas for recreation area development.	Hornblende K-Ar ages of 178 and 163 Ma, Rb-Sr whole rock age of 183 Ma. *Jir* records metamorphic conditions and regional tectonic events, possibly contemporaneous with *Jpk*
TRIASSIC	Union Wash Formation (TRu)	*TRu* consists of a 90 m (300 ft) thick upper member of dark gray micritic limestone, pink shale, and light-brown siltstone, a middle member of medium to dark gray, thin-bedded mudstone, siltstone, very fine-grained to fine-grained sandstone, and micritic limestone about 680 m (2,200 ft) thick, and locally a 60 m (200 ft) thick lower member of ledge-forming, light gray to brown limestone and silty to fine-grained sandy limestone.	Moderate	Prominent cleavage, thin to massive bedding, heterogeneous composition and minor dissolution in these units may render them too weak on slopes for heavy development.	Slaty layers are prone to slides and conglomeratic blocks may pose rockfall hazard if underlain by weaker siltstone and mudstone units.	Ammonoids	None documented	Some dissolution is possible for this unit, pervasive cave formation is unlikely	Building material from ledge-forming limestone and sandstone. Hydrothermal and metamorphic talc also present.	Unit supports wide range of habitats.	Unit is suitable for most recreation unless exposed on a steep slope.	Records the development of Triassic basins in the area
TRIASSIC & PERMIAN	Owens Valley Group divided into: Conglomerate Mesa Formation (TRPc) Lone Pine Formation, Reward Conglomerate Member and member C, upper part (Plu) members A and B lower part (Pll)	*TRPc* contains a 40 m (130 ft) thick upper unit of brown, ochre, and gray chert pebble conglomerate, pebbly calcareous sandstone and noncalcareous sandstone, as well as a 130 m (430 ft) thick lower unit of gray to brown limestone, silty and sandy limestone, and some grayish-orange-maroon shale. *Plu* contains 200 m (660 ft) of dark gray to brown, thick-bedded, medium to coarse-grained quartzite and chert and quartzite pebble conglomerate. *Pll* contains 180 m (590 ft) of greenish-gray to reddish-brown, thin-bedded calcareous mudstone, siltstone, and calc-hornfels rocks with some gray bioclastic limestone-marble up to 3 m (10 ft) thick. Lower beds are 500 m (1,600 ft) of metamorphosed gray to reddish-brown argillite, siltite, quartzite, and calc-hornfels with metamorphic grade decreasing eastwards.	Moderate to moderately high for quartzite layers	Unit is suitable for most types of development; avoid areas of relatively high slope, alteration, heterogeneity and/or fracture density.	Heterogeneity of rock types within these units render them prone to mass wasting on slopes. Especially if water-saturated, cobbles may weather out of conglomerate layers and pose a local rockfall hazard.	Brachiopods, gastropods, bryozoans, echinoderm debris	Chert pebbles may have provided tool material and trade goods for American Indians	Some dissolution is possible for this unit; pervasive cave formation is unlikely.	Marble, quartzite for building stones. Calc-hornfels and associated contact metamorphic minerals also present.	None documented	More resistant layers (quartzite, conglomerate) may attract climbers.	Units record Permian–Triassic transition in an open basin environment.
MESOZOIC	Metavolcanic rocks (MZv) Mafic plutonic rocks (MZm)	*MZv* contains metarhyolite and metadacite with some minor metabasalt flows. *MZm* contains quartz diorite, diorite, and hornblende gabbro, crosscut by *Kip* and *Klp*.	Moderately high	Suitable for most development unless highly altered; radon may be present from radioactive decay of certain minerals, avoid for basements.	Possibility of radon emission from metarhyolite and other K-bearing rocks; rockfall associated with outcrops present on slopes and ledges.	None	None documented	None	Amygdules may be present in metabasalt flows, calc-hornfels and associated contact metamorphic minerals	Units may weather to produce high Al, Ca, Mg, and Fe soils.	Suitable for most recreation; plutonic rocks may attract climbers.	Records metamorphism and deformation of Late Triassic-Jurassic.
PERMIAN & PENNSYLVANIAN	Keeler Canyon Formation (PPNk)	*PPNk* is approximately 500 m (1,600 ft) of light to medium gray, medium- to thick-bedded limestone and silty and sandy limestone. Some calc-hornfels areas. All layers have undergone metamorphism.	Moderate	Unit is suitable for most development; avoid areas of relatively high heterogeneity or fracture density.	Units are associated with blockfall on slopes where more resistant layers form undercut ledges	Unit may contain metamorphosed fossil remains.	None documented	Some dissolution, perhaps even caves, is possible for this unit	Marble, calc-hornfels minerals	Unit weathers to produce Ca-, Mg- rich soils	Unit is suitable for most recreation unless fractured on a slope.	Unit records metamorphic conditions and a former basin depositional setting during the late Paleozoic.
PALEOZOIC?	Metasedimentary rocks (PZm)	*PZm* contains undifferentiated calcitic marble and calc-hornfels metamorphic rocks forming a small pendant-shaped area within the *Kah* unit.	Moderately high	Suitable for most development unless locally fractured and/or heavily altered.	If undercut on a slope or highly fractured, unit may pose a rockfall hazard.	Unit may contain metamorphosed fossil remains.	None documented	Very minor dissolution is possible.	Marble and calc-hornfels minerals	Unit weathers to produce Ca-, Mg- rich soils.	Unit is suitable for most recreation.	Unit records sedimentary deposition environment throughout the Paleozoic as well as metamorphic changes.

Geologic History

This section describes the rocks and unconsolidated deposits that appear on the digital geologic map of Manzanar National Historic Site, the environment in which those units were deposited, and the timing of geologic events that created the present landscape.

The area surrounding Manzanar National Historic Site is geologically dynamic, showing active crustal extension throughout the Cenozoic (see fig. 9 for a geologic timescale). The mountain ranges and valleys record a complex tectonic history of the growth of the western coast of the North American continent. This section contextualizes the rocks of the Manzanar area, at scales ranging from the immediate Manzanar vicinity to the western North American continent, with a primary focus on southeastern California.

Paleozoic Era

The oldest rocks in the region, the marine sedimentary rocks exposed in the Inyo-White Mountains to the east, record an oceanic basin setting of sediment deposition from the North American continental margin to the east. Marine fossils are preserved in some exposures. Some volcanic intrusion during local extension of the crust is also evident (Hollett et al. 1991). Intermittent deposition of these rocks from the Paleozoic through the early Mesozoic formed part of the Cordilleran miogeocline, a thick and extensive assemblage of basin sediments along the western North American margin. This Inyo Mountains assemblage is one of the most southwesterly preserved miogeocline segments (Stone et al. 2000).

Over 350 million years ago, the Devonian and Mississippian Antler Orogeny shoved huge mass of rocks eastward onto the North American continental margin along a major thrust fault—the Roberts Mountains Thrust. The thrust fault carried deep marine, continental slope and rise deposits up over the relatively shallow marine carbonate deposits on the margin (Miller et al. 1992). This tectonic activity folded and faulted the marine sediments in the Manzanar area (Hollett et al. 1991). Metamorphism resulted from burial of the sediments and high tectonic pressure (Stone et al. 2000). In geologic terms, the Antler Orogeny was rapid, lasting only about 25 million years. However, this orogeny was the start of a compressional regime along the western coast of the United States that would last until the Mesozoic Era.

The next tectonic event to affect the western margin of the North American continent was the Sonoma Orogeny. This orogeny followed the deposition of chert-pebble conglomerates, sandstones, and limestones atop the deformed rocks of the Antler Orogeny that locally comprise the upper part of the Lone Pine and Conglomerate Mesa formations of the Owens Valley Group (Stone et al. 2000). The Sonoma Orogeny involved the thrusting of an allochthonous (rocks that have been moved a great distance from their original source) block containing volcanic sediments atop the continental margin (Silberling and Roberts 1962; Miller et al. 1992). This happened during the Late Permian and Early Triassic, and a regional unconformity separating the limestone and sandstone units of the Conglomerate Mesa Formation records local uplift (Stone et al. 2000).

Mesozoic Era

The Mesozoic Era brought significant expansion to the western margin of the continent including the intrusion of great batholiths, seated beneath the magmatic arcs. Entire landmasses, some associated with the western margin and some foreign to the western shore, were sutured onto the western margin of California. These landmasses are called displaced terranes (fig. 10).

Accretion of a major Paleozoic island-arc terrane in the northwest Nevada-northern California region (north of Manzanar National Historic Site) marks the primary tectonic activity of the Early Triassic. Following the Sonoma orogeny, however, a new subduction zone formed. The subduction zone trended north-northwest to south-southeast and dipped eastward beneath the continental margin. Early to Middle Triassic (245–230 million years ago) igneous rocks were emplaced along this subduction zone, forming a prominent continental arc by the Late Triassic (230–208 million years ago) (Saleeby et al. 1992). Along the California and Arizona margin, south of Manzanar, the Late Triassic-Early Jurassic arc occupied an extensional graben sediment-trap system (Saleeby et al. 1992). Evidence of this volcanic arc setting is preserved in the metavolcanic and metasedimentary rocks found along the then western margin of California, often covering rocks with compositions similar to oceanic crust and upper mantle typical of mid-ocean ridge settings.

Compressional tectonics continued into the Middle Jurassic during the Elko Orogeny, localized in Nevada. Volcanoes formed a north-south island arc through what is now central Nevada. During this time, the direction of the North American Plate changed from westward movement to a north-northeast direction at a rate of about 45 km/million years (28 mi/million years) (Saleeby et al. 1992).

The plutonic, volcanic, and volcanogenic sedimentary rocks exposed in the Sierra Nevada east of the historic site are evidence of the Sierran magmatic arc (described below) that was active in the region throughout most of the middle to late Mesozoic (Stone et al. 2000). Magmatic activity was widely distributed across the western United States at this time, from the Pacific margin in California to the edge of the Paleozoic craton (old continental crust) in Utah (fig. 11) (Suppe 1985). The Nevadan

Orogeny, a major deformation and metamorphic event of regional scale, accompanied the magmatic activity.

The Nevadan Orogeny was short-lived and may have been the result of colliding terranes along the western continental margin (Suppe 1985; Saleeby et al. 1992). In the western Sierra Foothills, a complex pattern of shortening, extension, and sinistral (relative movement across the fault was to the left) strike-slip faulting formed during the Nevadan orogeny.

The Cretaceous Sevier Orogeny followed the Nevadan orogeny (Stewart 1980). Originally, the term "Sevier Orogeny" applied to the fold and thrust belt of western Utah, but it has been expanded to include the Sevier belt, the eastern branch that extends through Utah and southern Nevada into southeastern California. The development of this thrust system is a classic example of "stacked-shingle" geometry, wherein the structurally highest and oldest fault systems formed in the west and were then carried piggy-back fashion to the east on sequentially younger and lower thrusts as the basal large displacement fault propagated eastward (Cowan and Bruhn 1992). In southeastern California and southern Nevada, thrusting took place over a period from before 200 million years ago to about 85 million years ago.

Associated with the series of orogenic events throughout the Mesozoic, episodic compression deformation in the Manzanar area was concentrated along the East Sierran thrust system that trends southeastward through the area. In the earliest phases, layered volcanic and volcanogenic deposits of Middle and Late Jurassic age in the Inyo Mountains and Alabama Hills were steeply tilted southwestward and locally folded (Dunne and Walker 1993). Eastward thrusting placed Triassic and Devonian age sedimentary rocks over Mississippian age units (Stevens 1995). Later activity produced numerous igneous dikes that were then further deformed (Stone et al. 2000).

During thrusting in the eastern part of the Sevier-affected region, a belt of Late Jurassic to Cretaceous age granitic plutons were emplaced along the converging plate boundary from southern California in a north-northeast trend. This Sierran batholithic belt intruded the margin of North America after the Late Jurassic Nevadan Orogeny and before about 80 million years ago. Individual plutons within the belt vary widely in size and shape.

In the Manzanar area, the intrusive igneous activity associated with the Sierran arc is divisible into two broad age groups: Middle to Late Jurassic, and late Early to Late Cretaceous. In the Inyo Mountains and Alabama Hills, Middle to Late Jurassic volcanic and volcanogenic rocks are widespread and include silica-rich ash layers and welded ash flows. This volcanism occurred at the same time as intense magmatism to the west along the Sierran igneous arc. The Pat Keyes quartz monzonite to quartz monzodiorite pluton is an intrusive representative of Middle Jurassic magmatism (Stone et al. 2000).

Granitic plutons emplaced during the late Early and Late Cretaceous magmatic episodes are widespread throughout the Sierra Nevada (Glazner and Coleman 1994). Local plutons include the Dragon Pluton, Independence Pluton, Granite of Carroll Creek, and Alabama Hills Granite. Late Cretaceous intrusive activity produced the leucocratic Kern Knob Pluton and the granodioritic masses of the Mt. Whitney Intrusive Suite (approximately 85 million years ago), followed by the emplacement of the granodiorite of Lone Pine Creek and the Paradise Granodiorite in the Manzanar area (Stone et al. 2000).

The Sevier Orogeny evolved into the Late Cretaceous - Early Tertiary Laramide Orogeny. Instead of thin-skinned thrusts carrying shallow layers of sedimentary rock, the Laramide Orogeny involved deep thrusts, carrying basement rocks from below and stacking them atop younger rocks. Both the Sevier and Laramide orogenies involved subduction of the Farallon Plate (a forebearer of the present-day Pacific Plate) beneath the western margin of North America. The east-dipping, oceanic Farallon Plate subducted at a steep angle during the Sevier Orogeny, causing extensive melting. This influx of molten rock was responsible for widespread igneous activity along the continental margin.

Near the end of the Cretaceous, the subducting Farallon Plate may have changed its angle of dip from steep to relatively flat (Dickinson and Snyder 1978; Livaccari 1991; Fillmore 2000). Subducting at a flatter angle, the oceanic plate would not readily melt, thereby extinguishing the magma source for volcanic activity. In the Manzanar area, most widespread magmatism stopped during the Late Cretaceous. Tremendous shear stresses generated between the two slabs. Stresses at the base of the thick continental crust transferred upward in the form of compression, thrusting great wedges of basement rock skyward to form the Laramide Rocky Mountains.

Cenozoic Era

The Laramide Orogeny caused regional uplift throughout the western United States, including the Manzanar area. Widespread erosion followed this uplift. The deformation regime changed from compressional to extensional during the late Tertiary, signaling the beginning of the Basin and Range formation. As the crust extension initiated about 15 million years ago, the surface began to break into the parallel, linear ranges and alternating basins characteristic of the topography in western Utah, parts of California, Nevada, Arizona, and the Rio Grande Rift in New Mexico (figs. 2 and 12) (Dickinson 1979). The amount of extension has been significant. The Sierra Nevada Batholith was probably displaced as a block about 200 km (120 mi) westward in response to Cenozoic extension in the Basin and Range Province to the east.

Basin and Range faulting ultimately produced the present Owens Valley structure. In the Great Basin section of the Basin and Range physiographic province, two episodes of faulting are recognized. These are delineated by fault orientations and cross-cutting relationships. The first event, occurring during the Miocene–Pliocene epochs, produced northeast- and northwest-trending faults. This event is not widely recognized in the rocks of Owens Valley; volcanic rocks in the White Mountains, however, dip up to 25° to the east, recording Miocene uplift and tilting (Hollet et al. 1991; Stockli et al. 2003). The second episode of faulting is characterized in the western Great Basin section by north-south trending normal faults that bound downdropped graben valleys. This faulting was most active in the Owens Valley area between 3 and 6 million years ago (Hollett et al. 1991).

Three major, intermittently active, north-south trending fault zones have controlled the development of the Owens Valley: the Sierra Nevada Frontal, Owens Valley, and Inyo-White Mountains fault zones. As described in the "Geologic Features and Processes" section of this report, the faults accommodated much normal and strike-slip movement, and thick mantles of unconsolidated deposits cover their traces. Small-scale recent fault scarps, depressions, stream diversions and offset features, pressure ridges, and other linear features mark recent seismicity and indicate that Owens Valley is among the younger valleys of the Basin and Range Province (Stone et al. 2000; Hollett et al. 1991).

Following Basin and Range development, the boundary between the Pacific and North American plates became more transform in nature. The effects of this transition occurred in different places at different times, and are probably related to the impinging of the North American Plate on the western margin, the development of the San Andreas Fault system, and the opening of the Gulf of California beginning in the Oligocene (Bally et al. 1989; Christiansen and Yeats 1992). Many of the previously dip-slip normal faults locally reactivated as right-lateral (dextral) strike-slip faults (Stockli et al. 2003).

The heights of the uplifted Sierra Nevada underwent alpine glaciation during the Pleistocene and Holocene epochs. Local advances date from 3.2 million years ago to as recently as 400 years ago. Glaciers are efficient mechanisms of erosion, and easily entrained glacial deposits are present in the alluvial fans spreading across Owens Valley (described in the "Geologic Features and Processes" section above) (Hollett et al. 1991; Stone et al. 2000; Blair 2002).

The deposition of vast amounts of volcanic and sedimentary material occurred contemporaneously with the development of the Owens Valley graben during the past 6 million years (Gillespie 1988). Pleistocene Lake Owens was an extensive feature that intermittently filled Owens Valley, leading to the deposition of vast lacustrine sediments (Hollett et al. 1991; Stone et al. 2000). Lake highstands occurred at 20,000, 13,000, and 9,000 years ago, with intermittent lowstands (Orme and Orme 2000).

Today, active seismicity throughout the area attests to the dynamic geologic processes occurring below the surface. Alluvial fans and bajadas continue to develop along the margins of Owens Valley as wind and water erode, transport, deposit, and rework sediment on the surface. Anthropogenic structures and land use practices such as agriculture, groundwater pumping, and the Los Angeles aqueduct have had a dramatic effect on the landscape of Owens Valley. Owens Lake is now a dry playa (Hollett et al. 1991).

Eon	Era	Period	Epoch	Ma		Life Forms	North American Events
Phanerozoic	Cenozoic	Quaternary	Holocene	0.01	Age of Mammals	Modern humans	Cascade volcanoes (W)
			Pleistocene	1.8		Extinction of large mammals and birds	Worldwide glaciation
		Tertiary	Pliocene	5.3		Large carnivores	Sierra Nevada Mountains (W)
			Miocene	23.0		Whales and apes	Linking of North and South America
			Oligocene	33.9			Basin-and-Range extension (W)
			Eocene	55.8		Early primates	Laramide Orogeny ends (W)
			Paleocene	65.5			
	Mesozoic	Cretaceous		145.5	Age of Dinosaurs	**Mass extinction** Placental mammals Early flowering plants	Laramide Orogeny (W) Sevier Orogeny (W) Nevadan Orogeny (W)
		Jurassic		199.6		First mammals	Elko Orogeny (W)
		Triassic		251		**Mass extinction** Flying reptiles First dinosaurs	Breakup of Pangaea begins Sonoma Orogeny (W)
	Paleozoic	Permian		299	Age of Amphibians	**Mass extinction** Coal-forming forests diminish	Supercontinent Pangaea intact Ouachita Orogeny (S) Alleghanian (Appalachian) Orogeny (E)
		Pennsylvanian		318.1		Coal-forming swamps Sharks abundant Variety of insects	Ancestral Rocky Mountains (W)
		Mississippian		359.2		First amphibians First reptiles	Antler Orogeny (W)
		Devonian		416	Fishes	**Mass extinction** First forests (evergreens)	Acadian Orogeny (E-NE)
		Silurian		443.7		First land plants	
		Ordovician		488.3	Marine Invertebrates	**Mass extinction** First primitive fish Trilobite maximum Rise of corals	Taconic Orogeny (E-NE)
		Cambrian		542		Early shelled organisms	Avalonian Orogeny (NE) Extensive oceans cover most of North America
Proterozoic		Precambrian		2500		First multicelled organisms Jellyfish fossil (670 Ma)	Formation of early supercontinent Grenville Orogeny (E) First iron deposits Abundant carbonate rocks
Archean				≈4000		Early bacteria and algae	Oldest known Earth rocks (≈3.96 billion years ago)
Hadean				4600		Origin of life? Formation of the Earth	Oldest moon rocks (4–4.6 billion years ago) Formation of Earth's crust

Figure 9. Geologic timescale. Included are major life history and tectonic events occurring on the North American continent. Red lines indicate major unconformities between eras. Absolute ages shown are in millions of years (Ma). Compass directions in parentheses indicate the regional location of individual geologic events. Adapted from the U.S. Geological Survey, http://pubs.usgs.gov/fs/2007/3015/.

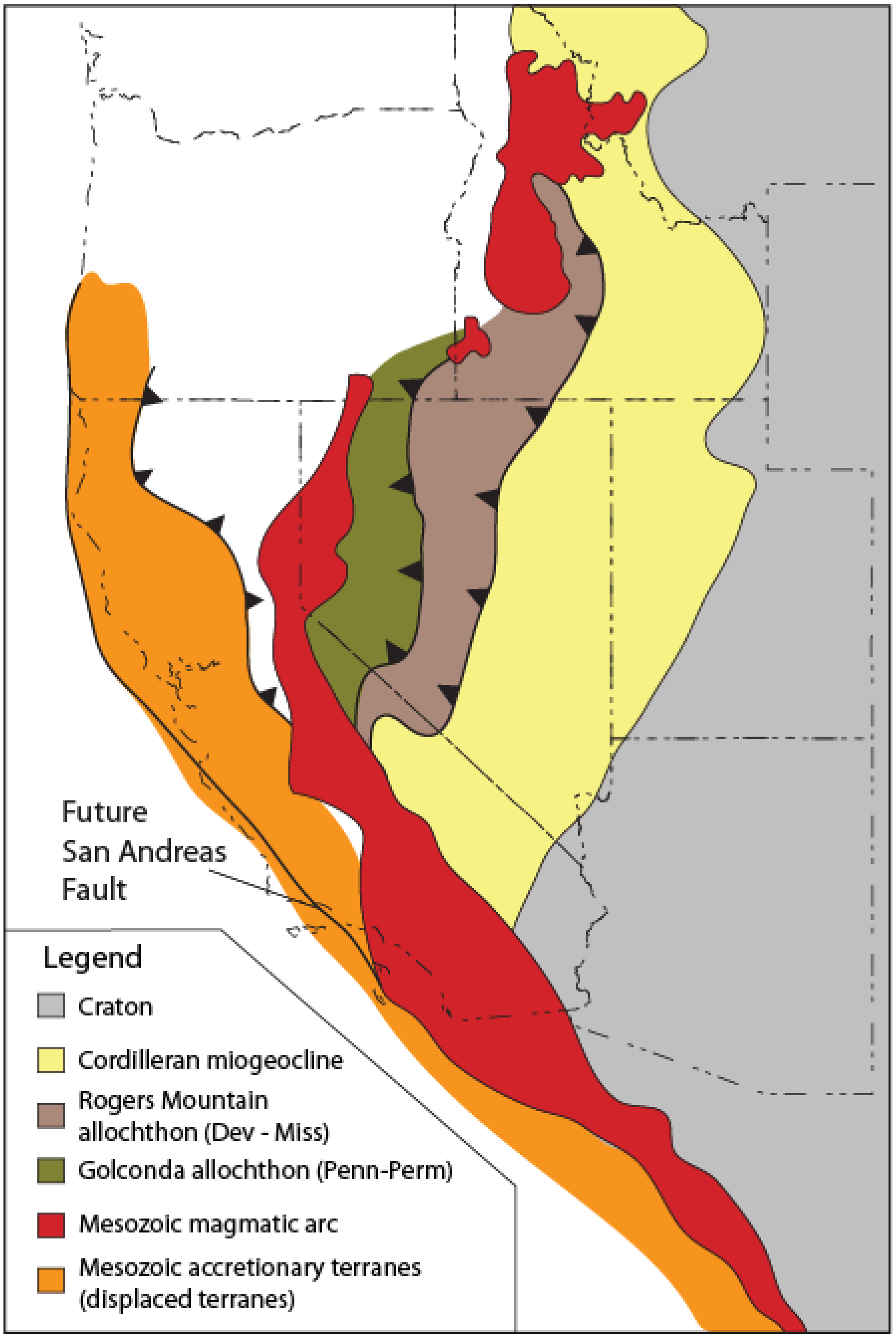


Figure 10. Location of tectonic features during the early Mesozoic Era (Triassic to Late Jurassic). Note the northeast-southwest trend of the Paleozoic features and the truncation of their southwest margin by the Mesozoic magmatic arc and accreted terranes. Solid triangles mark the emplacement of major thrust belts with the triangles on the upper, hanging blocks of strata. Dev=Devonian Period; Miss=Mississippian Period; Perm=Permian Period. Manzanar National Historic Site is located in the Cordilleran miogeocline of eastern California. Modified from Suppe (1985) by Trista L. Thornberry-Ehrlich (Colorado State University).

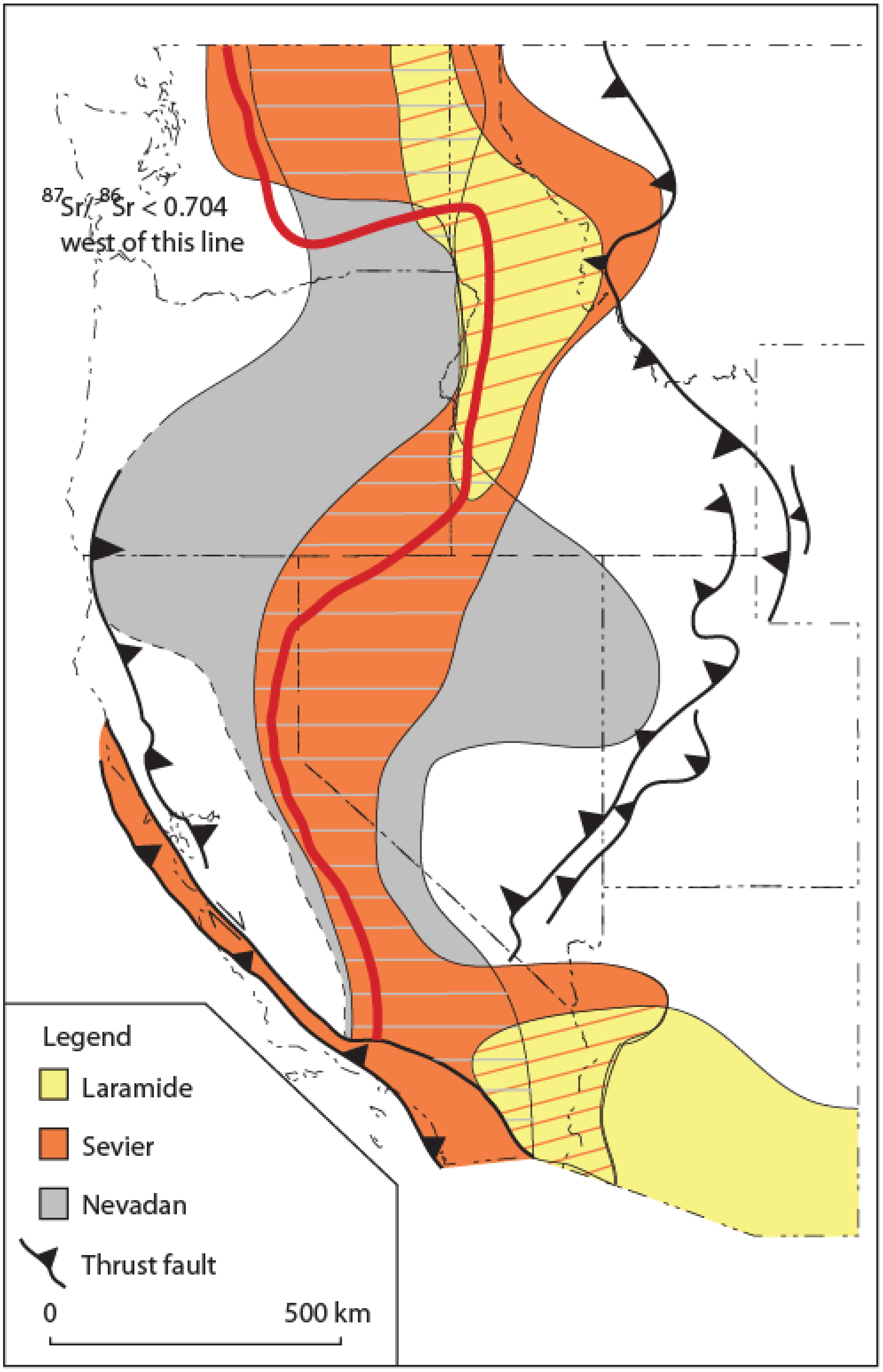


Figure 11. Location of magmatism in the western United States during the Nevadan (160-125 million years ago), Sevier (105-75 million years ago), and Laramide (50-75 million years ago) orogenies. The thick red line marks the western edge of the Precambrian Continental crust where the $^{87}Sr/^{86}Sr$=< 0.704 in granites indicating a young mantle source of magma as from an island arc. Modified from Suppe (1985).

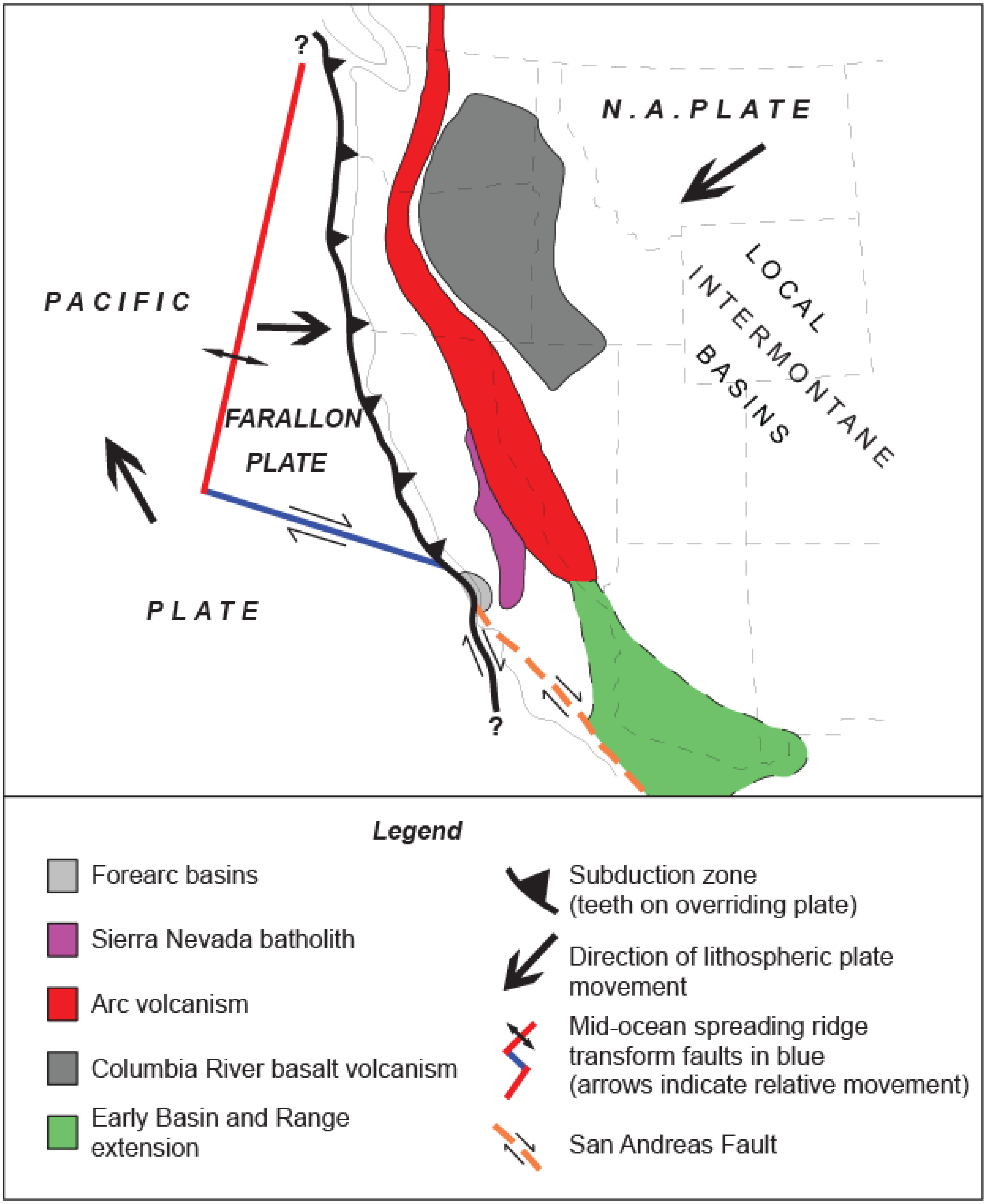


Figure 12. Paleotectonic map of western United States in the Miocene Epoch (approximately 15 million years ago). Initiation of basin-and-range faulting and the San Andres fault system takes place about this time. Modified from Dickinson (1979).

Glossary

This glossary contains brief definitions of technical geologic terms used in this report. Not all geologic terms used are referenced. For more detailed definitions or to find terms not listed here please visit: 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.

active margin. A tectonically active margin where lithospheric plates converge, diverge or slide past one another (also see "passive margin"). Typically associated with earthquakes and, in the case of convergent and divergent boundaries, volcanism.

allochthonous. Describes rocks or materials formed elsewhere than in their present location.

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 mountain front into an area such as a valley or plain.

alluvium. Stream-deposited sediment.

aphanitic. The texture of a fine-grained, igneous rock wherein the components are not distinguishable with the unaided eye.

aquifer. A rock or sedimentary unit that is sufficiently porous that it has a capacity to hold water, sufficiently permeable to allow water to move through it, and currently saturated to some level.

ash (volcanic). Fine pyroclastic material ejected from a volcano (see also "tuff").

azimuth. A mathematical concept defined as the angle, usually measured in degrees, between a reference plane and a point.

bajada. A broad, continuous alluvial slope extending from the base of a mountain range into an inland basin; formed by the coalescence of adjacent alluvial fans.

barchan dune. A crescent-shaped dune with arms or horns of the crescent pointing downwind. The crescent or barchan type is most characteristic of inland desert regions.

basement. The undifferentiated rocks, commonly igneous and metamorphic, that underlie the rocks exposed at the surface.

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, greater than 100 sq km (40 sq mi) and often formed from multiple intrusions.

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 geology. The geology of underlying solid rock as it would appear with the sediment, soil, and vegetative cover stripped away.

block (fault). A crustal unit bounded by faults, either completely or in part.

calcareous. Describes rock or sediment that contains calcium carbonate.

caldera. A large bowl- or cone-shaped summit depression in a volcano formed by explosion or collapse.

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.

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

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.

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

cleavage (rock). The tendency of rock to break along parallel planes that correspond to the alignment of platy minerals.

concretion. A hard, compact aggregate of mineral matter, subspherical to irregular in shape, formed by precipitation from water solution around a nucleus such as shell or bone in a sedimentary or pyroclastic rock; concretions are generally different in composition from the rocks in which they occur.

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

continental crust. The crustal rocks rich in silica and alumina that underlie the continents; ranging in thickness from 35 km (22 mi) to 60 km (37 mi) under mountain ranges.

continental shield. A continental block of the Earth's crust that has remained relatively stable over a long period of time and has undergone only gentle warping compared to the intense deformation of bordering crust.

convergent boundary. An active boundary where two tectonic plates are colliding.

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

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

cross-bedding. Uniform to highly varied sets of inclined sedimentary beds deposited by wind or water that indicate distinctive flow conditions (e.g., 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. The 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").

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

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

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

delta. A sediment wedge deposited where a stream flows into a lake or sea.

dike. A tabular, discordant igneous intrusion.

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

dip-slip fault A fault with measurable offset where the relative movement is parallel to the dip of the fault.

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

drainage basin. The total area from which a stream system receives or drains precipitation runoff.

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

efflorescence. An encrusting fluffy powder formed by evaporation in an arid region.

en echelon. Describes geologic features (particularly faults) that overlap in a step-like pattern.

entrainment. The process of picking up and carrying along sediment, commonly by wind or water.

eolian. Formed, eroded, deposited by or related to the action of wind.

escarpment. A steep cliff or topographic step resulting from vertical displacement on a fault or by mass movement (Synonymous with "scarp").

evaporite. Chemically precipitated mineral(s) formed by the evaporation of solute-rich water under restricted conditions.

extrusive. Of or pertaining to the eruption of igneous material onto the Earth's surface.

facies (sedimentary). The depositional or environmental conditions reflected in the sedimentary structures, textures, mineralogy, fossils, etc. of a sedimentary rock.

fan delta. An alluvial fan that builds into a standing body of water. This landform differs from a delta in that a fan delta is next to a highland and typically forms at an active margin.

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

fault gouge. Soft clay-like material found along some faults formed by friction as the fault moves.

felsic. An igneous rock having abundant light-colored minerals such as quartz, feldspars, or muscovite. Compare to "mafic".

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).

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

groundmass. The material between the phenocrysts in a porphyritic igneous rock; also, the matrix of a sedimentary rock.

grus. A silica-rich sand derived from the weathering of a parent rock, usually granite.

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

horst. Areas of relative up between grabens. Sometimes referred to as upthrown blocks but this is an incorrect designation as the horsts simply represent the geologic surface left behind as graben's 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.

igneous. Describes a rock or mineral that originated from molten material. One of the three main classes of rocks—igneous, metamorphic, and sedimentary.

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

island arc. A line or arc of volcanic islands formed over and parallel to a subduction zone.

joint. A semi-planar break in rock without relative movement of rocks on either side of the fracture surface.

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

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

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

levee. Raised ridge lining the banks of a stream. May be natural or artificial.

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

lithology. The physical description or classification of a rock or rock unit based on characters such as its color, mineralogic composition, and grain size.

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

loess. Windblow silt-sized sediment, generally of glacial origin.

longitudinal dune. Dune elongated parallel to the direction of wind flow.

mafic. Describes dark-colored rock, magma, or minerals rich in magnesium and iron.

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

magmatism. Development and movement of magma and its subsequent cooling into an igneous rock.

mantle. The zone of the Earth's interior between crust and core.

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

matrix. The fine grained material between coarse (larger) grains in igneous rocks or poorly sorted clastic sediments or rocks. Also refers to rock or sediment in which a fossil is embedded.

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

mesa. A broad, flat-topped erosional hill or mountain bounded by steeply sloping sides or cliffs.

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.

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

mid-ocean ridge. The continuous, generally submarine, seismic, median mountain range that marks the divergent tectonic margin(s) in the Earth's oceans.

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

miogeocline. A wedge of shallow-water sediment building outward from the edge of the continent.

moment magnitude scale. A logarithmic scale measuring the size of an earthquake in terms of the amount of energy released. Abbreviated M_w.

mud cracks. Cracks formed in clay, silt, or mud by shrinkage during subaerial dehydration.

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

obduction. The process by which the crust is thickened by thrust faulting at a convergent margin.

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

orogeny. A mountain-building event.

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

outwash. Glacial sediment transported and deposited by meltwater streams.

paleontology. The study of the life.

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

parabolic dune. Crescent-shaped dune with horns or arms that point upwind.

parent material. Geologic material from which soils form; parent material is one of five soil-forming factors: climate, organisms, relief (topography), parent material, and time.

parent rock. The original rock from which a metamorphic rock was formed. Can also refer to the rock from which a soil was formed.

pediment. A gently sloping, erosional bedrock surface at the foot of mountains or plateau escarpments.

permeability. A measure of the relative ease with which fluids move through the pore spaces of rocks or sediments.

phenocryst. A coarse crystal in a porphyritic igneous rock.

plastic. Capable of being permanently deformed without rupture.

plateau. A broad, flat-topped topographic high (terrestrial or marine) of great extent and elevation above the surrounding plains, canyons, or valleys.

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

pluton. A body of intrusive igneous rock.

plutonic. Describes igneous rock intruded and crystallized at some depth in the Earth.

pluvial. Describes geologic processes or features resulting from rain.

porosity. The proportion of void space (e.g., pores or voids) in a volume of rock or sediment deposit.

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

pyroclastic. Describes clastic rock material formed by volcanic explosion or aerial expulsion from a volcanic vent; also pertaining to rock texture of explosive origin. In the plural, the term is used as a noun.

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

radiometric age. An age in years determined from radioactive isotopes and their decay products.

recharge. Infiltration processes that replenish groundwater.

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

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

rift valley. A depression formed by grabens along the crest of an oceanic spreading ridge or in a continental rift zone.

saltation. A mode of sediment movement, driven by wind or water, whereby materials move through a series of intermittent "leaps" or "jumps."

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.

scarp. A steep cliff or topographic step resulting from displacement on a fault, or by mass movement, or erosion.

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).

sequence. A major informal rock-stratigraphic unit that is traceable over large areas and defined by a major sea level transgression-regression sediment package.

sheet flow. An overland flow or downslope movement of water taking the form of a thin, continuous film over relatively smooth soil or rock surfaces and not concentrated into channels larger than rills.

sierra. An often-used Spanish term for a rugged mountain range.

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

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.

slope. The inclined surface of any geomorphic feature or rational measurement thereof. Synonymous with gradient.

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

soil. Surface accumulation of weathered rock and organic matter capable of supporting plant growth and often overlying the parent material from which it formed.

solifluction. Slow flow of water-saturated soil down a steep slope; commonly initiated by repeated freeze-thaw cycles.

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

strata. Tabular or sheetlike masses or distinct layers of

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 continuously or periodically covered by water.

stream terrace. One of a series of level surfaces in a stream valley, flanking and approximately parallel to the present stream channel. It is above the level of the stream and represents the dissected remnants of an abandoned floodplain, streambed, or valley floor produced during a former stage of erosion or deposition.

strike. The compass direction of the line of intersection of an inclined surface with a horizontal plane.

strike-slip fault. A fault with measurable offset where the relative movement is parallel to the strike of the fault. Said to be "sinistral" (left-lateral) if relative motion of the block opposite the observer appears to be to the left. "Dextral" (right-lateral) describes relative motion to the right.

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 the Earth's surface.

suture. The linear zone where two continental landmasses become joined via obduction.

syncline. A downward curving (concave up) fold with layers that dip inward; the core of the syncline contains the stratigraphically-younger rocks.

system (stratigraphy). The group of rocks formed during a period of geologic time.

tectonic. Relating to large-scale movement and deformation of the Earth's crust.

terrace. A relatively level bench or steplike 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, the Earth, or its inhabitants.

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. Dominantly unsorted and unstratified drift, generally unconsolidated, deposited directly by and underneath a glacier.

topography. The general morphology of the 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 fossils. Sedimentary structures, such as tracks, trails, burrows, coprolites (dung), etc., that preserve evidence of organisms' life activities, rather than the organisms themselves.

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.

transverse dune. Dune elongated perpendicular to the prevailing wind direction. The leeward slope stands at or near the angle of repose of sand, whereas the windward slope is comparatively gentle.

trend. The direction or azimuth of elongation of a linear geologic feature.

tuff. Generally fine-grained, igneous rock formed of consolidated volcanic ash.

unconformity. An erosional or non-depositional surface bounded on one or both sides by sedimentary strata. An unconformity thus marks a period of missing time.

uplift. A structurally high area in the crust, produced by movement that raises the rocks.

volcanic. Related to volcanoes. Igneous rock crystallized at or near the Earth's surface (e.g., lava).

volcanogenic. Describes material formed by volcanic processes.

water table. The upper surface of the saturated zone; the zone of rock in an aquifer saturated with water.

weathering. The set of physical, chemical, and biological processes by which rock is broken down.

References

*This section lists references cited in this report as well as additional references (indicated by an *) that may be of use to resource managers. A more complete geologic bibliography is available from the National Park Service Geologic Resources Division.*

Angerman, C. E. 2002. Geology and tectonics of the Poverty Hills basement structure in Owens Valley (California) and implications for the eastern California shear zone. B. S. thesis, Miami University, Oxford, OH.

Bacon, S. N. A. S. Jayko, and J. P. McGeehin. 2005. Holocene and latest Pleistocene oblique dextral faulting on the Southern Inyo Mountains Fault, Owens Lake basin, California. *Bulletin of the Seismological Society of America* 95 (6): 2472-2485.

Bacon, S. N., K. P. Silvio, and R. M. Burke. 2002. Paleoseismology on the Owens Valley Fault and Holocene stratigraphy of pluvial Owens Lake near Lone Pine, eastern California. *Geological Society of America Abstracts with Programs* 34 (6): 27.

Bally, A. W., C. R. Scotese, and M. I. Ross. 1989. North America; Plate-tectonic setting and tectonic elements. In *The Geology of North America; An Overview: Geological Society of America, The Geology of North America* A, eds. Bally, A. W., and A. R. Palmer, 1-16. Boulder, CO: Geological Society of America.

Bierman, P. R., and A. R. Gillespie. 1990. Range fire; a dramatic and significant factor in the dating and evolution of geomorphic surfaces. *Geological Society of America Abstracts with Programs* 22 (7): 109.

Bishop, K. M. 1998. Mega-rock-avalanche deposits of the Owens Valley Graben, eastern California. *Geological Society of America Abstracts with Programs* 30 (7): 295.

*Bishop, K. M. 1999. Structural reinterpretation of the northern Owens Valley Graben, eastern California based on recognition of large rock avalanche deposits. *Geological Society of America Abstracts with Programs* 31 (6): 38.

Bishop, K. M. 2005. The Poverty Hills, Owens Valley, Eastern California; transpressional uplift or long-runout rock avalanche? *Geological Society of America Abstracts with Programs* 37 (4): 78.

Blair, T. C. 2002. Alluvial-fan sedimentation from a glacial-outburst flood, Lone Pine, California, and contrasts with meteorological flood deposits. *Special Publication of the International Association of Sedimentologists* 32: 113-140.

Christiansen, R. L., and R. S. Yeats. 1992. Post-Laramide geology of the U.S. Cordilleran region. In *The Cordilleran Orogen: Conterminous U.S.: Geological Society of America, the Geology of North America* G-3, eds. Burchfiel, B. C., P. W. Lipman, and M. L. Zoback, 261-406. Boulder, CO: Geological Society of America.

Cowan, D. S., and R. L. Bruhn. 1992. Late Jurassic to early Late Cretaceous geology of the U.S. Cordillera. In *The Cordilleran Orogen: Conterminous U.*S.: *Geological Society of America, The Geology of North America* G-3, eds. Burchfiel, B. V., P. W. Lipman, and M. L. Zobackv, 169-203. Boulder, CO: Geological Society of America.

Dickinson, W. R. 1979. Cenozoic plate tectonic setting of the Cordilleran region in the United States. In *Cenozoic Paleogeography of the Western United States*, eds. Armentrout , J. M. M., R. Cole, and H. Terbest, Jr., 1-13. Pacific Section, Society of Economic Paleontologists and Mineralogists.

Dickinson, W. R., W. S. Snyder. 1978. Plate tectonics of the Laramide orogeny. In *Laramide folding associated with basement block faulting in the western United States*, ed. V. Matthews III, 355-366. Memoir 151. Boulder, CO: Geological Society of America.

Dunne, G. C., and J. D. Walker. 1993. Age of Jurassic volcanism and tectonism, southern Owens Valley region, east-central California. *Geological Society of America Bulletin* 105 (9): 1223-1230.

*Elmore, A. J. 2003. Great Basin vegetation response to groundwater fluctuation, climate variability, and previous land cultivation; the application of multitemporal measurements from remote sensing data to regional vegetation dynamics. Ph. D. diss., Brown University, Providence, RI.

Fillmore, R. 2000. *The Geology of the Parks, Monuments and Wildlands of Southern Utah*. Salt Lake City, UT: The University of Utah Press.

Fridrich, C. J., R. A. Thompson, M. N. Machette, and D. P. Miggins. 2000. Late Cenozoic stratigraphic record of tectonic evolution, volcanism, and climate change in the Death Valley region, California and Nevada. *Eos, Transactions, American Geophysical Union* 81 (48, Suppl.): 1127.

Gillespie, A. R. 1988. Quaternary subsidence of Owens Valley, California. *Geological Society of America Abstracts with Programs* 20 (3): 163.

Glazner, A. F., J. M. Bartley, D. S. Coleman, and A. R. C. Kylander-Clark. 2003. Evidence from the independence dike swarm for 65 km or more of Post-Jurassic dextral offset across Owens Valley, California.

Geological Society of America Abstracts with Programs 35 (4): 80.

Glazner, A. F., and D. S. Coleman. 1994. Cretaceous crustal construction around the Owens Valley between Bishop and Independence, California. *Eos, Transactions, American Geophysical Union* 75 (44, Suppl.): 583.

Hollett, K. J., W. R. Danskin, W. F. McCaffrey, and C. L. Walti. 1991. *Geology and water resources of Owens Valley, California*. Water-Supply Paper: B1-B77. Reston, VA: U. S. Geological Survey.

Jayko, A. S., R. M. Forester, D. S. Kaufman, S. A. Mahan, J. P. McGeehin, F. M. Phillips, and A. M. Sarna-Wojcicki. 2003. Climatic and tectonic links to paleogroundwater systems from surficial deposits mapping, Darwin Hills 1:100,000, Inyo County, California. *Geological Society of America Abstracts with Programs* 35 (6): 73-74.

*Jessey, D. R., and R. E. Reynolds, eds. 2009. *Landscape evolution at an active plate margin*. 2009 Desert Symposium Guidebook. Soda Springs, CA: California State University Desert Studies Center. http://biology.fullerton.edu/dsc/pdf/2009landscapeevolution.pdf (accessed September 8, 2009).

Jessey, D. R., and D. N. D. Wall. 2006. *Cenozoic/Mesozoic Volcanism of the Eastern Sierra Nevada: A field trip to Owens Valley/Mammoth Lakes, Cal Poly-Pomona University* http://geology.csupomona.edu/docs/sierra.html (accessed October 9, 2006).

Kim, B. C., and D. R. Lowe. 2004. Depositional processes of the gravelly debris flow deposits, South Dolomite alluvial fan, Owens Valley, California. *Geosciences Journal Seoul* 8 (2): 153-170.

Klingler, C. J. 2008. *A brief overview: recent Owens Valley water history and OVC*. Owens Valley Committee http://www.ovcweb.org/OwensValley/Waterhistory.html (accessed March 3, 2009).

Kylander-Clark, A. R. C., D. S. Coleman, A. F. Glazner, and J. M. Bartley. 2005. Evidence for 65 km of dextral slip across Owens Valley, California, since 83 Ma. *Geological Society of America Bulletin* 117 (7-8): 962-968.

Lee, J., J. Spencer, L. Owen, and T. Dixon. 2001. Paleoseismology along the Owens Valley Fault; accounting for the San Andreas discrepancy. *Geological Society of America Abstracts with Programs* 33 (3): 31.

Livaccari, R. F. 1991. Role of crustal thickening and extensional collapse in the tectonic evolution of the Sevier-Laramide orogeny, western United States: *Geology* 19: 1104-1107.

Lueddecke, S. B., N. Pinter, and P. Gans. 1998. Plio-Pleistocene ash falls, sedimentation, and range-front faulting along the White-Inyo Mountains front, California. *Journal of Geology* 106 (4): 511-522.

*Lyles, B. F., and G. F. Cochran. 1997. Terrestrial saltwater intrusion, Owens Lake, California. *Geological Society of America Abstracts with Programs* 29 (5): 26.

Martel, S. J. 1989. Structure and late Quaternary activity of the northern Owens Valley fault zone, Owens Valley, California. *Engineering Geology* 27 (1-4): 489-507.

*McCaffrey, W. F., and K. J. Hollett. 1988. Structure and depositional history of Owens Valley, California. *Geological Society of America Abstracts with Programs* 20 (3): 211.

McCarley Holder, G. A. D. M. Ono, and B. G. Cox. 1991. Dust storms from Owens (dry) Lake, Inyo County, California. In *Sedimentary and paleolimnological records of saline lakes*. Saskatoon, S.K., Canada: National Hydrologic Research Institute.

Milana, J. P. 2000. Characterization of alluvial bajada facies distribution using TM imagery. *Sedimentology* 47 (4): 741.

Miller, C. D. 1985. Holocene eruptions at the Inyo volcanic chain, California–implications for possible eruptions in the Long Valley caldera. *Geology* 13: 14-17.

Miller, E. L., M. M. Miller, C. H. Stevens, J. E. Wright, and R. Madrid. 1992. Late Paleozoic paleogeographic and tectonic evolution of the western U.S. Cordillera. In *The Cordilleran Orogen: Conterminous U.S.: Geological Society of America, The Geology of North America* G-3, eds. Burchfiel, B. V., P. W. Lipman, M. L. Zobackv. G-3: 57-106. Boulder, CO: Geological Society of America.

Norris, R. M., and R. W. Webb. 1976. *Geology of California*. New York, NY: John Wiley & Sons.

National Park Service. 2002. *Trip Report - Reconnaissance of erosional features at Manzanar National Historic Site, April 30, 2002 - May 1, 2002*. Department of Interior, National Park Service.

Orme, A. R., and A. J. Orme. 2000. Deformation of late Pleistocene shorelines at Owens Lake, eastern California; tectonic and hydrologic implications. *Geological Society of America Abstracts with Programs* 32 (7): 333.

*Reheis, Marith C., G. S. Plumlee, P. J. Lamothe, J. R. Budahn, P. L. Hageman, T. K. Hinkley, G. P. Meeker, T. Gill, R. Winn, D. Thames. 2001. Potential health hazards of Owens Lake dust. *Geological Society of America Abstracts with Programs* 33 (6): 237.

Reheis, M. C., and T. H. Dixon. 1996. Kinematics of the eastern California shear zone; evidence for slip transfer from Owens and Saline Valley fault zones to Fish Lake Valley fault zone. *Geology* (Boulder) 24 (4): 339-342.

Saleeby, J. R., and C. Busby-Spera. 1991. Early Mesozoic tectonic evolution of the western U.S. Cordillera. In *The Cordilleran Orogen: Conterminous U.S.: Geological Society of America, The Geology of North America* G-3, eds. Burchfiel, B. V., P. W. Lipman, M. L. Zobackv, 107-168. Boulder, CO: Geological Society of America.

Schroeder, J. M., J. Lee, L. A. Owen, and R. C. Finkel. 2003. Pleistocene dextral fault slip along the White Mountains fault zone, California. *Geological Society of America Abstracts with Programs* 35 (6): 346.

Sharp, R. P., and A. F. Glazner. 1997. *Geology Underfoot in Death Valley and Owens Valley*. Missoula, MT: Mountain Press Publishing Co.

Silberling, N. J., and R. J. Roberts. 1962. Pre-Tertiary stratigraphy and structure of northwestern Nevada. *GSA Special Paper* 72. Boulder, CO: Geological Society of America.

*Squires, L. J. 1994. The Sierra Nevada root question. *Seismological Research Letters* 65 (1): 15.

Stevens, C. H. 1995. Middle Devonian-Early Triassic unconformity in Owens Valley, Eastern California. *Geological Society of America Abstracts with Programs* 27 (5): 79.

Stewart, J. H. 1980. Geology of Nevada. *Nevada Bureau of Mines and Geology, Special Publication* 4.

Stockli, D. F., T. A. Dumitru, M. O. McWilliams, and K. A. Farley. 2003. Cenozoic tectonic evolution of the White Mountains, California and Nevada. *Geological Society of America Bulletin* 115 (7): 788-816.

Stone, P., G. C. Dunne, J. G. Moore, and G. I. Smith. 2000. *Geologic Map of the Lone Pine 15" Quadrangle, Inyo County, California*. Scale 1:62,500. Geologic Investigation Series I-2617. Reston, VA: U.S. Geological Survey.

Suppe, J. 1985. *Principles of Structural Geology*. Englewood Cliffs, NJ: Prentice-Hall, Inc.

Vandal, Q., and N. Pinter. 2003. Mountain-front development and tectonic setting as recorded in the Plio-Pleistocene alluvial-fan conglomerates of the White/Inyo Mountains, Owens Valley, California. *Geological Society of America Abstracts with Programs* 35 (2): 48.

Whipple, K. X., and T. Dunne. 1992. The influence of debris-flow rheology on fan morphology, Owens Valley, California. *Geological Society of America Bulletin* 104 (7): 887-900.

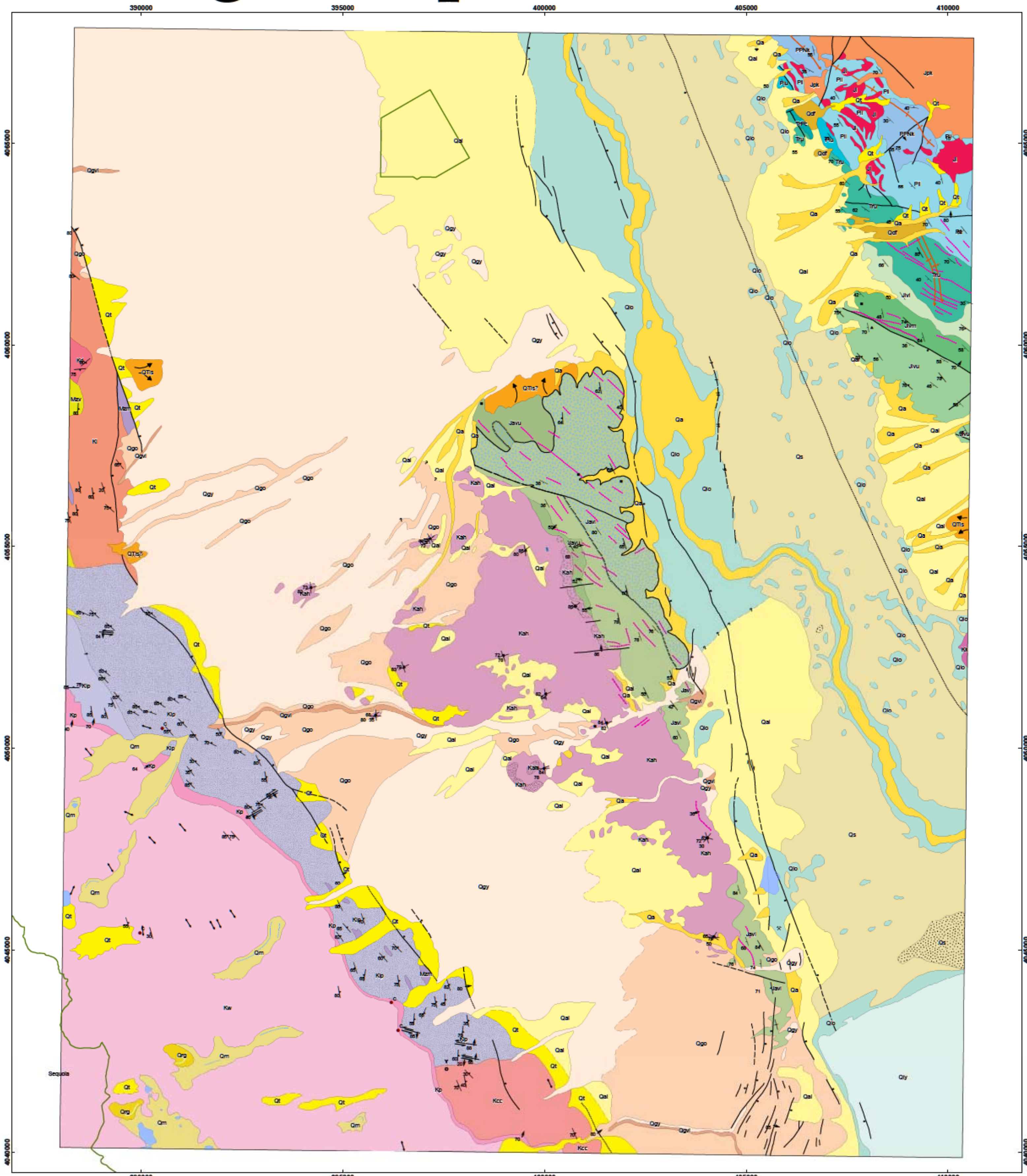
Willis, K. H. 2004. Vertical deformation of paleo-shorelines from active tectonics in Owens Valley, California. M. S. thesis, Purdue University, West Lafayette, IN.

Zekster, S., H. A. Loaiciga, and J. T. Wolf. 2005. Environmental impacts of groundwater overdraft; selected case studies in the Southwestern United States. *Environmental Geology Berlin* 47 (3): 396-404.

Appendix A: Geologic Map Graphic

The following page is a snapshot of the geologic map for Manzanar National Historic Site. For a poster-size PDF of this map or for digital geologic map data, please see the included CD or visit the Geologic Resources Inventory publications Web page (http://www.nature.nps.gov/geology/inventory/gre_publications.cfm).

Geologic Map of Manzanar National Historic Site



NPS Boundary

Geologic Attitude Observation Localities
- dip of inclined contact, dip direction indicated
- fault dip amount, dip direction indicated
- strike and dip of inclined beds
- strike and dip of inclined foliation
- strike and dip of inclined joints
- strike of foliation or trend of lineation, dip or plunge unknown
- strike of vertical beds
- strike of vertical joints

Geologic Point Features
- C - copper mineralization locality

Geologic Sample Localities
- radiometric age-date locality
- paleontological age-date locality

Mine Point Features
- gravel pit
- well

Hazard Feature Lines
- landslide direction, known or certain

Glacial Feature Lines
- moraine crest, known or certain
- rock glacier crest, known or certain

Fault, Fold and Other Map Symbology
- fold plunge arrow head
- fault down-side (bar and ball) indicator
- anticline symbol
- syncline symbol
- fault block movement direction arrow (right-lateral)
- fault block movement direction arrow (left-lateral)
- 'Y' (younger) age-relationship of contiguous geologic units
- 'O' (older) age-relationship of contiguous geologic units

Folds
- anticline, known or certain
- syncline, known or certain

Faults
- normal fault, known or certain
- normal fault, approximate
- normal fault, concealed
- right-lateral strike-slip fault, known or certain
- right-lateral strike-slip fault, approximate
- right-lateral strike-slip fault, concealed
- unknown offset/displacement fault, known or certain
- unknown offset/displacement fault, approximate
- unknown offset/displacement fault, concealed
- unknown offset/displacement fault, queried
- unknown offset/displacement fault, approximate and queried
- right-lateral fault, vertical displacement/offset unknown, known or certain
- left-lateral fault, vertical displacement/offset unknown, known or certain

Linear Dikes
- Kahd - Alabama Hills Granite - aplite and pegmatite dikes
- KJf - Felsic dike
- KJd - Mafic, intermediate-composition, and minor felsic dikes

Dike Swarm Contacts
- known or certain
- approximate
- gradational

Dike Swarms
- KJd - Mafic, intermediate-composition, and minor felsic dikes

Geologic Contacts
- known or certain
- approximate
- concealed
- queried
- approximate and queried
- gradational
- quadrangle boundary
- water or shoreline
- subaqueous (inferred)

Geologic Units
- water - Lakes and rivers
- Qal - Active alluvium
- Qes - Eolian sand
- Qesd - Eolian sand, areas of small dunes
- Qly - Younger lake deposits
- Qrg - Rock glaciers
- Qt - Talus, regolith, and colluvium
- Qai - Inactive alluvium
- Qgvl - Very large boulder gravels
- Qdf - Debris-flow deposits
- Qlo - Older lake deposits
- Qgy - Younger alluvial and debris-flow gravels
- Qm - Glacial moraines
- Qgo - Older alluvial and debris-flow gravels
- QTls - Landslide deposits
- Kwg - Whitney Granodiorite
- Kpg - Paradise Granodiorite
- Kah - Alabama Hills Granite
- Kahc - Alabama Hills Granite - mixed country rocks
- Kahh - Alabama Hills Granite - hypabyssal (?) facies
- Klp - Granodiorite of Lone Pine Creek
- Klpf - Granodiorite of Lone Pine Creek - fine grained, darker, and mixed facies
- Kkg - Kern Knob Granite
- Kd - Dragon pluton
- Kip - Independence Pluton
- Kcc - Granite of Carroll Creek
- Jivu - Inyo Mountains Volcanic Complex - upper part
- Jivm - Inyo Mountains Volcanic Complex - middle part
- Jivl - Inyo Mountains Volcanic Complex - lower part
- Javu - Volcanic complex of the Alabama Hills - upper part
- Javl - Volcanic complex of the Alabama Hills - lower part
- Jpk - Pat Keyes pluton
- Jir - Intrusive rocks marginal to Pat Keyes Pluton
- MZv - Metavolcanic rocks
- MZm - Mafic plutonic rocks
- TRu - Union Wash Formation
- TRPc - Conglomerate Mesa Formation
- Plu - Lone Pine Formation - upper part
- Pll - Lone Pine Formation - lower part
- PPNk - Keeler Canyon Formation
- PZm - Metasedimentary rocks

This map graphically presents digital geologic data prepared as part of the NPS Geologic Resources Division's Geologic Resources Inventory. The source map used in creation of the digital geologic data product was:

Stone, P., G. C. Dunne, J. G. Moore, and G. I. Smith. 2000. Geologic map of the Lone Pine 15' Quadrangle, Inyo County, California, Geologic Investigation Series I-2617. Scale: 1:62,500. Reston, VA: US Geological Survey.

Digital geologic data and cross sections for Manzanar National Historic Site, and all other digital geologic data prepared as part of the Geologic Resources Inventory, are available online at the NPS Data Store: http://science.nature.nps.gov/nrdata/

Source data scale is 1:62,500; scale as shown is 1:40,000. Map displays greater detail than source accuracy.

Appendix B: Scoping Summary

The following excerpts are from the GRI scoping summary for Manzanar National Historic Site. The contact information and Web addresses in this appendix may be outdated. Please contact the Geologic Resources Division for current information.

Executive Summary

Geologic Resource Evaluation scoping meetings for three parks in the Mojave Network were held April 28 - May 1, 2003, in St George, UT, Barstow, CA, and Twentynine Palms, CA, respectively. Unfortunately, due to time and travel constraints, scoping was not done at Manzanar National Historic Site (MANZ). The following report identifies the major geologic issues and describes the geology of MANZ and the surrounding the area.

The major geologic issues affecting the park are:
1. Flooding and erosion due to runoff from the Sierra Nevada mountains to the west.
2. Recurring seismic activity
3. The potential for volcanic activity from Long Valley Caldera
4. Proposed gravel pit upslope from MANZ

Introduction

The National Park Service held Geologic Resource Evaluation scoping meetings for three parks in the Mojave Network: Parashant National Monument, Mojave National Preserve, and Joshua Tree National Park. These meeting were held April 28 - May 1, 2003, in St George, UT, Barstow, CA and Twentynine Palms, CA respectively. The purpose of these meeting was to discuss the status of geologic mapping, the associated bibliography, and the geologic issues in the respective park units. The products to be derived from the scoping meeting are: (1) Digitized geologic maps covering the park units; (2) An updated and verified bibliography; (3) Scoping summary (this report); and (4) A Geologic Resources Evaluation Report which brings together all of these products. Although there was no onsite scoping for MANZ, these products will be produced for the historic site.

The Manzanar Relocation Center was established in March 1942, as the Owens Valley Reception Center, first run by the U.S. Army's Wartime Civilian Control Administration (WCCA) and later operated by the War Relocation Authority (WRA). The center was located at the former farm and orchard community of Manzanar, founded in 1910. The town was abandoned when the city of Los Angeles purchased the land in the late 1920s for its water rights. The Los Angeles aqueduct, which carries Owens Valley water to Los Angeles, is less than a mile east of Manzanar. The internment of Japanese Americans began on March 21, 1942. The national historic site was established March 3, 1992. Total area administered by the Park Service is 813.81 acres.

MANZ is located in the southern Owens Valley in east-central California. It lies mostly on the west side of U.S. Highway 395, 220 miles north of Los Angeles and 250 miles south of Reno, NV, between the towns of Lone Pine and Independence. The outlying portions of the relocation center are on land administered by the Los Angeles Department of Water and Power (LADWP) and public land administered by the Bureau of Land Management.

The only quad of interest is the Manzanar 7½' topographic quadrangle. Several geologic maps cover the quad and surrounding area including Beanland and Clark, 1994 (1:24,000); Stone, et. al., 2000 (1:62,500); and Ross, 1985, (1:62,500).

Physiography

Manzanar lies in the Owens Valley on the extreme western edge of the Basin and Range province. Immediately to the west is the Sierra Nevada physiographic province and to the east is the Inyo-White Mountains Range in the Basin and Range province. Owens Valley extends for about 150 miles, approximately from Haiwee Reservoir on the south to Lake Crowley on the north. Mount Williamson, the second highest peak in the Sierra Nevada at 14,375 feet, is 10 miles southwest. The National Historic Site is located where bajadas from the Sierra meet the valley floor at about 3,900 feet elevation.

The Owens Valley, in the rain shadow formed by the Sierra Nevada, has a mean annual precipitation of 5 to 6 inches. Although the valley is well-watered by streams, a considerable quantity of water is collected from the eastern flank of the Sierra Nevada by the LADWP via the Los Angeles aqueduct. The Historic Site is located between two perennial streams which flow east from the Sierra Nevada: Shepherd Creek on the north and Bairs Creek on the south. The water rights from both creeks are owned by the LADWP and the flow is captured by the Los Angeles aqueduct about one-half mile east of MANZ (National Park Service, 2002).

Geologic History and Stratigraphy

Manzanar National Historic Site lies in the Owens Valley on an easterly sloping alluvial fan approximately 5 miles east of the Sierra Nevada escarpment and 1 mile west of the Owens River. The gradient of this fan is approximately 6.5%, leveling to approximately 2.5% at the Historic Site.
The alluvial fan consists of poorly sorted granitic boulders, cobbles, gravel, and sand grading to finer sand and silt within the boundary of the Site and towards Owens River (NPS, 2002).

The Owens Valley is the westernmost graben in the Basin and Range Province, bounded by two nearly vertical faults. The upthrown sides are the Sierra Nevada Range to the west and the Inyo-White Mountains to the east. The valley began forming about 3 million years ago in the Pliocene, gradually developing the relief observed today. Near Lone Pine there are about 10,000 feet of sediments in the valley.

In the Sierra Nevada about 60% of the exposed rock is composed of intrusive igneous rock of the Sierra Nevada Batholith, and most of that material is granitic (Norris and Webb, 1976). The batholith intruded pre-Jurassic rock and has been dated between 70 and 210 million years (Middle Jurassic to Late Cretaceous/Early Tertiary). Similar rock of approximately the same age crops out in the Inyo-White Mountains east of MANZ. The oldest Sierran rock are Ordovician metasediments which crop out as roof pendants near Lake Crowley, northeast of MANZ and east of Yosemite National Park. The Paleozoic section from Ordovician through Pennsylvanian is represented in the southern Sierra.

Crustal compression during the Nevadan (Jurassic) and Laramide (Late Cretaceous-Early Tertiary) orogenies caused extensive folding and thrust faulting and the uplift of the Sierra. The compressional episodes subsided by Eocene time and by the Miocene, crustal forces converted to extensional. Basin- and-Range-type horst and graben block faulting, en echelon faulting, and extensive right lateral faulting predominated, forming the topography we see today.

Significant Geologic Resource Management Issues at Manzanar National Historic Site

Flooding and erosion

The most immediate geologic resource management issue at Manzanar is the significant erosional channeling on the western side and sediment deposition on the eastern side of the unit (NPS, 2002). Both Shepard Creeks on the north and Bairs Creek on the south naturally top their banks and overflow into subsidiary channels during flood stage. Numerous channels have been eroded in the alluvial fan, trending parallel with Shepherd and Bairs Creeks. Overflows southerly out of Shepherd Creek and northerly out of Bairs Creek follow channels that trend towards the western boundary of MANZ. Natural overflow channels from Shepherd and Bairs Creeks carry floodwaters towards, and sometimes through, MANZ (NPS, 2002).

Staff from Mojave National Preserve visited the park April 30 to May 1, 2002, to evaluate the existing erosional impacts to the park and the potential threat of continued erosion to park resources (NPS, 2002). In the trip report dated May 31. 2002, they offered two alternatives: (1) actively control flooding by diversions on Shepherd and Bairs Creeks and construction of a flood control berm upgradient to deflect flow to the north and south; and, (2) allow floodwaters to flow through MANZ in maintained channels and relocate impacted cultural resources. The first alternative was recommended "since it would mitigate imminent damage to cultural resources. However, the second alternative should be considered as, a potentially necessary, long-term solution" (NPS, 2002).

Recurring seismic activity

The Owens Valley is seismically active. Owens Valley is a down-dropped, fault bounded valley (graben) with large uplifted blocks (horsts) on either side (the Sierra and the Inyo-White Mountain Range). Major fault systems extend the length of the valley. Continued Basin-and-Range down-dropping of the valley and uplift of the mountains as well as right-lateral faulting sympathetic to the San Andres Fault have resulted in major earthquake activity. The Lone Pine earthquake of 1872 was one of the largest quakes to occur in California in recorded time, with probably a magnitude of 8 or greater on the Richter Scale. At Lone Pine, 23 people were killed and most of the existing structures were destroyed. The quake caused rock slides as far north as Yosemite Valley, 110 miles to the northwest (Sharp and Glazer, 1997). Along the base of the Alabama Hills near Lone Pine, there were displacements for120 miles (Norris and Webb, 1976) as much as 4 vertical feet and 18 feet horizontally (Jessey and Wall). In 1986, a magnitude 6.4 earthquake, as well as thousands of aftershocks, occurred near the town Chalfant, north of MANZ. The threat of further large seismic events in the Owens Valley remains high.

Volcanic activity from Long Valley Caldera

In the upper reaches of the Owens River, northwest of Bishop, CA, is the Long Valley-Mono Lake volcanic area. This has been an area of frequent rhyolitic eruptions, some as recent as 600 years ago, from the Inyo Craters. These eruptions of the Inyo chain from Glass Creek, Obsidian, and South Deadman vents, include ash falls, pyroclastic flows, and lava flows covering over 9,000 km2 (Miller, 1985). The Bishop Tuff is a welded volcanic ash and pumice deposited about 710,000 years ago from the eruption of the Long Valley Caldera. It has been estimated that 30 to 40 cubic miles of material was expelled. The threat of a major eruption from this area continues to the present.

Proposed gravel pit

A gravel pit for the extraction of fill material has been proposed for the an area to the west and upslope of MANZ. Any disturbance of surface material uphill from MANZ could result in increased erosion and sedimentation in the Historic Site.

Other potential issues

Surface subsidence resulting from the LADWP pumping large volumes of water from Owens

Valley aquifers and exporting the water

Windblown alkali dust from the desiccation of Owens Lake and Owens Valley.

References

Beanland, Sarah, and, Clark, Malcolm M., 1994, The Owens Valley fault zone, eastern California, and surface faulting associated with the 1872 earthquake, U.S. Geological Survey Bulletin 1982, 39p. map scale: 1:24,000.

California Division of Mines and Geology, 1990, Revised official map of Alquist-Priolo Earthquake Fault Hazard Zones, Manzanar Quadrangle, Calif. Div. Mines and Geology, scale 1:24,000.

Jessey, David R., and Wall, Danielle, N.D., Cenozoic/Mesozoic Volcanism of the Eastern Sierra Nevada: A field trip to Owens Valley/Mammoth Lakes, Cal Poly-Pomona University, website at: http://www.intranet.csupomona.edu/~geology/docs/sierra.html

Miller, C.D., 1985, Holocene eruptions at the Inyo volcanic chain, California -- implications for possible eruptions in the Long Valley caldera: Geology, v. 13, pp. 14-17.

National Park Service, 2002, Trip Report - Reconnaissance of erosional features at Manzanar National Historic Site, April 30, 2002 - May 1, 2002, 11p.

Norris, Robert M., and Webb, Robert W., 1976, Geology of California, John Wiley & Sons, N.Y., p.11-67; 91-122.

Pakiser, L.C., Kane, M.F., and Jackson, W.H., 1964, Structural geology and volcanism of Owens Valley region, California – a geophysical study, U.S. Geological Survey Professional Paper 438, map scale 1:96,000.

Ross, D.C., 1965, Geology of the Independence quadrangle, Inyo County, California, U.S. Geological Survey Bulletin 1181-O, scale 1:62,500.

Ross, D.C., 1963, New Cambrian, Ordovician, and Silurian formations in the Independence quadrangle, Inyo County, California, in Geological Research, Short papers in geology and hydrology, Articles 1-59, U.S. Geological Survey Professional Paper 475-B, Art. 21, map scale 1:136,000.

Ross, D.C., 1962, Preliminary geologic map of the Independence quadrangle, Inyo County, California, U.S. Geological Survey Mineral Investigations Field Studies Map MF-254, scale 1:48,000.

Sharp, Robert P., and Glazner, Allen F., 1997, Geology Underfoot in Death Valley and Owens Valley, Mountain Press Publishing Co., Missoula, MT, 319p.

Stone, Paul, Dunne, G. C., Moore, J. G., Smith, G. I., 2000, Geologic map of the Lone Pine 15' quadrangle, Inyo County, California, Geologic Investigations Series Map I-2617, scale 1:62,500.

Manzanar National Historic Site
Geologic Resources Inventory Report

Natural Resource Report NPS/NRPC/GRD/NRR—2009/130

National Park Service
Acting Director • Dan Wenk

Natural Resource Stewardship and Science
Associate Director • Bert Frost

Natural Resource Program Center
The Natural Resource Program Center (NRPC) is the core of the NPS Natural Resource Stewardship and Science Directorate. The Center Director is located in Fort Collins, with staff located principally in Lakewood and Fort Collins, Colorado and in Washington, D.C. The NRPC has five divisions: Air Resources Division, Biological Resource Management Division, Environmental Quality Division, Geologic Resources Division, and Water Resources Division. NRPC also includes three offices: The Office of Education and Outreach, the Office of Inventory, Monitoring, and Evaluation, and Office of Natural Resource Information Systems. In addition, Natural Resource Web Management and Partnership Coordination are cross-cutting disciplines under the Center Director. The multidisciplinary staff of NRPC is dedicated to resolving park resource management challenges originating in and outside units of the National Park System.

Geologic Resources Division
Chief • Dave Steensen
Planning, Evaluation, and Permits Branch Chief • Carol McCoy
Geoscience and Restoration Branch Chief • Hal Pranger

Credits
Author • Trista Thornberry-Ehrlich
Review • Debra Hughson and Jim Wood
Editing • Jennifer Piehl
Digital Map Production • Greg Mack and Heather Stanton
Map Layout Design • Josh Heise and Georgia Hybels
Report Production • Lisa Fay

NPS 359/100134, September 2009

National Park Service
U.S. Department of the Interior

Geologic Resources Division
Natural Resource Program Center
P.O. Box 25287
Denver, CO 80225

www.nature.nps.gov