In Cooperation with National Park Service and Idaho Department of Parks and Recreation

Geologic map and digital data base of the Almo quadrangle and City of Rocks National Reserve, Cassia County, Idaho

By David M. Miller, Richard L. Armstrong, David R. Bedford, and Marsha Davis

Open-File Report 2008-1103

July 25th. We are encamped tonight in what I shall call Rock Basin, a small one of about 100 acres with a beautiful stream on one side of it and surrounded by high vertical Rocks of quartz and granite some of them the most picturesque I ever saw. It is, take it all together, one of the most romantic places I was ever in, a very home for the fairies.

from the diary of Henry Rice Mann, 1849

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Geologic map and digital data base of the Almo quadrangle and City of Rocks National Reserve, Cassia County, Idaho, U.S.

David M. Miller[1], Richard L. Armstrong[2], David R. Bedford[1], and Marsha Davis[3]

Abstract

The City of Rocks, located near Almo in the Albion Mountains of south-central Idaho, was founded as a National Reserve in 1988 to preserve and protect historical and cultural resources and scenic quality, manage recreational use, and interpret nationally significant features unique to the reserve. The most prominent of these features are the spectacular rock spires that attracted visitors, beginning with commentary in the journals of travelers to California during the Gold Rush of 1849.

We studied the geology of the Reserve to update past mapping of the bedrock, to depict and understand the surficial geology, and to study the processes of formation and decay of the rock spires. The geology is presented in Geographic Information System format that can be combined with other information on the Reserve.

Bedrock of the Albion Mountains records a long and complex history spanning more than 2.5 billion years. Early intrusive activity was followed by sedimentation that lasted intermittently more than a billion years in both continental and marine settings. About 100-200 million years ago, mountain building caused metamorphism of the rocks, and later (100-7 million years ago) destruction of the mountains led to the structural assembly seen today. The final chapters in this bedrock history were intrusion of the Almo pluton 28 million years ago, volcanism about 10 million years ago, and continental extensional faulting flanking the Almo pluton.

The National Reserve centers on three upland basins of gently undulating topography. The basins are ringed by high mountains and spines of rock pinnacles; each is drained to the east through a canyon cut into resistant bedrock, and ultimately drains to the Raft River. Resistant quartzite underlies most of the high mountains, whereas the lower lying upland basins are underlain by granite. It is this granite that erodes to form the picturesque pinnacles. Pinnacles are shaped by joints along which the rock is more readily weathered. The rock surfaces of the pinnacles display cavernous weathering and durable crusts. Joints, crusts, and weathering are the main features identifiable for inventories of the fragility of the rock formations.

Most surficial materials surrounding and overlying the bedrock were deposited as alluvial fans and colluvium, although many other kinds of surficial materials are present that were deposited by a variety of surficial processes. The alluvium and colluvium appear to accumulate very slowly in all but the most active areas, such as the low parts of the upland basins. However, the slow accumulation of deposits does not imply stability of alluvial and colluvial surfaces because processes by which these deposits move, such as soil creep, landsliding, and debris flows, can be destructive to park infrastructure and life. Active

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stream channels and the steeper colluvial slopes are sites of repeated destructive events and are best avoided for construction of facilities.

A newly discovered fault that passes through the town of Almo offsets Pleistocene alluvial materials as much as 5 meters (18 ft) but does not appear to offset Holocene materials. Infrequent modern micro-seismicity and a larger poorly located earthquake that occurred in the area several decades ago raise the possibility that local earthquakes could shake the Reserve severely in the future.

Introduction

City of Rocks National Reserve is located in south-central Idaho, west of the town of Almo (fig. 1). It encompasses the heart of the southern Albion Mountains, a north-trending mountain range of high glaciated peaks and perennial streams. The streams provided early travelers along the California Trail in the mid-1800's, who had traversed hundreds of miles of dry desert, with a place to rest and rejuvenate. These travelers discovered in the southern Albion Mountains not only abundant water and forage, but a wonderland of fantastic rock spires and domes that they dubbed the Silent City of Rocks. This "city" later served as home for other settlers, fertile ground for agriculture and livestock grazing, and playground for the many who knew of its unusual scenery. When rock climbers began flocking to the area in the 1980's, a need for long-term management became critical, and a partnership among local, county, State, and Federal entities gave rise to the City of Rocks National Reserve.

Critical to wise and effective management of the City of Rocks is accurate understanding of the geology of the rock spires that attracted travelers and settlers for 150 years and of the landscape-forming processes that continue to shape the aesthetic character of the reserve. Some rock spires are fragile, as are some landforms on which travelers drive, walk, and camp. Without understanding the geology of these features, even those that treasure the aesthetics of the area could unintentionally contribute to degradation of the landforms. Natural geologic hazards such as floods, earthquakes, and rockfalls must also be understood and are best evaluated within the context of the long-term evolution of the landscape.

Rocks in the National Reserve include Archean igneous and metamorphic rocks, upon which strata of Neoproterozoic age were deposited; all of these rocks were metamorphosed, faulted, and then intruded by the granitic Almo pluton of Oligocene age. Oligocene and Miocene faulting and erosion exposed these rocks, which were then partially buried by Miocene volcanic flows and alluvial deposits of Pleistocene and Holocene age. The resistant Neoproterozoic Elba Quartzite forms most of the prominent mountains, including Smoky Mountain and the Cedar Hills in the east and Graham Peak in the north, and provides the mountainous frame for the basins within which the spectacular eroded granite spires of the Almo pluton are displayed.

The high point of the Reserve is Graham Peak, which, at 2,703 m (8,867 ft), juts about 460 m (1,500 ft) above the nearby rock formations of Circle Creek basin and about 920 m (3,000 ft) above the alluvial plains of Big Cove west of Almo. The low point in the Reserve is at Circle Creek, on the east side of the Reserve–1720 m (5,650 ft) elevation. Much of the Reserve centers on high upland basins that drain through narrow canyons eastward toward the Raft River Valley, which is 1606 m (5270 ft).

A small-scale geologic map of the Albion Mountains by Anderson (1931) first showed the rock units at City of Rocks, distinguishing granite, metamorphic rocks, and volcanic rocks. The southern Albion Mountains were first mapped with attention to the metamorphic and structural history by Armstrong (1968), who later mapped the area in detail but never published this mapping. His later mapping is incorporated in the map accompanying this

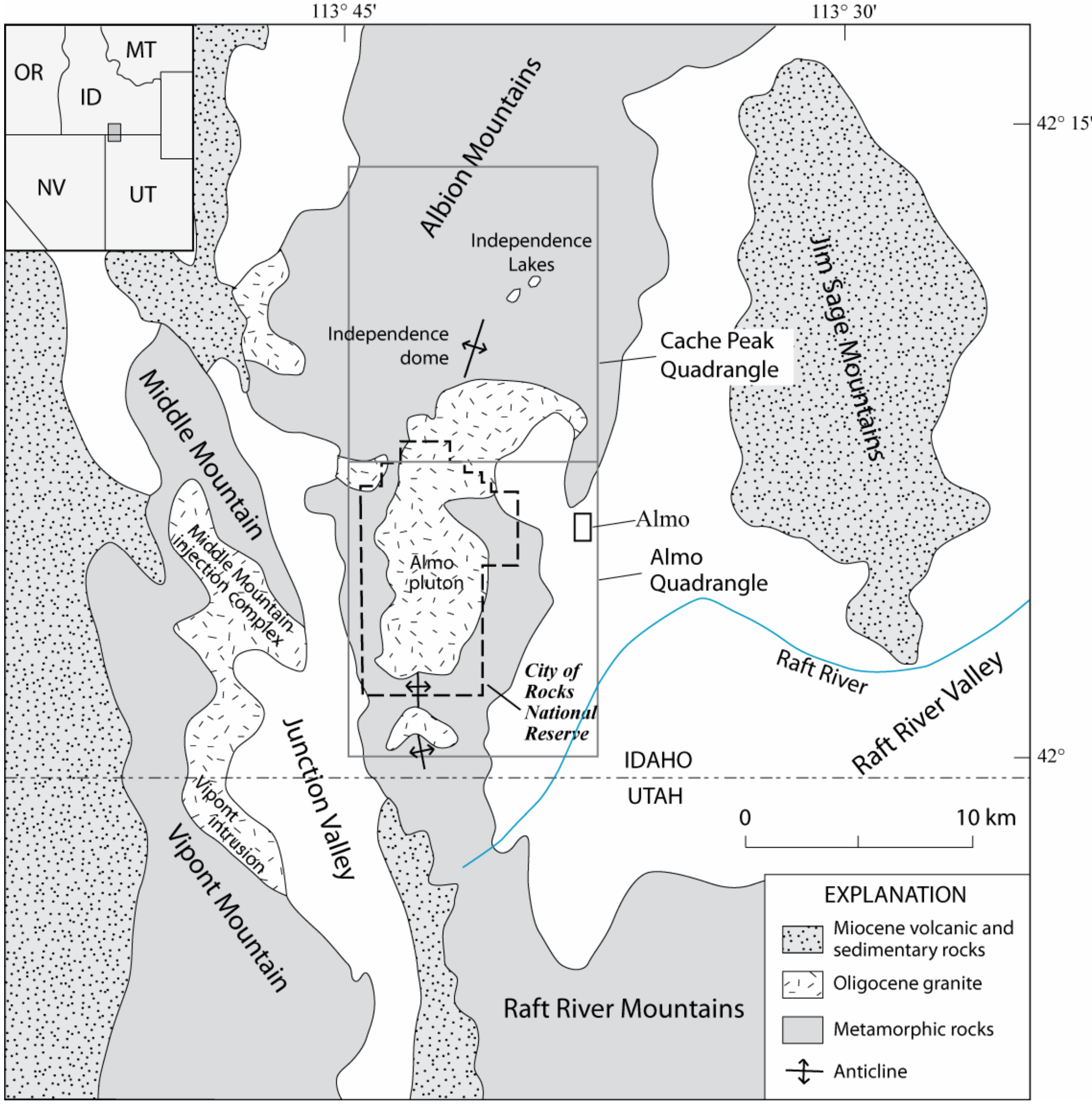


Figure 1. Location map showing general geologic features in vicinity of the City of Rocks National Reserve and selected features referred to in the text. Almo and Cache Peak 7.5-minute quadrangles are outlined by boxes. Dashed line shows City of Rocks National Reserve boundary. Geology modified from Armstrong and others (1978), Doelling (1980) and Williams and others (1974, 1982).

report. Armstrong (1968) showed that two ages of granites, Archean and Oligocene, occur in City of Rocks and that two ages of metamorphic rocks also occur; Archean metamorphic rocks are overlain by Proterozoic and Paleozoic metamorphic rocks. Armstrong also described the structure of the City of Rocks, and showed that the metamorphic rocks are bowed up into a large dome; he dated several different granitic and volcanic rocks to provide the temporal framework for understanding the evolution of magmatism, deformation, and metamorphism of the area. Thesis mapping by Bodnar (1983) and Gurney (1968) contributed to understanding the geology of the area as well.

Our studies of geologic history presented by bedrock geology have been published (Miller and Bedford, 1999) and provide the basis for summaries given in this report accompanying the geologic map. The primary focus of this report will be on geomorphology, surficial deposits, and applications for management. Information on database development was given in Bedford and Miller (1999).

Geologic History

The Albion Mountains are part of a larger region that shares a common set of rock units, deformation, and metamorphism; the larger region is commonly termed the Raft River–Grouse Creek–Albion Mountains metamorphic core complex. Throughout this metamorphic complex, the erosionally resistant Elba Quartzite, the lowest unit of the Neoproterozoic sequence, forms a prominent marker separating underlying Archean rocks from overlying Neoproterozoic schist and quartzite, and vividly outlines the structure of rocks in the mountain ranges. The geologic history of this complex is highly complex, and only after the pieces of the story from different parts are assembled does the whole appear. The following synopsis is condensed from several studies: Armstrong (1968, 1982), Armstrong and others (1975, 1978; unpublished ms.), Compton (1972, 1975, 1983), Compton and others (1977), Covington (1983), Forrest and others (1994), Malavieille (1987), Miller (1980, 1983), Miller and Bedford (1999), Miller and others (1983, 1997), Saltzer and Hodges (1986), Snoke and Miller (1988), Todd (1980, 1983), Wells (1997, 2001), Wells and others (1990, 1997, 1998, 2000), and Williams and others (1982).

The oldest rocks in the region are grouped as the Green Creek Complex. Within this group, oldest rocks are Archean schist and related rocks (unit Wgs) that originated as shale, siltstone, and minor sandstone; these rocks were metamorphosed to schist and deformed at an unknown time before 2.5 billion years ago. Granite (unit Wgg) intruded the schist as a series of large plutons about 2.5 billion years ago, cutting across layering in the older rocks; only narrow screens of schist are preserved between these plutons. Mafic dikes (unit Wga) intruded both granite and schist, probably immediately following or a as a late stage of, granite intrusion. All Archean rocks were metamorphosed during the Mesozoic and Cenozoic, at which time the mafic dikes were converted to amphibolite, the granite to granite gneiss, and schist was formed from an uncertain protolith. Deformation associated with the later metamorphism is recorded locally in the granite gneiss and amphibolite as foliation.

Following the Archean metamorphic and intrusive events, the rocks were uplifted to eventually lie at the surface, probably as a result of considerable erosional unroofing, but little is known of the geologic history during this time interval. The erosion surface on the Archean granite and schist in many places was modified to a thick argillaceous soil or regolith on which Neoproterozoic sediments were deposited. Tens of meters of local relief on this nonconformity can be seen north of City of Rocks behind Independence Lakes. The aluminum-rich soil has been metamorphosed, and is now represented by muscovite schist. The schist is more deeply weathered than the adjacent rocks, commonly forming a low-relief zone in the hillsides.

Neoproterozoic (1,000 to 545 Ma) sandstone, siltstone, and shale, along with minor limestone and volcanic rocks, were deposited across the eroded Archean platform. The lowest unit, the Elba Quartzite (unit Ze), is distinctive and widespread. The Elba and three succeeding rock units (Schist of Upper Narrows, Zun; Quartzite of Yost, Zy, and Schist of Stevens Spring, Zss) are questionably Neoproterozoic (Wells and others, 1998). They are lithologically similar to overlying Neoproterozoic units (Quartzite of Clarks Basin, Zcb and its included Schist of Mahogany Peaks, Zmp) that were dated by correlation of carbon isotope ratios with dated rocks. This sequence of six Neoproterozoic rock units is seen throughout the metamorphic complex, although in places faults and shear zones cut out some units. The sequence is topped everywhere by a major low-angle normal fault, subparallel to bedding, that places Ordovician strata on the Neoproterozoic rocks; this fault is named the Mahogany Peaks fault for the unit on which it typically rests. Because this fault is metamorphosed and is mapped only in short segments, we display it on the geologic map as a contact, not a fault.

Paleozoic (545 to 250 Ma) sediment deposited on Neoproterozoic rocks in the region consisted of basal sandstone followed by mostly carbonate rocks (limestone and dolomite). The Paleozoic sequence and overlying early Mesozoic strata are exceptionally thick (~10 km) in the region, but most of this section is faulted out in the metamorphic complex, much of the thinning of the section accomplished by the Mahogany Peaks fault. Widespread Paleozoic rock units preserved in the metamorphic complex are marble of the Ordovician Pogonip Group (unit Op), Mississippian schist, and Pennsylvanian and Permian sandstone and limestone; only the Pogonip is found in the mapped area. All of these rock units were metamorphosed to some degree during the Mesozoic and Cenozoic.

Paleozoic and older rocks were deformed and metamorphosed during late Jurassic (?) and Cretaceous orogeny (170 to 60 Ma). The general regional picture, from east to west, of this orogeny consists of: (1) a fold and thrust belt in southwest Wyoming where thin sheets of rock were thrust eastward over one another, (2) a hinterland or internal part of the orogen (south-central Idaho, eastern Nevada, northwestern Utah) where very thick stacks of rock resulted from overthrusting, creating high mountains and metamorphosing rocks in the deeply buried parts (Figure 2a), and (3) a magmatic arc of volcanoes and deeper plutons in western Nevada and eastern California. Deeply buried rocks in the internal orogen are represented in the metamorphic complex. These rocks experienced complex ductile flow that produced several foliation and lineation sets at high metamorphic grade. Contributing to the complex flow was periodic unroofing along some faults alternating in time and space with burial by other faults, as the building of the mountains was counteracted by gravitational flattening (fig. 2b). Foliations and lineations in the metamorphic rocks of City of Rocks National Reserve largely formed at this time, as did many of the small folds that are common in the Elba Quartzite, schist of the Upper Narrows, and quartzite of Clarks Basin.

During multiple events in the Cenozoic (50 million years [Ma] to present) the thick stack of rocks of the metamorphic complex was thinned and extended laterally (horizontally east-west), unroofing the once deep-seated ductilely deformed rocks. These extensional events, whose effects differed greatly from place to place within the metamorphic complex, took place during the Eocene (42 to 37 Ma), and Miocene (22 to 20 Ma and 13 to 7 Ma). During both events rocks high in the stack moved down to the west along west-dipping detachment faults (fig. 2c). The upper parts of these fault zones were brittle in character but deeper parts behaved as a ductile shear zone, forming mylonite (such as at Middle Mountain west of the National Reserve; fig. 1). The Eocene to early Miocene extensional events are distinguished from one another by slightly different directions of movement and by different temperatures. The older extension event (fig. 2c) occurred under hotter temperatures, which is consistent with the inference that the rocks were more deeply buried in the Eocene, partly unroofed to lower temperature as the Eocene event progressed, and then unroofed more during the early Miocene event (fig. 2e).

The late Miocene extensional event displaced the upper rocks down to the east on an east-dipping detachment fault system. This detachment fault was ductile in character in the eastern Raft River Mountains (fig. 1) but brittle elsewhere. In the Albion Mountains, this last event broke the blocks of volcanic rocks in the Jim Sage and Cottrell Mountains (which lie east of the Albion Mountains) away from the Albion Mountains, displacing them down and to the east (fig. 2f), and also formed the Raft River Valley basin. The west-dipping fault in Junction Valley (fig. 2e) probably formed during or soon after this Miocene event.

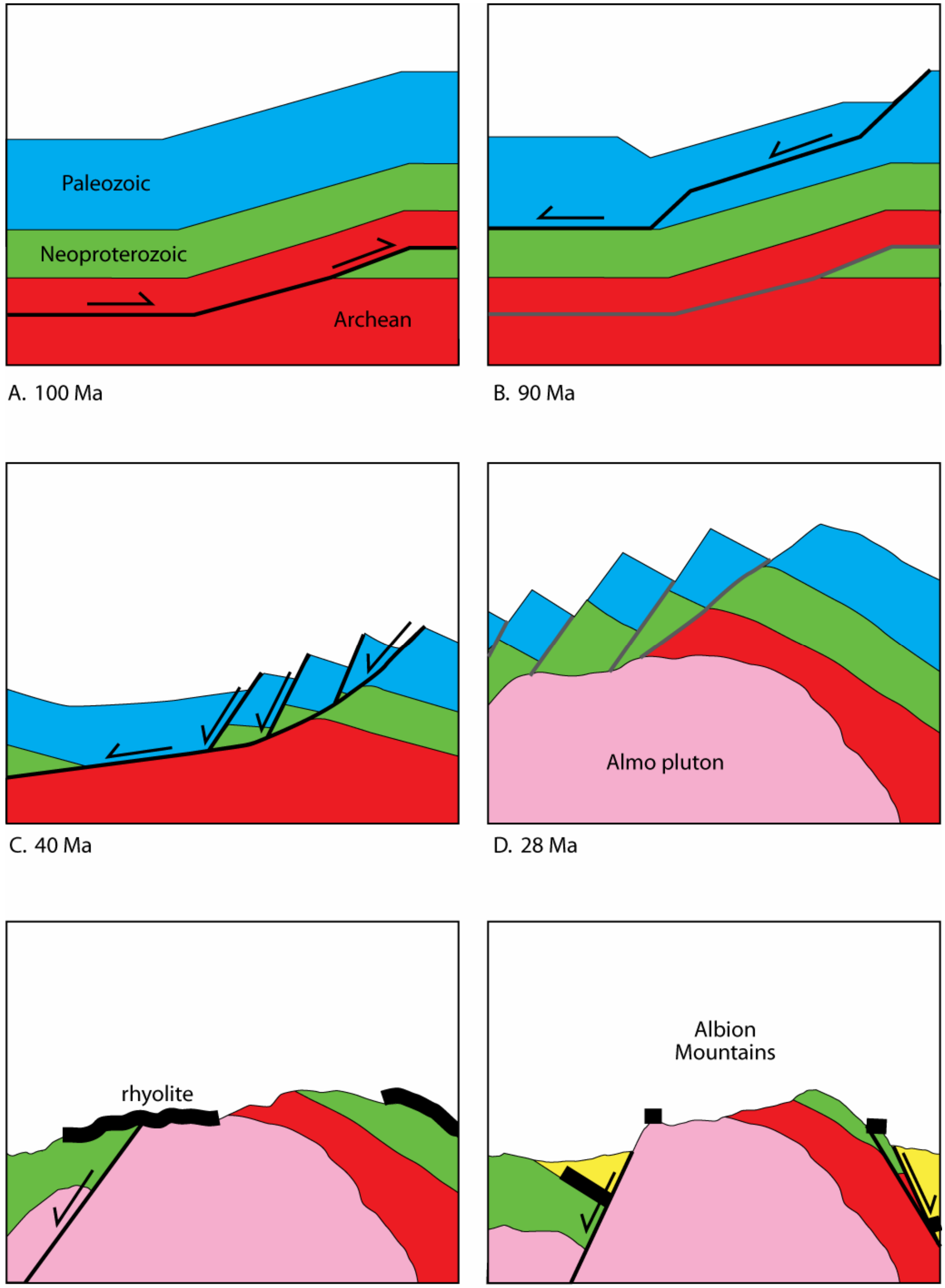


Figure 2. Illustrations of the tectonic evolution of the Raft River-Grouse Creek-Albion metamorphic core complex. Not all of the features are preserved in the Reserve Cross sections show effects of thrust and detachment faults and intrusion. (A) Late Cretaceous (~100 Ma), following significant thrust loading of the complex. (B) Removal of parts of the stratigraphic section by low-angle normal faults (~90 Ma). (C) Late Eocene (~40 Ma) following first detachment faulting event. (D) Oligocene (~28 Ma), following pluton emplacement. (E) Middle Miocene (~10 Ma), following second detachment event. (F) Late Miocene (~7 Ma), following third detachment event.

Other Cenozoic events include Oligocene (~28 ma) intrusion of the Almo Granite (fig. 2d) and similar granite bodies farther south. The plutons created new metamorphic minerals in their already-metamorphosed wall rocks. In the Albion Mountains, stope blocks that sank from the roof into the pluton are at highest metamorphic grade; stable indicator minerals in these blocks include cordierite, andalusite, and sillimanite. In contrast, kyanite and staurolite are stable in rocks farther north, apparently preserving the deeper (Mesozoic?) metamorphism indicated by those mineral assemblages. These contrasting mineral assemblages and their distribution are most easily reconciled as a thermal overprint of a hot pluton on already metamorphosed rocks. The pluton intruded at greater than ~3 kbar (roughly 10 km) based on stability of muscovite in granite, requiring unroofing of many kilometers of overlying rock after intrusion. The unroofing took place before ~10 Ma volcanic rocks were deposited onto an eroded surface cut into granite at Emigrant Canyon. Both the ~22 Ma and ~13 Ma extensional events probably contributed to this unroofing.

Extensive rhyolite ash flows emanated from nearby vents and calderas between about 11 and 9 Ma, forming thick stacks of volcanic rocks in the Jim Sage Mountains and the Goose Creek area west of the Albion Mountains. Thinner volcanic flows were deposited on metamorphic rocks and granite in the Albion Mountains, indicating that most unroofing of the metamorphic rocks was complete by that time.

The overall structure in pre-Tertiary rocks at the southern Albion Mountains is a large anticline with a roughly north-trending axis; the fold is reflected in the opposite dips of the resistant Elba Quartzite on east and west sides of the Reserve. The limbs of this fold are over 3 km (2 mi) long and symmetrically dip about 35 to 40 degrees (cross-section AA'). The anticline appears to plunge south near the south border of the Reserve and to plunge north near the north end of the Almo pluton before tightly kinking and climbing again northward to form the Independence dome. This fold probably formed during Eocene extension, before the pluton was emplaced, as indicated by: (1) The pluton is not deformed by the fold, and (2) stope blocks reveal a relict (Eocene) shear zone on the west side of the pluton that likely created a kink or anticline in the pre-Tertiary rocks (Miller and Bedford, 1999).

Deep Miocene(?) sedimentary basins lie east and west of the Reserve. Gravity data (Bankey and Kleinkopf, 1988) indicate that a significant thickness of low-density material underlies upper Raft River Valley and Junction Valley (fig. 1). Tertiary strata that are exposed in these areas are Miocene volcanic-rich sediment similar to dated 15- to 7-Ma strata of the region, suggesting that the basins formed during the 13- to 7-Ma extensional event.

Little information is available for the time period between ~10 Ma deposition of rhyolite and ~500 thousand years ago (ka) when surficial strata (described in the next section) were deposited. The City of Rocks area was eroded considerably during this time period but the changes in landforms is not well known.

Landscape History

Surficial deposits, landforms, and weathered rock formations can be interpreted to describe the recent evolution of the City of Rocks. Differential erosion of Tertiary granite created upland basins, whereas resistant rock units such as the Elba Quartzite form the highest ridges and peaks (Fig. 3). The oldest landforms of the area are pediments preserved by overlying Miocene sediment and volcanic rocks that armored them from erosion. Although Miocene rocks are perched high on the crest of the range near Trail Creek, they also lie essentially on the modern pediment surface in Emigrant Canyon. Some landforms along the west side of the mountains therefore are Miocene or older.

The oldest alluvial deposits (QTa) of the area form remnants of once extensive landforms that are now eroded to rounded caps on ridges in most cases. That most of these old deposits rest on ridges attests to several tens of meters of downcutting since their deposition, but the ages of the oldest deposits are poorly constrained; the downcutting may have occurred over a few million years or as little as a million years. These deposits rest across ~10 Ma volcanic rocks and associated sediments, indicating that the volcanic rocks were emplaced, eroded, and then buried, but the time period needed for this history is again poorly constrained. Along the west side of the mountains, these oldest sediments are not perched on ridges, indicating less downcutting in these locations.

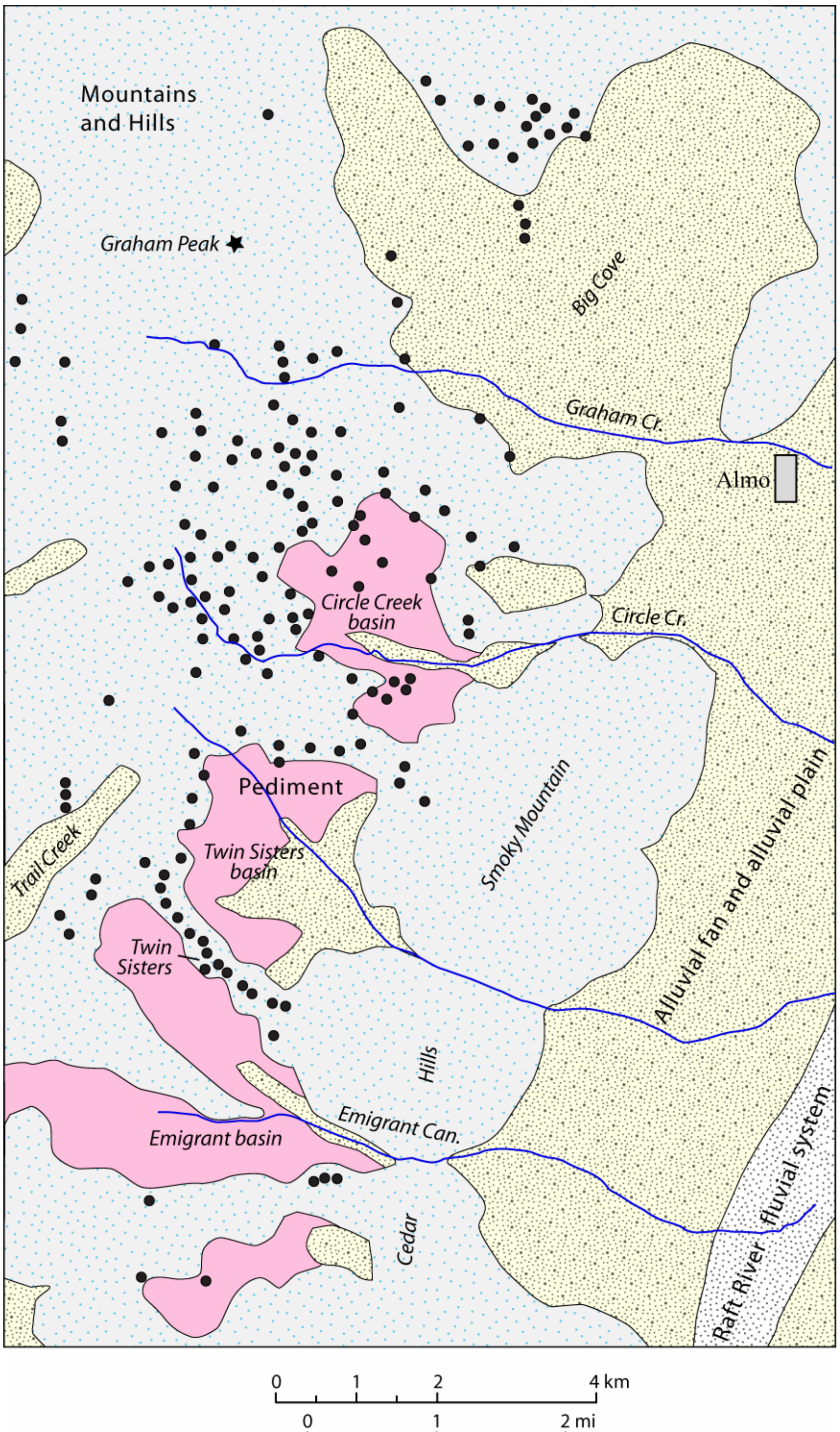


Figure 3. Map showing main landforms of the City of Rocks National Reserve, emphasizing upland basins, pediments, and mountainous areas. Black dots represent individual pinnacles. Coarsely dotted area is underlain by bedrock; pink represents pediments. Blue lines show creeks discussed in the report.

Roughly at the same time that very old alluvial deposits formed, much finer grained, thin-bedded fluvial deposits (QTf) aggraded east of the mountains and out into the raft River Valley. These deposits appear to represent large aggrading streams that were carrying locally-derived sediment. These very old deposits (QTa and QTf) may result from climatic and(or) tectonic drivers.

Flanking the Albion Mountains both on the east and west are old alluvial deposits (Qoa) that locally retain vestiges of their depositional landforms and possess soils similar to deposits elsewhere in the region that are ~500 to ~1000 ka (Machette, 1985). Their locations adjacent to the modern mountain fronts indicate that at the time of deposition mountain topography was similar to today's and by inference the range front was tectonically active. Roughly equivalent high terrace deposits of the Raft River (Qof) lack soils to judge their ages, but they predate two sets of inset terraces.

Late Pleistocene deposits (Qia, Qif) are widespread and indicate alluvial and fluvial aggradation in most valleys and on alluvial fans. Deposits of sediment transported by the Raft River and Almo Creek include glaciogenic silt ("rock flour") indicating that one or more pulses of glacial activity in the Raft River Mountains and Cache Peak coincided with aggradation. Loess on many of the intermediate age alluvial and fluvial deposits may date to the ~70 ka and ~20 ka loess depositional periods documented in the Snake River Plain (Forman and others, 1999). Landscape at the heads of the four major streams (north to south: Graham Creek, Circle Creek, "Twin Sisters" Creek, and Emigrant Creek), draining the Albion Mountains east to the Raft River, each contain intermediate age deposits, showing that they existed in late Pleistocene time. However, the greater extent of the intermediate deposits at the heads of the two southern streams suggests that those drainage systems are little-changed since that time. In addition, the two southern basins exhibit widespread pediments having thin alluvial veneers, in sharp contrast to the northern basins, which have deeply cut Holocene streams, little pediment, and widespread tall tors (Circle Creek) or alluvial plains (Big Cove).

Prominent knickpoints in the three southern stream channels exist where they cut through the Elba Quartzite (Fig. 4). The knickpoints effectively isolate the upper basins from Raft River base-level changes. The direct connection of Graham Creek and Big Cove with the Raft River and abundant detritus from glaciers on the south flank of Cache Peak may partly explain its lack of pediments. Youthful stream capture may explain the sparse Pleistocene deposits in Circle Creek basin. Where it cuts through the Elba Quartzite hills, Circle Creek lies in a narrow steep-walled canyon that contrasts with the wider canyons of other streams to the south, and also contrasts with a largely abandoned canyon one-half mile north. A youthful reduction in local base-level caused by stream capture and abandonment of the northern channel apparently exhumed the features in Circle Creek basin.

Holocene alluvial and fluvial deposits mostly are set into channels cut into Pleistocene deposits, but spread widely in fans (Qya) near Almo and as thin veneers on Pleistocene fans in a few places along the east side of the mountains. Holocene hillslopes of colluvium and talus are widespread in the mountains, indicating active delivery of eroding rock to stream channels below. Holocene fluvial deposits of the Raft River (Qyf) lie unconformably on glaciogenic deposits, and contain charcoal near the base of the unit that is 9,100 to 9,400 calibrated years before present (Table 1). At this dated location, a sapping channel in the floodplain formed during the time period bracketed by the two charcoal dates. The Mazama ash, about 6,700 years old, is preserved at two locations, in Circle Creek and Twin Sisters basins. In both basins, it lies in a sequence of organic rich, probable wetland sediment near the east side of the basin, apparently representing relatively mesic conditions at that time.

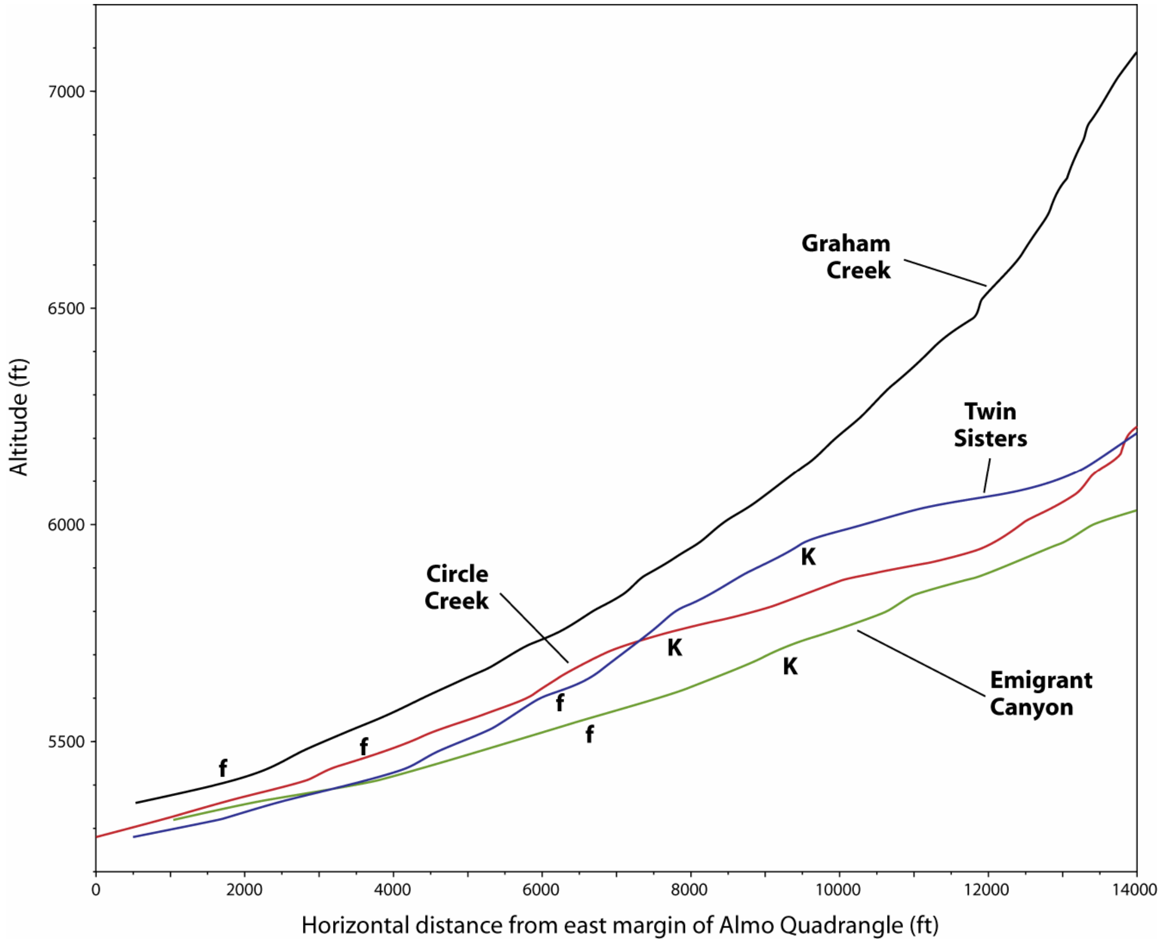


Figure 4. Stream profiles illustrating variations in profiles, effects of knickpoints (K), and positions of Almo fault (f) in the profiles. Profiles begin at east edge of Almo quadrangle (except for Emigrant which starts at the Raft River), and are based on topographic map contour lines.

Active Geologic Processes

Active geologic processes as used in this report are those operating during the Quaternary Period, approximately the last 2 million years. These are the relatively youthful geologic processes that have acted on the landscape over a variety of climatic and tectonic conditions, and provide the best clues to those processes likely to take place in the next several decades. We divide our discussion of these processes into two overlapping groups: those posing potential hazards (geologic hazards) and those that are more passively forming today's landscape.

Geologic hazards

Most Quaternary deposits of the City of Rocks and vicinity were created by alluvial and colluvial processes. Alluvial processes range from debris flows to sheetwash and concentrated flow in entrenched channels, whereas colluvial processes are driven by mass-wasting. These processes and their associated hazards are explained below.

Debris flows are fast-moving debris-laden flows of sediment and water, commonly the consistency of wet concrete, down steep slopes. They mostly affect the steeper reaches of younger alluvial fans (unit Qya) and channels (unit Qal) in these fans, but under some circumstances could extend onto intermediate age fans (unit Qia) during extreme events. Debris flows can be highly destructive because they are close to the density of the rocky debris they carry and they flow rapidly. They are initiated by rapid snow melt or intense rainfall and are capable of carrying large boulders, automobiles, and large trees. Deposits consist of poorly sorted debris, and are easily recognizable in parts of alluvial fans distant from the mountains where boulders lie on and within deposits composed of largely sand-size grains. Fans closer to the mountain front commonly are mostly made up of debris-flow deposits.

Sheetwash is a thin sheet of water flowing on a surface as a result of an intense rainstorm. Sheetwash can occur on nearly any Quaternary deposit. Although the water flows as a thin sheet, it is capable of transporting pebbles, sand, and mud. Vegetation and cryptogamic crusts such as mosses are very important in armoring surface materials, thereby inhibiting their erosion and improving absorption of water. As a result, removal of vegetation by fire, grazing, or mechanical stripping can increase the severity of sediment transport during sheetwash flooding. All colluvial and alluvial surfaces, and veneers on pediments, are subject to sheetflow.

Concentrated stream flow occurs in channels entrenched into alluvial fans (units Qya, Qia), pediment veneers (Qvp), and in areas underlain by alluvium (unit Qal) during snowmelt, sustained rainfall, and intense rainfall. If channels are filled by the streams, the water spills over the stream banks to form floodplains. Deposits from stream flow range from coarse gravel to muds in the channels and generally sand and mud on floodplains. Devegetated stream banks may collapse during high stream flow.

Mass wasting, the wholesale movement of rock and soil downslope by gravity, can have destructive consequences. Events such as rockfalls and landslides can be rapid and extremely powerful, whereas slow movement of landslides and gradual creep of rock and soil downslope can be equally destructive but are not catastrophic. The slower movement of rock and soil is commonly aided by sheetwash, as well as other processes. Many units shown on the geologic map are subject to mass wasting: Talus deposits (unit Qt), colluvium (unit Qc), landslides (unit Qls), and the upper (steeper) reaches of alluvial fan deposits (units Qya, Qia, Qoa). Slumps and scarps caused by slumps are mapped within colluvial and landslide units; most of these features are active.

Dust storms are caused by high-velocity winds that carry fine materials away and eventually deposit them. Windblown materials are mostly silt and fine sand, deposits here referred to as *loess*. Some loess is included in most alluvial map units. As with sheetflow, wind erosion of materials is greatly reduced by dense vegetation cover and cryptogamic crusts.

Earthquakes cause ground shaking, ground rupture, and related damage such as liquefaction. Northern Utah and southeastern Idaho are part of a seismic belt characterized by numerous small-magnitude earthquake events and a potential for infrequent large-magnitude events (Smith and Sbar, 1974; Christenson and others, 1987). Most of the known active faults lie well to the east of City of Rocks National Reserve, but earthquakes on these faults are capable of shaking the area nonetheless. There is no indication that Holocene faults are present at the Reserve, but Pleistocene and possible Holocene faults to the south (Compton, 1972) suggest a seismic potential in the region. Seismicity of the last 35 years includes sparse small magnitude ($M<2.0$) events 30 km north (Elba area) and 20 km east (Raft River Valley) of Almo (Christenson and others, 1987). Christenson and others (1987) placed a magnitude 5.4 earthquake that occurred November 18, 1937 approximately in Junction Valley west of Almo. Although the location of this earthquake is imprecise owing to inadequate instrumentation in the area, it indicates that moderate size earthquakes probably take place close to the Reserve. Ground-shaking due to earthquakes could dislodge material from the steep cliffs and cause landslides in unconsolidated sedimentary deposits, whereas liquefaction is a possible hazard in some water-charged sand-rich sediment at low altitudes, such as near the Raft River. Potential for earthquakes is determined not only by modern seismicity but also from the presence of young faults created by earthquakes that caused ground rupture.

Figure 5. Scarp of the Almo fault in shadow beyond farmhouse. South of Almo. View to the southwest in late afternoon sun. Photograph by D.M. Miller, 1998.

Although no Quaternary faults had been recognized in or near the Reserve, our mapping identified a fault just east of the Reserve. The Almo fault passes through the town of Almo and extends south-southwestward along the east margin of the Albion Mountains as a series of co-linear scarps that probably represent a single fault (fig. 5). It is recognized by a rounded scarp, consistently showing downward displacement to the east, suggesting that the fault is primarily a normal fault. The fault cuts Pleistocene alluvial fan deposits (Qia and Qoa) in many places. At the hill north of Almo, a rounded scarp 2.5 to 3 m high places coarse boulder alluvium against finer sandy pebble alluvium on the east. Along the road from Almo into the Reserve, the Almo fault deforms alluvium into a broad fold. The folded alluvium displays soil with a strongly developed argillic horizon and a Stage IV calcic horizon (the platy, laminar calcic horizon is 20-40 cm thick, and from 10 to 80% $CaCO_3$). The stage IV calcic horizon indicates this deposit is several hundred thousand years old (Machette, 1985). South of this road, a rounded scarp 3 to 5 m high (Figure 5) cuts intermediate alluvial fan deposits (unit Qia) with stage III calcic soils. Several springs and seeps occur along this scarp, and minor spring-mound deposits may be indicated by massive white sandy layers in the alluvial fan deposits. The stage III calcic horizon indicates this deposit is 50,000 to 200,000 years old (Machette, 1985). However, other intermediate alluvial fan deposits having similarly developed soils show little evidence for scarps (for instance, west of Almo), indicating either: (1) the agricultural tillage west of Almo has reduced the evidence for the fault, (2) the fault consists of discrete segments that are separated by stretches with no scarps, (3) that the fault has varying vertical offset along different segments, or (4) multiple fan-building events are represented by unit Qia, and the last fault rupture was intermediate in this depositional cycle. Holocene alluvium in Circle Creek appears to be unfaulted, suggesting that the fault has not been active during the

Holocene. In addition, several rock pinnacles appear to contain precariously balanced features, suggesting that recent earthquakes have not been very strong (Bell and others, 1998). More definitive study of the age of last rupture, the length of fault that ruptures in an earthquake, and the frequency of earthquakes requires dedicated investigations.

Most other faults mapped within the Reserve lie along steep slopes, in many cases among outcrops of the Elba Quartzite. The faults, with few exceptions, displace rocks down toward the valleys, as if they are calving sides of hillslopes away from ridge crests, much like deep seated landslides. Many of these faults cut rocks along the crest of the range, where they strike generally north but are parallel to local topography, and have a normal sense of separation. One well-exposed fault zone in the Almo pluton near the crest of Trail Canyon strikes N 35° E and dips 75° E; it consists of breccia in a zone nearly 3 m wide. There, Pleistocene soils overlie the fault without any evidence of disruption. Springs are common along these faults, and some faults pass along strike into features we map as lineaments, on the basis of dense vegetation and aligned springs. Many of these lineaments could represent faults, but the lineaments also parallel the main joint set and could represent large joints. We could not determine the ages of most of these faults. None are demonstrably Holocene in age, and one is older than late Pleistocene.

Landscape

The National Reserve centers on three upland valleys or basins, which are surrounded by high mountains on the east and west (fig. 3). Narrow canyons cut the mountains on the east, draining the upland basins to the Raft River. The basins are separated by low ridges or ‘spines’ of pinnacles into three broad, nearly flat uplands (from north to south): Circle Creek basin, Twin Sisters basin, and Emigrant basin. The western part of Emigrant basin is divided into two parts by a high ridge, and its southern part wraps across a low topographic divide into the upper part of a westward-flowing drainage to Junction Valley. It is the rock pinnacles and related landscape features within and bordering these three basins that attracted the imaginations of settlers and overland emigrants during the last two centuries.

Pediments underlie much of the three basins (fig. 3). Pediments are low-relief surfaces cut into rock, and to the casual observer are no different from a typical valley floor. However, on careful inspection, many flat outcrops of granite can be found scattered across the basins, particularly in their upper, western parts. A thin veneer of alluvium and colluvium on the granite obscures the pediment in many places. Lower (eastern) parts of each basin have thicker accumulations of alluvium, in general. The processes that form pediments are not completely understood, but many experts consider the weathering of granite to a flat surface to take place under thick soils; when the soils are stripped by erosion they reveal the bedrock surface.

Pediments are generally restricted to a few rock types, granite being the most common. The weathering characteristic of grain-by-grain disintegration is a common attribute of rocks underlying pediments. The pediments may have formed under more humid climate conditions than today’s although paleoclimate factors are difficult to ascertain (Migon and Thomas, 2002). A recent model (Strudley and others, 2006) integrates several features of arid landscapes to arrive at a feedback mechanism for development of pediments. By this model, the interplay between sediment production by weathering of granite and by sediment removal by streams is tightly coupled. For instance, thinning of a pediment veneer by streamflow causes soil development to increase, tending to thicken the veneer. Conversely, if the veneer thickens due to reduced streamflow, soil development is retarded. These feedbacks tend to create smooth rock surfaces with thin veneers of weathered material, and the mechanism accounts for steep lateral scarps with adjacent rocky hills.

The span of time over which the pediments developed is not well established, but the oldest is Miocene. Rhyolite about 10 million years old in Emigrant basin dips gently northeast, partly on a surface parallel to the present valley floor. In places, this rhyolite evidently flowed onto eroded surfaces cut into rocks of the Green Creek Complex and Almo pluton, suggesting that these rocks had eroded to form a pediment similar to the present pediment by 10 Ma. The rhyolite outcrops climb west from that pediment and past the present drainage divide to Junction Valley, as if that west-draining valley did not exist in the Miocene. Apparently, any topographic divide to a Miocene precursor to Junction Valley was higher and farther west at the time of rhyolite emplacement.

In contrast, Twin Sisters basin is younger than the rhyolite, which caps a high ridge west of the basin. The rhyolite and its underlying sediment were eroded off to form the present pediment in the basin floor. Circle Creek basin may be younger yet. Tops of pinnacles in that basin may represent relics of a pediment, much of which has been fairly recently exhumed by erosion of the valley floor. This basin also is much lower in elevation (by about 60 m; 200 feet) than the two basins to the south. Any possible pediment in Almo Creek basin (Big Cove area, fig. 3) north of the Reserve is buried by Pleistocene alluvial deposits. Only a few tors in that basin attest to a granite floor, perhaps a pediment.

Joints are apparent as cracks or planar zones of preferential weathering in all pinnacles and pediment exposures of granite, as well as most other rocks. In most cases, three or four *sets* of joints (repeatedly occurring orientations of joints) are observed, as well as isolated, unrepeated joints at various orientations. Joints with nearly north strikes and steep dips to the east are most common. These joints are parallel to some faults. Also common is a joint set nearly parallel to the earth's surface. These gently curve (convex upward), to give a domal or helmet shape, and are generally referred to as *exfoliation* joints or as *sheeting*. Chapman and Rioux (1958) made a strong case that sheeting joints form parallel to the earth's surface by pressure release as the load on the rock is removed by erosion. In some western U.S. mountains, sheeting joints are over 10,000 years old, as seen by the fact that they predate the last glacial advance.

Pinnacles are rock projections of several shapes. We use the term as a general description for the many granitic landforms that are the primary feature of the Reserve. Geomorphology literature generally terms these features as *tors* or *bornhardts*, but the definitions overlap considerably so we use a generic term. While the shapes are exceedingly variable, three forms are common: we call these *loaves, spires, and domes*. Table 2 gives examples of named popular rocks in the Reserve that exhibit these forms. Loaves are elongate, rectangular masses with dome-shaped tops (fig. 6), and probably form as a result of weathering along one prominent set of steep joints, parallel to the long direction for the loaf. Domes probably form from exfoliation joints in a rock mass with weakly expressed or widely spaced steeply-dipping joints (fig. 7). Spires may result from erosion of rock with two strongly developed sets of steeply-dipping joints (fig. 8).

Pinnacles are most heavily concentrated along the west, south, and north parts of the Circle Creek basin, but also can be found in the western parts of Emigrant and Twin Sisters basins and along the west base of Smoky Mountain. Groups of pinnacles form three northwest-oriented 'spines' that separate the basins, best exemplified by the row of pinnacles including Twin Sisters (fig. 3). As outlined in a previous section, recent local base-level reduction may have exhumed the Circle Creek basin floor, exposing many short pinnacles whose accordant crests once defined the basin floor. Higher pinnacles in this basin may have projected above this older basin floor.

The basic ideas of how pinnacles form were best articulated by Linton (1955) for examples in the British Isles and Iberian peninsula. Linton presented compelling evidence

Figure 6. King on the Throne, an example of a loaf shape pinnacle having few prominent joints, and a pitted surface on part of the loaf. Note flare around base, where pitted surface is truncated.

that pinnacles are heavily jointed masses of intact rock, commonly rising above a gently undulating plain, which in many cases is underlain by thinly covered or bare rock of a pediment. The rock masses are not products of atmospheric weathering, which is actually slowly destroying them by forming caverns and pan holes (described below), but rather are products of earlier deep weathering of adjacent rock in the unsaturated zone above the water table. There, capillary movement of water along inter-grain microcracks weakens the rock to form grus (Migon and Thomas, 2002), and along with chemical weathering, greatly reduces rock strength, particularly if joints are closely spaced (Twidale, 1982; Ehlen and Gerrard, 1997). The shape and architecture of pinnacles is strongly influenced by joints, so Linton (1955) reasoned that joints guided these disintegration processes. Examples of this disintegration of rock are exposed in many quarries as *core stones* within disintegrated granite.

Figure 7. Shingle Butte, an example of a dome shape pinnacle. Curving 'exfoliation' joints are convex up and define overall dome shape.

This model requires a two-stage process: First, rock is disintegrated within soils, leaving more resistant core stones and masses of granite. Second, the disintegrated weathered rock is eroded by running water and related processes to expose the resistant masses as pinnacles. Linton noted that pinnacles develop in many kinds of rocks but are best displayed in sandstone and granite, both of which are made up of large amounts of feldspar and quartz. He suggested that the chemical weathering of feldspar in combination with the resistance of quartz together promoted the development of pinnacles but others have noted that chemical weathering can be minor in grus (Migon and Thomas, 2002). We have noted that in many cases, medium- and coarse-grained granite and sandstone most readily form pinnacles, suggesting that grain size is also a factor. The Strudley an others (2006) model for pediment development and maintenance by sediment production and streamflow feedbacks also can explain pinnacles. If sediment erosion locally exposes bare granite, soil development and sediment production on the bare rock will be much slower than on surrounding veneered granite. The exposed rock area will erode much more slowly than the surrounding pediment, forming a pinnacle with steep sides.

Pinnacles form over long time periods. Linton noted that pinnacles formed in Great Britain before the last glaciation, and pointed out that the disintegrating stage might occur long before the erosional stage. King (1966) pointed out that pinnacles as high as 300 to 500 m are difficult to reconcile with the process described above, and advocated modern stream-cutting as the cause of these towering pinnacles. However, repeated cycles of disintegration and erosion could form very high pinnacles. Pinnacles that appear to be partly exhumed along the flanks of the basins, such as the east and west sides of Twin Sisters basin, are unlikely to be resulting from fluvial erosion.

At the City of Rocks, the early disintegration of rock may have produced parts of the pediments seen in Twin Sisters and Emigrant basins, in which case this weathering cycle was Miocene in age. This old weathering event is not unreasonable, for pinnacles and pediments formed during the Eocene (~55 Ma) are known in the Rocky Mountains (Cunningham, 1969; Eggler and others, 1969).

Figure 8. Private Idaho, an example of a spire-shape pinnacle. Numerous joints, both vertical and horizontal, are evident. Horizontal features low in the pinnacle are mineralized and resistant, rather than recessive weathering like many joints.

Weathering features on pinnacles include several surface features and spheroidal cavities within the pinnacles. Weathering of the granite produces clay minerals from plagioclase feldspar and mica, and later from potassium feldspar (Harriss and Adams, 1966). Unless protective surfaces form, this weathering accelerates disintegration of granite with moisture changes, as the clays shrink and swell, and enhances capillary movement of moisture into the disintegrating granite. Disintegration typically causes grains of feldspar and quartz to crumble from the rock face, producing a feldspar-quartz gravel at the base of a pinnacle. Barton (1916) demonstrated that in Egypt the presence of moisture-enhanced disintegration of granite, while temperature changes above the freezing point had little effect. At City of Rocks, freeze-thaw cycles may also be important (Migon and Thomas, 2002). Another process leading to disintegration is differential thermal expansion between minerals of different composition and size (Gomez-Heras and others, 2006).

Case hardening is a general term for the hardening of the surface of the granite by chemical processes that add cement to the granite grains, causing the surface to be more resistant to weathering and erosion. Anderson (1931) described the case hardening at City of Rocks and proposed that during dry periods capillary action draws water and dissolved elements from the rock. As the water evaporates near the surface, it deposits its dissolved materials, forming a cement between mineral grains. This general model was accepted by White (1944), who showed that hematite was the primary cementing agent. We observed three forms of surfaces related to case hardening. Two surfaces characterized by case hardening, originally described by Cunningham (1971), we term *blisters* and *crusts*. A third very common surface is not easily related to case hardening but appears to be much more durable than the non-hardened surfaces; we term it *pitted*.

A.

B.

Figure 9. Photographs of blisters on granite. A, Blisters or flakes a few mm thick appear to be expanded and bowed out compared to underlying rock, perhaps as a result of mineral deposition in the thin flakes. Dime for scale. B, Blisters formed across granite with mineral segregations forming stripes. Note brown varnish and light colored areas that represent recently flaked blisters.

Blisters form widely on granite as dark, thin (~0.5 cm thick) reddish hardened surfaces with curled edges or domed shapes (fig. 9), commonly giving the appearance that the blisters are peeling off. Blisters are readily broken with fingers or boots, and reveal lighter color granite beneath. Blisters form fairly rapidly, because: (1) crystals are sharp and angular (little-weathered) on the surfaces of blisters, and (2) similar blisters observed in glaciated Sierran granites formed after the latest Pleistocene glaciation (~15 ka). Of the thousands of emigrants' names written on the rocks 150 years ago (Wells, 1984), only a few tens remain. Because the grease used to inscribe names may have washed away, this observation does not imply, but supports, rapid blistering of rock. This rapid erosion of rocks may indicate that blisters are breaking off, and may also indicate that rock without any case hardening is eroding rapidly. Blisters low on sides of pinnacles may form and spall due to wildfire processes (Bierman and Gillespie, 1991). Features similar to blisters in Egypt, called exfoliation by Barton (1916), formed and spalled off within 2,000 years on archeological relics. Barton estimated that average rates of granite disintegration in Egypt, whether from grain-by-grain disintegration or by spalling of blisters, is 1 to 2 mm in 1,000 years. In contrast, granite pinnacles in arid foothills of the Sierra Nevada form thicker sheets (1-3 cm thick) that spall at a rate of 3 to 7 mm/1000 yr (Nichols and others, 2006).

Crusts are thicker and more durable than blisters. They typically exhibit polygonal shrinkage cracks, like bread crusts, on a very dark brown exterior and are firmly attached to the pinnacle core (fig. 10). Crusts are generally 1 to 2 cm thick, and cannot be cracked with bare hands. Their outside surfaces have smoothly polished, abraded crystals, similar to ventifacts created by sandblasting during repeated windstorms. This polishing suggests long residence time of exterior crystals. Crusts are associated with cavernous weathering and other fragile erosional formations in that many of these caverns form where the crusts eroded away and no longer protect the rock surface from erosion (Cunningham, 1971).

Figure 10. Photograph of crusts showing bread-crust like polygonal fractures of the crust.

Many pinnacles exhibit dark-colored, pitted or pocked, irregular durable surfaces (fig. 11). The pitted surfaces form both on inclined and nearly horizontal surfaces, and are hard and smooth, suggesting that they are the oldest of the case hardening features. They are several cm to tens of cm thick. Rock is strongly cemented in the surface layer. Pits are a few cm deep, as wide as 20 cm, and are themselves cemented and smooth.

Figure 11. Photograph showing pitted granite surface that wraps from top down along sides of loaf-shaped pinnacle.

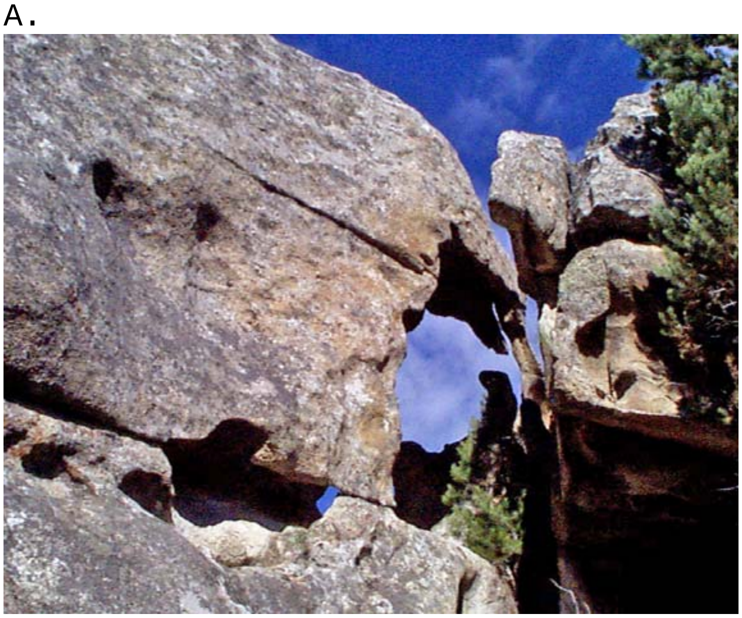
Cavernous weathering creates spheroidal cavities, or hollows, behind or under case-hardened surfaces. As summarized by Hejl (2005), cavernous weathering results from capillary movement of moisture into granular rocks, which enhances the disintegration, forms a hollow, and then the hollow has a higher-moisture environment than the surroundings, enhancing disintegration. *Panholes* (solution pans) form on the upper surfaces of pinnacles and on pediments as rounded, irregularly shaped holes that widen with depth and have flat floors covered by granitic sand (fig. 12). Panholes form independent of joints (Cunningham, 1969) and may arise from lichen or moss growths. Plants on the rock would destroy blisters and crusts by adding organic acids to the water in the rock (White, 1944).

Figure 12. Photograph of pan holes in the surface of a small pinnacle in Emigrant basin. Note water retained in pan holes from previous night's rain and flared walls of pan holes.

During plant growth, rock may weather, and after the plants die, exposed rock may readily erode. Panholes appear to form by lateral widening, rather than deepening, after a breaching of more resistant case-hardened surface materials has taken place. The process is not related to pothole formation, which is accomplished by the circular grinding of pebbles in a stream (Wentworth, 1944). The panholes on top of Bath Rock are unusually large examples. Panholes contain water during wet seasons, and may have archeological significance as sites for grinding pine nuts or other pre-historic activities.

Honeycomb weathering and other caverns (*tafoni*) form on sides of pinnacles (fig. 13) where case-hardened surfaces are breached and grain-by-grain disintegration of the granite is more rapid. Walls and ceilings of caverns typically are rounded, and floors are covered by granite sand. Walls readily disintegrate to sand when even gently brushed. Honeycombs and other caverns are among the most fragile rock formations in the Reserve.

A.



B.

Figure 13. Photographs of honeycomb weathering in granite. A, Dense array of honeycombs. B, Honeycomb hollows in margin of pinnacle and along a sub-horizontal joint.

Microenvironments are important for the initiation of honeycomb weathering, such as salt crystallization in small hollows, (Rodriguez-Navarro and others, 1999). After the hollow has formed, microenvironmental effects such as enhanced moisture and shielding from sun probably accelerate growth of the honeycomb (Hejl, 2005). *Flared walls*, concave zones adjacent to the soil line (fig. 14), probably result from enhanced capillary moisture from adjacent soils, which leads to enhanced rates of cracking and disintegration (Hejl, 2005). The widespread presence of flared walls indicates that soil levels at bases of pinnacles have been stable for an unknown, but probably long, period of time, but in some cases appearances of multiple flares at several heights suggests soil-level lowering (fig. 14).

Figure 14. Photograph of flared base of a pinnacle. Note that flare begins at a nearly horizontal position about 3.5 meters above modern ground level. Inflection about 1.5 meters above ground (about two shovel lengths above the shovel) may represent a temporary ground level at which the above flare formed. Shovel handle is about 50 cm long.

Periglacial processes are those that occur at high elevation where frost-wedging and ice movement predominate. Effects of these processes can be seen on Graham Peak and nearby ridges. Bedrock is broken by frost wedging into *block fields* of scattered rocks (Dahl, 1966). Patterned ground, identified by circles and polygons of dark earth or stones, is also formed by frost wedging processes, and can be seen near Graham Peak. Frost wedging may follow upon shrinkage of earth as it slowly freezes and water is withdrawn to form ice in cracks. Glaciers have not existed in the recent past within the Reserve, but several small glaciers were active on Cache and Independence Peaks. Stepped topography that creates the appearance of an enormous flight of terraces exists on the east side of the ridge extending north from Graham Peak, west of Castle Rocks. Origins for the topography are uncertain, but features of this sort tend to be associated with periglacial environments. A combination of freeze-thaw processes and slope creep probably are at play.

Economic Geology

Mining of non-metallic and metallic materials has occurred on a small scale in the area of the National Reserve, but City of Rocks Reserve itself has seen little mining activity. Buehler (1993) conducted a systematic study of mineral occurrences in the area, and we noted a few prospect pits that explored pegmatite and skarn minerals. In the vicinity of the Reserve, quartzite flagstone has been quarried for decorative building stone but no suitable sources are known in the reserve. The following features within the Reserve are of potential note.

Skarn minerals Neoproterozoic and Paleozoic carbonate rock units have developed skarn mineral associations (lime-rich silicates) in a few places where they are close to the Almo pluton. Skarn minerals are most commonly found in micaceous marble of the Pogonip Group and the adjacent schist of Mahogany Peaks; they more rarely form within the schist of Upper Narrows. Minerals noted during field work include diopside, talc, hornblende, feldspar, biotite, and phlogopite. In a few locations, small prospect pits, now abandoned, have been developed in these skarn zones.

Mineralized joints and fractures Prominent north-south joints in the Almo pluton are visible in many pinnacles and are identified by linear zones of lush vegetation in pediment settings. Rock in and near the largest joints is rarely observable, but in the few localities where it is exposed it consists of strongly mineralized granite. Typically these rocks are medium gray, fine to medium grained, sericite-quartz rock traversed by white to cream-colored thin sheets of silica. Nearby manifestations of this sericitic and silicic alteration are joint planes coated with selvages of muscovite within the granite. Minor sulfide mineralization, apparently all pyrite and oxides derived from pyrite, occurs at three localities. At two locations small prospect pits in this rock have explored sulfide mineralization.

Minerals in pegmatite dikes Pegmatite dikes in the Almo pluton commonly carry books and sprays of muscovite, in places in very coarse accumulations. Some of the larger accumulations have been prospected, and muscovite was separated and reportedly shipped in small quantities for use as insulation. The main ‘mica mines’ are near the pass to Trail Canyon and near Register Rock. Smaller dikes also have minor prospects. Rare examples of terminated smoky quartz crystals may also be related to the pegmatite dikes.

Mineralization in Archean rocks Although Archean granite, schist, and amphibolite are generally unmineralized, one small occurrence of massive specular hematite was noted. No accompanying minerals were noted.

Sand and gravel Alluvial sand and gravel deposits within the Reserve are poorly sorted but may be suitable for use in road construction and as fill for local construction. Better-sorted sand and gravel deposits are available east of the Reserve in the fluvial deposits (units QTf, Qof, Qif) south of Almo.

Disintegrated granite The Almo Granite is weathered to grus in many locations, where disintegrated granite can be easily quarried. Disintegrated granite makes a good source for road metal because it lacks large rock fragments and does not contain large amounts of clay. Alluvium derived from disintegrated granite may also prove valuable as a disintegrated granite source. Superior disintegrated granite sources generally lie near the crest of the range, where erosion has not been pronounced. Examples are the passes to Emery and Trail Canyons, and the head of Emigrant Canyon.

Applications

Applying earth-science information to resource management relies on understanding the geologic processes involved in depositing and eroding surface materials, as well as destructive processes such as earthquakes. Because most deposits identified as distinct map units on the accompanying geologic map accumulated by, and were modified by, well-known geologic processes, many management issues can be addressed by study of specific map units.

Preliminary qualitative estimates of management issues associated with map units are presented in Table 3 . These features include ability to excavate, ground and slope stability for development purposes, and geologic hazards. *Stability* of unconsolidated material is a function of coarseness and sorting of constituent materials (gravel is more stable than sand, etc.), the percentage of coarse materials, a lack of expanding clays, surface slope, and mobility of the deposit. *Flood hazards* are estimated by determining the processes active at the time of deposition of the materials in a given map unit. Given the modern topography, the likelihood that the same process can occur in the near future is estimated. These estimates are for the natural systems and may be significantly modified by the presence of irrigation ditches, dams, and roads, all of which divert channelized and overland sheetflow of water.

Seismic stability is not evaluated in Table 3 because it is related to several factors in addition to the listed map-unit characteristics. In general, ground shaking from a nearby earthquake is more severe in thick unconsolidated deposits. Liquefaction is likely in water-charged deposits with significant sand-size material.

Description of Map Units

Note on mapping conventions: Where a Quaternary map unit is present as a thin (<2 m thick) deposit, that unit is mapped with the (/) notation to denote the unit it is overlying; for instance, Qya/Qia indicates that a thin sheet of Qya overlies Qia.

Qal **Alluvium (Holocene)—**Dark brown, organic-rich, sand and mud deposited in active washes and on adjacent flood plains; subordinate gravel in places. Typically supports dense vegetation. Unit typically 2 to 3 m thick

Qya **Younger alluvial fan deposits (Holocene)—**Dark brown, organic-rich, gravel, sand, and silt forming alluvial fans. Most alluvial fans issue from steep hills and pass from steep upper parts to low-gradient lower parts. In lower, eastern parts of Circle Creek and Twin Sisters basins, fan deposits consist of muddy sand, organic rich in places. Locally contains the Mazama ash (~6,700 years old) in these locations. As mapped, unit incorporates some colluvium and debris flows in upper, steep parts of fans and locally incorporates alluvium in lower reaches. Fan deposits may have thick A horizon due to loess influx in Holocene. Unit typically 1 to 4 m thick

Qyf **Younger fluvial deposits (Holocene)—**Sand, mud and gravel associated with the perennial Raft River system. Active river floored largely by gravel. Deposits largely sand and fine gravel, but with mud beds and drapes. Deposits lie unconformably on glacial-derived gray muds of unit Qif. Floodplain terraces have an organic horizon and weak calcic horizon. In tributary channels, charcoal in fluvial sediments of the river plain is dated at about 8,265 ± 35 radiocarbon years before present (9,410 to 9,120 calibrated years; Table 2)

Qvp **Veneer on pediment (Holocene and Pleistocene)—**Sediment forming thin veneer on pediment cut into granite. Sediment consists of colluvium, alluvium, and alluvial fan deposits of variable age. As mapped, includes small patches of pediment (bedrock exposure). Grades in many cases to alluvial deposits of intermediate age (unit Qia). Deposits generally less than 1 m thick; in all cases less than 3 m thick

Qls **Landslide deposits (Holocene and Pleistocene)—**Dark-colored, bouldery, disaggregated deposits showing slump-block morphology. Springs and dense vegetation typically occur on and near landslide deposits. Most common on steep slopes at base of outcrops of Elba Quartzite. In a few places, forms stepped slopes of regularly repeated slumps. Mostly unforested. Deposits less than 10 m thick

Qc **Colluvium (Holocene and Pleistocene)**—Light to dark brown, loose, unsorted rubble of rock and soil, generally on steep slopes. Deposits move mainly by gravity (slumping, tumbling, and creep) and less as transport by water (sheetwash). Includes blocky material on and near Graham Peak that has moved by frost action. Less than 5 m thick

Qt **Talus (Holocene and Pleistocene)**—White, blocky boulder deposits on very steep slopes. Angular and generally lacks matrix of fine-grained materials. Forms mostly in areas of rockfall and colluvium derived from Elba Quartzite; locally at base of prominent spires of granite such as Twin Sisters. Accumulates mainly by rockfall and downslope creep. Mostly unforested and less than 5 m thick

Qia **Intermediate alluvial fan deposits (Pleistocene)**—Medium- to dark-brown, gravelly sand and sandy loam deposited mainly as alluvial fans, but including colluvium in steeper upland areas and small deposits of alluvium in low-gradient areas. Cobbles and boulders prevalent on steep slopes, less on flatter areas; large clasts composed of quartzite. Sand and loam composed of decomposed granite and quartz in most places. In places, includes overlying loess of varying thickness, typically 20 to 50 cm. Deposits display broad alluvial fan morphology with flat crests, but are incised by active streams associated with Holocene deposits. Distinguished from younger and older deposits by landform and presence of one or two well-developed soils, including argillic and calcic horizons; soils in places separated by loess. Stage II calcic soil of Machette (1985) common; stage IV soil also present. Thickness of unit less than 5 m in upland areas and greater than 10 m near Almo and Big Cove

Qif **Intermediate fluvial deposits (Pleistocene)**—Sand, gravel, and mud of Raft River depositional system. Weak pavement on surface. Defining characteristic is gray mud beds that are compositionally similar to rock flour carried by glacial streams. Suggests deposits are contemporaneous with glacial activity in the Raft River Mountains. Mud lies on well sorted pebble to cobble gravel. Bt and calcic (stage II) horizons in upper part of deposit distinguish it from younger fluvial deposits

Qoa **Older alluvial fan deposits (Pleistocene)**—Medium-brown, gravelly sand deposited mainly as alluvial fans, but including colluvium in steeper upland areas. Cobbles and boulders form an erosional pavement on rounded crests of deposits; clasts typically composed of quartzite. Sand and loam derived from disintegrated granite and quartz in most places. Unit displays well-developed calcic horizon, where surface not strongly eroded, including more than 1.4 m thickness of stage IV calcic soils likely to be several hundred thousand years old. Because deposits are highly eroded, geomorphology not clearly connected to modern sources (mountains) and sinks (valley bottoms). Thickness of unit 15 to 25 m

Qof **Older fluvial deposits (Pleistocene)**—High terrace adjacent to Raft River, composed of rounded clasts derived from upstream mixed with less rounded clasts of adjacent alluvium. Loess cap greater than 1 m thick. Soils not observed; unit may be younger than unit Qoa

QTa **Alluvium and landslide deposits (Pleistocene and Pliocene?)**—Light-colored boulder and gravel deposits typically forming high hills that represent eroded high terraces. Commonly mantled by rounded boulders as large as 1 m diameter and derived from Elba Quartzite. Deposits south of Smokey Mountain and south of Twin Sisters contain huge boulders (as large as 5 m diameter) that are not obviously derived from present topography; probably formed by gigantic landslides from old mountains considerably different from current geomorphology. Deposits generally thicker than 10 m; may be as thick as 25 m

QTf **Fluvial deposits (Pleistocene and Pliocene?)**—Brown sand, gravelly sand, gravel, and silt underlying rounded terraces southeast of Almo and in the southeast corner of the Almo quadrangle. Southeast of Almo, unit has thin, nearly flat bedding, common cross-lamination. Sand and silt beds very well sorted; gravelly beds moderately sorted. Parallel thin bedding and sorting of beds in deposit suggest fluvial origin. Gravel source is granite and quartzite of southern Albion Mountains. Capped by wind-blown(?) fine brown sand 1 to 2 m thick in many exposures; sand overlies stage III or stage IV calcic soil. Deposit underlies a composite surface that dips gently toward Raft River, but is incised by the river. Late Pleistocene alluvial deposits lie on incised surfaces cut into fluvial deposits; relation indicates that fluvial deposits are much older. Thickness greater than 10 m. In southeast corner of map, unit is moderately indurated gravel whose clasts were derived from the Raft River Mountains

Tr **Rhyolite (Miocene)**—Bright red to brownish red or, less commonly, gray, resistant welded rhyolite tuff. Medium-size (3-6 mm diameter) grains of smoky quartz (2 to 3%) and sanidine (6 to 10%) indicate rhyolite composition. Black vitrophyre near base and locally at top. In well-exposed outcrops, central unit shows distinctive large (2 x 8 cm) flattened vesicles and is abruptly overlain by dense, highly flattened rhyolite containing strongly stretched fiamme (pumice blocks). Welded tuff contains sparse lithic fragments of granite as large as 1.5 cm diameter. Overlain by alluvium and landslide deposits (unit QTa). Deposit is 9 m thick in Emigrant Canyon and 17 to 20 m thick southeast of Trail Creek. Similar rhyolite lying on metamorphic rocks farther north in Albion Mountains dated by Armstrong (1976) at 8.8 million years

Ts **Sedimentary deposits (Miocene)**—Light brown, slope-forming unit consisting of cobbley sand. Clasts are from the Almo pluton and Elba Quartzite; latter more abundant by factor of ten. Clasts commonly as large as one meter diameter; a few as large as 4 m. Overlies Almo pluton and older rocks; overlain by rhyolite. Unit is 5 to 10 m thick at most, tapering to zero northeastward on ridge southeast of Trail Creek

Tg **Granite (Oligocene)—**White to light-gray, medium-grained, subequigranular, granite forming the Almo pluton. Ranges from biotite granite containing 10 to 12% biotite and no other characterizing minerals, to biotite-muscovite granite, to muscovite granite containing 12% muscovite, to muscovite granite containing as much as 5% red garnet. Quartz is light gray, generally about 30% of rock. Typically massive, but locally is layered due to mineral accumulations that form alternating light and dark bands. Pegmatite-aplite dikes are common; most are muscovite-bearing, and a few contain garnet as well. Some joint surfaces coated by muscovite selvages. Roughly zoned from muscovite granite near center of pluton outward to biotite granite, but many reversals and irregularities occur. Typically intrudes Archean rocks along east side of pluton as a series of parallel light-colored dikes that dip moderately to the east and northeast over a zone as wide as 500 m. Dated by Armstrong (1976) at 28.6 ± 1.0 Ma by the Rb-Sr method. Unit includes small stocks of fine to medium grained biotite granite and granodiorite in Emigrant Basin area

Op **Metamorphosed Pogonip Group (Ordovician)—**Brown to bluish gray coarse calcite marble in narrow band of outcrops near head of Emery Canyon and southwest of the Twin Sisters. Brown color generally associated with micaceous marble, gray with pure marble. Represents metamorphosed clean and silty limestone, minor dolomite. Minerals include calcite, dolomite, and phlogopite. Unit 10 m thick

Zmp **Schist of Mahogany Peaks (Neoproterozoic)**--Black coarse-grained pelitic schist. Mapped north of Emery Canyon in stope blocks; elsewhere, included with underlying unit. Age follows assignment by Wells and others (1998)

Zcb **Quartzite of Clarks Basin (Neoproterozoic)—**Silvery white, light gray, and tan, very thinly layered flaggy quartzite with micaceous parting seams. Typically exhibits small folds. Where mapped adjacent to Pogonip Group marble south of Emery Canyon and southwest of the Twin Sisters, unit includes 2 to 5 m thickness of the Schist of Mahogany Peaks. Unit 20 m thick. Age follows assignment by Wells and others (1998)

Zss **Schist of Stevens Spring (Neoproterozoic?)—**Brown to silvery brown, coarse-grained pelitic schist. Typically has a wavy, silvery foliation that locally has knobby texture caused by muscovite, sillimanite, and biotite wrapped around porphyroblasts of garnet, andalusite, and biotite. Locally, 2- to 7-cm-wide lenses or discs containing kyanite are preserved. Distinctive amphibolite present locally, generally near the base of unit. Unit about 300 m thick. Age follows assignment by Wells and others (1998)

Zy **Quartzite of Yost (Neoproterozoic?)—**White, thinly layered, pure quartzite. Contains only sparse muscovite layers. Locally has pronounced green tint. Unit 40 m thick. Age follows assignment by Wells and others (1998)

Zun **Schist of the Upper Narrows (Neoproterozoic?)—**Light- to dark-brown and grayish-brown, fine-grained, thinly layered, quartz-rich muscovite-biotite schist and schistose quartzite. Where little deformed, thinly layered aspect suggests unit could have been derived from laminated fine sandstone and siltstone. Quartzite layers are white to pale brown, generally 2 to 12 cm thick. Schist commonly contains veins and stringers of quartz and feldspar. Pure limestone marble within unit is present west of Indian Grove. Contains a few coarse grained quartzite beds near base. Epidote and actinolite minerals locally present in a stoped block in Almo pluton, and near base of unit at Indian Grove. Unit about 70 m thick. Age follows assignment by Wells and others (1998)

Ze **Elba Quartzite of Armstrong (1968) (Neoproterozoic?)—**White to pale gray and grayish brown, thick bedded quartzite. Lower part contains fairly abundant white, yellow, and bluish gray vitreous quartzite beds; upper part contains darker colored thick beds that are less pure than quartzite in remainder of unit. Zone of conglomerate generally separates lower and upper parts. Quartzite beds commonly show tabular cross-lamination. Schist interbeds very close to top are lithologically similar to the Schist of Upper Narrows. Elba typically underlies high ridges because it is resistant to erosion. Nonconformably overlies Archean rocks; muscovite schist commonly marks the contact, and represents metamorphosed argillaceous soil. Unit is about 200 m thick. Age follows assignment by Wells and others (1998)

Green Creek Complex of Armstrong and Hills (1967) (Archean)—Basement complex that underlies metasedimentary rock units. Includes:

Wga **Amphibolite**—Black, coarse- to medium-grained, hornblende-plagioclase and hornblende-plagioclase-garnet mafic rock. Contains minor quartz. Forms linear, dark bands a few meters to tens of meters wide in granite (unit Wgg) of the Archean complex, relations we take as indicating it intruded granite as dikes

Wgg **Granite and granite gneiss**—Light- to dark-gray, coarse-grained, porphyritic biotite granite. Microcline phenocrysts as large as 5 x 2 cm in a medium- to coarse-grained matrix of quartz, biotite, and plagioclase. Phenocrysts typically aligned as magmatic foliation. Biotite about 15 to 20 percent of groundmass. Where deformed to gneiss, phenocrysts are stretched to augen porphyroblasts in fine groundmass. Dated at about 2.5 billion years old by Armstrong and Hills (1967). Equivalent to Adamellite of Compton (1972)

Wgs **Schist**—Dark-brown, coarse-grained muscovite-biotite schist and related rocks. Schist is biotite rich; typically contains veins, stringers, and knots of quartz and feldspar. Unit includes minor amounts of fine-grained quartzo-feldspathic rocks. Intruded by granite (unit Wgg). Equivalent to Older Schist of Compton (1972)

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Table 1. Radiocarbon data for charcoal samples collected in the Raft River fluvial deposits. Analyses by Jack McGeehin, U.S. Geological Survey radiocarbon laboratory.

Sample ID	Lab ID	Radiocarbon age (yr)	Calibrated age range[1]	UTM[2] East	UTM[2] North
M99CR-04A	WW-3683	8230 ± 30	9033-9302	282284	4654554
M99CR-04B	WW-3684	8265 ± 35	9127-9404	282284	4654554

[1]Calibrated years B.P., 2σ range from Calib v. 5.0
[2]UTM locations in NAD 83, zone 12.

Table 2. Popular named rocks at the City of Rocks National Reserve as examples of pinnacle shapes.

Loaves	Domes	Spires
Bread Loaves	Kaiser's Helmet	Lost Arrow
Stripe Rock	Camp Rock	Twin Sisters
Bath Rock	Treasure Rock	
Elephant Rock		

Table 3. Selected attributes for surficial materials and rocks at the City of Rocks National Reserve and vicinity.

Map Unit	Material Type	Ease of Excavation	Foundation Stability	Flood Hazards	Mass–wasting Hazards	Possible Uses
Alluvial Fan Deposits						
Qya	Moderately to poorly sorted sandy cobble to boulder gravel. Boulders larger on steeper parts of fans	Generally easy occasional boulders	Moderate to high; slight compaction possible expansive clays may be in low gradient deposits	High; unit marks areas of historic flooding, especially during thunderstorms	Low overall moderate risk of soil creep at steeper parts of fan	Source of sand and gravel. Source of disintegrated granite (DG) where unit derived from granite
Qia	Moderately to poorly sorted sandy cobble to boulder gravel containing clay–rich near–surface soil horizons. Weakly to strongly carbonate cemented. Boulders larger on steeper parts of fans	Variable; moderately difficult where carbonate–cemented or where upper clay–rich soil horizons are thick. Boulders common	Variable; high where upper soil horizons are non–expansive, but low if significant expansive clay exists in upper soil horizons	Moderate to low. Some surfaces could be inundated during heavy rain	Low overall; moderate risk of soil creep at steeper parts of fan	Source of gravel where carbonate cementation is weak. Upper clay-rich soil horizons can be highly slippery when wet; makes poor road surface
Qoa, QTa	Poorly sorted, heavily carbonate–cemented cobble to boulder gravel	Difficult; strongly carbonate–cemented gravel may be up to 2 m thick; boulders common	High	Low, except for local sheetwash	Low overall; moderate risk of soil creep at steeper parts of fan	Possible source of coarse aggregate if possible to excavate carbonate–cemented deposits
Stream Deposits						
Qal	Mud, sand, and gravel; deposits commonly wet and muddy	Easy; sparse boulders	Low; compaction possible	High; intense flow probable in channels; sheet–flooding on flanking flood plains	Low overall; moderate risk of collapse along cut banks soil creep at steeper parts of fan	Moderate source for sand and gravel
Qyf, Qif, QTf	Moderately to well sorted silt, sand, and gravel	Easy	Moderate; could be subject to liquefaction	Low except for local sheetwash and seas-onal snowmelt floods	Low	Good source for sand and gravel
Colluvial Deposits						
Qc	Poorly sorted, angular, cobble to boulder gravel with sand and silt matrix	Moderate	Low; usually occurs on steep slopes subject to creep	Variable; sheet–flooding during heavy rain intensified on steep slopes	Moderate; accumulates near cliffs and steep areas where rockfall occurs	Moderate to poor source of coarse aggregate
Qt	Poorly sorted, angular cobble to boulder gravel	Moderate to difficult depending on amount of carbonate cement	Low; occurs on very steep slopes subject to creep	Variable; steep slopes intensify sheet–flooding, but unit often is open–work, allowing rapid infiltration	High accumulates near cliffs and steep areas where rockfall occurs	Moderate to poor source of coarse aggregate and rip–rap
Qls	Poorly sorted, angular cobble to boulder gravel and sand	Moderate	Low; usually occurs on steep, unstable slopes	Variable; sheet–flooding during heavy rain intensified on steep slopes	High; landslide deposits may be actively creeping	Moderate to poor source of coarse aggregate

Table 3. (Continued)

Map Unit	Material Type	Ease of Excavation	Foundation Stability	Flood Hazards	Mass–wasting Hazards	Possible Uses
Pediment Deposits						
Qvp	Moderately to poorly sorted sand and gravel	Easy	Moderate to high	Variable; subject to sheet flooding and channelized flow	Low	Good source of sand and gravel but deposits are very thin
Older Sediment						
Ts	Moderately sorted silt and clay containing minor sand	Easy	Moderate to high	Low	Moderate; underlies steep slopes where creep occurs	Poor source of sand and gravel
Granite						
Tg	Medium–grained granite	Moderate to difficult	High	Low to moderate; pediment exposures subject to sheet flow	Moderate; rockfall on steep sides of pinnacles	Source of disintegrated granite where weathered; possible source of rip–rap
Wgg	Coarse–grained granite and granite gneiss	Moderate to difficult	High	Low	Moderate; rockfall on steep sides of pinnacles	Source of disintegrated granite where weathered; possible source of rip–rap
Volcanic Rocks						
Tr	Dense, fine–grained rhyolite	Difficult	High, but weathered rhyolite produces extensive clays	Low to moderate	Moderate; steep slopes subject to creep and rockfall	Poor source of rip–rap due to rapid breakdown during weathering. Poor road base; best to lay road metal over volcanic rock
Metamorphosed Sedimentary Rocks						
Wgs, Zun, Zss	Coarse–grained mica schist containing muscovite, biotite	Moderate to easy: rock is generally highly weathered	High to moderate	Low	Moderate; steep slopes subject to creep	Poor source of rip–rap and building stone, even where fractured into proper size
Ze, Zy, Zcb	Hard quartzite and flaggy quartzite	Difficult	High	Low	Moderate; steep slopes subject to creep; cliffs of Elba Quartzite to rockfall	Source of angular rip–rap, and flaggy forms may serve as dimension stone or building stone. Hard and durable
Op	Coarse–grained, layered marble; schistose marble	Moderate	High	Low	Low	Source of minerals such as garnet, tremolite, phlogopite. Not economic due to limited extent of unit in area