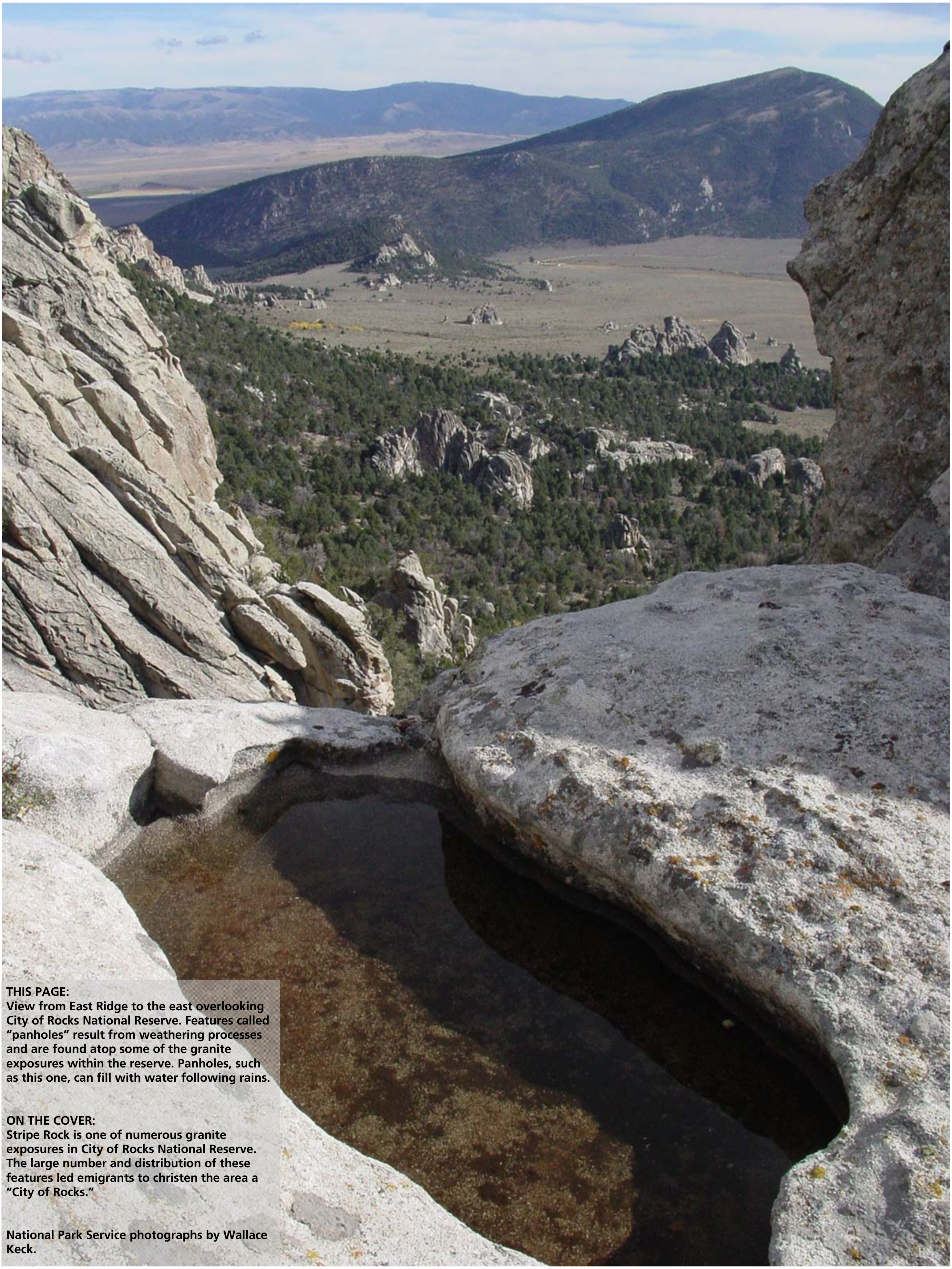
National Park Service
U.S. Department of the Interior

Natural Resource Program Center

City of Rocks National Reserve

Geologic Resources Inventory Report

Natural Resource Report NPS/NRPC/GRD/NRR—2010/191



THIS PAGE:
View from East Ridge to the east overlooking City of Rocks National Reserve. Features called “panholes” result from weathering processes and are found atop some of the granite exposures within the reserve. Panholes, such as this one, can fill with water following rains.

ON THE COVER:
Stripe Rock is one of numerous granite exposures in City of Rocks National Reserve. The large number and distribution of these features led emigrants to christen the area a “City of Rocks.”

National Park Service photographs by Wallace Keck.

City of Rocks National Reserve

Geologic Resources Inventory Report

Natural Resource Report NPS/NRPC/GRD/NRR—2010/191

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

April 2010

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

The National Park Service, Natural Resource Program Center publishes a range of reports that address natural resource topics of interest and applicability to a broad audience in the National Park Service and others in natural resource management, including scientists, conservation and environmental constituencies, and the public.

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

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

Printed copies of this report are produced in a limited quantity and they are only available as long as the supply lasts. This report is available from the Geologic Resources Inventory website (http://www.nature.nps.gov/geology/inventory/gre_publications.cfm) and the Natural Resource Publications Management website (http://www.nature.nps.gov/publications/NRPM).

Please cite this publication as:

Thornberry-Ehrlich, T. 2010. City of Rocks National Reserve: geologic resources inventory report. Natural Resource Report NPS/NRPC/GRD/NRR—2010/191. National Park Service, Ft. Collins, Colorado.

NPS 003/102081, April 2010

Contents

List of Figures

Executive Summary

This report accompanies the digital geologic map for City of Rocks National Reserve in Idaho, produced by the Geologic Resources Division 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.

City of Rocks National Reserve resembles a silent city on the landscape of southern Idaho, which is on the northern edge of the Basin and Range physiographic province. Within its stone monuments are some of the oldest rocks in North America—previously molten and metamorphosed rocks of the Green Creek Complex, the oldest of which are more than 2.5 billion years old. These are juxtaposed against a large body of much younger once-molten rock that intruded and cooled beneath the surface to form the granite of the Almo pluton. The Almo pluton is approximately 28 million years old, or Oligocene in age. This age gap, a tangible contact, represents billions of years of geologic history. The Green Creek Complex and Almo pluton met at depth during mountain building and later Basin and Range extension when Earth's crust began pulling apart. Uplift, erosion, and movement along faults exposed them at the surface; then wind, water, and the elements began sculpting, chipping, cracking, exfoliating, hollowing, and molding the rock into an "urban" landscape. City of Rocks National Reserve is a showcase for granitic weathering processes. It encompasses a landscape of spires, fins, and domes in the midst of the southern Albion Mountains.

Geologic issues and concerns pertain to protecting the delicate geologic features at City of Rocks, as well as providing safe access for visitors to the reserve. Humans have modified the landscape surrounding City of Rocks, and, consequently, have modified its geologic system. This system is dynamic and capable of noticeable change within a human life span (less than a century). Additionally, current visitors are placing increasing demands on the resources available at City of Rocks National Reserve. The following features, issues, and processes were identified as having the most geological importance and the highest level of management significance for the reserve:

- Erosion and slope processes. Erosion and weathering have sculpted the rocks at the reserve. Deposition of eroded, unconsolidated sediments in valleys creates hazards when these rocks are saturated and exposed on a slope. Rockfall and slope failure are possible almost everywhere along the roads and trails within City of Rocks National Reserve.
- Recreational demands. The park was created to preserve and protect a special landscape of geologic forms and some of the historic features of the pioneer experience during westward expansion of the United States. This area is also attractive to rock climbers, mineral collectors, and four-wheel-drive enthusiasts. Activities related to climbing and use of roads and trails increase erosion, and modern graffiti obscure and mar the historic signatures and other human markings.
- Mine-related issues and disturbed lands. Features such as mica mines, borrow pits, animal grazing areas, mining claims, woodcutting tracts, and other development adjacent to park lands create a situation where the resources of the park, including landforms, rock formations, vegetation, and viewshed, are jeopardized. Park management could establish cooperative relationships with the parties involved to remediate and restore disturbed areas.
- Relation between historical landscape and present condition. Geology had a profound effect on the decisions of the early pioneers who charted a safe passage through the area. It presented challenges to crossing mountains and valleys. City of Rocks National Reserve is charged with preserving the historical landscape from the 1840s through the stagecoach era. This entails understanding and, where appropriate, mitigating the natural geological processes of erosion and weathering.

Other geologic features and issues such as water, wind erosion and deposition, seismicity, volcanism, joints and fragile features, and geologic research were also identified as important resource management issues for City of Rocks National Reserve.

The Albion Mountains contain Granite Pass, a passage for thousands of emigrants heading west on the California and Oregon trails. This silent city inspired many journal entries of early emigrants on their way to California and Oregon. The emigrants left their mark on the landscape with trails, roads, and graffiti, both carved into the rocks and smeared on with axle grease. This setting, defined by the geology, attracted 96,649 visitors in 2009. The stark beauty of the landscape with its pinnacles, fins, tors, spires, arches, tafoni, and panholes, combined with the tangible history reflected by the names of pioneers etched in the pinnacles, are primary attractions for park visitors. The history of the area reflects the geology and anthropogenic changes to the landscape. The preservation of the historic context at City of Rocks and interpretation of geologic features and processes and their influences on the history merits attention to enhance the visitors' experiences.

Geologic maps provide a fundamental tool for resource management and understanding the geology at City of

Rocks National Reserve. The "Map Unit Properties" section details the different geologic units shown on the digital geologic map of City of Rocks National Reserve and potential resources, concerns, and issues associated with each mapped unit.

The glossary on page 35 contains explanations of many technical terms used in this report, including terms used in the Map Unit Properties Table.

Acknowledgements

The Geologic Resources Inventory (GRI) is one of 12 inventories funded under the National Park Service (NPS) Natural Resource Challenge. This program, administered by the Geologic Resources Division of the Natural Resource Program Center, relies heavily on partnerships with institutions such as the U.S. Geological Survey, Colorado State University, state geologic surveys, local museums, and universities in developing GRI products.

Special thanks to: Wallace Keck (City of Rocks National Reserve) for providing information and images for use in the report; Deanna Greco (NPS Geologic Resources Division) provide information and images regarding hazards and disturbed land reclamation within the reserve; John Burghardt (NPS Geologic Resources Division) supplied information regarding Abandoned Mineral Lands; and Kevin Pogue (Whitman College) granted permission for reproduction of his figures illustrating the formation of geologic features in the reserve.

Credits

Author
Trista Thornberry-Ehrlich (NPS-Colorado State University)

Review
David Miller (U.S. Geological Survey)
Marsha Davis (NPS Pacific West Region)
Bruce Heise (NPS Geologic Resources Division)

Editing
Bonnie Dash (Envirocal)

Digital Geologic Data Production
Greg Mack (NPS Pacific West Region)
Stephanie O'Meara (NPS-Colorado State University)

Digital Geologic Data Overview Layout Design
Josh Heise (NPS Geologic Resources Division)
Georgia Hybels (NPS Geologic Resources Division)

Introduction

The following section briefly describes the National Park Service Geologic Resources Inventory and the regional geologic setting of City of Rocks National Reserve.

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. This program, administered by the Geologic Resources Division of the Natural Resource Program Center, is designed to provide and enhance baseline information available to park managers. The GRI team relies heavily on partnerships with institutions such as the U.S. Geological Survey, Colorado State University, state geologic surveys, local museums, and universities in developing GRI products.

The goals of the GRI are to increase understanding of the geologic processes at work in parks and to provide sound geologic information for use in park decision making. Sound park stewardship requires an understanding of the natural resources and their role in the ecosystem. Park ecosystems are fundamentally shaped by geology. 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 these goals, the GRI team is systematically conducting a scoping meeting for each of the 270 identified 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. The digital data sets provide geologic data for use in park GIS and facilitate the incorporation of geologic considerations into a wide range of resource management applications. The newest maps contain interactive help files. This geologic report assists park managers in the use of the map and provides 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/).

Park Setting

City of Rocks National Reserve was established on November 18, 1988 to preserve the area's historical and geological features, scenery, and recreational opportunities. It is managed cooperatively by the National Park Service and the Idaho Department of Parks and Recreation. The reserve is adjacent to Castle Rocks State Park to the north in Cassia County (fig. 1A). The reserve covers 5,709 ha (14,107 ac) of rocky scrubland in south-central Idaho, south of the Snake River Plain and near the town of Almo (fig. 1B). The place was named "City of Rocks" by early travelers on the Oregon-California trails for its unique geological formations and erosional features. Emigrants passed this way over a 50-year period in the nineteenth century on their way to the California Gold Rush beginning in 1849 and more recently on the stagecoach route between Salt Lake City, Utah and Boise, Idaho. They scratched names, their signatures, and other graffiti on some of the pinnacles in the area (Haymond 1984; Bedford and Miller 1999).

Geologic Setting

City of Rocks is located in the southern part of the Albion Mountains, bordered on the east by the Raft River valley and on the north by the Snake River valley (fig. 1C). The Albion Mountains extend for 60 km (37 mi) and are the highest and westernmost mountains of a group of north-south-trending ranges in southeastern Idaho (Pogue 2008). The reserve centers on three upland valleys or basins (Circle Creek basin, Twin Sisters basin, and Emigrant basin). These basins are underlain by broad erosional plains (pediments) cut into the granite and surrounded by high mountains to the east and west that are cut by narrow canyons (Miller et al. 2008). Headward erosion of Almo Creek, Circle Creek, and their tributaries created these basins, which are filled with granitic erosional remnants of City of Rocks and Castle Rocks (Pogue 2008). The primary rock types in the Albion Mountains in the vicinity of City of Rocks include very old metamorphic and igneous rocks, metamorphosed sedimentary rocks, and a large body of much younger granite, the Almo pluton.

Local elevations rise from a low of 1,722 m (5,650 ft) where Circle Creek meets the boundary of the reserve to 2,703 m (8,867 ft) at the top of Graham Peak, north of the park, to 3,151 m (10,339 ft) at the top of Cache Peak. The much smaller and lower Cotterel and Jim Sage mountains separate the Albion Mountains from the Raft River Valley to the east (Pogue 2008). East of the Raft River Valley are the Sublett, Deep Creek, Bannock, and Portneuf ranges as well as the Blue Spring Hills. These mountains average about 16 km (10 mi) in width (Cunningham 1971).

In the vicinity of City of Rocks National Reserve, three geologic provinces—the western North American fold and thrust belt, the Basin and Range, and the Snake River Plain—intersect. The fold and thrust belt province formed during Mesozoic mountain-building events as east-west compressional (pushing together) stresses folded and thrust huge rock slabs tens of kilometers eastward. Exposures of the fold and thrust belt may be seen east of City of Rocks near the Idaho-Wyoming border; however local folds attest to Mesozoic compression at City of Rocks (Pogue 2008).

City of Rocks National Reserve is located on the northern edge of the Basin and Range province. The principal ranges are between about 1,200 and 1,800 m (about 4,000 and 6,000 ft) above sea level and trend roughly north-south as parallel ranges separated by linear valleys. Normal faults, which allow rocks on one side of the fault to move down and away from those on the other side, separate the parallel ranges and valleys (fig. 1C). These formed as a result of extensional (pulling apart) tectonic forces. The Albion Mountains were affected by a relatively greater amount of extension and uplift than was the rest of the Basin and Range. Because of the greater amount of uplift, erosion and normal faulting removed a thick layer of sedimentary rock cover, exposing much older igneous and metamorphic rocks. The rocks of this hyper-extended subprovince of the Basin and Range compose a metamorphic core complex (Compton and Todd 1977; Pogue 2008).

The Raft River and Goose Creek primarily drain the Albion Mountains and are in turn tributaries of the Snake River (Pogue 2008). The relatively flat, crescent-shaped Snake River Plain dominates the southern half of Idaho (fig. 1C). It descends from 1,800 m (about 6,000 ft) above sea level near the Wyoming border to less than 760 m (2,500 ft) at the Oregon border, to the west. Thick lava flows that cover or underlie almost the entire plain erupted from volcanoes associated with the eastward migration of the Yellowstone hot spot (Pogue 2008). Among the volcanic features present are numerous thermal springs, flows, cinder cones, and high basaltic cliffs. Craters of the Moon National Monument and Preserve interprets the volcanic landscape and processes of the eastern Snake River Plain. The plain is far wider than the Snake River valley which runs along the southern part of the plain, and it extends northward for as much as 80 km (50 mi) from the river.

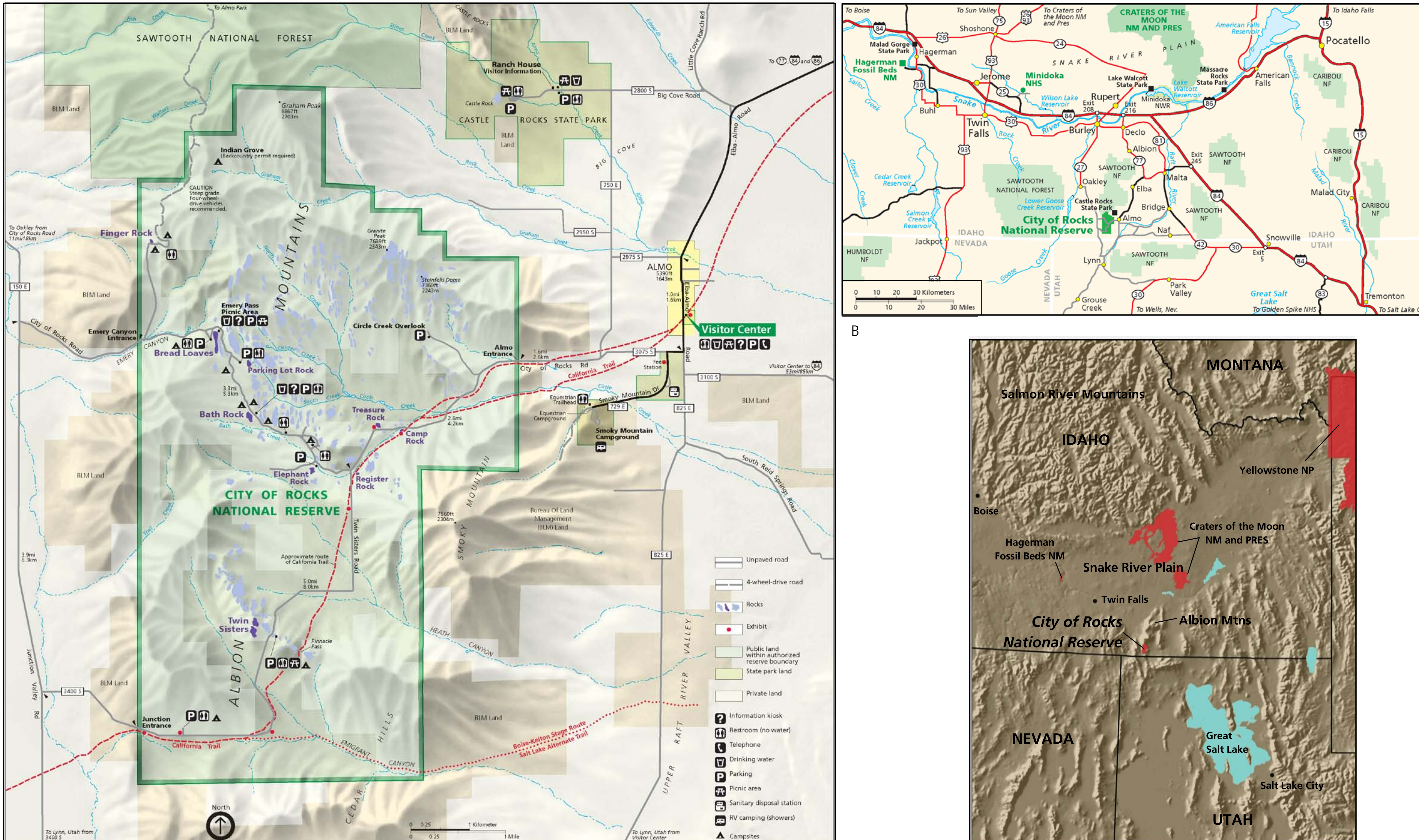


Figure 1. Maps of City of Rocks National Reserve and the surrounding area. A) Location map of City of Rocks National Reserve and Castle Rocks State Park in Idaho. B) Regional map of the area surrounding City of Rocks National Reserve with other public lands indicated. C) Map of the physiographic setting of City of Rocks National Reserve. Note the locations of City of Rocks and the Albion Mountains range. East of the Albion Mountains, the mountains are arranged in roughly parallel, linear chains characteristic of basin-and-range physiography. A and B) National Park Service maps. C) Compiled by Phil Reiker (NPS Geologic Resources Division).

Geologic Issues

The Geologic Resources Division held a Geologic Resources Inventory scoping session for City of Rocks National Reserve on June 16–17, 1999, 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. Contact the Geologic Resources Division for technical assistance.

Erosion and Slope Processes

City of Rocks is defined by its erosional features. Erosional processes transport the products of weathering and mass wasting away from their source, and in the Albion Mountains water is the most effective erosive agent (Pogue 2008). Accompanying the weathering that created the hollow balls, pinnacles, and other features in the park are slope failures, rockfall and topple, debris flows, slides, creep, soil deformation, and colluvium deposits (fig. 2). The rate at which these processes occur ranges from gradual to catastrophic, but all rates of change can be equally destructive given time (Miller et al. 2008). The most active areas of slope formation and erosion are in the low parts of the upland basins at City of Rocks (Miller et al. 2008). Slumps and scarps caused by mass wasting appear on the digital geologic map as colluvial and landslide units, most of which are geologically active (Miller et al. 2008).

In addition to the highly weathered rock, the unconsolidated material mantling the slopes (alluvial fans and colluvium) and present in the valleys and on much of the level surfaces at City of Rocks is especially susceptible to mass wasting in the form of debris flows, slumps, slides, and slope creep when saturated with water after a heavy rain or snow melt. The debris flows have the consistency of wet concrete and can rapidly and destructively transport objects at least as large as car-sized boulders (Miller et al. 2008). Debris flows are most common at the base of steep slopes and near the heads of alluvial fans (Pogue 2008). Debris-flow deposits appear as conspicuous accumulations of boulders in deposits otherwise composed of sand-size grains in those parts of alluvial fans relatively distant from the mountain fronts (Miller et al. 2008).

Floods may create hazards in much of the park. Intense seasonal thunderstorms combined with a scarcity of stabilizing vegetation and cryptogamic crusts on slopes lead to sheetwash and flooding, sending torrents of water and debris down slopes and potentially damaging trails and other facilities. Nearly all Quaternary deposits in the reserve are subject to flooding and sheetwash (Miller et al. 2008)

Stream flow, concentrated as gully erosion following snowmelt, sustained precipitation, and intense storms, has occurred in many areas underlain by unconsolidated to moderately consolidated materials (alluvial fans, pediment veneers, and alluvium) and are also prevalent in weathered Archean-aged schist (Miller et al. 2008). As they are formed, the gullies can damage or destroy trails, buildings, and other resources and provide conduits for further floods. Active steam channels and steep colluvial slopes are sites of repeated destructive mass wasting and thus are unsafe and undesirable sites for visitor recreation or construction of facilities (Miller et al. 2008)

Erosion has been locally increased by drainage diversions where they cross roads and trails. Soil erosion is of particular concern at City of Rocks because the thin granitic soils of the area are being removed by storm washes and raindrop spatter (GRI scoping notes 1999). Loss of granitic soils affects the hard rocks because, it is believed, salts and expanding (shrink-and-swell) clays are intensely weathering much of the rock in specific places due to variations in moisture. The alteration of minerals by chemical weathering commonly produces minerals having a greater volume than does the original rock. For example, some clay minerals that result from weathering have a greater volume than the minerals in the rock from which it is derived. The growth of these new minerals wedges apart adjacent grains. Similarly, if water containing dissolved salts infiltrates tiny cracks and evaporates, the resulting precipitate crystallizes and exerts a strong force on the walls of the crack (Pogue 2008).

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

- Comprehensively study the erosion and weathering processes active at City of Rocks National Reserve, taking into account the different rock formations versus slope aspects, location, and likelihood of instability.
- Compile a rockfall-susceptibility map by plotting rock unit versus slope aspect in a GIS. Potential uses of such a map include determining future infrastructure locations and resource management of trails, buildings, and recreation areas.
- Compare weathering rates between burned areas and unburned areas as well as between different geologic units to quantify the impact of vegetation in the park.
- Determine the outcrop extent (focusing on particular geologic units containing clays such as unconsolidated Quaternary deposits or units prone to weather to clay such as rhyolite and granite) of shrink-and-swell clays such as bentonite, which is unstable for building and roads.
- Study Camp Rock (an exfoliating dome in close proximity to a road) for potential impacts that vehicle

exhaust may have on rock exfoliation (GRI scoping notes 1999).

- Study the weathering of granitic rocks in thin section and by geochemical analysis to better understand the grain-by-grain weathering patterns.
- Inventory and monitor potential for debris flow near visitor use areas; relate the data to slope and loose rock deposits.
- Inventory areas susceptible to flash floods; relate the data to climate and to confluence areas.
- Study the stability of trails and determine which trails are most at risk and in need of further stabilization.
- Study the role of enlarging fractures in the rock through solution weathering and freeze-thaw cycles.
- Study scarp retreat and subsequent pinnacle development. Use Ground Penetrating Radar to monitor subaerial pinnacle development.
- Study how different rock types weather and erode.
- Monitor effects of four-wheel-drive trails in the park related to erosion and slope stability.

Joints and Fragile Features

Some of the granitic rock spires exposed at City of Rocks National Reserve are among the oldest in North America. In their long history, these rocks were affected by multiple phases of deformation, resulting in folds, faults, joints, and other planes of weakness. These features compromise the strength of any rock unit and in many cases profoundly affect the geomorphological processes that shape the landscape at City of Rocks. Younger rock units, such as the granite of the Almo pluton, are also traversed by cracks, known as joints. Joints are fractures in rock produced by stresses that cause the rock on either side of the fracture to be displaced perpendicular to the fracture plane. The orientation and spacing of joints strongly affects the size, shape, and distribution of spires. As described in the "Geologic Features and Processes" section, joints within the granite at City of Rocks formed by contraction, extensional tectonic forces, and expansion (Pogue 2008).

Regional deformation is still occurring at City of Rocks. Basin-and-Range extension is ongoing. As erosion removes more material from the overlying surface, a release of pressure causes the rocks to expand and crack. Earth materials are responding to pressures within the earth, and recent small-scale fractures and joints attest to this. A newly discovered fault passes through the town of Almo, offsetting Pleistocene-aged alluvial materials as much as 5 m (16 ft) (Miller et al. 2008). Features such as these attest to active faulting processes and the potential for seismic activity in the City of Rocks area. As mentioned below under "Seismicity," an earthquake could profoundly alter the fragile spires, fins, and arches at City of Rocks.

Understanding the nature of the deformational features at the reserve allows predictions of where weathering and erosion are likely to be concentrated and provides a sound basis for resource management. Recent mapping reveals that joints, crusts on rock outcrop surfaces, and weathering are identifiable features for inventories of the fragility of the unique rock formations at City of Rocks National Reserve (Miller et al. 2008).

Inventory, Monitoring, and Research Suggestions for Joints and Fragile Features

- Study the role of jointing versus faulting (both strike-slip and thrust faulting) to determine control relationships on the formation of spires as well as understanding a future seismic potential that may pose a threat to fragile features within the reserve.

Recreational Demands

Recreational demands present resource management challenges at the reserve. With rock spires as much as 60 stories tall, City of Rocks is a magnet for rock climbers. Since climbers discovered the area, more than 700 different climbing routes have been scouted. Rock climbing that includes the use of power drills to set climbing gear has recently begun to raise questions as to how it may be degrading the resources. It is unknown exactly how much climbing has affected the rock spires. However, human use of roads and trails crossing the granitic sediments of the area beneath the spires results in localized erosion and diminishing wildlife and vegetation. The Climbing Management Plan outlines rules and regulations related to climbing within the reserve (National Park Service 1998). Climbing is not permitted on the Twin Sisters nor other pinnacles in the Research Natural Area. Installation of bolts via manual or power drills requires a permit.

Other public-use concerns are damages to pinnacles along easily accessible trails and vandalism in the form of spray-painted graffiti in various locations throughout the park (GRI scoping notes 1999). In addition to these threats within the park boundaries, woodcutting around the reserve leads to increased erosion and run-off problems that may extend into the park.

Mineral collecting is an important recreational pursuit in the City of Rocks area. The unique mineralogy at the park lends itself to collectors' interests. Mineral specimens cannot be collected on federal land within the reserve.

Inventory, Monitoring, and Research Suggestions for Recreational Demands

- Study historic land-use practices and their effects on the modern environment.
- Study and determine ways to effectively remove vandal graffiti from the rocks in the park. Consult with organizations that restore vandalized granite statues and like items to determine the best ways to remediate without further impacting the geologic features.
- High resolution photodocumentation could be used to record the historic signatures and preserve their record. Digital photographs could be used to build a virtual and searchable "Register Rock" for park visitors.

Mine-Related Issues and Disturbed Lands

Some anthropogenic features on the landscape at City of Rocks may be targets for remediation. These include a few prospect pits dug in exploration for pegmatite and skarn minerals (lime-rich silicates), mica mines, animal grazing areas, four-wheel-drive trails, development adjacent to NPS land, mining claims, and diverted culverts (GRI scoping notes 1999; Miller et al. 2008). The National Park Service Abandoned Mineral Lands database (accessed March, 2010) lists seven AML features at six sites including dozer trenches, surface mines, and one abandoned, plugged oil and gas well. Remediation of these features would help to fulfill the goal of the park to preserve and restore the historical landscape of early westward emigration. Figure 3 illustrates reclamation efforts at an abandoned aggregate "borrow pit" within the reserve. Morris (2006) and Historical Research Associations and Amphion (1996) contain brief descriptions of historical mining activity within the reserve.

Furthermore, if park boundaries expand in the future, knowledge of regional mining of nonmetallic and metallic minerals would be invaluable for park resource management. Regionally, quartzite deposits have been quarried for building stones, sulfide-mineralized veins were the target of small prospect pits, pegmatite micas attracted prospectors in search of insulation materials, and river aggregate and disintegrated granite have been used for local construction (Miller et al. 2008).

Inventory, Monitoring, and Research Suggestions for Mine-Related Issues and Disturbed Lands

- Determine the status of agricultural and grazing areas as disturbed lands.
- Contact the NPS Geologic Resources Division for assistance with AML and disturbed lands issues.

Water Issues

In southern Idaho annual precipitation (rainfall and snowfall) varies greatly. It averages between about 200 and 500 mm (between about 8 and 20 in.) in most valley-and-plain areas, including City of Rocks (Idaho Department of Water Resources 2009). Water is scarce in dry years at City of Rocks, which makes it a valuable and important resource to monitor and protect.

Knowledge of how groundwater is moving through the subsurface is an important component of resource management at the reserve. The hydrogeologic system is likely highly influenced by the presence of prominent joint patterns within the bedrock. Open cracks within the bedrock are preferential pathways for groundwater flow. The unconsolidated surficial deposits likely host unconfined aquifers and this water is part of the subsurface differential weathering responsible for the topography at City of Rocks National Reserve (Pogue 2008). Refer to the "Geologic Features and Processes" section for additional information.

Geology and geologic history of the area include a marked influence on the presence of hot springs and hot wells near the Albion Mountains. Such features are evidence of active crustal extension whereby the crust has thinned to such an extent as to allow for increased heat flow from the hotter than usual upper mantle underlying the area (Pogue 2008). Water likely flows down to depth along regional joints and fractures, then, once heated, quickly emerges back at the surface as hot springs.

Water quality is a significant issue at City of Rocks, degrading significantly from Circle Creek to the visitor center, where it meets minimum drinking-water standards (Stan Lloyd, oral communication, 1999). This degradation is probably from the polluting impacts of livestock on surface water in surrounding areas. Baseline water quality data for the reserve was compiled by National Park Service (1999).

Inventory, Monitoring, and Research Suggestions for Water Issues

- Contact the NPS Water Resources Division for technical assistance regarding water issues.
- Survey water quality, addressing the down-gradient changes between Circle Creek and Emigrant and Twin Sisters basins.
- Inventory springs within the reserve and note any instances of heavy metal concentrations within the water.

Wind Erosion

In addition to water, wind is a major force that redistributes fine-grained materials, such as sand, soil, and soil resources (e.g., litter, organic matter, and nutrients) within and among ecosystems. Erosion and deposition by wind are important at City of Rocks National Reserve and can be affected by human activities that disturb stabilizing ground features.

During dust storms, sand and soil from disturbed surfaces may blow onto undisturbed ground, burying and killing vegetation. Even biological cryptogamic crusts can be damaged or destroyed by windblown sediment, exposing more soil to erosion (Miller et al. 2008). Human impacts within the parks that disturb the surface are primarily associated with off-trail hiking in high-use areas because park management practices limit or prohibit off-road travel. Soil erosion is accelerated where livestock grazing or herding is still permitted.

A soils resource inventory of the reserve was completed in 2009 and includes a digital GIS soils map. The soils program, based at the NPS Geologic Resources Division, should be contacted for assistance with soil-related issues.

Inventory, Monitoring, and Research Suggestions for Wind Erosion

- Determine geologic controls of parent material on soil type development using the park's digital GIS soil and geologic maps.

- Determine patterns of wind erosion and areas most susceptible to soil loss.
- Study the distribution and species composition of biological soil crusts with the intent to create a plan to increase cover of the crust (D. Miller, written communication, 2009).

Seismicity

The Basin and Range province is still seismically active. Small-scale earthquakes happen in southeastern Idaho and northern Utah almost every day. Most of these micro-earthquakes are too small to be detected by humans without a seismometer; however, there is potential for infrequent large-magnitude events (Christenson et al. 1987; GRI scoping notes 1999). The region has been affected by considerable historical seismic activity, and on November 18, 1937, an earthquake (magnitude 5.4) occurred in the reserve area in Junction Valley west of Almo (Christenson et al. 1987; Miller et al. 2008).

Faults mapped within the reserve tend to lie along steep slopes, commonly among outcrops of Elba Quartzite. These fault traces tend to trend north-south. The faults displace rocks downslope, toward the valleys, as normal faults (Miller et al. 2008). A Pleistocene fault, the Almo fault (described below under "Basin and Range Features"), extends south-southwestward along the east margin of the Albion Mountains and is traceable along a series of scarps showing downward displacement to the east. Springs and seeps occur along this and other local faults (Miller et al. 2008). The presence of this fault and Pleistocene (and possible Holocene) faults to the south indicates continued potential for local seismic activity (Compton 1972; Miller et al. 2008).

The Wasatch Front, southeast of City of Rocks, is still considered seismically active. No historical earthquakes associated with surface rupture have occurred along the Wasatch fault zone since at least the 1870s. However, the recurrence interval, or time between major seismic events, for the entire Wasatch fault zone may be 50–430 years (Swan et al. 1980). The Wasatch fault zone and related faults 50 km (30 mi) to the east project westward at moderate angles, presenting a potential for a major seismic event that could strongly shake the City of Rocks region. In addition to hazards from ground shaking and surface rupture, lateral spreading and liquefaction could result from an earthquake (Miller et al. 2008).

The delicate geological features and historical landscape are the primary reasons the reserve was established. Ground shaking could dislodge material from steep cliffs within the reserve, cause landslides in unconsolidated deposits, and damage the pinnacles and domes of the City of Rocks (Miller et al. 2008). The effect on the geomorphology at City of Rocks must be considered a significant resource management issue because of the potential for severe ground shaking in the area due to natural or man-made causes such as mine blasts (GRI scoping notes 1999). Seismic modeling could help estimate the intensity of ground shaking associated with various earthquake magnitudes possible in the City of Rocks area. Such modeling would help determine which features are particularly under threat of damage from seismicity.

Inventory, Monitoring, and Research Suggestions for Seismicity

- Comprehensively study any faulting (start with those faults identified on the included GRI digital geologic data) and seismic processes active at City of Rocks National Reserve, taking into account rock formations, slope aspects, location, and likelihood of instability. Such studies could be performed cooperatively though agencies such as the U.S. Geological Survey or the Idaho Geological Survey.
- Comprehensively study seismic activity and active faults in close proximity to the City of Rocks area, including the mapping of small-scale faults and shear fractures.
- Real-time and historic earthquake information is available from the U.S. Geological Survey (http://earthquake.usgs.gov/earthquakes/).
- Inventory recent fault scarps in the area. These are commonly present in Quaternary (less than 2.6 million years old) surficial deposits.

Volcanism

The area of southern Idaho famous for Craters of the Moon, the Snake River Plain, and City of Rocks contains volcanic features formed during Miocene-aged volcanic events, the passing of the area over the Yellowstone hot spot, and other intermittent volcanic episodes. There are numerous Pliocene and younger shield volcanoes north of the reserve along the southern flank of the Snake River Plain province (D. Miller, written communication, 2009). Though a distant possibility, volcanic events could affect the area in the future. Potential threats include ash falls downwind of volcanic eruptions and localized seismic events accompanying volcanism.

Inventory, Monitoring, and Research Suggestions for Volcanism

- Inventory and date numerous Pliocene and younger shield volcanoes north of the reserve along the south flank of the Snake River Plain to determine the timing of relatively recent local volcanic activity; focus on features likely to be upwind of the reserve during an eruption (D. Miller, written communication, 2009).

General Geology and Research

The possibilities for research arising from the geologic features at the park are endless. This section includes suggestions made by scoping meeting participants in 1999 (Appendix B). An understanding of the geological processes and resources at City of Rocks is fundamental to management decisions. This report is intended to aid decision making at City of Rocks with further suggestions and baseline information, including the digital geologic map of the park to be incorporated into a natural resources GIS. The geology at City of Rocks influenced westward expansion and the decisions made by emigrants as they passed through as described in

"Geologic Features and Processes." The tie between history and geology should be interpreted in the park.

Inventory, Monitoring, and Research Suggestions for General Geology

- Develop a detailed geology-themed brochure with roadlogs and park wayside exhibits for visitors to the park.
- Develop curriculum-oriented teaching guides featuring the geology of City of Rocks.
- Highlight geologic resources at the park's visitor center by incorporating a three-dimensional, raised relief map of the park showing locations and features. A kiosk displaying GIS themes and geology in an interactive format could be featured.
- One area well-suited for geology interpretation is Bath Rock. This area has good examples of rockfall, pediments, and inclusion in granite that typify the rest of the park.
- Twin Sisters is another site well-suited for geology interpretation. This feature displays the significant difference in rock ages between the two sisters and the relevance and cultural implications of the California Trail.
- Additional sources of geologic information for use by interpreters include Pogue (2008) and Link and Phoenix (1996); the latter takes a wider regional approach and is also available online: http://imnh.isu.edu/DIGITALATLAS/geog/rrt/RRTfr.htm.
- Research the potential of a project using ground-penetrating radar to test the hypothesis that the City of Rocks dome forms originate under an alluvial and soil cover and then are exhumed. If possible, outsource work to Idaho State University as graduate student projects.
- Investigate a geochemical project combining geochemistry, isotope studies, and thin section/x-ray work on mineralogy of the crust, comparing the honeycomb rocks with the case-hardened ones to determine controls on erodability of the rocks.
- Initiate paleoecological studies of pack-rat middens and climate change relationships.
- Use isotopes to study geochemistry and mineralogy on case hardening.
- Study panhole formation.
- Ensure that geologic features and materials are part of the inventory of any newly acquired lands in the park.
- Map the Circle Creek area in geologic detail.
- Conduct a detailed three-dimensional cartographic survey of the area that includes man-made features.

Figure 2. Rockfalls are a potential geologic hazard throughout City of Rocks National Reserve. This photo shows broken down rubble from the west side of Steinfells Dome. National Park Service photograph by Wallace Keck (City of Rocks National Reserve).

Figure 3. These photos illustrate the use of restoration projects to restore disturbed areas within City of Rocks National Reserve. The 2003 photo shows an abandoned aggregate borrow pit near the eastern entrance to the park. This man-made feature was visible from the California Trail, impacting the historic landscape of the area. The project restored natural contours to the site to establish a geologically and hydrologically stable landscape. Vegetation was subsequently planted on the restored area after the 2004 photo was taken. National Park Service photographs and information courtesy Deanna Greco (NPS Geologic Resources Division).

Geologic Features and Processes

This section describes the most prominent and distinctive geologic features and processes in City of Rocks National Reserve.

Introduction

The following discussion briefly introduces some of the more unusual features and processes in City of Rocks National Reserve. Readers are urged to refer to the report accompanying the geologic map by Miller et al. (2008), which served as the source of the GRI digital geologic map described under "Map Unit Properties" and is included on the enclosed CD. Another excellent source of descriptions and illustrations is Pogue (2008).

Joint Sets

Joints are among the most conspicuous features of the granitic rocks exposed at City of Rocks National Reserve. Joints are cracks or planar zones of preferential weathering in pinnacles and eroded pediments at City of Rocks (Miller et al. 2008). In general, joints are fractures that display displacement perpendicular to the plane of fracture and form through myriad processes (Pogue 2008). At City of Rocks, many of the joints or fractures resulted from (1) extensional tectonic forces, (2) contraction when the rock cooled, or (3) expansion when overlying materials eroded away and eliminated the confining pressure (fig. 4). The three or four joint sets (repeatedly occurring orientations of neighboring joints) in the area and their relative density are the most important factors in the spacing, distribution, and shape of the various rock outcrops (Pogue et al. 2001; Miller et al. 2008; Pogue 2008).

Tectonic joints—those resulting from extensional tectonics—commonly form distinct sets having a common orientation consistent with the regional stress field (Pogue 2008). Individual sets of joints may be related to separate tectonic events. One set, trending north-south and dipping to the east, is related to tectonic extension (pulling apart) during the Oligocene and displays hydrothermal alteration and mineralization. This set characteristically focuses and localizes the formation of gaps, or large "avenues," of the City of Rocks region (Pogue et al. 2001). Other joints, at angles to the north-south trending set, allow wind and water to erode around pillars of rock, eventually forming the isolated pinnacles and fins in the granite (Miller et al. 2008). The parallel orientation of these joints in large part determines the orderly distribution of the shapes and lends more of an organized "urban" look to the features (fig. 5).

As the granitic rocks cooled slowly at depth, the subsequent reduction in mass during contraction caused a nearly vertical set of joints with random trends to develop (fig. 6). These joints vary in length from less than 1 m to hundreds of meters (Cunningham 1971; Pogue 2008). Another set, oriented parallel to Earth's surface, weathers to produce a dome-like shape and is referred to as exfoliation joints (fig. 7). These joints are oriented subparallel to the surface topography and derive from the release of pressure as erosion removes confining overlying rock (Chapman and Rioux 1958; Barber 1962; Pogue 2008).

Landform Types and Geomorphological Evolution

The overall geology at City of Rocks is characterized by the Oligocene-aged granitic intrusion into Precambrian rocks, such as schist, granite, amphibolite, and Elba quartzite, and the subsequent erosion of the intrusion. This juxtaposition of rock ages, lithologies, and weathering properties provides an interesting and scenic contrast (Wells 1984). The bizarre shapes of City of Rocks are found in granitic rock and are developed by the processes of weathering along various joints as described above. Most of the fantastic rock shapes are developed through myriad processes, including chemical dissolution, frost wedging, mass wasting, mineral wedging, and exfoliation by which thin rock plates and scales of various sizes are sloughed off along joints in the rocks formed by stress associated with expansion. Unconsolidated alluvial fans and colluvial deposits mantle the slopes below weathered bedrock outcrops (Miller et al. 2008).

Pinnacles

The most notable landform features of the park are the prominent, steep-sided, smooth, and rounded granitic pinnacles, also referred to specifically as "domed bornhardts," "tors," and "fins." A bornhardt is an isolated domed granitic outcrop whose shape is controlled by upwardly convex exfoliation joints (Cunningham 1971; Bedford and Miller 1999; Pogue 2008). Isolated blocky granitic outcrops whose shape is controlled by vertical and horizontal joint sets are tors ("towers" in the Cornish language) (Cunningham 1971; Pogue 2008). Fins are high and relatively narrow granitic outcrops that are elongated in one direction (Pogue 2008). Pinnacles are most heavily concentrated along the west, south, and north reaches of the Circle Creek Basin. Groups of these define northwest-oriented spines that separate the three main upland basins in City of Rocks National Reserve (Miller et al. 2008).

Shapes of the pinnacles may be described as fins, loaves, spires, and domes. The name "City of Rocks" refers to this assemblage of rock formations, which resembles the assortment of tall and short buildings found in a city, especially when viewed from a distance. These rock features are as high as 60 stories and are found in a landscape that varies nearly 610 m (2,000 ft) in elevation from low basins to high ridges, but is mostly concentrated along the west, south, and north parts of the Circle Creek Basin.

Most pinnacles have formed in the granite of the Oligocene Almo pluton. Following the two-stage model of Linton (1955), geologists believe the shape and architecture of pinnacles are strongly influenced by joints. Parallel joint sets oriented nearly north-south are the most strongly developed in the area, causing many of the pinnacles to be elongate north-south. At roughly right angles to the dominant joint set is a secondary set. The formations developed due to deep weathering of adjacent rock in the unsaturated zone above the local water table. Water flowed along the joints, slowly dissolving the walls of the rocks away. Joints in effect guide the long disintegration process (Linton 1955; Miller et al. 2008). Differential weathering controlled by contrasts in joint density determines which bedrock surfaces remain to be exposed as granite spires (Pogue 2008). Once the rock is disintegrated within the adjacent unconsolidated regolith, running water erodes the weathered material (grus) and exposes the resistant core mass (Linton 1955; Miller et al. 2008). This process is repeated to form very high pinnacles (Miller et al. 2008). See Cunningham (1971) and Pogue (2008) for more detailed descriptions of the formation of pinnacles and tors. Pogue (2008) presented a sequential model for the evolution of a granite spire, such as that at City of Rocks National Reserve (fig. 8).

Loaf-shaped pinnacles form as a result of weathering along one prominent set of steep fractures or joints parallel to the long direction of the rock, whereas domes form from exfoliation joints in a rock mass with weakly expressed or widely spaced, steeply dipping joints (Miller et al. 2008). Named examples of loaf-shaped pinnacles include Bread Loaves (fig. 6), Stripe Rock, Bath Rock, and Elephant Rock. Named domes include Kaiser's Helmet, Camp Rock, and Treasure Rock (Miller et al. 2008).

Most of the pinnacles are composed of the City of Rocks Adamellite (dated at ≈30 million years ago). This is a muscovite-biotite monzogranite that is relatively coarse grained and roughly equigranular. It is part of the large Oligocene Almo pluton. Other pinnacles are composed of Archean gneiss that is similar in composition to the Oligocene pluton but foliated and that has a porphyritic texture (large crystals surrounded by a much smaller-grained matrix). Some pinnacles at City of Rocks may be as old as Miocene (Miller et al. 2008).

Surface Crusts and Case Hardening

The surfaces of the granite pinnacles and other weathered formations display cavernous weathering and durable crusts. Once exposed, the tops of granitic rocks began to dissolve. Granular disintegration followed by case hardening by iron oxide and other mineral deposition form a relatively resistant outer shell. This chemical precipitate crust may be 1–3 cm (0.4–1.2 in.) thick (Pogue 2008). Observations of crusts produced by case hardening suggest the process combines several factors, including (1) deposition of chemical weathering residue left when water evaporates from the surface, (2) precipitation of mineral deposits transported to the outcrop by wind and rain, and (3) biochemical precipitation of silica by lichens (Pogue 2008).

At City of Rocks, surface shells appear as blisters (fig. 9; dark, thin, reddish hardened surfaces with curled edges or domed shapes) and crusts (thicker, dark brown, with polygonal shrinkage cracks), as well as durable, dark-colored pitted surfaces (Maley and Randolph 1993; Miller et al. 2008). The pitted surfaces form on inclined and nearly horizontal surfaces and can be as much as tens of centimeters thick. They may be the oldest case-hardened surfaces. This type of surface is undulating, cemented and smooth with pocks as wide as 20 cm (8 in.) (Miller et al. 2008).

Surface crusts are brittle compared to the unmineralized underlying rock and more likely to crack under stress (Pogue 2008). If the crust is breached, then the softer, more erodable inner core is removed by wind and water in the process of cavernous weathering. Small remnants of armored surface crust form knobs called "chickenheads" on otherwise featureless walls (Pogue 2008). Removal of the inner core results in the caves, bathtubs, arches, and hollow balls found today (Maley and Randolph 1993). Arches are more commonly associated with eroding sedimentary rocks in the southwest and are especially rare in granitic terrains (fig. 10).

Cavernous Forms

There are more than 500 panholes in one small, 230-m^2 (2,500-ft^2) area in the reserve. Panholes are basin-shaped hollows, usually about 0.3 m (1 ft) in diameter (see inside front cover and fig. 11) (Cunningham 1971). The most notable panhole is located on top of Bath Rock and frequently fills with water from rain or snow melt. Panholes play a large role in shaping and lowering the rock outcrop surfaces. Their shape and size evolve over time in a predictable manner, but appear unrelated to joints unless in areas where they are elongated along the strike of a joint on which they originated (Cunningham 1969; Pogue et al. 2001; Miller et al. 2008; Pogue 2008).

Panholes begin at small depressions or cracks where water and snow linger and promote weathering. Once a depression forms and holds water, the excavation of the panhole is enhanced. Biological activity from lichen and moss can accelerate weathering within the panhole (Pogue 2008). Nested panholes within larger panholes indicate a local drop in the water supplied to the larger panhole. When their bottoms (usually the hardened crusts) are breached, weathering of the interior of a dome is accelerated. The last remnants of hard coating left after panholes have coalesced and weathered away are spike-shaped features called "pickelhauben" (Pogue 2008).

Honeycomb weathering forms networks of marble-sized holes on the sides of pinnacles at City of Rocks National Reserve that are among the most fragile rock formations there. The honeycomb-like surfaces form when case-hardened surfaces are breached and the granite rapidly disintegrates grain-by-grain (Miller et al. 2008). Hollows and cavities that form by cavernous weathering on the sides of granitic spires and boulders are called "tafoni" and may be as large as a room (fig. 12). They typically have relatively narrow entrance holes armored by an overhanging lip of case-hardened crust, and flat floors (Pogue 2008). Geologists surmise that these features form on areas protected from rainfall by the crystallization of salts within microcracks deposited by mist, fog, and wind-borne dust. This process is self-sustaining as salts are precipitated in repeated microcracks formed from previous cracking (Rodriquez-Navarro et al. 1999; Hejl 2005; Pogue 2008). The Great Salt Lake Desert, south of City of Rocks, is likely the source of the salt responsible for the fragile tafoni formations within the reserve area (Pogue 2008).

Twin Sisters

When the tops of granitic exposures are weathered and dissolved by rainwater, minerals such as iron oxide are redeposited to form crustlike caps. These caps are more resistant to weathering than the underlying rock and are left standing as spires and pinnacles such as the Twin Sisters (fig. 13).

Juxtaposed with the weathered shapes of the Oligocene granite at City of Rocks are the harder Precambrian outcrops. These provide a contrast of sharper outlines. Twin Sisters and Lost Arrow, are two examples of spires at City of Rocks National Reserve (Miller et al. 2008). The Twin Sisters—two adjacent rock towers on opposite sides of a contact between Precambrian gneiss to the southeast and Oligocene granite to the northwest—represent each formation (Wells 1984).

The history of the Twin Sisters is in many ways representative of the evolution of the City of Rocks landscape. The geologic gap in time between them is more than two billion years of Earth history. The darker sister is rock from the Green Creek Complex. It is 2.5 billion years old and is some of the oldest rock in North America. The lighter sister is rock from the far younger (≈28 million years old) Almo pluton. Both rock formations were once buried deep below other layers of rock. The Almo pluton intruded the Green Creek Complex at a depth of approximately 10–14 km (6–9 mi) (Pogue 2008). Regional tectonic events, such as extension and uplift (described under "Geologic History"), caused large masses of rock to slide away from the core of the Albion Mountains. Masses of overlying rock slid east and west along large-scale normal faults. The removal of overburden and excess heat locally caused the rocks to rise. The uplifted rocks were intensely weathered, and erosion removed much of the overlying material. These processes acted in concert to expose the once-buried Almo pluton and Green Creek Complex in the City of Rocks area.

Other Weathering Features

Flat structures along the bases of many outcrops have a nonrandom distribution that can be attributed to parameters such as aspect, slope, and soil moisture (Pogue et al. 2001). In the upper parts of some drainage basins, erosional surfaces of granitic bedrock, called pediments, have very low relief. Their formation is somewhat enigmatic, but they may be produced by the erosion and retreat of a mountain scarp in the semiarid climate by a repetitive sequence of events (Strudley et al. 2006; Pogue 2008). This sequence consists of sediment production by weathering of granite and subsequent removal of the sediment by streams. For example, thinning of a pediment veneer by flowing water causes soil to develop more rapidly and thickens the veneer, whereas thickening of the veneer when streamflow is reduced causes soil to develop more slowly. This repeated sequence creates smooth rock surfaces through grain-by-grain disintegration characteristic of granite (Strudley et al. 2006; Miller et al. 2008). The oldest landforms in the area are pediments preserved from erosion and weathering by overlying Miocene sediment and volcanic rocks (Miller et al. 2008).

Periglacial conditions that occur at high elevation promote the process of frost-wedging whereby rocks are broken apart by the expansion of water (≈9% volume change) freezing along fractures, cracks, and joints within the rock (Miller et al. 2008; Pogue 2008). Formations resulting from frost-wedging locally include patterned ground and scattered rocks in block fields on Graham Peak and other local ridges (Miller et al. 2008).

Many of the lower flanks of the granite spires in the Albion Mountains have smooth, concave, and locally overhanging walls ranging in height from 1 to 10 m (3 to 33 ft). These flared surfaces are commonly covered with blisters and flakes produced by small-scale exfoliation because they are not exposed to precipitation that would form a surface crust. These features form prior to exhumation in the subsurface amidst water-saturated regolith and require prolonged periods of relative stability (Pogue 2008).

Weathering Processes

A principle natural phenomenon at City of Rocks is the display of active weathering processes shaping the landscape (Jones 1973). The area is considered a type section for the origin of weathered granitic landforms (Cunningham 1971; Jones 1973). Two major categories of weathering—chemical and mechanical—alter the rocks at City of Rocks and occur at all scales. Chemical weathering decomposes rocks at the molecular scale by decomposition through interactions between the rocks and water and dissolved chemicals. Mechanical weathering breaks rocks apart by applied physical force. The interplay of these two types of weathering is complex, and in granitic rocks the different reactions are controlled by factors such as (1) mineral composition of the rock, (2) chemistry of the water in contact with the rock, (3) regional climate, and (4) abundance of fractures or joints within the rock (Pogue 2008). Thoroughgoing, continuous fractures allow constant exposure of rock surfaces to water. Dissolved minerals are either flushed out of the rock (widening preexisting cracks) or redeposited as encrustations (Pogue 2008). Mechanical weathering processes such as frost wedging, mineral wedging, expansion from unloading, biomechanical weathering, thermal expansion, and root wedging expose new fractures to further mechanical weathering or chemical dissolution (Pogue 2008).

The different scales at which weathering occurs at City of Rocks demonstrate the pervasive influence of geologic processes on evolution of landforms. The entire Circle Creek Basin, at an elevation of 1,890 m (6,200 ft), in which City of Rocks is located, has developed through a complex erosional history consisting of discrete stages of stability followed by periods of intense erosion of the weathered granite. This erosion was accelerated as a result of tectonic uplift, climate changes, or both (Pogue et al. 2001). Most weathering occurs in the region below the surface where the rock and unconsolidated regolith are commonly saturated with groundwater (Pogue 2008). Erosion removes the mantling regolith, exposing the granitic bedrock. Weathering on this scale is in stark contrast to the molecular level of chemical dissolution along the tiniest fracture within an intact granitic outcrop.

Historical Connections with Geology

City of Rocks became a prominent fixture on the California and Oregon Trails. Experienced mountain men, such as Joseph P. Chiles and Joseph R. Walker, led the early emigrant groups through the area. Granite Pass funneled traffic into the area because no road could be found south of the pass, and a northern detour would have been unnecessarily long. Granite Pass is a V-shaped notch in the middle of a ridge of Middle Mountain quartzite and gneiss. It is more than 2 km (1.25 mi) wide and more than 305 m (1,000 ft) deep. Because of the parallel, north-south-trending ridges across this part of the western United States, such notches and passes were vital to westward travel (Wells 1984).

After 1842, thousands of men, women, and children passed near City of Rocks to reach a passage through the Humboldt Valley of northern Nevada to the Willamette Valley in Oregon and the Sacramento Valley in California, as well as other destinations, such as the Mormon settlements in Utah (Cunningham 1971; Wells 1984). In 1849 the California Gold Rush accelerated this traffic. In 1852 some 52,000 people passed through the City of Rocks area on their way west to the alluring California gold fields. These travelers often noted in journals and diaries the interesting geological features found in the area (Wells 1984).

"We encamped at the city of the rocks, a noted place from the granite rocks rising abruptly out of the ground," wrote James Wilkins in 1849. "They are in a romantic valley clustered together, which gives them the appearance of a city." Wilkins was among the first wagon travelers to fix the name "City of Rocks" to what looked like "a dismantled, rock-built city of the Stone Age."

They scratched and spread axle grease (fig. 14) to mark names of rocks, their own names, and other graffiti on some of the pinnacles in the area, one of which is believed to have the largest historic graffiti collection in the United States (Ekman 1962; Jones 1973; Miller 1984). It is called "Register Rock" (Miller 1984). The remnants of these features are in danger of eroding away by the geologic process of small-scale exfoliation, which has already removed much of this graffiti (Pogue 2008). Frost wedging, which occurs when water seeps into cracks on the sides of spires and then freezes (and expands), causes great slabs of rock to crack off and has also removed some of the layers of rock bearing 150-year-old signatures left by the pioneers.

The overland wagon routes began to pass into history when the transcontinental railroad was completed in 1869 at Promontory Point (now Golden Spike National Historic Site) in the Promontory Mountains ,south of City of Rocks. However, stagecoaches and wagons were in continued use on regional supply routes that spread out north and south from the railroad lines. A stage route established by John Halley connected the railroad at Keton, Utah, with Boise, Idaho's mining hub. The route passed through City of Rocks. A stone-built stagecoach station was set on the junction of the old California Trail and the Salt Lake Alternate on the Salt Lake City–Twin Falls stage route. The building was vacated in 1878 after the route changed. This historical treasure was bombed by vandals in the early 1980s (Miller 1984).

Settlers began to homestead southern Idaho in the late 1800s. City of Rocks was attractive for dry farming, which declined during the drought years of the 1920s and 1930s, but livestock ranching continues today. A vast and significant historical heritage is preserved in the rocks and landscape at City of Rocks (Historical Research Associations, Inc. and Amphion 1996). The scope and shape of the regional geology played a part in the western expansion of the United States. Granite Pass allowed relatively safe passage through the mountains. Geologic features attracted the interest of travelers then as now, and this connection should be emphasized.

The earliest geologic studies of the area noted that the best use of the Silent City of Rocks was as a national monument (Anderson 1931). Although mineral resources such as skarn minerals, pegmatites containing muscovite and smoky quartz, hematite, sand and gravel, and disintegrated granite exist at the reserve, mining activity was not a significant part of the history of City of Rocks National Reserve and only a few old prospect pits were noted in recent mapping within the reserve (Miller et al. 2008). City of Rocks is a National Natural Landmark following recommendations and evaluations by Jones (1973). Many landmark studies on the exposure of metamorphic core complexes and the formation of eroded granitic pinnacles conducted at City of Rocks are now classic geology and are still widely cited by modern geologists.

Albion Mountains Metamorphic Core Complex

The southern Albion Mountains are part of a larger region that is commonly termed the "Raft River–Grouse Creek–Albion Mountains metamorphic core complex." This is a complex of rocks that crop out in the Albion, Raft River, and Grouse Creek mountains and that share a common history of deformation and metamorphism (Compton and Todd 1977; Miller et al. 2008).

A metamorphic core complex is characterized by high-grade metamorphic rocks overlain by shear zones (mylonite), other unmetamorphosed rocks and, in places, igneous intrusive rocks. The complexes often form as a result of overthickened crust that is later thinned. Massive lateral pulling apart of the crust (tens of kilometers of extension) and unroofing were required for the metamorphic core complex to be exposed at the surface (Compton and Todd 1977; Miller and Bedford 1999).

The area was deformed during mountain building events (orogenies) during the late Jurassic(?) and Cretaceous. It consisted of eastward thrusting and thickening through metamorphism and emplacement of subsurface molten material (plutonism). Rocks buried deep below the surface were affected by ductile deformation and metamorphism. Regional folds, including a set trending north to northeast, formed during metamorphism (Compton and Todd 1977). The crustal thinning in the City of Rocks area was likely driven in part by thermally-weakened crust accompanying the intrusion of molten rocks as well as regional basin-and-range extension (Miller and Bedford 1999).

The rocks within the metamorphic core complex span more than two billion years of Earth history. The ≈2.5-billion-year-old Archean Green Creek Complex is white mica schist and amphibolite in a batholith of granite and gneissic granite that is overlain unconformably by the white, pure, thin-bedded basal member of the Elba Quartzite (Miller 1984; Miller and Bedford 1999; Miller et al. 2008). In the City of Rocks area these rocks, as well as other Archean-aged igneous and metamorphic rocks, Neoproterozoic-aged quartzite and schist, are capped everywhere by a major low-angle normal fault—the Mahogany Peaks fault. This fault is nearly parallel to bedding and places Ordovician Pogonip Group (youngest metamorphic rocks in the Albion Mountains) strata on the older metamorphic rocks. These rocks represent some of the oldest rocks found in North America. They are juxtaposed against much younger intruding granitic plutonic rocks—the Twin Sisters being a particularly dramatic example (fig. 13) (Miller and Bedford 1999).

The Almo pluton is one of three Oligocene plutons that intruded the western part of the metamorphic core complex (figs. 15 and 16). The plutons intrude into shear zones and are themselves involved in ductile deformation in shear zones. Because of this, they provide key information as to the timing of the extensional shear that helped to create the complex (Miller and Bedford 1999). The largest exposure of the pluton is west of Almo, 24 km (15 mi) in length from north to south, and is approximately 8 km (5 mi) across (Cunningham 1971).

The Almo pluton consists of five domes of granite-like rock ranging from quartz-monzonite to biotite-granodiorite. This pluton forms a significant part of the plutonic/metamorphic infrastructure of the Albion Mountains metamorphic core complex. It has a complex relationship with the Archean gneiss, schist, and granite that compose the rest of the core complex. Contact metamorphism surrounding the pluton locally recrystallized the older rocks. Some contacts between the two are orientated at an angle to the surrounding rock layers (discordant) other contacts are nearly parallel (concordant). In many places it appears that the metamorphic rocks collapsed into the pluton, forming a variety of subsidence structures and "stoped" blocks.

The emplacement of this pluton may have occurred along with tectonic extension about 28 million years ago (Miller et al. 2008). Sheared blocks incorporated into the pluton indicate that it postdates the Eocene-aged extensional shear zone. This shear zone may have caused a kink or anticline (arch) in the crust at the future location of the Almo pluton (fig. 16) (Miller and Bedford 1999; Miller et al. 2008).

Then during the early Miocene (≈20–25 million years ago) nearby rocks to the west were sheared again, nearly parallel to the earlier Eocene shear zone. Elsewhere, undeformed dikes of granite cut previously sheared rocks. Thus, it is inferred that the pluton was emplaced between extensional shear events (Miller and Bedford 1999). Other geologists interpret the doming of the Albion metamorphic core complex as the result of isostatic uplift and warping and uplift of the Almo pluton after the development of an east-west-trending shear zone (Bandy 1989).

Basin-and-Range Features and Almo Fault

City of Rocks sits on the northern edge of the Basin and Range physiographic province. City of Rocks displays many of the features that are characteristic of the province, including parallel ranges and valleys (fig. 1C). High-angle normal faults cut all preexisting structures in the area surrounding City of Rocks National Reserve. Most of these faults trend north-south, parallel to the dominant joint set. These faults are usually steeply inclined with dips greater than 50°. Many faults having large inferred offsets are covered with unconsolidated Quaternary deposits, which make documentation and measurement difficult (Miller 1991).

Major low-angle normal faults typically occur (1) near the base of the Paleozoic rocks, (2) in Mississippian metamorphosed shales (not exposed at City of Rocks), and (3) within Middle Permian formations (also not exposed at City of Rocks) (Compton and Todd 1977). Along steep slopes within the reserve, commonly among outcrops of the Elba Quartzite, most exposed faults displace rocks down toward the valleys with a normal sense of separation (rocks above the fault plane slide downwards with respect to rocks beneath the fault plane). Springs are common along the faults in the reserve (Miller et al. 2008). In many places these faults cut rocks along the crest of the range and strike generally north. Within the Almo pluton, one fault zone strikes N35°E and dips 75°E, cropping out as a brecciated zone nearly 3 m (10 ft) wide (Miller et al. 2008).

Just east of City of Rocks National Reserve, the Almo fault passes through the town of Almo and extends in a south-to-southwest trend along the east margin of the

Albion Mountains as part of the Basin and Range geologic province. A series of co-linear scarps define the fault trace in outcrop (Miller et al. 2008). The scarps are rounded and consistently show displacement downward to the east (normal offset). The fault typically cuts Pleistocene alluvial-fan deposits, indicating the fault occurred after deposition of the alluvial-fan deposits. Along the road from Almo into the reserve, the fault deforms alluvium into a broad fold. A stage IV calcic horizon in the soil of the alluvium deposits indicates that this deposit is several hundred thousand years old (Machette 1985; Miller et al. 2008). Other local areas of alluvium having similar soil development do not contain scarps, an absence indicating either that (1) agricultural practices are obscuring the fault trace, (2) only discrete segments of the fault trace are visible, (3) the fault has varying vertical offset along strike, or (4) deposition of some alluvium postdates the last local fault rupture (Miller et al. 2008).

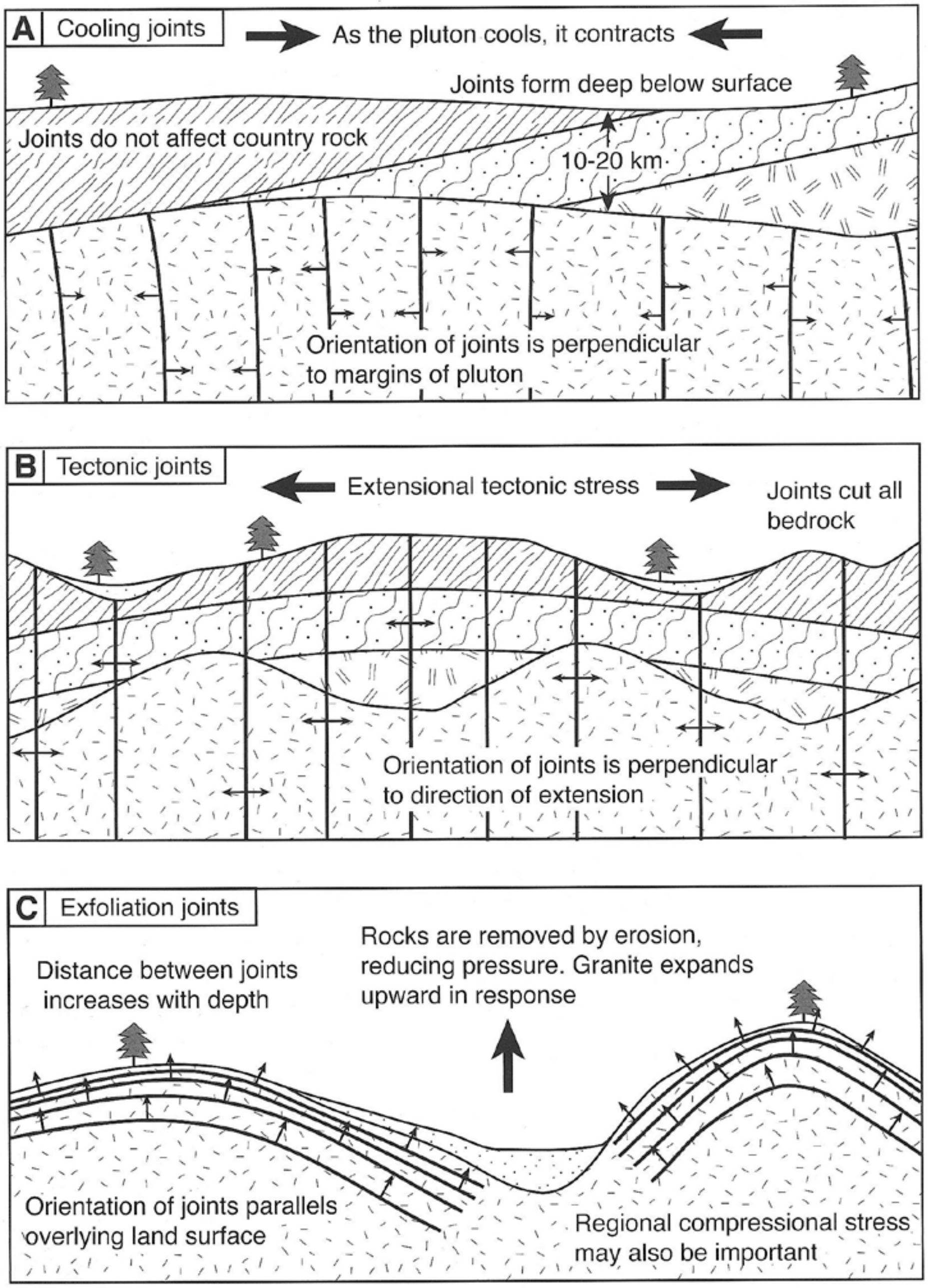


Figure 4. Three mechanisms by which joints form in granitic rocks. A, joints formed by cooling; B, joints formed by tectonic forces; C, joints formed by exfoliation. Diagram is figure 13 from Pogue (2008), used with permission.

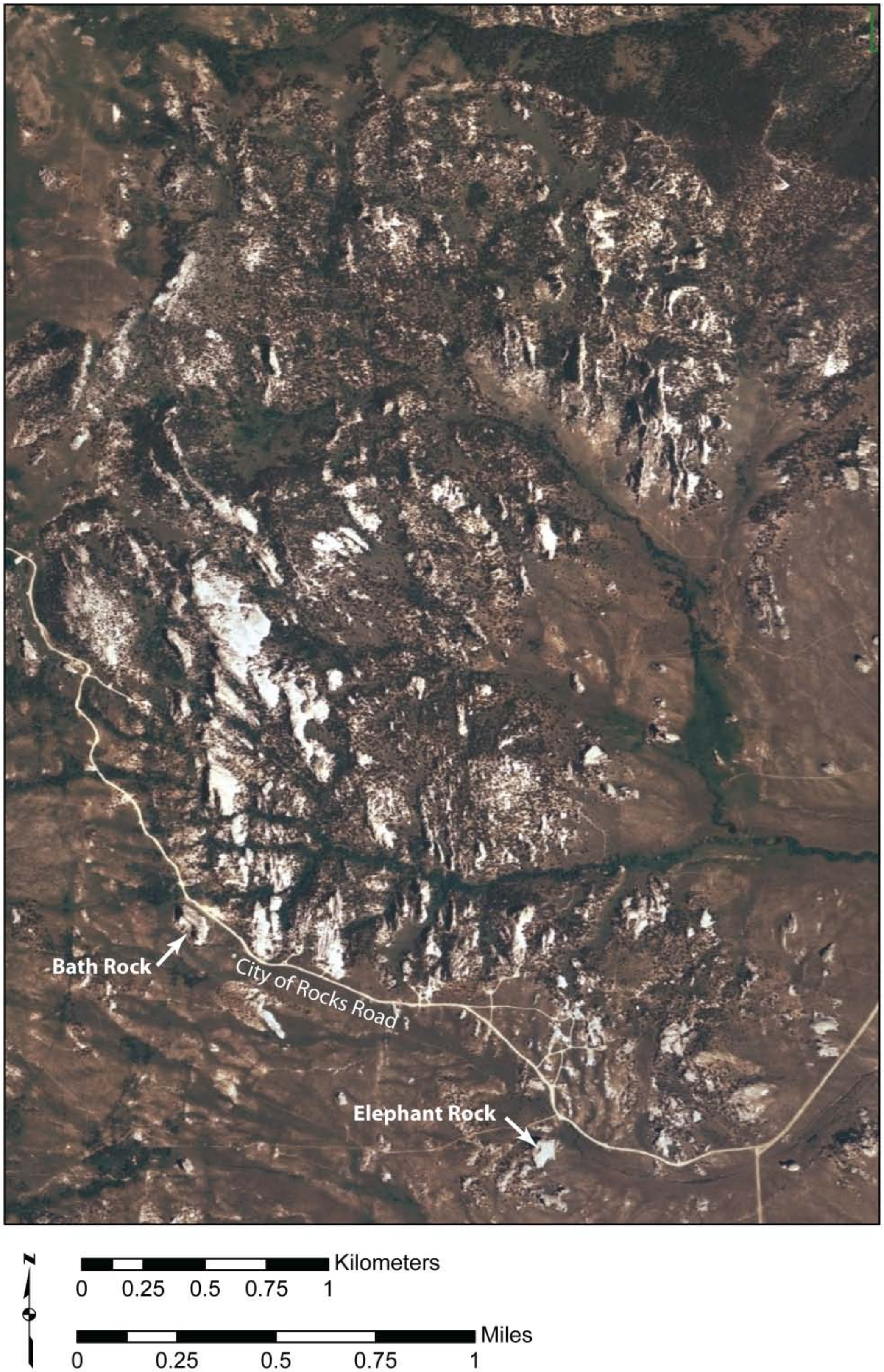


Figure 5. Aerial image of the central area of City of Rocks National Reserve. The light colored features are exposures of granite. Note the north-south orientation of many of the features, this orientation is influenced by one of the main joint sets that developed in the area. The arrangement of features separated by these large "avenues" and similarity to an "urban" landscape led emigrants to dub the area "City of Rocks." Two named features are indicated on the image. The Twin Sisters (fig. 13) are located south of this image. Aerial imagery compiled from ESRI Arc Image Service, USA Prime Imagery.

Figure 6. Aerial view of the Bread Loaves. The Bread Loaves are one type of granitic pinnacle found within the reserve. Joints parallel to the long axis of the "loaves" likely influenced their development. Other joints, perpendicular to the long axis of the loaves lend their "sliced bread" appearance. Note road and vehicle in right-center for scale. National Park Service photograph by Wallace Keck (City of Rocks National Reserve), available online: http://www.nps.gov/ciro/photosmultimedia/index.htm, accessed March 2010.

Figure 7. Exfoliation joints in the Almo pluton. As granite cools, it contracts forming joints. Exfoliation is just one of three processes responsible for the joints at City of Rocks National Reserve (fig. 4). National Park Service photograph by Wallace Keck (City of Rocks National Reserve), available online: http://www.nps.gov/ciro/photosmultimedia/index.htm, accessed March 2010.

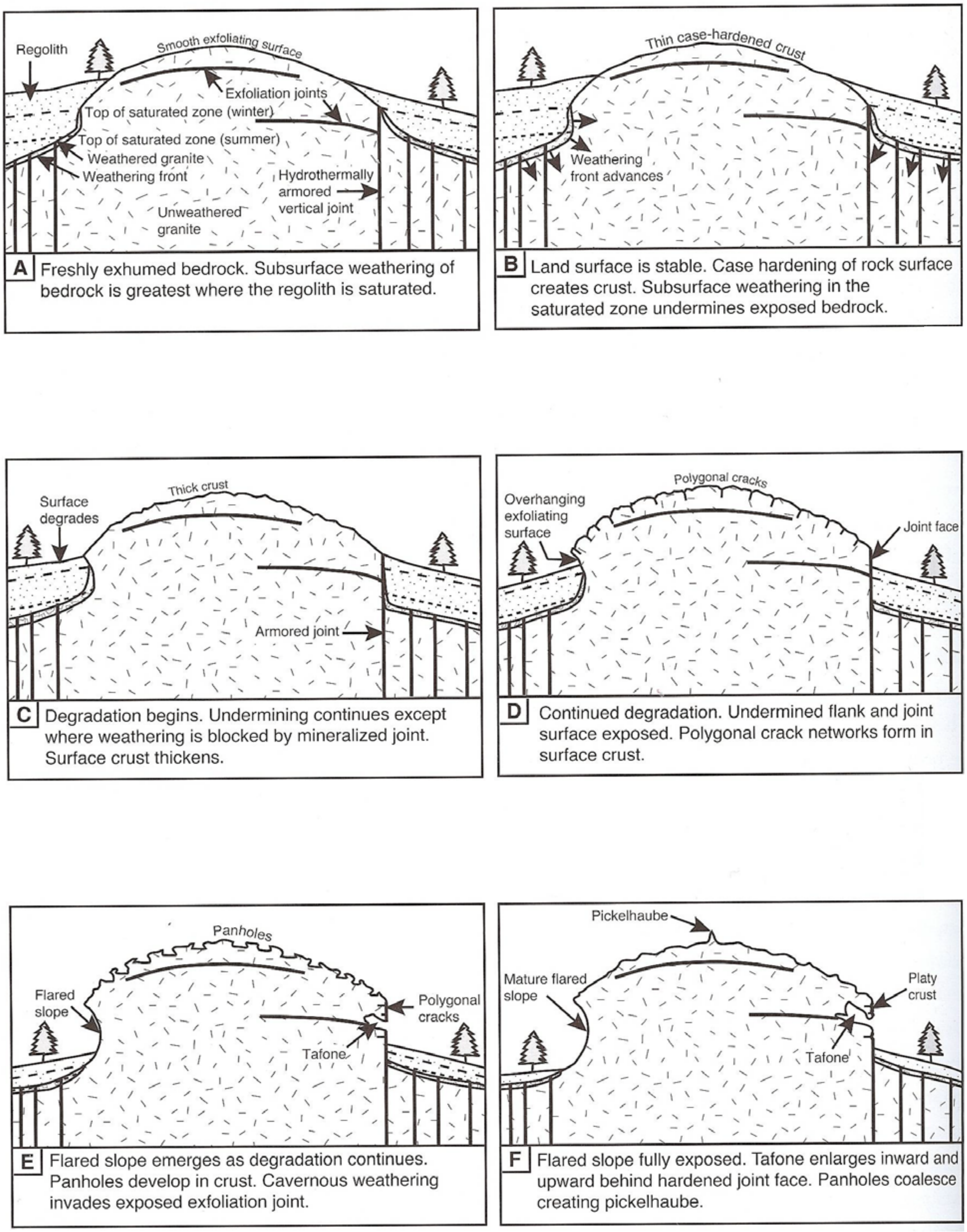


Figure 8. Modeled cross sectional view of the evolution of small-scale landforms on an emerging granitic spire during a period of landscape degradation (net removal of material). Diagram is figure 21 from Pogue (2008). Used with permission.

Figure 9. Blisters are a type of "case hardening" on the surface of granite rocks in City of Rocks National Reserve. The thin (few millimeters thick) reddish hardened surfaces form relatively quickly and are easily removed, exposing the lighter colored rock beneath. Crusts (not pictured) are much thicker and more durable. U.S. Geological Survey photograph from Miller and others (2008).

Figure 10. Window Arch is an example of fanciful features shaped by weathering of granite pinnacles in City of Rocks National Reserve. National Park Service photograph, available at http://www.nps.gov/ciro/photosmultimedia/index.htm, accessed March 2010.

Figure 11. Panholes on Bath Rock at City of Rocks National Reserve. Panholes begin as shallow depressions in the hardened crusts that catch water or snow. Weathering accelerates when the crust is breached. The inside front cover of this report also shows panholes within the reserve. National Park Service photograph by Wallace Keck (City of Rocks National Reserve), available online: http://www.nps.gov/ciro/photosmultimedia/index.htm, accessed March 2010.

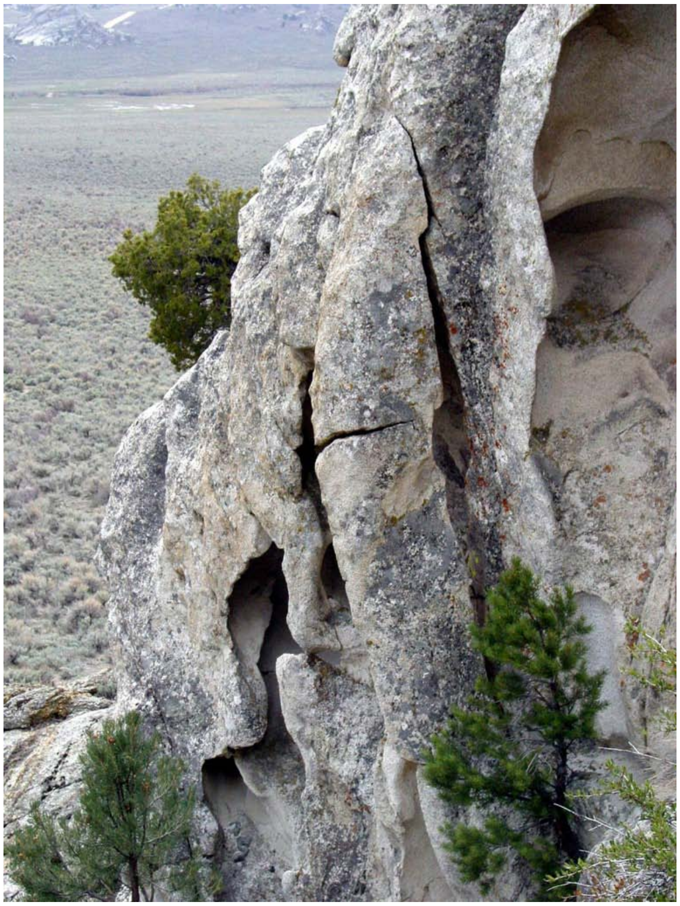


Figure 12. Tafoni visible on a pinnacle along the Geology Trail. Tafoni is a form of cavernous weathering on the sides of granite pinnacles. Crystallization of salt (likely from the Great Salt Lake) in cracks contributes to the formation of tafoni. National Park Service photograph by Wallace Keck (City of Rocks National Reserve), available online: http://www.nps.gov/ciro/photosmultimedia/index.htm, accessed March 2010.

Figure 13. The Twin Sisters are granite pinnacles in City of Rocks National Reserve. Despite their proximity to each other, the "twins" are actually separated by more than 2.5 billion years of geologic time. The darker-colored sister on the left is 2.5 *billion*-year-old granite—some of the oldest rocks in North America. The lighter-colored sister on the right is approximately 28 *million* years old granite associated with the Almo pluton. U.S. Geological Survey photograph, available online: http://3dparks.wr.usgs.gov/ciro/index.html, accessed March, 2010.

Figure 14. Emigrant signatures on Register Rock within City of Rocks National Reserve. The "city of rocks" was an important landmark along the Oregon and California trails. Emigrants left their names and other "historical graffiti," often written in axle grease (as shown here), on a number of the granite pinnacles. National Park Service photographs courtesy Wallace Keck (City of Rocks National Reserve).

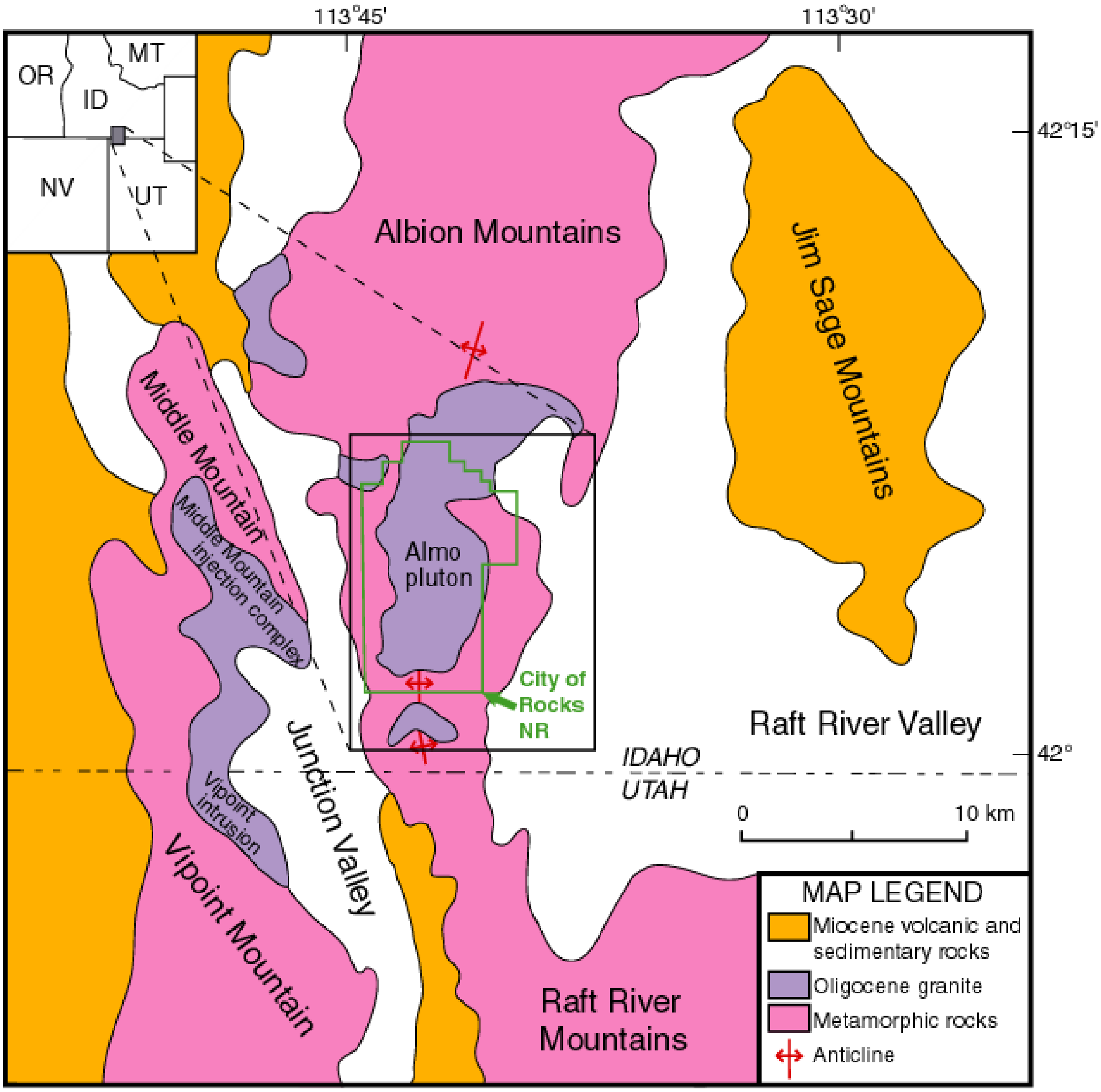


Figure 15. Generalized geologic map of the rock types surrounding City of Rocks National Reserve. Note the location of the Almo pluton. Areas in white are underlain by valley fill and other unconsolidated deposits. Graphic adapted from Miller and Bedford (1999).

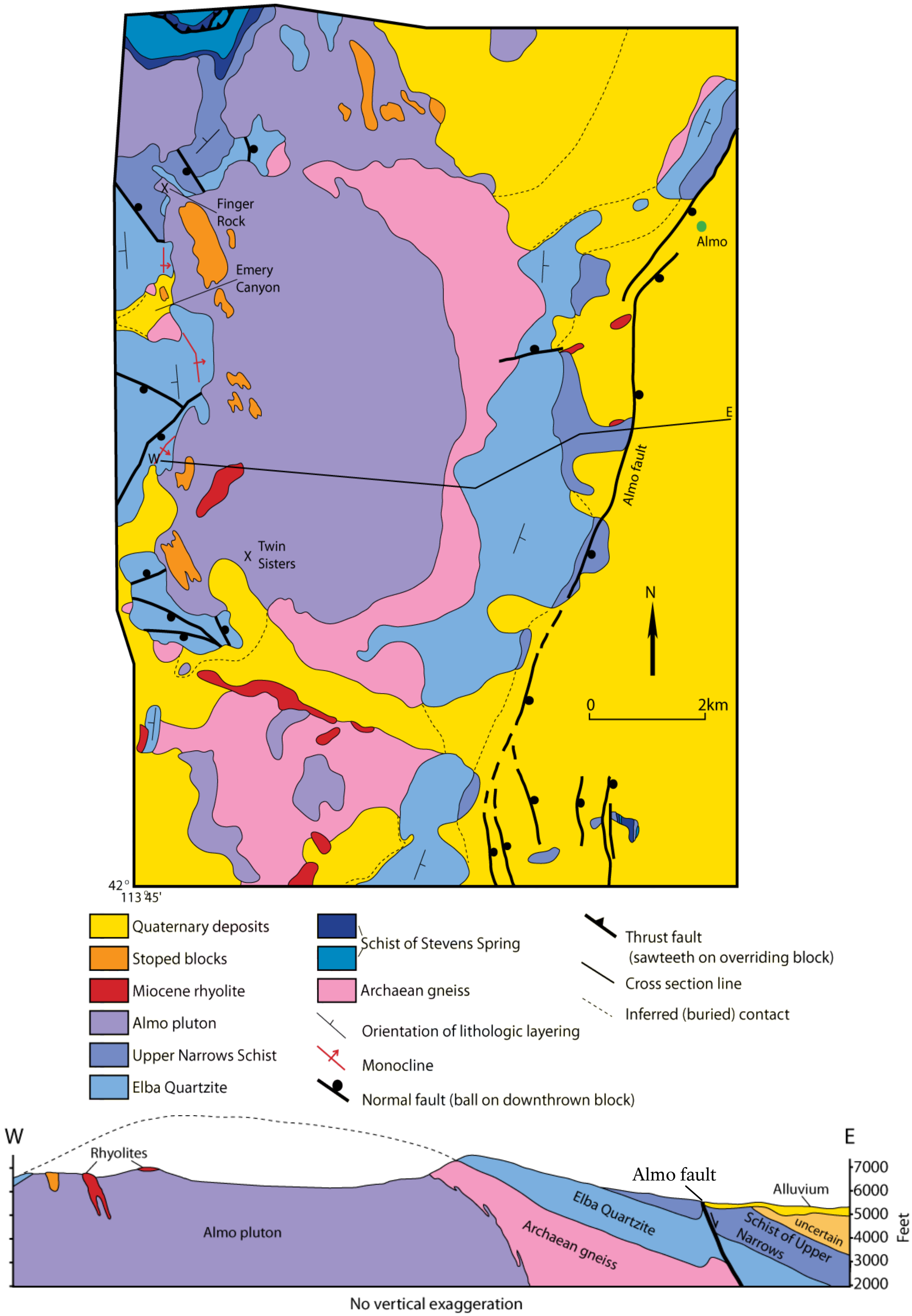


Figure 16. Generalized geologic map and cross section of the City of Rocks National Reserve area, southern Idaho. The section illustrates the major arch in the southern Albion Mountains. Graphic adapted from Miller and Bedford (1999).

Map Unit Properties

This section identifies characteristics of map units that appear on the Geologic Resources Inventory digital geologic map of City of Rocks National Reserve. 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 maps facilitate an understanding of Earth, its processes, and the geologic history responsible for its formation. Hence, the geologic map for City of Rocks National Reserve provided information for the "Geologic Issues," "Geologic Features and Processes," and "Geologic History" sections of this report. Geologic maps are two-dimensional representations of complex three-dimensional relationships; their color coding illustrates 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 among geologic features, 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 are not soil maps, and do not show soil types, 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. Similarly, map units show areas that have been susceptible to hazards such as landslides, rockfalls, and volcanic eruptions. Geologic maps do not show archaeological or cultural resources, but past peoples may have inhabited or been influenced by depicted geomorphic features. For example, alluvial terraces may have been preferred use areas 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. 17) for the age associated with each time period. The table highlights characteristics of map units such as: susceptibility to erosion and hazards; the occurrence of paleontological resources (fossils), cultural resources, mineral resources, and caves or karst; and suitability as habitat or for recreational use. Some information on the table are conjectural and 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 the source for the GRI digital geologic data for City of Rocks National Reserve:

Miller, D. M., R. L. Armstrong, D. R. Bedford, and M. Davis. 2008. *Preliminary geologic map and digital data base of the Almo quadrangle and City of Rocks National Reserve, Cassia County, Idaho*. Scale 1:24,000. Open-File Report OF 2008-1103. 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, and increases the overall utility of the data. GRI digital geologic map products include data in ESRI personal geodatabase and shapefile 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 and connects the help file directly to the map document. 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 Units within City of Rocks National Reserve

Early mapping efforts by Anderson (1931) and Armstrong (1968) distinguished granite, metamorphic rocks, and volcanic rocks at City of Rocks, as well as some of the rudimentary geologic structure and metamorphic history. Four unis—the Green Creek Complex, Elba Quartzite, schist of Upper Narrows, and Almo pluton—dominate the bedrock at City of Rocks National Reserve (Pogue 2008). The Archean Green Creek Complex of Armstrong and Hills (1967) includes amphibolite, granite and granite gneiss, and schist. The dark-brown, biotite-rich schist is the oldest rock of the complex (Miller et al. 2008; Pogue 2008). Granite intruded the schist and has a porphyritic texture. Local metamorphism and deformation (especially near the Almo pluton) converted some of the granite into granitic gneiss (Pogue 2008). The amphibolite appears as dark, linear bands within the granite, possibly in an intrusive relationship (Miller et al. 2008).

The Neoproterozoic Elba Quartzite of Armstrong (1968) is one of the most distinctive units in the Albion Mountains, having nearly pure quartz composition, zones of conglomerates, and very light color (Miller et al. 2008; Pogue 2008). It nonconformably overlies the Archean rocks and has a gradational relationship with the overlying Schist of Upper Narrows (Miller et al. 2008). Mud, silt, and carbonate sediments were deposited atop the quartz sands of the Elba Quartzite and metamorphosed into dark-brown and gray schist interlayered with quartzite and marble (Pogue 2008).

Throughout the Albion and Raft River mountains are exposures of a thick sequence of metasedimentary rocks, including the Quartzite of Yost, Schist of Stevens Spring, Quartzite of Clarks Basin, Schist of Mahogany Peaks, and the metamorphosed Pogonip Group (Miller et al. 2008; Pogue 2008). Within City of Rocks National Reserve, rocks of these units appear only in roof pendants and xenoliths in the Almo pluton, having been otherwise eroded away (Pogue 2008).

From a distance, exposures of the Green Creek Complex granite and the Almo pluton granite appear similar; upon closer inspection, however, the Almo pluton granite lacks the strong porphyritic texture of the darker Green Creek Complex granite (Pogue 2008). The Almo pluton is of granitic to granodioritic composition with massive textures and common pegmatite-aplite dikes (Miller et al. 2008).

The bedrock geology is strikingly displayed at City of Rocks as myriad geomorphologic forms indicative of the geologic history of the area, recently dominated by regional erosion, uplift, and extension. The extension of the Basin and Range province followed the late Cretaceous to early Tertiary compressional Sevier–Laramide orogenic events. The Miocene rhyolitic volcanic rocks, including welded tuff, erupted during the passage over the Yellowstone hot spot approximately 10 million years ago to the north of the Albion Mountains (Miller et al. 2008; Pogue 2008). They were deposited as pyroclastic flows atop the weathered granite of the Almo Pluton and Green Creek Complex and now appear in small isolated outcrops within the reserve (Pogue 2008).

Sedimentary deposits from the Tertiary and Quaternary periods include cobbley sand (containing clasts of Almo pluton granite and Elba Quartzite), fluvial deposits, several generations of alluvial-fan deposits, talus, landslide deposits, alluvium, and colluvium (Miller et al. 2008). These weathered from, and were deposited atop, the older metamorphic and igneous rocks in small valleys, at the base of slopes, and in Circle Creek Basin. The various generations of unconsolidated deposits at City of Rocks record climate changes throughout the Cenozoic Era (Pogue 2008). Erosion upon continued uplift carved into these unconsolidated units, weathering them into the ravines, gulleys, sweeping valleys, and channels present at City of Rocks National Reserve today.

Map Unit Properties Table: City of Rocks National Reserve

Age	Unit Name (Symbol)	Features and Description	Erosion Resistance	Suitability for Infrastructure	Hazards	Mineral Specimens	Habitat	Recreation	Geologic Significance
QUATERNARY	Alluvium (**Qal**) Younger alluvial fan deposits (**Qya**) Younger alluvial fan deposits over intermediate alluvial fan deposits (**Qya/Qia**) Younger fluvial deposits (**Qyf**) Veneer on pediment (**Qvp**)	Unit **Qal** contains 2–3 m (7–10 ft) of dark-brown sand and mud along active washes and floodplains with some gravel deposited locally. Unit **Qya** includes dark-brown, organic-rich sand, gravel, and silt that form 1- to 4-m- (3- to 13-ft)-thick alluvial fans from steep hills to lower gradient areas. Unit **Qya/Qia** is mixed thin (<2 m [7 ft] thick) sheets of younger and intermediate alluvial fan deposits. Unit **Qyf** contains mud, sand, and gravel associated with active river processes. Unit **Qvp** consists of mixed colluvium, alluvium, and alluvial fan deposits as thin (<3 m [10 ft] thick) veneers on nearly flat erosional bedrock surfaces (pediment).	Low unless carbonate cement present.	Units are associated with river environments, such as floodplains and stream banks; avoid for heavy development.	Units are prone to flooding and slumping when undercut. Stream deposits could be prone to liquefaction. May contain shrink-and-swell clays.	Sand, gravel	Units contribute to organic-rich soils along riparian zones; some calcic horizons are present in unit **Qyf**.	Units are associated with active geomorphological processes and fragile riparian areas; avoid for any recreation beyond light seasonal use.	Units contain the Mazama ash layer (eruption that formed what is now Crater Lake in Oregon) dated at approximately 7,700 years old. Unit **Qyf** contains charcoal layers dated at 8,265±35 years before present.
QUATERNARY	Landslide deposits (**Qls**) Colluvium (**Qc**) Talus (**Qt**)	Unit **Qls** contains bouldery, dark-colored deposits less than 10 m (33 ft) thick displaying slump-block morphology in outcrop. Unit **Qc** is light- to dark-brown, unsorted and unconsolidated rubble of rock and soil on steep slopes less than 5 m (16 ft) thick. Unit **Qt** includes white, blocky boulder fields (<5 m [16 ft] thick) on steep slopes with angular edges and an overall lack of a finer grained matrix.	Low	Units are associated with unstable and steep areas and should be avoided for development.	Units are associated with active mass-wasting processes, including repeated slumping, tumbling, rockfall, sheetwash, and slope creep. Some frost wedging also associated with these units.	Boulders	Units are associated with springs and dense vegetation locally. Unit **Qls** is mostly unforested.	Units form stepped slopes at the bases of steeper exposures and should be avoided for most recreational use.	Units are associated with prominent local features, including Twin Sisters.
QUATERNARY	Intermediate alluvial fan deposits (**Qia**) Intermediate alluvial fan deposits over older alluvial fan deposits (**Qia/Qoa**) Intermediate alluvial fan deposits over Quaternary and Tertiary alluvium and landslide deposits (**Qia/QTa**).	Unit **Qia** includes gravelly sand and sandy loam in medium- to dark-brown, 5- to 10-m-(16- to 33-ft) thick exposures as alluvial fans and some colluvium. Some loess deposits in 20- to 50-cm- (8- to 20-in.)-thick lenses locally. Unit **Qia/Qoa** overlies older alluvial-fan deposits with a thin (<2 m [7 ft] thick) sheet of mixed sand and gravel. Unit **Qia/Qta** resembles unit **Qia/Qoa** in thickness and composition overlying alluvium and landslide deposits.	Low unless carbonate cement present.	Units are present as unstable alluvial fans prone to erosion, mass wasting, and flash flooding and are unsuitable for most development.	Units are associated with flash-flood deposition and active erosion and are prone to gullying.	Gravel, sand, silt	Unit contains decomposed granite and one or two well-developed soils with argillic and calcic horizons. Stage II calcic soil and stage IV soil present.	None documented	Units record history of uplift and erosion throughout the area.
QUATERNARY	Intermediate fluvial deposits (**Qif**) Older alluvial fan deposits (**Qoa**) Older fluvial deposits (**Qof**).	Unit **Qif** contains sand, gravel, and mud with some Bt and calcic (stage II) soil horizons in uppermost layers of the deposit. Unit contains characteristic surficial pavements and gray mud beds atop well-sorted pebble to cobble gravel. Unit **Qoa** contains 15–25 m (49–82 ft) of medium-brown, gravelly sand deposited as alluvial fans and colluvial layers in steeper areas. Coarser cobbles and boulders form an erosional surface on rounded crests with sand and loam matrix. Unit **Qof** contains rounded clasts, mixed with adjacent alluvium, and loess caps greater than 1 m [3 ft] thick.	Low	Units are highly permeable and may be unsuitable for waste-water treatment-facility development.	Units are prone to slumping and slope creep if undercut or exposed on slopes.	Sand, gravel, mud, cobbles, pebbles, loam.	Unit **Qoa** contains well-developed calcic horizon in soils including more than 1.4 m of stage IV calcic soil. Unit **Qof** contains loess-rich areas.	Boulder fields are unstable and unsafe trail base and should be avoided for recreational use.	Unit **Qif** may contain glacial deposits recording activity in the Raft River Mountains. Unit **Qoa** contains soils that may be several hundred thousand years old. Units are used to determine erosional and depositional history of the area.
QUATERNARY -TERTIARY	Alluvium and landslide deposits (**QTa**) Fluvial deposits (**QTf**).	Unit **Qta** includes boulder and gravel deposits forming high hills that are light colored in outcrop exposures as thick as 25 m (82 ft). Unit **QTf** is a 10-m-(33 ft) thick mixture of brown sand, gravelly sand, gravel, and silt with some bedding and cross-lamination depositional structures. Well to moderately sorted. Brown sand of this unit is of wind-blown origin and overlies river (fluvial) deposits.	Moderately low.	Units are highly unsorted and heterogeneous and may be unstable if undercut for foundation construction.	Units contain large boulders atop less competent layers and may be prone to mass wasting during extreme precipitation.	Quartzite boulders, gravel, fine sand, silt.	Unit **QTf** resembles rounded terraces and contains stage III or stage IV calcic soil horizons.	Unit **QTa** is flanked by large boulders (1–5 m diameter) that may be unsuitable for trails and other uses.	Unit **QTa** associated with Smokey Mountain and Twin Sisters with deposits from now-eroded heights.

Age	Unit Name (Symbol)	Features and Description	Erosion Resistance	Suitability for Infrastructure	Hazards	Mineral Specimens	Habitat	Recreation	Geologic Significance
TERTIARY	Rhyolite (**Tr**) Sedimentary deposits (**Ts**) Granite (**Tg**)	Unit **Tr** consists of bright-red, brownish-red, to gray welded rhyolite tuff with some black vitrophyre near the base and top, locally. Lithic fragments of granite as large as 1.5 cm (0.6 in.) within vesicular (flattened) central unit. Unit ranges in thickness from 9 m to 17–20 m (30 ft to 56–66 ft). Unit **Ts** includes cobbly sand in light-brown, slope-forming deposits. Boulders from this unit are as large as 4 m (13 ft) in diameter in 5- to 10-m- (16- to 33-ft)-thick deposits. Unit **Tg** is white to light-gray granite of the Almo pluton. Compositions range from biotite granite, to biotite-muscovite granite, to muscovite granite in massive, banded outcrops. Dikes of pegmatite and aplite intrude locally.	High for units **Tr** and **Tg**, low for unit **Ts.**	Igneous units may weather to radon-producing soils and should be evaluated prior to any infrastructure construction.	Unit **Ts** is prone to slumping and sliding if exposed on slopes or undercut. Unit **Tg** may be present as large blocks and slabs that may be subject to frost wedging and rockfall. Units may weather to produce shrink-and-swell clays.	Smoky quartz (3–6 mm), pumice (vesicles may be filled with secondary minerals locally), quartzite boulders, biotite, muscovite, garnet, granite, pegmatite.	None documented	Granitic exposures form much of the “City of Rocks” features. They are popular for rock-climbing.	Nearby rocks similar to unit **Tr** were dated to 8.8 million years old. Unit **Tg** represents the Almo pluton and has a Rubidium-Strontium radiometric age of 28.6±1.0 million years and forms the younger of the Twin Sisters.
ORDOVICIAN	Metamorphosed Pogonip Group (**Op**)	Unit contains brown to bluish-gray, calcitic marble in 10-m- (33-ft)-thick, narrow outcrops.	Moderate	Unit may contain dissolved conduits and should be investigated before any infrastructure construction.	Unit could dissolve away from beneath intact rocks and present a rockfall hazard.	Brown ,micaceous marble; gray, pure marble; calcite; dolomite; phlogopite.	Unit weathers to produce calcium- and magnesium-rich soils. Dissolved crevices may provide bat habitat.	Unit may be subject to karst dissolution that may produce caves or small cavities that could attract visitors.	Unit represents clean and silty limestone deposition in a marine environment.
PROTEROZOIC	Schist of Mahogany Peaks (**Zmp**) Quartzite of Clarks Basin (**Zcb**)	Unit **Zmp** contains black schist with coarse-grained textures. Unit **Zcb** includes thinly layered, flaggy 20-m- (66-ft)-thick quartzite with mica-rich joints or layers. Unit appears silvery white and tan to light gray.	Moderate, moderately high for quartzite.	Heterogeneous and locally schistose nature of these units may render them unsuitable for infrastructure.	Mica-rich joints and layers may provide planes of weakness within resistant quartzite that may present rockfall hazards.	Quartzite	None documented	Quartzites may form resistant ledges and ridges that may provide nesting habitat or attract climbers.	Units record mixed marine and near-shore depositional environments.
PROTEROZOIC	Schist of Stevens Spring (**Zss**) Quartzite of Yost (**Zy**)	Unit **Zss** is brown to silvery-brown schist with coarse-grained, wavy to knobby textures. Near the base of this unit is distinctive amphibolite. Unit is approximately 300 m (980 ft) thick. Unit **Zy** is pure white quartzite. Scant muscovite (mica) layers define the thin bedding of this 40-m- (130-ft)-thick unit.	Moderate to high for quartzite.	Coarse-grained schist may prove too friable locally for infrastructure.	Quartzite is susceptible to blockfall if undercut on slopes. Schist can pose mass-wasting problems, especially if slope is aligned parallel to schistosity.	Muscovite, sillimanite, biotite, garnet, andalusite, kyanite in 2- to 7-cm- (0.8- to 2.8-in.) wide lenses, white quartzite.	None documented	Quartzite may form resistant ledges and ridges that may provide nesting habitat.	Unit **Zss** records a complex regional metamorphic history.
PROTEROZOIC	Schist of the Upper Narrows (**Zun**) Elba Quartzite of Armstrong (**Ze**)	Unit **Zun** includes thinly layered, quartz-rich muscovite-biotite schist and (2- to 12-cm- [0.8- to 4.7-in.]-thick) schistose quartzite that appears light to dark brown and grayish brown in outcrop. Unit is approximately 70 m (230 ft) thick. Pure limestone marble is present locally. Unit **Ze** is approximately 200 m (660 ft) of white to pale gray and grayish-brown quartzite in thick beds. Unit grades from vitreous (glassy) quartzite beds at the base to darker, less pure, thick quartzite beds. Some tabular cross lamination and schist interbeds present locally.	High	Layered and weathered nature of these units may render them unsuitable for infrastructure.	Quartzite is subject to blockfalls and frost wedging. The presence of unit **Ze** clasts in younger units suggest it is deeply eroded. Schist can pose mass wasting problems if slope is aligned parallel to schistosity.	Muscovite, biotite, quartzite, pure limestone marble, feldspar, epidote, actinolite.	Unit **Ze** tends to underlie well-drained high ridges due to its high resistance to erosion.	Unit forms resistant ridges that may be attractive to climbers.	Unit **Zun** may have been part of a shallow marine depositional environment with laminated sand and silt. In unit **Ze,** muscovite schist may represent metamorphosed argillaceous soil horizon above Archean rocks.
ARCHEAN	Amphibolite (**Wga**) Granite and granite gneiss (**Wgg**) Schist (**Wgs**)	Unit **Wga** includes black hornblende-plagioclase and hornblende-plagioclase-garnet metamorphosed mafic rock with coarse- to medium-grained textures. Unit appears as linear, dark bands in granite and is a few tens of meters wide. Unit **Wgg** is porphyritic biotite granite that appears light to dark gray and coarse grained in outcrop. Large crystals are aligned as magmatic foliation. Granite is locally deformed to augen gneiss. Unit **Wgs** contains coarse-grained muscovite-biotite schist that appears dark brown in outcrop. Schist locally contains veins, stringers, and knots of feldspar and quartz and is intruded by unit **Wgg**.	High to moderately high for schist.	Granitic unit may weather to produce radon-emitting soils and should be tested prior to basement construction.	Unit subject to blockfall if undercut on slope. Weathered exposures can be friable and unstable on slopes. Mica-rich joints and layers may provide planes of weakness within resistant granite and quartzite that may present rockfall hazards.	Hornblende, plagioclase, garnet, quartz, 5x2-cm (2x0.8-in.) microcline phenocrysts, biotite, coarse granite.	None documented	Units are suitable for most recreation; large crystals may attract illegal sampling.	Archean rocks are among the oldest in North America. Unit **Wga** likely represents dike swarms intruding the granite. Unit **Wgg** is 2.5 billion years old and forms the older of the Twin Sisters.

Geologic History

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

Precambrian (prior to 542 million years ago)

The rocks present within and surrounding City of Rocks National Reserve record a vast span of geologic history as part of the regional Raft River–Grouse Creek–Albion Mountains metamorphic core complex (see fig. 17 for a time scale). The oldest rocks provide a rare glimpse into the tectonic setting of the Archean Eon, more than 2.5 billion years ago. They are among the oldest rocks in North America. The Green Creek Complex consists of a metamorphic rock called schist that formed from sediments originally deposited as mud, silt, and sand in a shallow sea (Pogue 2008). Following a metamorphic event, granitic and basaltic magma intruded the metamorphosed sediments around 2.5 billion years ago (Compton and Todd 1977; Miller and Bedford 1999; Miller et al. 2008). Subsequent metamorphism and deformation events (much later in the Mesozoic and Cenozoic eras) converted some of these rocks into gneiss and amphibolite and produced regional folds (Compton and Todd 1977; Pogue 2008). After the Archean-aged metamorphic and intrusion events, significant uplift and erosion exposed these rocks at the surface during the Proterozoic (Miller et al. 2008; Pogue 2008). One of the Twin Sisters is composed of this Archean-aged granite (fig. 13).

Late Proterozoic-aged rifting created a new continental margin along western North America. The thinned crust subsided, and shallow seas inundated the lowest areas. Sometime between 1,500 and 600 million years ago, pure quartz sediments derived from weathering of the ancient continent covered the eroded Archean-aged rocks (Pogue 2008). The City of Rocks area was located near the western shoreline in this passive margin paleoenvironment, similar to today's East Coast of North America. The Elba Quartzite is the widespread unit that records this environment. It is a prominent marker unit between the underlying Archean rocks and overlying Neoproterozoic-aged rocks such as the Schist of the Upper Narrows, Quartzite of Yost, Schist of Stevens Spring, Quartzite of Clarks Basin, and Schist of Mahogany Peaks, that were originally deposited as sandstone, siltstone, shale, and volcanic rocks (Wells et al. 1998; Miller and Bedford 1999; Miller et al. 2008).

During the Late Precambrian and Cambrian, deposits of shallow-water marine sediments thousands of feet thick accumulated along a passive plate-tectonic margin on the western side of the Transcontinental Arch. This arch was an upland area that stretched from northern Minnesota southwestward across Nebraska, Colorado, and northwestern New Mexico (Speed 1983; Sloss 1988). As more sediment accumulated, the basin subsided and the shallow sea became deeper. At the beginning of the Cambrian, marine invertebrates with shells of calcium carbonate flourished in the local sea. Accumulations of their remains formed thick limestone deposits (Pogue 2008).

The Precambrian units now crop out at the surface at City of Rocks due to extensive erosion and normal faulting. The missing rock record makes it difficult to determine the paleoenvironments of millions of years at City of Rocks. Geologists refer to surrounding areas to determine the history in a regional context.

Paleozoic Era (542 to 251 million years ago)

Beginning in the Cambrian and throughout the Paleozoic Era, cycles of erosion from small-scale tectonic uplifts contributed mud, silt, and sand lenses to the predominantly carbonate deposition within the marine basin. During the Late Cambrian, North America was oriented so that the panhandle of Idaho was parallel to and very near the equator. Limy muds accumulated under these warm-water conditions in much the same way as they do in the broad lime-mud shoal-bank area in the Bahaman Islands today (Hintze 1988). The Paleozoic rocks elsewhere record remarkably thick accumulations of sediment, each unit being as much as 2,100 m (7,000 ft) thick in some places, in a marine environment (Cunningham 1971). For example, near Golden Spike National Historic Site, south of City of Rocks, dolomite and other carbonate rocks record broad carbonate shelves evolving into open and restricted marine environments and later near-shore marine environments. This was a time of shifting regional shorelines in a passive-margin setting. This relatively stable depositional environment persisted in southern Idaho for approximately 400 million years (Pogue 2008).

Although most of the rocks from the Paleozoic and Mesozoic eras are missing, Paleozoic sediments, such as sandstone, limestone, and dolomite, deposited in a longstanding basin are present in the metamorphic core complex as the marble of the Pogonip Group, some Mississippian schist, and Pennsylvanian and Permian sandstone and limestone (Cunningham 1971; Miller et al. 2008). Only the Pogonip Group appears in the mapped area of City of Rocks National Reserve, where it overlies the Precambrian rocks separated by the metamorphosed Mahogany Peaks fault contact (Miller et al. 2008).

Mesozoic Era (251 to 65.5 million years ago)

At the beginning of the Mesozoic Era, the passive depositional setting of the marine basin began to change (fig. 18A). During the Jurassic, the Farallon plate was subducting beneath the western edge of North America. A chain of volcanoes developed over the subducting plate, and compressional stress translated far into the interior of western North America during several mountain-building events (orogenies), including the Sevier and Laramide orogenies. Between 170 and 60 million years ago intermittent compressional stress forced kilometer-thick slabs of Proterozoic, Paleozoic, and Early Mesozoic sedimentary rocks to buckle and detach from the Archean-aged basement rocks of eastern Idaho and western Wyoming. They were then thrust up and over rocks to the east on a series of thrust faults (fig. 18B) (Pogue 2008).

The Sevier and Laramide orogenies were the last of the mountain-building episodes that formed the Rocky Mountains. The orogenies were characterized by two different styles of deformation. The Sevier orogeny was characterized by relatively thin slabs of older, upper Precambrian and lower Paleozoic sedimentary rocks being shoved eastward over younger, upper Paleozoic and lower Mesozoic rocks. In south-central Idaho, compressional stress of the Laramide orogeny thickened the crust by thrust faults that were steep near the surface and shallower deep within the earth. Unlike the thrust faults of the Sevier orogeny, the Laramide faults cut into and thrust upward the Archean-aged basement rocks. The Laramide orogeny forming a mountain range and resulting in broad uplift, buckling, and fracturing of the crust along north to south-trending (potentially reactivated) faults (fig. 18C) (Cunningham 1971; Pogue 2008). The Late Cretaceous to early Tertiary rocks exposed to the south of City of Rocks record the Sevier-style deformation and its evolution into Laramide-style deformation (Goldstrand 1990).

The rocks exposed today in the Albion Mountains were deeply buried beneath overthrust slabs of rock during this mountain-building event. This deep burial caused widespread metamorphism through exposure to heat and intense pressure. The metamorphism formed gneiss, amphibolite, schist, and quartzite, as well as regional foliation and lineation sets and many small folds common in the Elba Quartzite (Compton and Todd 1977; Miller et al. 2008; Pogue 2008).

Cenozoic Era (65.5 million years ago until today)

Paleogene and Neogene periods (together called the "Tertiary;" 65.5 to 2.6 million years ago)

By the Paleogene, compressional (pushing together) stress tapered off along the western edge of North America, and by the middle Eocene extension (pulling apart) was the dominant tectonic force in southern Idaho (Pogue 2008). City of Rocks is very near the boundary of two major physiographic provinces—the Basin and Range and the Eastern Snake River Plain. The present landscape was influenced by the processes associated with the formation of both provinces. The Basin and Range is characterized by normal faults and pulling apart of Earth's crust while the Eastern Snake River Plain characterized by volcanism associated with the Yellowstone hot spot.

Along the northern edge of the Basin and Range, City of Rocks National Reserve experienced three major extensional events during the Eocene (42–37 million years ago), the early Miocene (≈25–20 million years ago), and later Miocene (13–7 million years ago) (fig. 18D–G) (Compton and Todd 1983; Miller et al. 2008). Large slabs of rock moved down and laterally away from the thickened and heated crust of south-central Idaho (Pogue 2008). The net result of these extensional events was the vertical thinning and lateral extension of the rocks of the Albion Mountains metamorphic core complex (Miller et al. 2008). Uplift produced by excess heat in the mantle and extensional faulting caused the rocks, now exposed in the Albion Mountains, to slowly rise relative to the surrounding rocks. The first two thinning events moved upper rocks down to the west and northwest along west-dipping regional faults. This deformation was brittle closer to the surface, but at depth more ductile conditions prevailed and resulted in shear zones such as the Middle Mountain shear zone (Miller and Bedford 1999).

The later Miocene extensional event displaced the upper rocks down to the east on a separate east-dipping detachment fault system (Miller et al. 2008). In the eastern Raft River Mountains near City of Rocks, the fault was ductile in character, forming mylonites—elsewhere it was brittle in nature. This brittle deformation caused the rupture of the volcanic rocks in the Jim Sage Mountains, faulting them away from the Albion Mountains, moving down to the east. The rocks of the southern Albion Mountains bowed up as an arch-like dome (Compton and Todd 1977; Pogue 2008). Extension during the Miocene also formed Junction Valley and the Raft River Valley Basin. Other deep basins related to the late Miocene extension lie east and west of the southern Albion Mountains. These basins are all filled with Miocene volcanic-rich sediment (Miller and Bedford 1999).

Excess heat from the mantle and decompression of the rising dome in the Albion Mountains induced partial melting of the lower crust and produced a large magma body that would later become the Almo pluton. The less dense magma rose upward through the surrounding dense solid rock by intruding along cracks and incorporating blocks of surrounding country rock in a process called "stoping" (Pogue 2008). Once the magma reached a certain depth (between 10 and 15 km, or between 6 and 9 mi beneath the surface), cooler ambient temperature and lower pressures initiated crystallization and slowed upward movement (Pogue 2008). The mica minerals that attracted the interest of miners were emplaced in pegmatite dikes associated with the Almo pluton. The emplacement of the Almo pluton in the Oligocene (≈28 million years ago) and similar bodies farther south was in the midst of extensional events in the Tertiary (fig. 18D) (Miller et al. 2008). This intrusion was accompanied by contact metamorphism with the already metamorphosed country rock. This thermal overprint is recorded in the Archean age units at City of Rocks (Miller et al. 2008). As the pluton cooled and solidified, joints formed throughout the rock as a result of contraction. Regional east-west extensional stress also formed joints in the new rock body oriented in a roughly north-south trend.

Uplift, erosion, and tectonic thinning along extensional normal faults intermittently throughout the Tertiary caused the Almo pluton and surrounding metamorphic rocks in the City of Rocks area to rise quickly to the surface (fig. 18F–G) (Pogue 2008).The thick stack of rocks of the ductilely deformed metamorphic complex thinned and extended laterally (east-west). In the Albion Mountains, removal of about 14 km (8.7 mi) of rock that sat atop the pluton exposed the granite to erosion (Miller et al. 2008).

Approximately 10 million years ago, several rhyolite ash flows were deposited onto the eroded metamorphic rocks at the surface as the North American plate passed over a stationary mantle plume (the Yellowstone hot spot) (fig. 18G) (Miller et al. 2008; Pogue 2008). This mantle plume gave rise to the series of calderas and volcanic deposits of the Snake River Plain stretching from the Idaho-Oregon border to Wyoming (Pogue 2008). The passage over the hot spot caused further uplift and exhumation due to increased heat and buoyancy of the mantle. The resulting regional volcanism spewed blankets of rhyolite ash flows over the entire area (Baars 2000; Fillmore 2000). Within the Albion Mountains, solidified Miocene ash flows detached from the underlying metamorphic rocks and slid down along a low-angle normal fault during the later Miocene extensional event to compose the Jim Sage and Cotterel mountains due east and northeast of the reserve, respectively (Compton and Todd 1983; Miller et al. 2008; Pogue 2008). The last local volcanic event produced silica-rich lava flows that covered much of the surface west of the Cotterrel Range, exceeding 2,100 m (7,000 ft) in elevation (Cunningham 1971). The North American plate continued to migrate westward, and the hot spot is now fueling the geothermal features of Yellowstone National Park (Pogue 2008).

Throughout the Cenozoic, regional uplift and subsequent erosion of the ranges in the Basin and Range province largely gave rise to the topography of southern Idaho (Pogue 2008). Fault-bounded valleys filled with a variety of sediments in alluvial fans shed from the newly exposed highlands (fig. 18H–I). Conglomerate and reworked volcanic deposits were distributed across the region during periods of intense regional erosion (Baker and Crittenden 1961). The oldest alluvial deposits are remnants eroded to rounded caps on local ridges atop ≈10-million-year-old volcanic rocks at City of Rocks. Relief on some of these ridges records at least several tens of meters of downcutting since their deposition (Miller et al. 2008).

Quaternary Period (2.6 million years ago until today)

The Pleistocene Epoch was a time when Earth's climate cooled significantly. The increased precipitation and decreased evaporation created many lakes in the Basin and Range and caused glaciers to form on the highest peaks in the area, including Mount Harrison and Cache Peak (Pogue 2008). These glaciers carved bowl-shaped cirques on mountain slopes—now filled with water forming Lake Cleveland and Independence Lakes (Pogue 2008). The Pleistocene "ice ages," characterized by multiple episodes of world-wide continental and alpine glaciation, caused great continental glaciers thousands of feet thick to advance and retreat over approximately 100,000-year cycles. Huge volumes of water were stored in the glaciers during glacial periods so that sea level dropped about 120 m (390 ft) (Clark and Mix 2002). In central Idaho north of City of Rocks National Reserve, glaciers rarely descended below 2,100 m (7,000 ft) (Cunningham 1971). Deposits of glacially-derived silt and loess in sediments from Raft River and Almo Creek record local pulses of glacial activity within the Raft River Mountains and Cache Peak (Miller et al. 2008). Moraine deposits locally record at least two periods of glaciation at approximately 140,000 and 20,000 years ago. Late Pleistocene deposits are widespread in the area and indicate periods of overall alluvial and fluvial deposition in most valleys and alluvial fans during that time (Miller et al. 2008).

During the Late Pleistocene large lakes flooded many of the valleys (basins) of the Basin and Range province throughout western Utah, Nevada, Idaho, and Oregon. Ancient Lake Bonneville, one of these lakes, covered an area of more than 51,800 km^2 (20,000 mi^2) of Utah and parts of Nevada and Idaho, including the valleys between the parallel ranges surrounding City of Rocks (Cunningham 1971). Lake Bonneville was as much as 300 m (1,000 ft) deep and crested over a pass at Red Rocks into southern Idaho and City of Rocks approximately 14,500 years ago. This breach sent a torrent of water out of Lake Bonneville and into the Snake River drainage to the north of City of Rocks. The water carved deep valleys and left deposits of sand, gravel, and even boulders as it rushed out. The Bonneville flood lasted less than one year and lowered the lake level by 122 m (400 ft). As the region's climate changed to become warmer and drier, Lake Bonneville slowly evaporated, leaving remnants now known as Great Salt Lake (fig. 1C) and Utah Lake. Salt from the Great Salt Lake likely contributed to the formation of the tafoni features within the park (Pogue 2008).

At City of Rocks National Reserve, surficial deposits, landforms, and the weathered rock formations attest to the recent geological evolution throughout the Quaternary. Erosion of Cenozoic granite such as the Almo pluton created upland basins, and the resistant Proterozoic quartzite persists as high ridges and peaks (Miller et al. 2008). The oldest surficial deposits are alluvial remnants left on ridges tens of meters above active stream erosion. Later terrace, fluvial, and alluvial deposits located adjacent to the modern mountain fronts indicate relatively stable mountain topography over the last 500,000 to 1 million years (Machette 1985; Miller et al. 2008).

Global climate warmed and global sea level rose as glaciers retreated following the end of widespread glaciations about 19,000 years ago and the beginning of the Holocene Epoch about 12,000 years ago.

Geologically, the landscape of the region around City of Rocks has not changed much during the Holocene. The entire area has been subjected to repeated earthquakes and extensional uplift and downdrop of the blocks on either side of regional normal faults, such as the Almo fault. The Almo fault cuts Pleistocene alluvial fans between Almo and the entrance to City of Rocks National Reserve (Pogue 2008). Major streams, such as Circle Creek and Almo Creek, have carved new landscapes since the end of the Pleistocene, eroding the bedrock and older stream deposits (Pogue 2008).

Alluvial and fluvial deposits are set into channels downcutting through older Pleistocene deposits and spread into alluvial fans near Almo. Colluvium and talus that accumulated at the base of hill slopes throughout the region indicate active erosion of rocks, delivering sediments to streams below (Miller et al. 2008). Human activities in the area including mining and trail and road development, were influenced by the underlying geology. Those activities shaped the cultural landscape at City of Rocks National Reserve.

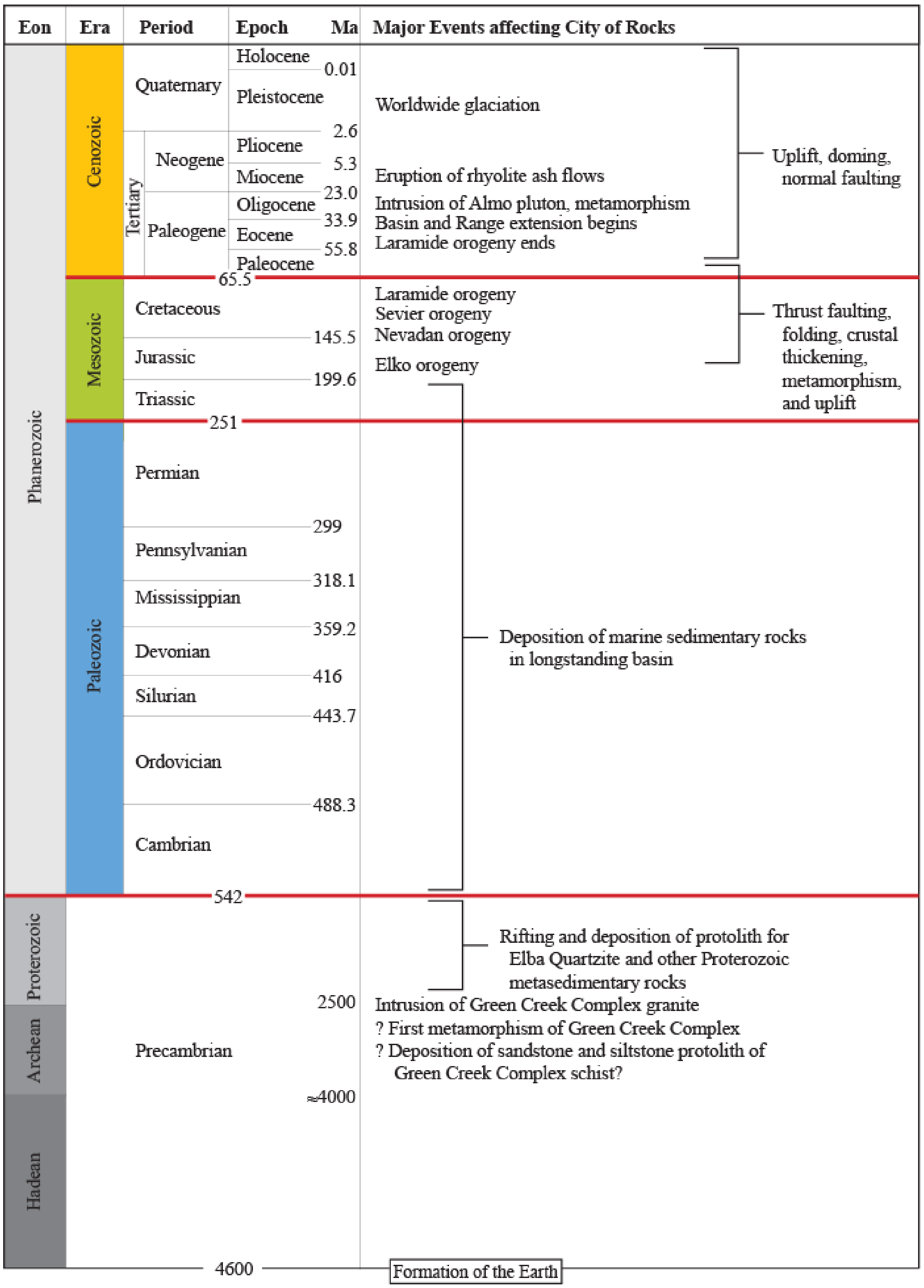


Figure 17. Geologic time scale; adapted from the U.S. Geological Survey (http://pubs.usgs.gov/fs/2007/3015/). Red lines indicate major unconformities between eras. Included are major events of the geologic history of City of Rocks after Pogue (2008). Absolute ages shown are in millions of years (Ma, or mega-annum).

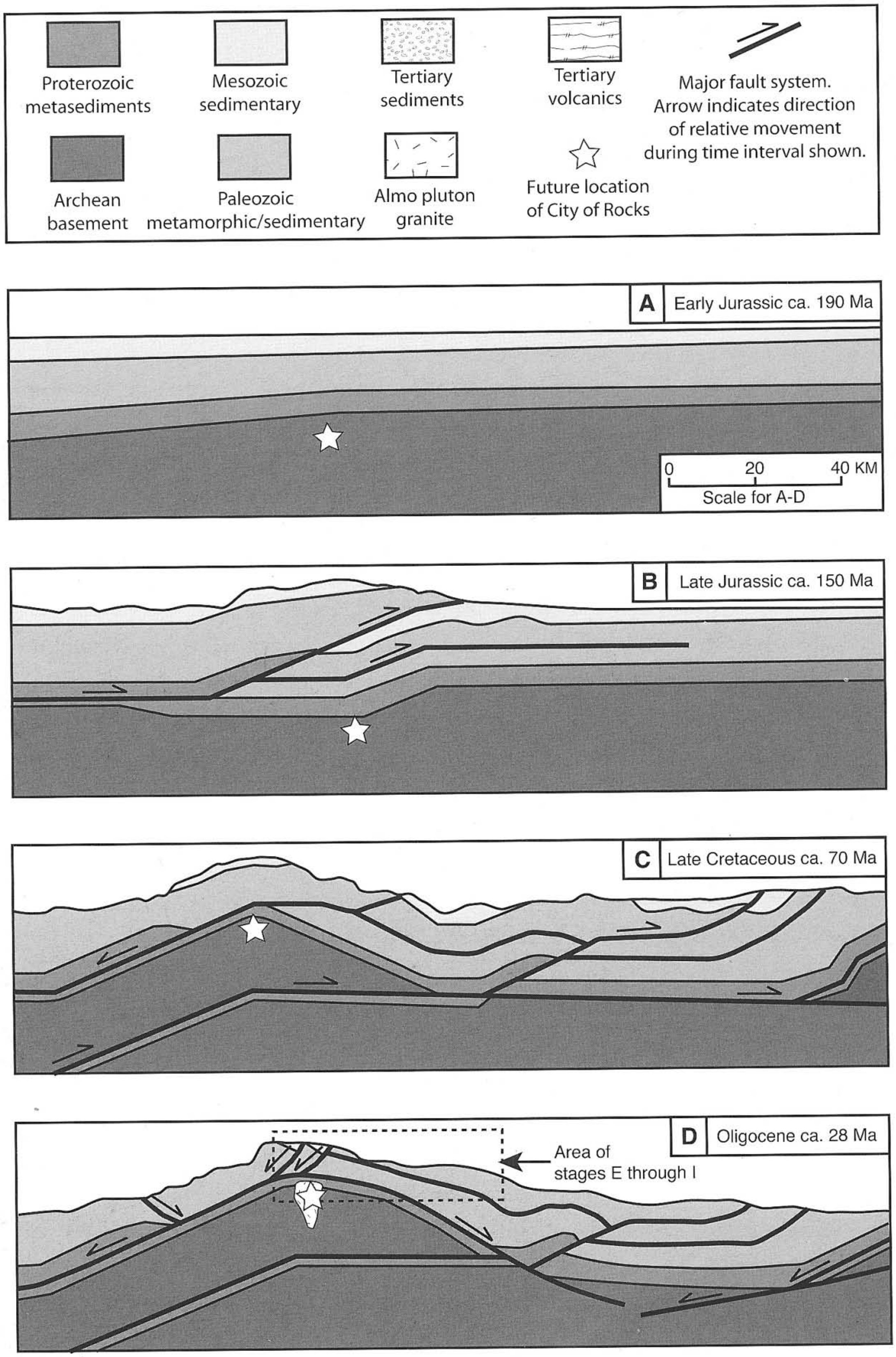


Figure 18. Diagrammatic geologic cross sections depicting major events in southeastern Idaho between the Early Jurassic and the present. Diagram is figure 7 from Pogue (2008), based on information from Covington (1983), Camilleri et al. (1997), and Miller (1991). Used with permission.

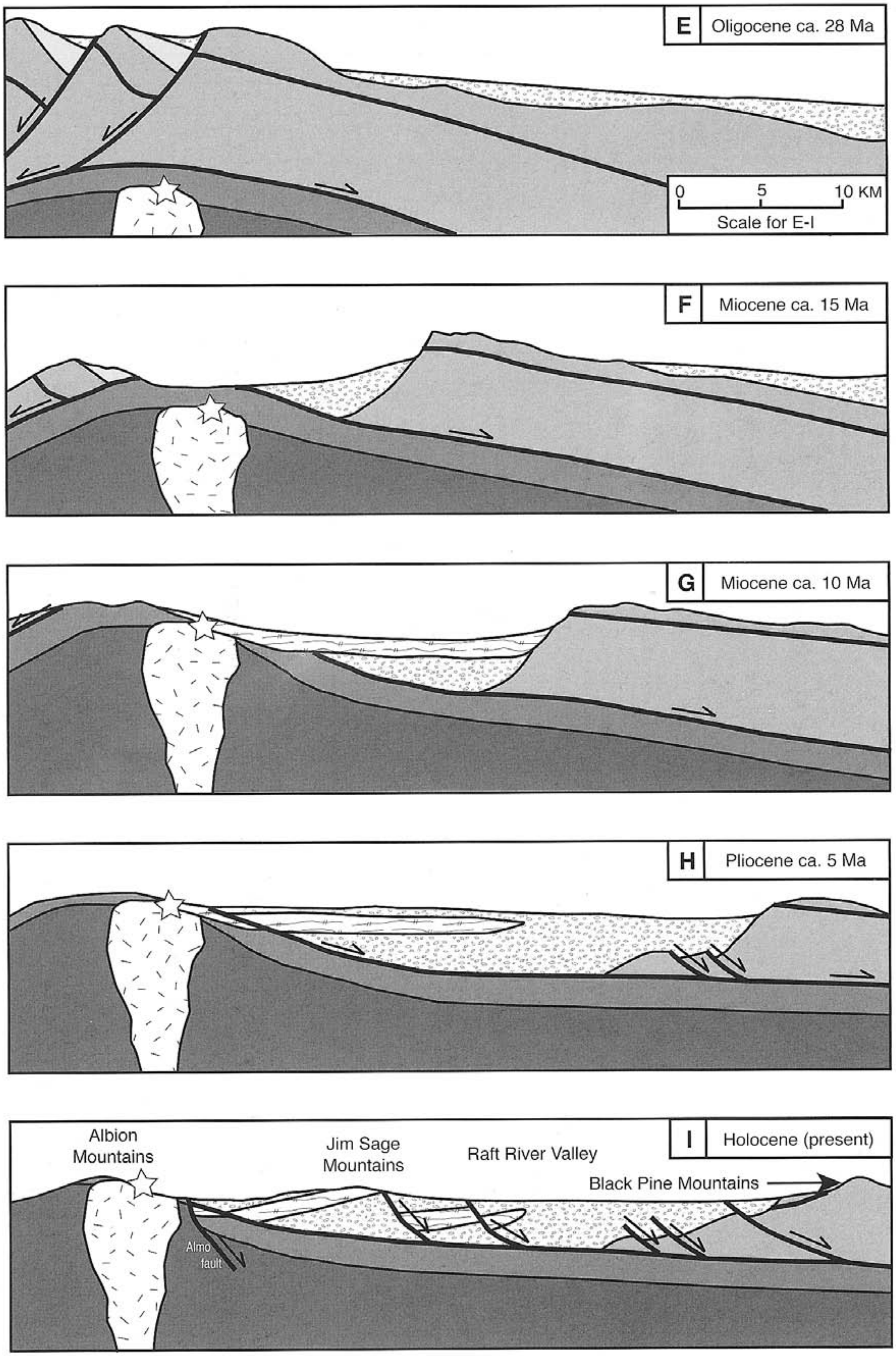


Figure 18 (continued). Diagrammatic geologic cross sections depicting major events in southeastern Idaho between the Early Jurassic and the present. Diagram is figure 7 from Pogue (2008), based on information from Covington (1983), Camilleri et al. (1997), and Miller (1991). Used with permission.

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. Definitions are based on those in the American Geological Institute Glossary of Geology (fifth edition; 2005).

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.

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 material ejected from a volcano (also see "tuff").

asthenosphere. Earth's relatively weak layer or shell below the rigid lithosphere.

axis (fold). A straight line approximation of the trend of a fold, which divides the fold's two limbs. "Hinge line" is a preferred term.

basement. The undifferentiated rocks, commonly igneous and metamorphic, that underlie 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, larger than 100 km^2 (40 mi^2), and often formed from multiple intrusions of magma.

bed. The smallest sedimentary strata unit, commonly ranging in thickness from one centimeter to a meter or two and distinguishable from beds above and below.

bedding. Depositional layering or stratification of sediments.

bedrock. A general term for the rock that underlies soil or other unconsolidated, superficial material.

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

calcareous. Describes rock or sediment that contains the mineral calcium carbonate ($CaCO_3$).

caldera. A large bowl- or cone-shaped depression at the summit of a volcano. Formed by explosion or collapse.

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

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 (mineral). The tendency of a mineral to break preferentially in certain directions along planes of weaknesses in the crystal structure.

cleavage (rock). The tendency of a rock to split along parallel, closely spaced planar surfaces. It is independent of bedding.

colluvium. A general term applied to any loose, heterogeneous, and incoherent mass of rock fragments deposited by unconcentrated surface runoff or slow continuous downslope creep, usually collecting at the base of gentle slopes or hillsides.

concordant. Strata with contacts parallel to the orientation of adjacent strata.

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 Earth's crust that has remained relatively stable over a long period of time and has undergone minor warping compared to the intense deformation of bordering crust (also see "craton").

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

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 flow conditions such as water flow direction and depth.

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

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

cryptogamic crust. The brown crust on sandy, desert soils that is composed of an association of algae, lichen, mosses, and fungi. Helps stabilize the soil.

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

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

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).

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

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

dip-slip fault. A fault with measurable offset where the relative movement is parallel to the dip of the fault.
discordant. Having contacts that cut across or are set an angle to the orientation of adjacent rocks.
dome. General term for any smoothly rounded landform or rock mass. More specifically refers to an elliptical uplift in which rocks dip gently away in all directions.
drainage basin. The total area from which a stream system receives or drains precipitation runoff.
ductile. Describes a rock that is able to sustain deformation (folding, bending, or shearing) before fracturing.
eolian. Formed, eroded, or deposited by or related to the action of the wind. Also spelled "Aeolian."
ephemeral stream. A stream that flows briefly only in direct response to precipitation in the immediate locality and whose channel is at all times above the water table.
exfoliation. The breakup, spalling, peeling, or flaking of layers or concentric sheets from an exposed rock mass caused by differential stresses due to thermal changes or a reduction in pressure when overlying rocks erode away.
extrusive. Describes igneous material that has erupted onto Earth's surface.
facies (metamorphic). The pressure and temperature conditions that result in a particular, distinctive suite of metamorphic minerals.
facies (sedimentary). The depositional or environmental conditions reflected in the sedimentary structures, textures, mineralogy, fossils, etc. of a sedimentary rock.
fault. A break in rock along which relative movement has occurred between the two sides.
felsic. Describes 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; also any break in a rock (e.g., crack, joint, or fault).
frost wedging. The breakup of rock due to the expansion of water freezing in fractures.
graben. A down-dropped structural block bounded by steeply-dipping, normal faults (also see "horst").
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").
hinge line. A line or boundary between a stable region and one undergoing upward or downward movement.
horst. Areas of relative "up" between grabens, representing the geologic surface left behind as grabens drop. The best example is the basin and range province of Nevada. The basins are grabens and the ranges are weathered horsts. Grabens become a locus for sedimentary deposition (also see "graben").
igneous. Refers to a rock or mineral that originated from molten material; one of the three main classes of rocks—igneous, metamorphic, and sedimentary.
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 break in rock without relative movement of rocks on either side of the fracture surface.
laccolith. A mushroom- or arcuate-shaped pluton that has intruded sedimentary strata and domed up the overlying sedimentary layers. Common on the Colorado Plateau.
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.
lithology. The physical description or classification of a rock or rock unit based on characters such as its color, mineral composition, and grain size.
lithosphere. The relatively rigid outmost shell of the Earth's structure, 50 to 100 km (31 to 62 miles) thick, that encompasses the crust and uppermost mantle.
loess. Windblown silt-sized sediment, generally of glacial origin.
mafic Describes dark-colored rock, magma, or minerals rich in magnesium and iron. Compare to "felsic."
magma. Molten rock beneath Earth's surface capable of intrusion and extrusion.
mantle. The zone of Earth's interior between crust and core.
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.
mechanical weathering. The physical breakup of rocks without change in composition. Synonymous with physical weathering.
member. A lithostratigraphic unit with definable contacts; a member subdivides a formation.
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, formation, and/or recrystallization from increased heat and pressure.
mineral. A naturally occurring, inorganic crystalline solid with a definite chemical composition or compositional range.
mylonite. A fine-grained, foliated rock typically found in localized zones of ductile deformation, often formed at great depths under high temperature and pressure.
normal fault. A dip-slip fault in which the hanging wall moves down relative to the footwall.
oceanic crust. Earth's crust formed at spreading ridges that underlies the ocean basins. Oceanic crust is 6 to 7 km (3 to 4 miles) thick and generally of basaltic composition.
orogeny. A mountain-building event.
outcrop. Any part of a rock mass or formation that is exposed or "crops out" at Earth's surface.

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

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

panhole. A flat-floored pit on the surface of an outcrop produced by weathering.

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

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

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

phenocrysts. A coarse crystal in a porphyritic igneous rock.

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 Earth's surface above a more fluid asthenosphere.

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

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

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

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

progradation. The seaward building of land area due to sedimentary deposition.

provenance. A place of origin. The area from which the constituent materials of a sedimentary rock were derived.

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

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

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

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

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

scarp. A steep cliff or topographic step resulting from displacement on a fault, or by mass movement, or erosion. Also called an "escarpment."

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

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

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

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

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

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

siltstone. A variably-lithified sedimentary rock with 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.

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

strata. Tabular or sheet-like masses or distinct layers (e.g., of rock).

stratigraphy. The geologic study of the origin, occurrence, distribution, classification, correlation, and age of rock layers, especially sedimentary rocks.

stream. Any body of water moving under gravity flow and confined within a channel.

stream terrace. Step-like benches surrounding the present floodplain of a stream due to dissection of previous flood plain(s), stream bed(s), and/or valley floor(s).

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.

subduction zone. A convergent plate boundary where oceanic lithosphere descends beneath a continental or oceanic plate and is carried down into the mantle.

subsidence. The gradual sinking or depression of part of Earth's surface.

tafone (plural: tafoni). A large hollow in a rock produced by cavernous weathering.

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

tectonics. The geological study of the broad structural architecture and deformational processes of the lithosphere and.

terrestrial. Relating to land, 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.

topography. The general morphology of Earth's surface, including relief and locations of natural and anthropogenic features.

trace (fault). The exposed intersection of a fault with Earth's surface.

transgression. Landward migration of the sea due to a relative rise in sea level.
trend. The direction or azimuth of elongation of a linear geological 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 that marks a period of missing time.
uplift. A structurally high area in the crust, produced by movement that raises the rocks.
vent. An opening at Earth's surface where volcanic materials emerge.
volcanic. Describes anything related to volcanoes. Can refer to igneous rock crystallized at or near Earth's surface (e.g., lava).
water table. The upper surface of the saturated zone; the zone of rock in an aquifer saturated with water.
weathering. The set of physical, chemical, and biological processes by which rock is broken down.

Literature Cited

This section lists references cited in this report. A more complete geologic bibliography is available from the National Park Service Geologic Resources Division.

Anderson, A. L. 1931. *Geology and mineral resources of eastern Cassia County, Idaho*. Bulletin 14. Moscow, ID: Idaho Bureau of Mines and Geology.

Armstrong, R. L. 1968. Mantled gneiss domes in the Albion Range, southern Idaho. *Geological Society of America Bulletin* 79:1295–1314.

Armstrong, R. L., and F. Hills. 1967. Rubidium-strontium and potassium-argon geochronologic studies of mantled gneiss domes, Albion Range, southern Idaho, USA. *Earth and Planetary Science Letters* 3: 114–124.

Baars, D. L. 2000. *The Colorado Plateau*. Albuquerque, NM: University of New Mexico Press.

Baker, A. A., and M. D. Crittenden, Jr. 1961. *Geology of the Timpanogos Cave Quadrangle, Utah*. Scale 1:24,000. Geologic Quadrangle Map GQ-0132. Reston, VA: U.S. Geological Survey.

Bandy, P. J. 1989. Emplacement of the Almo Pluton and its association to doming kinematics of the Albion Mountains metamorphic core complex. *Geological Society of America Abstracts with Programs* 21 (5): 53.

Barber, D. A. 1962. The origin of sheet joints and exfoliation in the upper San Joaquin Basin, California. MS Thesis, University of Idaho (Moscow).

Bedford, D. R., and D. M. Miller. 1999. Digital resource database for management, in City of Rocks National Reserve. In *Digital Mapping Techniques '99, Workshop Proceedings* Open-File Report OF 99-386 .Reston, VA: U.S. Geological Survey.

Camilleri, P., A. Yonkee, J. Coogan, P. DeCelles, A. McGrew, and M. Wells. 1997. Hinterland for foreland transect through the Sevier Orogen, northeast Nevada to north central Utah; structural style, metamorphism, and kinematic history of a large contractional orogenic wedge. *Geology Studies* 42 (Part 1): 297–309.

Chapman, C. A., and R. L. Rioux. 1958. Statistical study of topography, sheeting, and jointing in granite, Acadia National Park, Maine. *American Journal of Science* 256:111–127.

Christenson, G. E., K. M. Harty, and S. Hecker. 1987. Quaternary faults and seismic hazards, western Utah. In *Cenozoic geology of western Utah*, ed. R. S. Kopp and R. E. Cohenour, 389–400. Publication 16. Salt Lake City, UT: Utah Geological Association.

Clark, P. U. and A. C. Mix. 2002. Ice sheets and sea level during the last glacial maximum. *Quaternary Science Reviews* 21: 1-7.

Compton, R. R. 1972. *Geologic map of the Yost Quadrangle, Box Elder County, Utah, and Cassia County Idaho*. Scale 1:31,680. Miscellaneous Geologic Investigations Map I-873. Reston, VA: U.S. Geological Survey.

Compton, R. R., and V. R. Todd. 1977. Tectonics of core and cover rocks in Raft River Mountains, Grouse Creek Mountains, and Albion Range, Utah and Idaho. *Geological Society of America Abstracts with Programs* 9 (7): 933.

Compton, R. R., and V. R. Todd. 1983. Late Miocene displacement of cover rocks of the Raft River–Grouse Creek–Albion Mountain core complex, NW Utah. *Geological Society of America Abstracts with Programs* 15 (5): 403.

Covington, H. R., 1983. Structural evolution of the Raft River Basin, Idaho. In *Tectonic and stratigraphic studies in the Eastern Great Basin*, ed. D. M. Miller, V. R. Todd, and K. A. Howard, 229–237. Memoir 157. Boulder, CO: Geological Society of America.

Cunningham, F. F. 1969. The Crow tors, Laramie Mountains, Wyoming, USA. *Zeitschrift für Geomorphologie* 13:56–74.

Cunningham, F. F. 1971. The Silent City of Rocks, a bornhardt landscape in the Cotterrel Range, South Idaho, USA. *Zeitschrift für Geomorphologie* 15 (4): 404–429.

Ekman, L. C. 1962. *Scenic geology of the Pacific Northwest*. Hillsboro, OR: Binford and Mort.

Fillmore, R. 2000. *The geology of the parks, monuments and wildlands of Southern Utah*. Salt Lake City, UT: The University of Utah Press.

Goldstrand, P. M. 1990. *Stratigraphy and paleogeography of Late Cretaceous and Early Tertiary rocks of southwest Utah*. Miscellaneous Publication MP90-2. Salt Lake City, UT: Utah Geological and Mineral Survey.

Haymond, J. M. 1984. Historical guidebook for the Utah Geological Association. In *Geology of northwest Utah, southern Idaho and northeast Nevada*, ed. G. J. Kerns and R. L. Kerns, Jr., 9–13. Publication 13. Salt Lake City, UT: Utah Geological Association.

Hejl, E. 2005. A pictorial study of tafoni development from the 2nd millennium BC. *Geomorphology* 78:236–249.

Hintze, L. F. 1988. *Geologic history of Utah*. Geologic Studies Special Publication 7. Salt Lake City, UT: Brigham Young University.

Historical Research Associations, Inc. and Amphion. 1996. Historic Resources Study City of Rocks National Reserve, Southcentral Idaho. Prepared for National Park Service Pacific West Field Area, Seattle, WA. http://www.nps.gov/history/history/online_books/ciro/hrs.htm, accessed March, 2010.

Idaho Department of Water Resources. 2009. Water Information. http://www.idwr.idaho.gov, accessed, 2009.

Jones, R. W. 1973. Evaluation of Cassia Silent City of Rocks, Cassia County, Idaho for eligibility for Registered Natural Landmark designation. Unpublished, Moscow, ID: University of Idaho.

Link, P. K. and E. C. Phoenix. 1996. *Rocks, rails, and trails* (2nd edition). Pocatello, ID: Idaho State University Press. http://imnh.isu.edu/DIGITALATLAS/geog/rrt/RRTfr.htm, accessed March 2010.

Linton, D. L. 1955. The problem of tors. *The Geographical Journal* 121:470–487.

Machette, M. N. 1985. Calcic soils of the southwestern United States. In *Soils and Quaternary geology of the southwestern United States,* ed. D. L. Weide and M. L. Faber, 1–21. Special Paper 203. Boulder, CO: Geological Society of America.

Maley, T., and B. Randolph. 1993. Unique and geologically significant resources on federal lands. In *Proceedings—Geoscience Information Society* 24, 197–204. Alexandria, VA: American Geological Institute.

Maley, T. S., and P. Oberlindacher. 1994. Scientifically significant geologic features of the upper Snake ecosystem, southern Idaho. *Geological Society of America Abstracts with Programs* 26 (7): 350.

Miller, D. M. 1984. North half. In *Geology of northwest Utah, southern Idaho and northeast Nevada,* ed. G. J. Kerns and R. L. Kerns, Jr., 269–275. Publication 13. Salt Lake City, UT: Utah Geological Association.

Miller, D. M. 1991. Mesozoic and Cenozoic tectonic evolution of the northeastern Great Basin. In *Geology and ore deposits of the Great Basin,* ed. R. H. Buffa and A. R. Coyner, 202–228. Reno, NV: Geological Society of Nevada.

Miller, D. M., R. L. Armstrong, D. R. Bedford, and M. Davis. 2008. *Preliminary geologic map and digital data base of the Almo quadrangle and City of Rocks National Reserve, Cassia County, Idaho*. Scale 1:24,000. Open-File Report OF 2008-1103. Reston, VA: U.S. Geological Survey.

Miller, D. M., and D. R. Bedford. 1999. Pluton intrusion styles, roof subsidence and stoping, and timing of extensional shear zones in the City of Rocks National Reserve, Albion Mountains, southern Idaho. In *Geology of northern Utah and vicinity,* ed., L. E. Spangler and C. J. Allen, 11–26. Publication 27. Salt Lake City, UT: Utah Geological Association.

Morris, L. A. 2006. The Ecological History of the City of Rocks National Reserve, Part I: The Human Archive. National Park Service, Idaho State Parks and Recreation, and Utah State University Report. Task Agreement J8R07040013. http://www.nps.gov/ciro/naturescience/naturalfeaturesandecosystems.htm, accessed March 2010.

National Park Service. 1998. City of Rocks National Reserve Climbing Management Plan and Finding of No Significant Impact. Washington, DC: National Park Service. http://www.nps.gov/ciro/parkmgmt/planning.htm, accessed March 2010.

National Park Service. 1999. *Baseline Water Quality Data Inventory and Analysis, City of Rocks National Reserve*. Technical Report NPS/NRWRD/NRTR—99/209. Fort Collins, CO: National Park Service Water Resources Division. http://www.nature.nps.gov/water/horizon.cfm, accessed March 2010.

Pogue, K. R. 2008. *Etched in Stone: The Geology of City of Rocks National Reserve and Castle Rocks State Park, Idaho*. Information Circular 63. Moscow, ID: Idaho Geological Survey, University of Idaho.

Pogue, K. R., P. Karabinos, M. Brislen, A. G. Hereford, J. S. Levine, G. G. Shopoff, M. L. Wolfson, and C. H. Woodruff. 2001. Geology of City of Rocks National Reserve; new insights from Keck Geology Consortium undergraduate research. *Geological Society of America Abstracts with Programs* 33 (6): 123.

Reese, J. F., and P. K. Link. 1996. The City of Rocks, Albion Range, south-central Idaho; tectonic evolution of the Western Cordillera in a nutshell. *Geological Society of America Abstracts with Programs* 28 (7): 143–144.

Rodriguez-Navarro, C., E. Doehne, and E. Sebastian. 1999. Origins of honeycomb weathering: The roles of salts and wind. *Geological Society of America Bulletin* 111:1250–1255.

Sloss, L. L. 1988. Tectonic evolution of the craton in Phanerozoic time. In *Sedimentary cover—North American craton,* ed. L. L. Sloss, 25–52. Geology of North America D-2. Boulder, CO: Geological Society of America.

Speed, R. C. 1983. Evolution of the sialic margin in the central western United States. In *Studies in continental margin geology,* ed. J. S. Watkins and C. L. Drake, 457–468. Memoir 34. Tulsa, OK: American Association of Petroleum Geologists.

Strudley, M. W., A. B. Murray, and P. K. Haff. 2006. Emergency of pediments, tors and piedmont junctions from a bedrock weathering–regolith thickness feedback. *Geology* 34:805–808.

Swan, F. H., III, D. P. Schwartz, and L. S. Cluff. 1980. Recurrence of moderate to large magnitude earthquakes produced by surface faulting on the Wasatch fault zone, Utah. *Bulletin Seismological Society of America* 70:1431–1432.

U.S. Congress, Senate Subcommittee on Parks and Recreation, Washington, D.C., United States (USA). 1987. *Hagerman Fossil Beds and City of Rocks national monuments*. Washington, D.C: U.S. Government Printing Office.

Wells, M. W. 1984. City of Rocks and Granite Pass. In *Geology of northwest Utah, southern Idaho and northeast Nevada,* ed. G. J. Kerns and R. L. Kerns, Jr., 15–19. Publication 13. Salt Lake City, UT: Utah Geological Association.

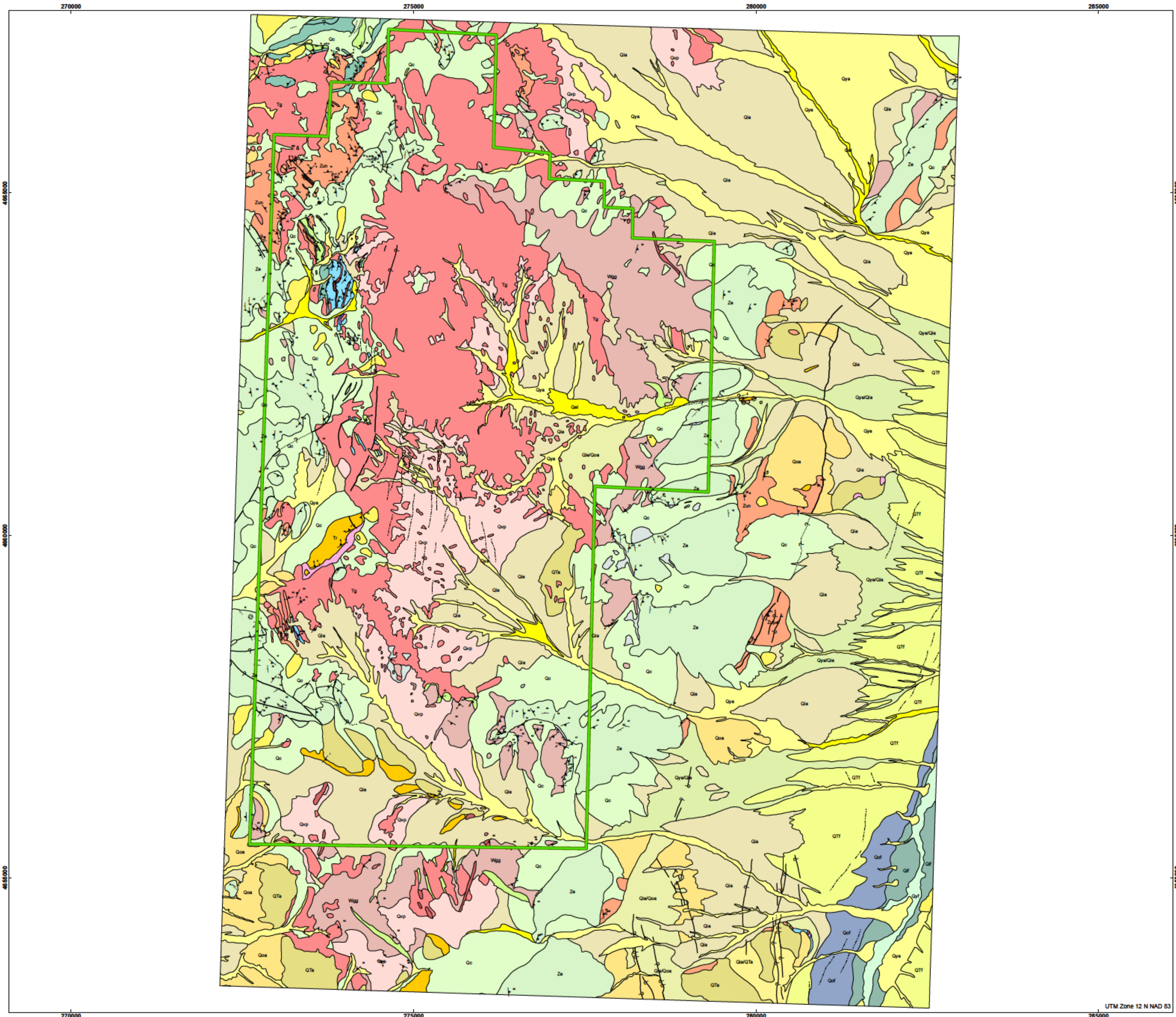
Wells, M. L. 1997. Alternating contraction and extension in the hinterlands of orogenic belts; an example from the Raft River Mountains, Utah. *Geological Society of American Bulletin* 109 (1): 107–126.

Wells, M. L., T. D. Hoisch, M. T. Peters, D. M. Miller, E. D. Wolff, and L. M. Hanson. 1998. The Mahogany Peaks fault, a Late Cretaceous-Paleocene(?) normal fault in the hinterland of the Sevier orogen. *Journal of Geology* 106: 623-634.

Appendix A: Overview of Digital Geologic Data

The following page is an overview of the digital geologic data for City of Rocks National Reserve. For a poster-size PDF of this overview and complete digital data, please see the included CD or visit the Geologic Resources Inventory publications web site (http://www.nature.nps.gov/geology/inventory/gre_publications.cfm).

Overview of Digital Geologic Data for City of Rocks National Reserve



NPS Boundary

Geologic Attitude and Observation Localities
- strike and dip of inclined beds
- strike of vertical foliation and bedding
- strike and dip of inclined foliation
- horizontal foliation
- trend and plunge of inclined lineation

Landslide Scarp
- landslide scarp, known or certain

Lineaments
- lineament, known or certain

Faults
- unknown offset/displacement, known or certain
- unknown offset/displacement, queried
- unknown offset/displacement, concealed and queried

Geologic Contacts
- known or certain
- queried
- concealed and queried
- map boundary

Geologic Units
- Qal - Alluvium
- Qya - Younger alluvial fan deposits
- Qya/Qia - Holocene age alluvial fan deposits over Pleistocene age alluvial fan deposits
- Qyf - Younger fluvial deposits
- Qvp - Veneer on pediment
- Qls - Landslide deposits
- Qc - Colluvium
- Qt - Talus
- Qia - Intermediate alluvial fan deposits
- Qia/Qoa - Alluvial fan deposits deposited onto Pleistocene age older alluvial fan deposits
- Qia/QTa - Alluvial fan deposits deposited onto Pleistocene and Pliocene? age alluvium and landslide deposits
- Qif - Intermediate fluvial deposits
- Qoa - Older alluvial fan deposits
- Qof - Older fluvial deposits
- QTa - Alluvium and landslide deposits
- QTf - Fluvial deposits
- Tr - Rhyolite
- Ts - Sedimentary deposits
- Tg - Granite
- Op - Metamorphosed Pogonip Group
- Zmp - Schist of Mahogany Peaks
- Zcb - Quartzite of Clarks Basin
- Zss - Schist of Stevens Spring
- Zy - Quartzite of Yost
- Zun - Schist of the Upper Narrows
- Ze - Elba Quartzite of Armstrong (1968)
- Wga - Amphibolite of the Green Creek Complex of Armstrong and Hills (1967)
- Wgg - Granite and granite gneiss of the Green Creek Complex of Armstrong and Hills (1967)
- Wgs - Schist of the Green Creek Complex of Armstrong and Hills (1967)

N

0 2 4 Kilometers

0 1 2 Miles

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:

Miller, D.M., R.L. Armstrong, D.R. Bedford, and M. Davis. 2008. *Preliminary geologic map and digital data base of the Almo quadrangle and City of Rocks National Reserve, Cassia County, Idaho*. Scale 1:24,000. U.S. Geological Survey Open-File Report 2008-1103.

Digital geologic data and cross sections for City of Rocks National Reserve, 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/

Appendix B: Scoping Meeting Participants

The following is a list of participants from the GRI scoping session for City of Rocks National Reserve, held on June 16–17, 1999. The contact information and email addresses in this appendix may be outdated; please contact the Geologic Resources Division for current information. The scoping meeting summary was used as the foundation for this GRI report. The original scoping summary document is available on the GRI web site: http://www.nature.nps.gov/geology/inventory/gre_publications.cfm.

NAME	AFFILIATION	PHONE	E-MAIL
Bruce Heise	NPS, Geologic Resources Division	(303) 969-2017	Bruce_Heise@NPS.gov
Joe Gregson	NPS, Natural Resources Information Division	(970) 225-3559	Joe_Gregson@NPS.gov
Tim Connors	NPS, Geologic Resources Division	(303) 969-2093	Tim_Connors@NPS.gov
Marsha Davis	NPS, Columbia Cascades Support Office	(206) 220-4262	Marsha_Davis@NPS.gov
Dave Miller	USGS	(650) 329-4923	Dmiller@usgs.gov
Paul Link	Idaho State University	(208) 236-3365	Linkpaul@isu.edu
Stan Lloyd	CIRO cooperator	(208) 638-5542	
Ted Scherff	CIRO/IDPR	(208) 824-5519	Ted_Scherff@NPS.gov
Carolyn Firth	College of Southern Idaho	(208) 438-8215	
John Russell	CIRO/IDPR	(208) 824-5519	Ciro_interpretation@NPS.gov
Greg Sprouse	CIRO, SCA volunteer		Gtsprouse@yahoo.com
Andy Millott	CIRO, Americorps		Aj.millott@eudoramail.com
David Landrum	Lake Walcott State Park	(208) 436-1258	
Chris Gee	CIRO	(208) 824-5519	
Whitney Warner	CIRO	(208) 824-5519	

NPS 003/102081, April 2010

National Park Service
U.S. Department of the Interior

Natural Resource Program Center
1201 Oakridge Drive, Suite 150
Fort Collins, CO 80525

www.nature.nps.gov