

CHAPTER 13

Metamorphic Core Complexes and Related Features

Continental and Oceanic Core Complexes

A core complex “is a domal or arched geologic structure composed of ductilely deformed rocks and associated intrusions underlying a ductile-to-brittle high-strain zone that experienced tens of kilometers of normal-sense displacement in response to lithospheric extension” (Whitney and colleagues, 2013, p. 274). Core complex structures occur in both oceanic and continental crust in regions where extension of the crust has produced the exhumation of ductile portions of the deep crust and/or upper mantle. These regions include slow-spreading mid-ocean ridges, core complexes in the continents, and at continental rifted margins. Extension causes the brittle upper crust to pull apart along normal faults. If the extension occurs along a few faults, ductile lower crust or mantle material moves upward to shallow levels of the crust and is exhumed in the footwall of normal faults and exposed at the surface.

Oceanic core complexes were first discovered in seafloor images of the Mid-Atlantic Ridge; they were characterized by fault-bounded domal structures similar to the metamorphic core complexes of the continents. Since then, oceanic core complexes have been found in the Southwest Indian Ridge, the Caribbean-North American Ridge, and the Australian-Antarctic Discordance.

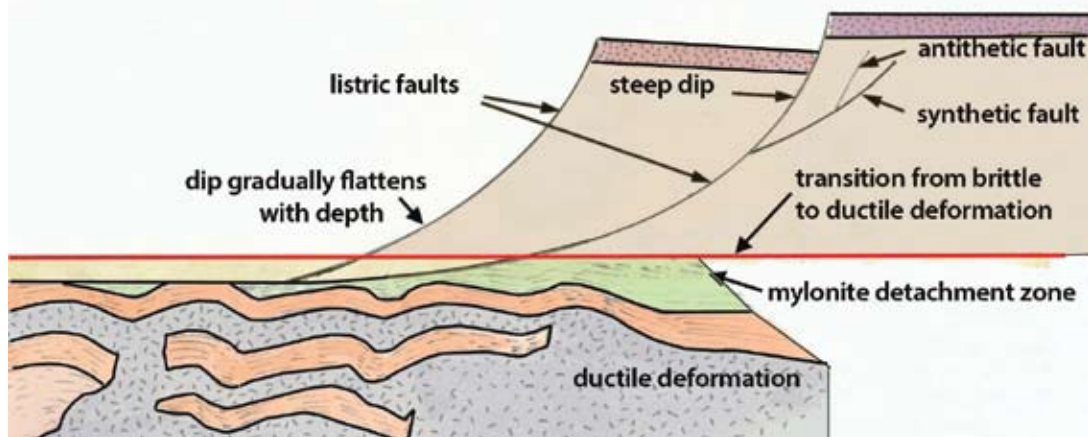
Both continental and oceanic core complexes may have corrugated or undulating detachment fault surfaces. In such cases, the corrugation axis is aligned parallel to the direction of extension; and the corrugations may have wavelengths of hundreds of meters to tens of kilometers and amplitudes of tens



Cordilleran metamorphic core complex locations in the American west. Modified after Coney (1973).

to hundreds of meters. Corrugations may be called “megamullions” for oceanic core complexes.

Typically, continental core complexes are elliptical in plan view and have a long axis between 6 and 24 miles (10 and 40 km), although a few are larger such as the Shuswap complex. Also, the footwall tends to be elevated above surrounding rocks by as much as 1.2 miles (2 km) of relief. Most of the Cordilleran core complexes are characterized by mylonite zones several hundred meters thick.



Listric faults are normal faults with a concave-upwards fault plane that gradually flattens at depth.

Detachment Faults

In areas of extreme extension, such as the Basin and Range Province, many areas (referred to as metamorphic core complexes) have had the upper layers of brittle rock stripped off the underlying ductile rocks along detachment faults. The east-west extension occurs along parallel to subparallel listric normal faults that merge at depth with the detachment fault. The detachment fault, which is commonly represented by a thick zone or layers of mylonite, occurs along the transition zone separating the ductile metamorphic and plutonic core rocks below from the overlying brittle rocks. The brittle rocks above are moved tens of kilometers to the east or west along detachment faults and the metamorphic and plutonic rocks that had previously been buried by as much as 12 miles (20 km) are exposed. Rocks below the detachment fault are generally represented by one or more layers of mylonite with gently dipping foliation. In some cases the mylonitic rocks are deformed by cataclasis indicating a change from ductile to brittle deformation as the rocks were exposed to a lower pressure and temperature environment. There is a close association of the magmatism and large-scale extension of the upper crust in the Basin and Range Province.

Cenozoic extension in the Cordilleran of North America has revealed metamorphic core complexes in several locations in Idaho. Core complexes typically have a window to a lower plate of high-grade metamorphic and igneous rocks separated by a low-angle detachment fault from an upper plate of less deformed rocks. In the detachment fault system, the upper layers are characterized by brittle deformation producing breccia and the deeper more ductile portions produce mylonites; however, they are all related to the same extensional event.

The displacement of the brittle surface rocks or upper plate occurred along low-angle detachment faults. The deep, highly deformed middle crustal rocks of the lower plate are exposed by the removal of the brittle relatively undeformed rocks along the detachment fault. These detachment structures are characterized by parallel bands of mylonite formed along the shear zone in the lower plate.

In the detachment zone, structural fabric indicates the direction of transport of the upper plate, which may be in response to regional tectonics. Most core complexes are characterized by broad domal uplift presumably caused by isostatic adjustment to tectonic removal of the upper layers. The once planar detachment faults or layers of mylonite are now arched upwards; however, the direction of tectonic transfer of the upper plate rocks is consistent throughout the complex. Extension of many metamorphic Core complexes appears to be influenced or facilitated by plutonism but the role of these intrusions is somewhat controversial.

Development of Gneissic Domes

Again, there are two kinds of extensional faults in the Basin and Range Province: low-angle normal detachment faults associated with metamorphic core complexes where horizontal extension may exceed 200 percent and the more typical high-angle normal faults that caused the Basin and Range Province.

Metamorphic domes in the metamorphic core complexes develop along detachment faults. The detachment fault merges into a ductile shear zone in the crust. Above the shear zone, curved or listric normal faults merge with the detachment fault. The fault blocks are tilted because they move down the curved listric faults.

As the extension faulting thins and removes the upper plate, the lower plate rises from thermal expansion and from isostatic adjustment. Consequently, the footwall is at least partially exposed at the surface having risen from 6 to 12 miles (10 to 20 km) below the surface by a process called tectonic exhumation. Finally, a dome of high-grade metamorphic rocks is exposed at the surface.

Timing of Metamorphic Core Complex Extension

The termination of the flat slab subduction followed by the Siletzia accretion and then the Cascadia subduction, gravitational collapse of the thickened crust could cause extension. Immediately after the Siletzia accretion, Laramide orogeny compression was changed to metamorphic core complex extension and ignimbrite flare-up. This ignimbrite volcanism was most likely caused by the flat-slab removal and slab rollback. The ignimbrite flare-up propagated from 45 Ma in the north to 21 Ma in the south. Most of the core complexes started 50 to 15 Ma—well before Basin and Range faulting.

Clearwater and Priest River Metamorphic Core Complexes

Vervoort and colleagues (2016) have examined the Precambrian crystalline basement underlying the North American Cordillera in northern Idaho at the Clearwater and Priest River metamorphic core complexes. They identified and dated two basement gneisses that represent two discrete periods in the Neoproterozoic and Paleoproterozoic. They determined that these gneisses were generated by two periods of magmatism: and initial formation of the crust at 2.66 Ga and a later addition to the crust at 1.86 Ga involving a mix of pre-existing Neoproterozoic crust and juvenile mantle.

These Neoproterozoic basement rocks represent the largest area of Paleoproterozoic and Archean crust exposed in the northwest excluding the Wyoming Province. The Clearwater complex was exhumed from depths of 20 to 30 km during the early Eocene as a consequence of crustal extension and gravitational collapse.

Pioneer Metamorphic Core Complex

The Pioneer metamorphic core complex is located in the Pioneer Mountains east of Ketchum. A lower

plate of Precambrian gneisses dated at 2 Ga and Cretaceous to Early Paleogene granitic rocks are exposed in the metamorphic core. An upper plate of unmetamorphosed Paleozoic sedimentary rocks overlain by Challis volcanic rocks surrounds the metamorphic core. The Wild Horse detachment system separates the upper plate from the lower plate.

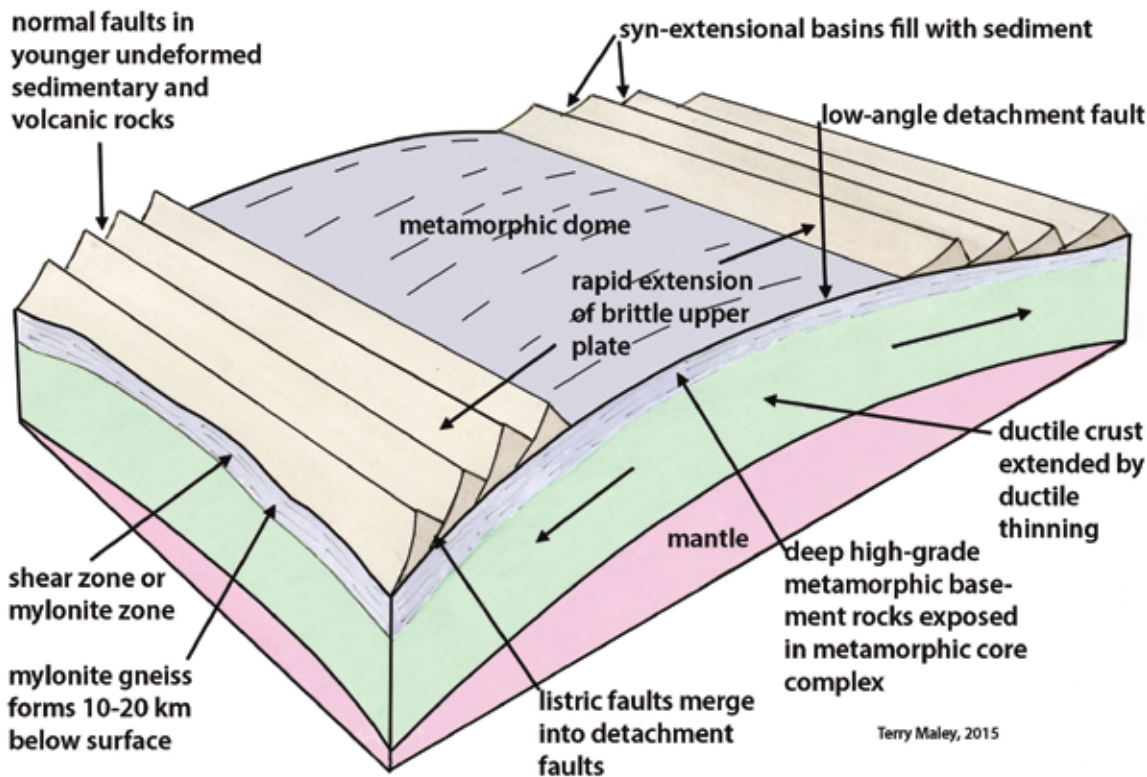
Through the Mesozoic, the subduction of the Pacific plate and the intrusion of the Idaho batholith produced east-west compression and thickening of the crust. By the early Paleogene (50 Ma) the transition to extension produced structures such as the Wildhorse detachment fault. This detachment fault involved about 10 miles (17 km) of separation and the upper plate moved northwest relative to the lower plate. The Challis volcanic episode that occurred 50 to 40 Ma and extension related to the trans-Challis fault system was also part of this extension. Low-angle faults removed the brittle sedimentary cover of the uppercrustal rocks from the Pioneer Mountains about 40 to 50 Ma. From 37 to 34 Ma, final uplift and removal of the overlying upper crust exposed high-grade metamorphic rocks up to 2.3 billion years old.

Bitterroot Metamorphic Core Complex

The Bitterroot metamorphic core complex is an unroofed metamorphic complex straddling the Idaho-Montana border in east-central Idaho. Like the other core complexes, the area experienced crustal thickening during the Cordilleran east-west compression followed by extension starting about 50 Ma. Granitic intrusions associated with extension led to exhumation of the complex.

METAMORPHIC CORE COMPLEX OF THE ALBION MOUNTAINS

The Albion Mountains are a representative portion of a larger region referred to as the Raft River-Grouse Creek-Albion Mountains metamorphic core complex. This metamorphic core complex has resulted in diverse igneous, metamorphic and sedimentary rocks with ages extending back more than 2.5 billion years brought together in a small geographic area. Consequently, the area is an exceptional place to study these well-exposed rocks and deformational structures. The most significant rocks are the Archean igneous and metamorphic rocks overlain by the Neoproterozoic quartzites and intruded by the Almo pluton, a granitic intrusion of Oligocene age. The older rocks were exposed by Oligocene and Miocene faulting and erosion



Block diagram showing structural features associated with a typical metamorphic core complex.

but later partially buried by Miocene volcanic flows of ash-flow tuffs. The spectacular pinnacles and unusual rock forms at the City of Rocks National Reserve and the remarkable building stone extracted from Middle Mountain were formed as a result of this metamorphic core complex.

The metamorphic-core complex in the Albion Mountains of south-central Idaho is referred to as the Raft River—Grouse Creek—Albion Mountain metamorphic core complex. High-grade metamorphic rocks are overlain by a mylonite zone; and above the mylonite zone, unmetamorphosed upper Paleozoic and Tertiary strata were removed by lateral extension along the ductile mylonite zone. These zones may occur where continental crust is thinned by ductile extension. The heat generated by the intrusion of Oligocene Almo plutonic rock weakened the crust and facilitated crustal thinning. The area is characterized by at least three periods of lateral ductile extension represented by flat mylonite layers, which range from Late Cretaceous to late Miocene.

Cenozoic Extensional History

Three Cenozoic extension events led to vertical thinning, lateral extension, and unroofing of originally deep rocks. Eocene extension between 42 - 37 Ma and early Miocene extension between 22 - 20 Ma moved

upper rocks down to west and northwest along west-dipping detachment faults; the deeper rocks were deformed as ductile shear zones and formed mylonites. The upper layers of the detachment zone experienced brittle deformation, but the deeper parts were ductile such as at the Middle Mountain shear zone. A later Miocene event 13 - 7 Ma displaced upper rocks down to the east along an east-dipping detachment fault. Approximately 9 miles (14 km) of rock was unroofed in the Albion Mountains exposing the Almo pluton. Later, over the eroded surface of the Almo pluton, rhyolite ash flow tuffs were deposited. Finally, the widespread ash-flow tuffs were broken into fault blocks of the Basin and Range Province.

In 2012, Konstantinou and colleagues proposed a Cenozoic extensional history of the Albion—Raft River—Grouse Creek (ARG) metamorphic core complex based on three distinct stages in development and exhumation:

Stage 1 of ARG—Precursor Eocene Magmatism, 42-34 Ma. Between 55 and 20 Ma, calc-alkaline magmatism started in southern Canada and migrated south to southern Nevada. This southward movement of magmatism was likely caused by asthenospheric upwelling after removal of the shallowly dipping Farallon slab beneath the North American plate. The rise of the hot asthenosphere into the base of the North American

plate resulted in heating and melting of the lower and middle crust. This created mixing-assimilation-storage-hybridization (MASH) zones. In the ARG area, this led to the intrusion of shallow plutons of intermediate to felsic composition and eruption of volcanic rocks between 42 and 34 Ma.

Stage 2 of ARG—Diapiric Rise of Pluton-Cored Gneiss Domes, 32-25 Ma. After the intrusion and eruption of the 42 to 34 Ma magmas, heating and melting continued in the crust and the MASH zone resulted in episodic creation of melts in the crust that became plutonic cores of the Oligocene gneiss domes. These plutons and crustal welts (gneiss domes) rose diapirically to depths of 6 to 9 miles (10-15 km) in an extensional environment. During this process, thinning and stretching of the roof rocks occurred at high metamorphic grade, which resulted in the development of strong lineation and foliation.

Stage 3—Basin and Range Extension/Faulting and Exhumation of Core Complex, 14-7 Ma. Approximately 10 to 12 million years after the diapiric rise of Oligocene plutons and their wall rocks, Basin and Range faulting began. Rapid extension was accompanied by faulting and syn-extensional basins; these basins were filled with sediments and high-temperature basalts and rhyolites. Between 14-10.5 Ma the metamorphic core complex experienced rapid uplift.

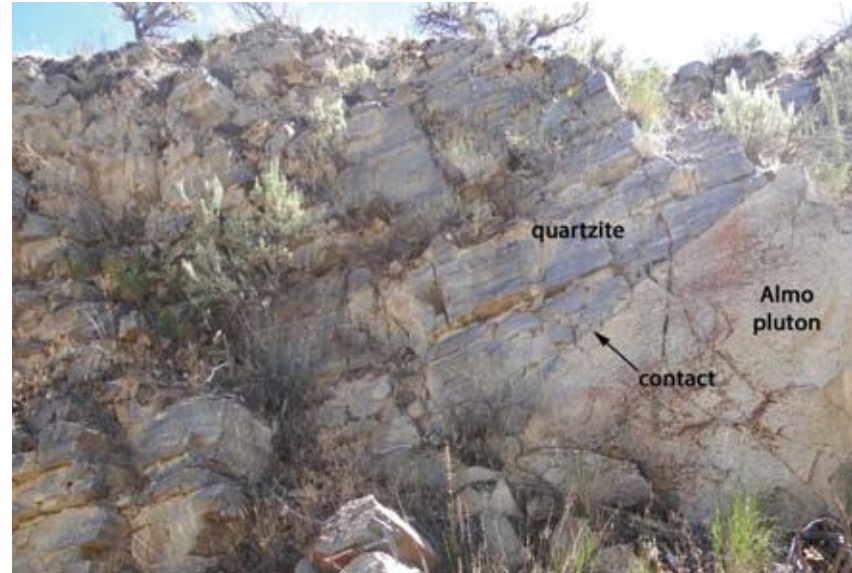
Green Creek Complex Represents Oldest Rocks.

The Green Creek Complex represents the oldest rocks in the region. They were originally deposited as shale, siltstone, and sandstone and later metamorphosed and deformed into schists and gneisses sometime before 2.5 billion years ago. These rocks were subsequently intruded by granitic plutons about 2.5 billion years ago. Mafic dikes intruded the granitic rocks and schists, also about 2.5 billion years ago.

Neoproterozoic Quartzite and Schist. Between 1,000 and 545 million years ago (Neoproterozoic) shale, siltstone, and sandstone as well as volcanic rocks were deposited across an eroded platform of Archean rocks. The Elba Quartzite is the lowest and most widespread of these units. The Elba Quartzite is followed by the Schist of the Upper Narrows, the Quartzite of Yost, the Schist of Stevens Spring, the Quartzite of Clarks Basin and at the top of the column the Schist of Mahogany Peaks. An extensional shear zone subparallel to the bedding separates the Neoproterozoic schists and quartzites from the overlying Ordovician Pogonip Group.

Almo Pluton

The granite of the Almo pluton has been dated at 28.6 Ma by the Rb-Sr method (Armstrong, 1976). Apparently, the granite of the Almo Pluton and the Middle Mountain injection complex have similar ages—both Oligocene. The Almo pluton was emplaced at depths greater than 9 miles (14 km) with subsequent rapid decompression while the pluton was still hot.



Almo pluton of granitic rock discordantly intrudes quartzite. Southeast of Oakley, Idaho.

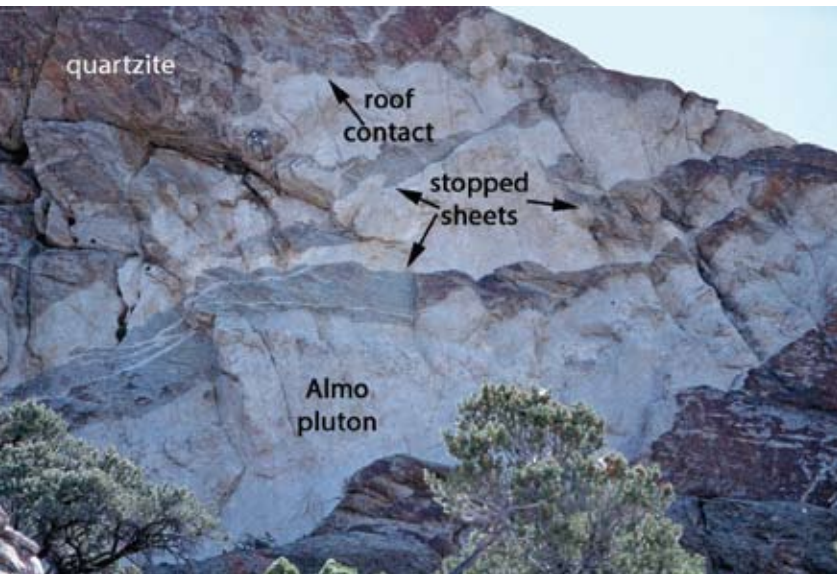
The Almo pluton consists of medium grained, granite, which ranges from biotite granite (12% biotite) to biotite-muscovite granite to garnet-muscovite granite (12% muscovite) with up to 5% red garnet. Muscovite-bearing aplite and pegmatite dikes are common.

Ductile deformation of the granite is uncommon except for a few locations on the west side of the pluton. However, these plutons are deformed in places to mylonite in the Grouse Creek Mountains and Vipont Mountain; and, the Middle Mountain Injection complex is extensively deformed.

The Almo pluton in the City of Rocks area occurs in a large north-trending upright anticline or arch. The pluton intrudes into Archean granitic rocks on the east limb of the fold. The Almo pluton did not form the dome that it intruded because other domes in the area are not cored by plutons.

A 7-km-long zone at the west margin of the Almo pluton contains stoped blocks and sags. The stoped blocks, which are typically steeply dipping panels or

sheets of sheared strata, formed as a result of roof subsidence or gravitational collapse into the pluton.



Roof contact between the 28-million-year-old Almo pluton and quartzite country rock. A 7-km-long zone at the west margin of the Almo pluton contains stopped blocks and sags. The stopped blocks or sheets of sheared quartzite formed as a result of roof subsidence or gravitational collapse into the pluton. The large stopped sheets in the photograph are more than 50 m long. City of Rocks National Reserve, Idaho.

CITY OF ROCKS NATIONAL RESERVE

The City of Rocks National Reserve was established in 1988; it is situated 15 miles (25 km) southeast of Oakley and about 4 miles (7 km) west of Almo. You can reach the City of Rocks by traveling through Oakley on the west side or through Almo on the east.

Panorama of the City of Rocks National Reserve, Idaho.



Historical Background

The junction of the California and Salt Lake-California connection trails is located 1.5 miles (2.5 km) south of Twin Sisters. The California Trail, which passes through the City of Rocks was established in 1843. Joseph Walker led a wagon train off of the Oregon Trail at Raft River 50 miles (83 km) to the northeast, through Almo, then through the City of Rocks and on to California. Immigrants were fascinated by the City of Rocks and those who maintained diaries recorded their impressions. Typical is the following description given by Mr. Lord on August 17, 1849:

... numerous artificial hydrants forming irregular pointed cones. Nearby they display all manner of fantastic shapes. Some of them are several hundred feet high and split from pinnacle to base by numerous perpendicular cracks or fissures. Some are domelike and the cracks run at different angles breaking up the large masses into huge blocks many of which hang tottering on their lofty, pointed beds... I have not time to write the hundredth part of the marvels of the valley or rocks...

The Three Basins

A large portion of the National Reserve covers three basins, which are separated by ridges or rows of pinnacles. These basins are Circle Creek basin, Twin Sisters basin and Emigrant basin. Most of the pinnacles either bordering or within the three basins represent the unique landscape features that attract visitors.

Most of the land within the basins is underlain with pediments. Pediments are low-relief surfaces of eroded bedrock. Granite in the basins is thought to weather under a thick layer of soil or alluvium, which was subsequently stripped by erosion revealing the granitic bedrock.

Pegmatite Dikes

Scattered pegmatite dikes, which have the composition and texture of coarse-grained granite, may be observed throughout the Almo Pluton. Pegmatite ranges from thin seams to lenticular bodies up to 50 feet (15 m) across and several hundred feet long. One exceptionally large pegmatite crops out in the City of Rocks. This pegmatite may be one of the largest to be found in Idaho with exposed dimensions of 200 to 300 feet (61 to 92 m) wide and 400- to 500-feet (122 to 153 m) long. Large clusters of orthoclase feldspar, quartz and muscovite are well exposed over two rounded knolls that reveal the pegmatite. Smoky quartz and miarolitic cavities are common. Numerous small workings over this large pegmatite show evidence of past interest and activity.



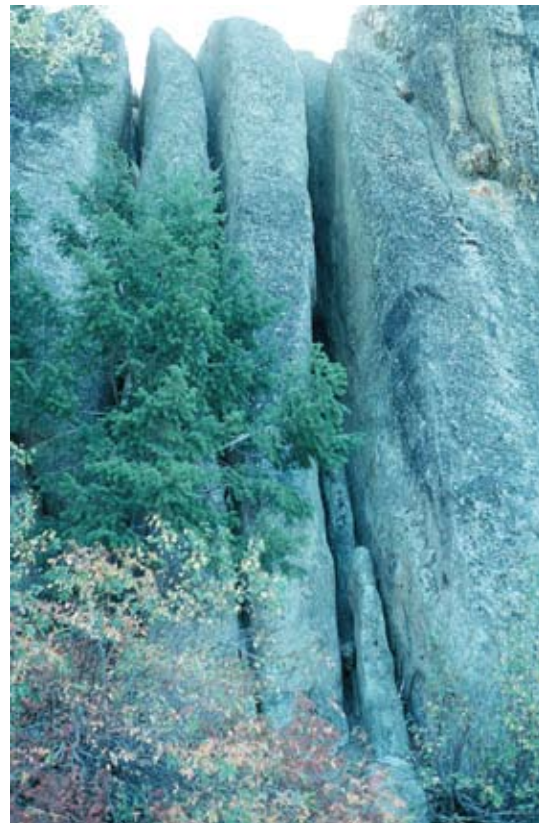
Large quartz and plagioclase feldspar crystals in the pegmatite at the City of Rocks National Reserve, Idaho.

Jointing

Jointing is exceptionally well developed in the Almo pluton and is particularly important in controlling the basic rock forms in the City of Rocks. There are three basic joint sets: one has subvertical dip with a northwest trend, another has a subvertical dip with a northeast trend, and a third has a horizontal trend and may represent unloading or sheeting joints. Jointing controls the arrangement of the outcrops and facilitates the weathering process by providing a plumbing system for solutions to migrate into the subsurface and cause the alteration, hydration and disintegration of the surface layers of granite. At some outcrops, weathering has caused joint spaces to widen to the extent that blocks are separated and form tall, isolated monoliths such as spires and turrets.



This granitic “loaf” is cut by three prominent joint sets: two orthogonal vertical sets and one horizontal set of unloading joints. The two vertical sets were developed first while the maximum principal stress direction was vertical. Much later when the erosion of overlying rock brought the rocks shown in the photo to the surface, the vertical stress direction became the minimum principle stress. Then the horizontal expansion joints formed. City of Rocks National Reserve, Idaho.



Extensive weathering along subvertical fracture set in granitic rock (loaf) creates a pseudo-karst appearance.



Exfoliation joints parallel to the upper surface of Shingle Butte, City of Rocks National Reserve, Idaho.

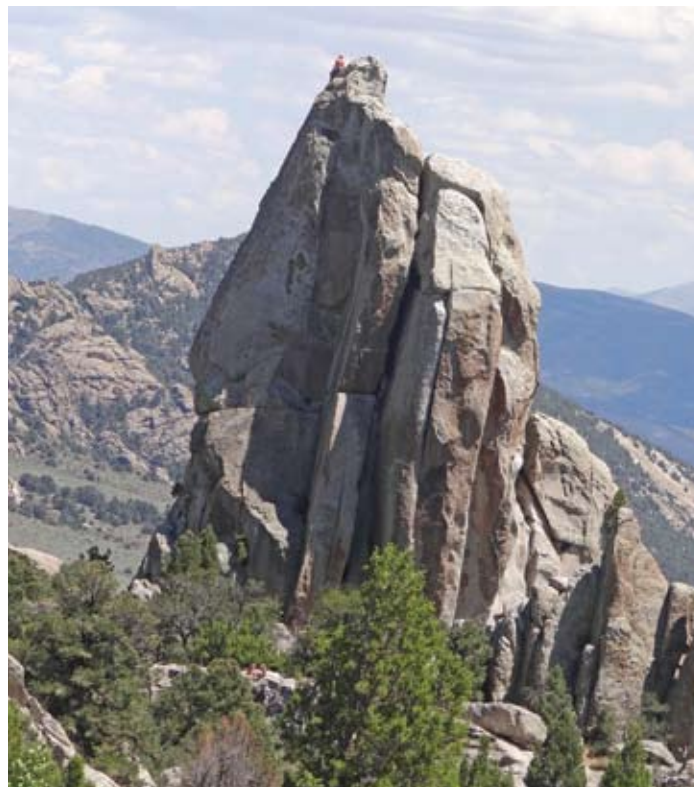
Origin of Pinnacles

Miller and colleagues (2008) have used the term pinnacles as a general description of the various projecting granitic landforms in the reserve. They further proposed three forms of pinnacles called loaves, spires and domes to cover most of the common shapes within the reserve (Miller and colleagues, p. 17 (2008):

Loaves are elongate, rectangular masses with dome-shaped tops, 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. Spires may result from erosion of rock with two strongly developed sets of steeply dipping joints.



An excellent example of a loaf with a dominant fracture set giving it the appearance of sliced bread. City of Rocks National Reserve, Idaho.

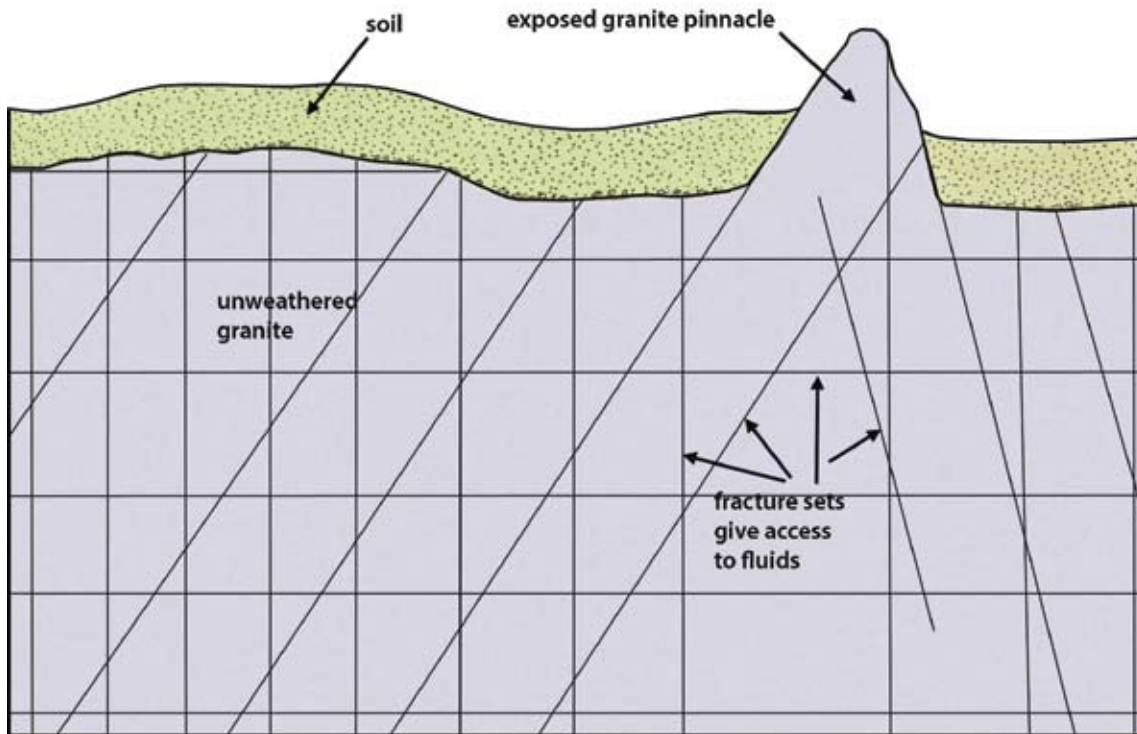


Morning Glory Spire is an excellent example of a spire with a dominant vertical fracture set. Notice the climber near the top of the spire for scale. City of Rocks National Reserve, Idaho.

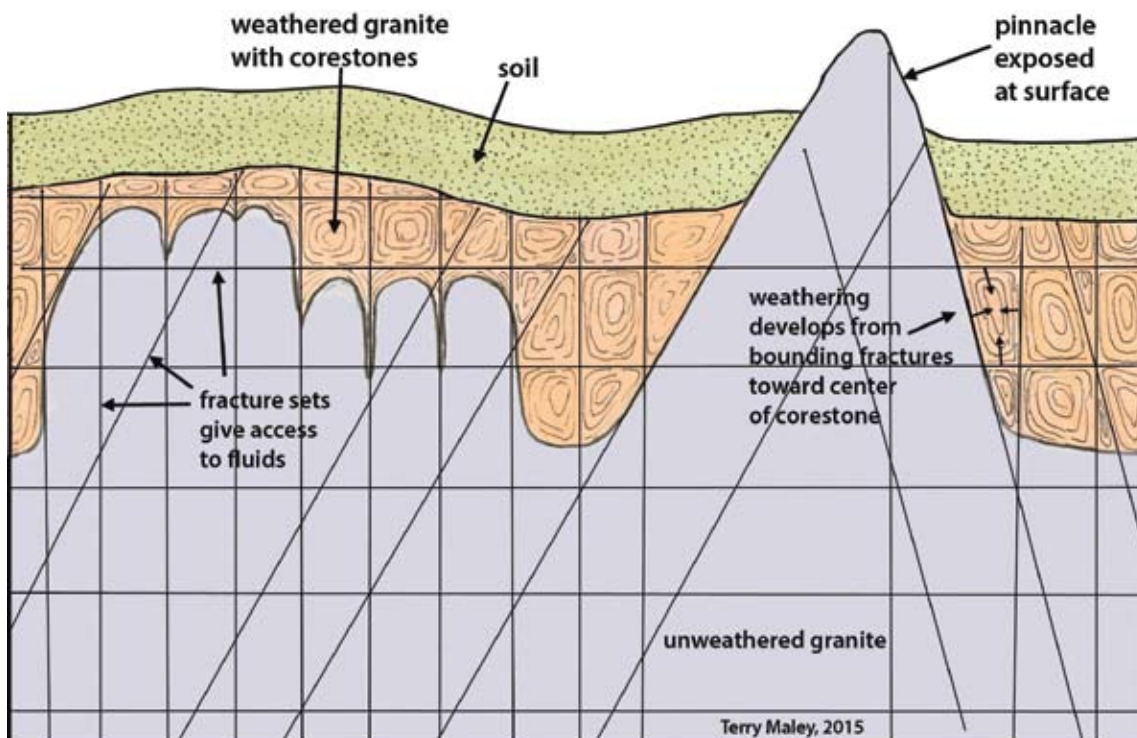


Shingle Butte is a dome-shaped pinnacle. The curving, convex up exfoliation joints enhance the dome shape. Note that the joints thicken away from the top of the dome. City of Rocks National Reserve, Idaho.

There are three stages to the development of pinnacles: (1) the granite is first cut by several sets of joints; (2) then the granite is disintegrated under thick soil or alluvium leaving resistant cores of granite or core stones; and (3) finally the disintegrated weathered rock is removed by erosion to expose the pinnacles. So, the pinnacles are not formed by atmospheric weathering but are instead caused by deep weathering of adjacent rock in the unsaturated zone above the



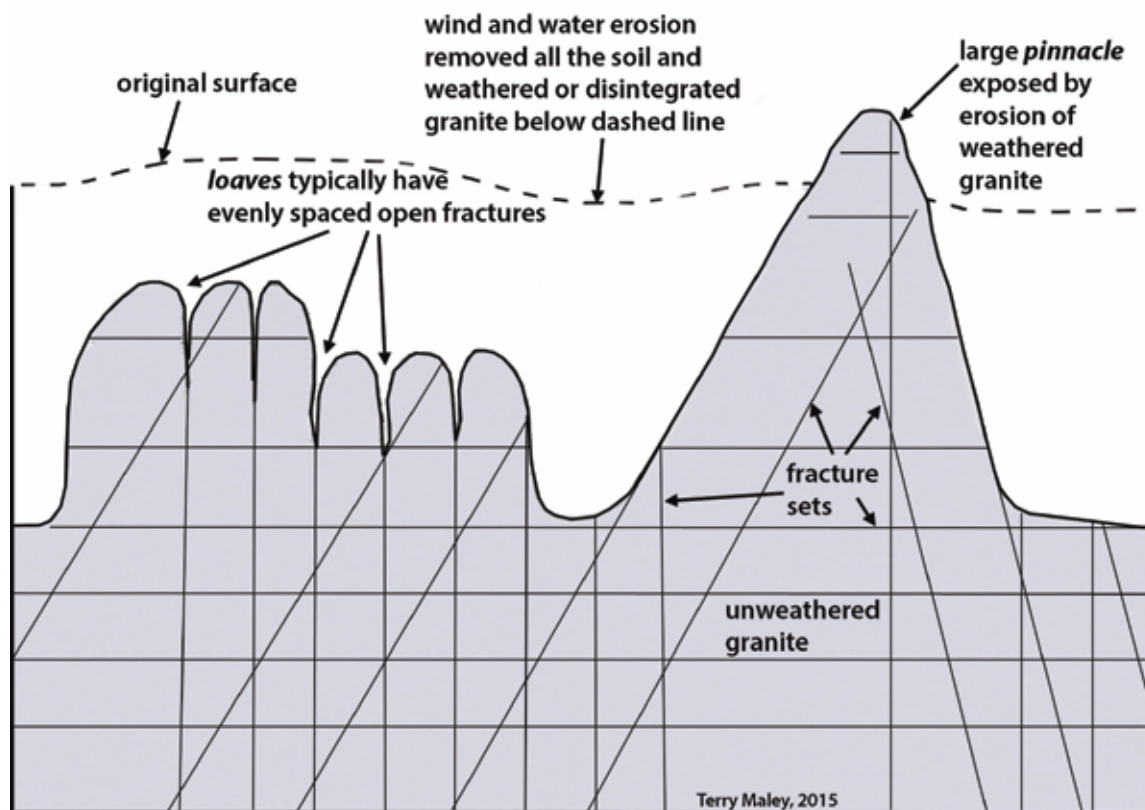
Stage one in the development of pinnacles, loaves and spires at the City of Rocks National Reserve. Below the soil layer, granite of the Almo pluton has been cut by several joint sets. Although most of the basin is covered with a mantle of soil, a few small outcrops of granite penetrate upward through the soil.



Stage two in the development of pinnacles, loaves and spires at the City of Rocks National Reserve. Deep weathering of the granite in the subsurface is enhanced by surface water moving down through the intersecting fracture sets and the intergrain boundaries. The pinnacles, loaves and spires are fully formed in the subsurface as unweathered granite "corestones."

water table while the pinnacle was deeply buried. Water moves through inter-grain boundaries by capillary action and chemical weathering weakens the rock to form grus; the presence of closely spaced joints greatly promotes this activity. The shape or

morphology and size of the pinnacles are controlled by the spacing and attitude/orientation of the joint sets. The disintegration of granite can be seen as core stones in deeply weathered granite in road cuts and quarries. Short pinnacles would be exposed when erosion



Stage three in the development of pinnacles, loaves and spires at the City of Rocks National Reserve. Wind and water erosion removes all soil and weathered granite exposing the granite pinnacles, loaves, and spires in much their present form. Since exhumation, the forms have been modified slightly by surface weathering.

stripped the weathered granite from the basin floor. Taller pinnacles may have projected above the older basin floor. In many cases, the pinnacles rise above a plain of bare rock or pediment that may or may not have a thin veneer of sediment.

Weathering Features on Pinnacles

A variety of surface features (case hardening, blisters, crusts, pitted surfaces, cavernous weathering, and honeycomb) and spheroidal cavities along the surface of the pinnacles give them unique characteristics. Weathering of the feldspars in the granite produces clay minerals, which have the capacity to shrink and swell with moisture changes. If there is no protective surface formed over the granite, this process can accelerate. Freeze-thaw cycles and differential thermal expansion between minerals of varied composition and size can also enhance weathering and the disintegration of granite.

Weathering

Although Jointing controls the general form of outcrops in the City of Rocks, weathering is the agent responsible for creating the bizarre and fantastic shapes that characterize the area. On the surface of the outcrops, weathering occurs by granular disintegration. In

other words, one layer of crystals after another is successively removed from the surface. This leaves the newly exposed surface in a smooth and rounded condition with no sharp or ragged edges or corners. The detrital material weathers from the granite and is carried by wind and water to low areas among the prominent forms. The grains of quartz, feldspar and mica at the surface of outcrops are friable and easily disintegrated with hand tools.

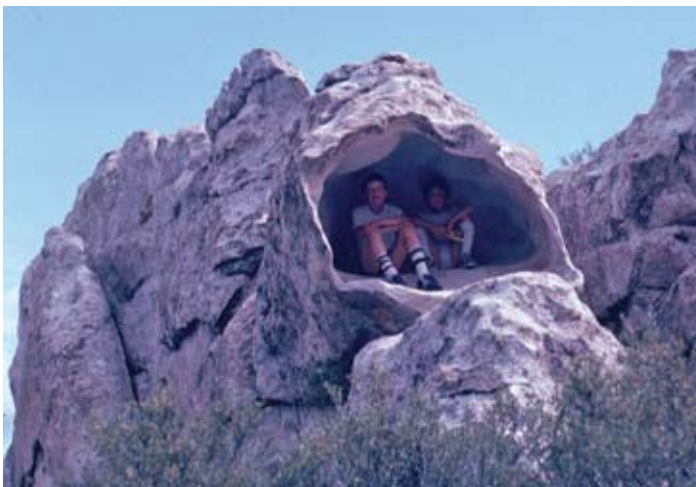
Chemical weathering is caused by solutions penetrating the cleavage cracks in crystals and between mineral grains. Once the solutions are in these narrow boundaries, new minerals form, which have a larger volume than the space available. This process of hydration and other chemical changes cause the disintegration and exfoliation.

Case Hardening

In addition to granular disintegration, case hardening is important in developing the unusual erosional forms. Case hardening refers to hardening of the surface by chemical processes that add cement to the mineral grains at the surface. Capillary processes carry water with dissolved mineral to the surface where they are deposited during dry periods. In some areas, an outer layer has been hardened by the deposition of other



Spheroidal weathering of granitic rock occurs by exfoliation or spalling of thin layers less than 1 cm thick. Spheroidal weathering leads to rounded forms, which are very common in granitic rocks and somewhat less common in volcanic and sedimentary rock. Chemical weathering transforms feldspars to clay. Because clay absorbs water, the volume of the original feldspar expands by a process called granular disintegration. In order for chemical weathering to occur, water must have access to the feldspar minerals so feldspar near the surface or along joints is altered to clay. As the near-surface altered feldspar expands, the expansion disintegrates or breaks up the interlocking mineral grains towards the exposed face and thin flakes spall off. Movement of water along fracture planes also causes feldspar to progressively decomposed from the outside towards the interior. So, each successive shell towards the interior becomes more and more rounded. City of Rocks National Reserve, Idaho.



Shallow cave in granite of the Almo pluton formed by cavernous weathering. City of Rocks National Reserve, Idaho.



A large hollow boulder with the lower and central portions removed by cavernous weathering. Penetration of the hard-cased shell of the boulder allows the soft interior to be removed by weathering and wind erosion. City of Rocks National Reserve, Idaho.



Natural arch in granite of the Almo pluton at least partly formed by cavernous weathering. City of Rocks National Reserve, Idaho.

minerals such as iron oxides. Once a form has a case-hardened protective shell, the granular surface material is removed much more quickly underneath the shell. In some cases only the protective outer shell is left. In this way, caves, niches, arches, bathtubs or pans, toadstools and hollow boulders are formed. The case-hardened crust is generally darker in color than the lighter under sides. Blisters, crusts and pitted surfaces are associated with case hardening. Blisters tend to be thin, hardened, reddish surfaces with domed forms. Crusts are thicker than blisters and tend to have polygonal shrinkage



Hollow forms from cavernous weathering of granite. Penetration of the hard-cased shell of these forms allows the soft interior to be removed by weathering and wind erosion. City of Rocks National Reserve, Idaho.



Surface of case-hardened granite has numerous weathering pans (also called pits) formed when weathering processes break through the relatively thin hardened surface and excavate the pans by granular disintegration and spalling. During periods of precipitation, these pans fill with water, which accelerates weathering. Neighboring pans coalesce as a result of the expansion of each pan. The loose granular material called grus is released in the pan and may be blown out during windy, dry periods. City of Rocks National Reserve, Idaho.

cracks on a dark brown surface. They appear to be associated with cavernous weathering where the crust has been eroded away. Pitted surfaces appear to be the oldest of the case-hardened features. Pits range from 1-inch (3 cm) deep to 8-inches (20-cm) wide.

Cavernous Weathering

Cavernous weathering occurs where spheroidal cavities or hollows are excavated out from beneath or behind case-hardened surfaces. This process is accomplished by capillary movement of water into granular rocks, so as to increase the disintegration of the granite. Once the hollow is formed, it has higher moisture content than adjacent areas so disintegration is further enhanced. **Panholes** or **solution pans** form on the upper surface of granite. They may have round to irregularly shaped holes that widen at depth and typically have flat floors. Bath Rock is an uncommonly large example. Honeycomb weathering or tafoni are a form of cavernous weathering that originate on the sides of pinnacles.



Cavernous weathering is responsible for the caves, arches, hollow forms, niches and alcoves characteristic of granitic rocks. This types of weathering tends to occur in rocks that are vulnerable to (1) case hardening by iron and manganese oxides, and (2) granular disintegration. City of Rocks National Reserve, Idaho.

Twin Sisters

The Twin Sisters are both composed of granite, but are of vastly different ages. The tall spire is the 29-million-year-old Tertiary “sister” and the spire to the south of it is the 2.5-billion-year-old Archean “sister.” The Tertiary granite is composed of plagioclase, biotite, quartz and contains muscovite-bearing aplite dikes. The gneissic granite of the Archean sister has similar composition but is megacrystic (relatively large crystals), is strongly foliated (parallel layers of biotite mica), weathers brownish, and is cut by dikes of the Tertiary granite.



Photograph of the Twin Sisters. The tall spire on right (north side) consists of the 28-million-year-old Almo pluton and the spire on the left (south side) consists of the 2.5-billion-year-old Archean Green Creek Complex. Although the sisters are of similar composition, the Archean sister has been strongly deformed and is a metamorphic rock called a granitic gneiss. City of Rocks National Reserve, Idaho.

The Remarkable Quartzites of Middle Mountain

In contrast to the Elba Quartzite in the Albion Mountains, the Quartzite on Middle Mountain has a higher metamorphic grade, injection of granitic intrusives and development of mylonite fabric with WNW-trending lineation. The northern part of Middle Mountain has many quarries of flaggy quartzite. The quartzite was intruded by several large bodies of foliated monzogranite and granodiorite; also, many dikes and sills of granitic and pegmatitic rocks intrude



Looking southeast along the west flank of Middle Mountain. The quartzite layers dip to the west and are subparallel to the topography. This quartzite is selectively mined as a building stone. Middle Mountain, south-central Idaho.



Large-scale, dip-slope lineations on plane of cleavage of micaceous quartzite. At this location, cleavage is parallel to bedding and the lineations formed by undulations (small open folds) of the cleavage. Middle Mountain, south-central Idaho.

the quartzite. The granitic rocks of Middle Mountain are progressively more deformed from east to west. As a rule, the micaceous quartzite dips to the west and has a well-developed lineation on the micaceous layers trending W to WNW. All deformation of the quartzites may have occurred during the Tertiary.

The **Middle Mountain shear zone** or detachment fault is exposed over much of the upper surface of Middle Mountain. It strikes NNE-SSW and dips to the west. At one time the thickness of the shear zone may have exceeded 2.5 miles (4 km). Eocene and Miocene extension moved upper rocks down to west along the west-dipping detachment faults at Middle Mountain; the deeper rocks were deformed as ductile shear zones and formed mylonites at Middle Mountain.

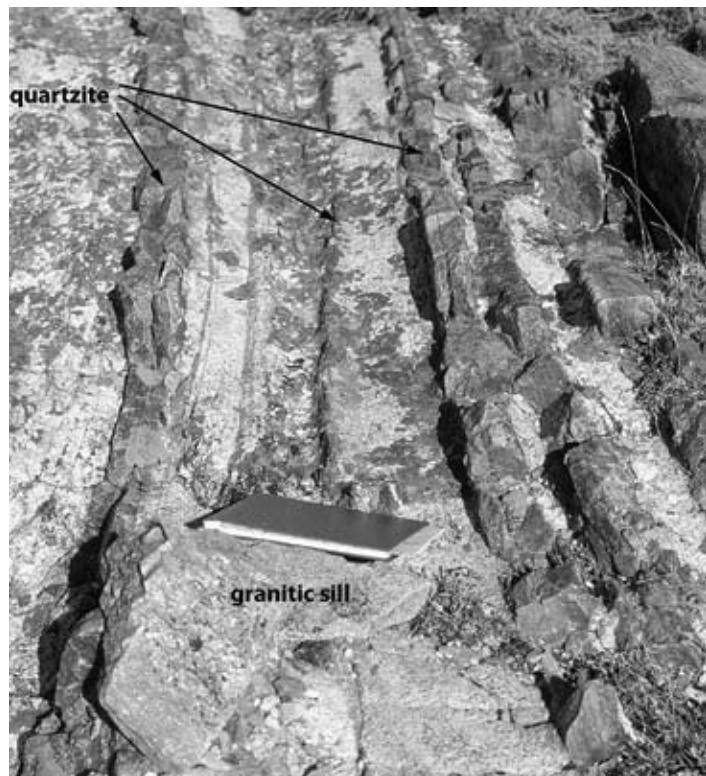
Lit-Par-Lit Gneiss. An unusual 1-m-thick layer of lit-par-lit gneiss is exposed in several flagstone quarries on the west side of Middle Mountain. This gneiss layer is conformable to the well-developed spaced cleavage in the quartzite and is typically underlain by a 3-foot-thick (1-m) mylonite layer. Felsic layers, which were injected along the cleavage planes of the quartzite, tend to maintain a constant thickness of about 0.5 to 1 inch (1 to 2 cm) for more than 328 feet (100 m). Perhaps most intriguing is the consistent 1-cm-thick spacing of the foliation planes (spaced cleavage) and the



Tightly folded micaceous quartzite with cleavage surface exposed on the upper side of the block. Cleavage was formed during the first folding event. Middle Mountain, south-central Idaho.



Approximately 1- to 1.5-m-thick layer of lit-par-lit injection gneiss exposed in building stone quarry; the felsic layers, which are intruded along spaced cleavage in the quartzite, maintain a constant thickness for more than 100 m along the quarry wall. At most exposures, the lit-par-lit gneiss is underlain by a 1-m-thick layer of light-gray mylonite. Middle Mountain, south-central Idaho.



Lit-par-lit gneiss with granitic material injected along the cleavage layers in dark-gray quartzite. The granitic layers have secondary foliation or foliation formed of aligned mica grains parallel to the cleavage in the quartzite. Middle Mountain, south-central Idaho.

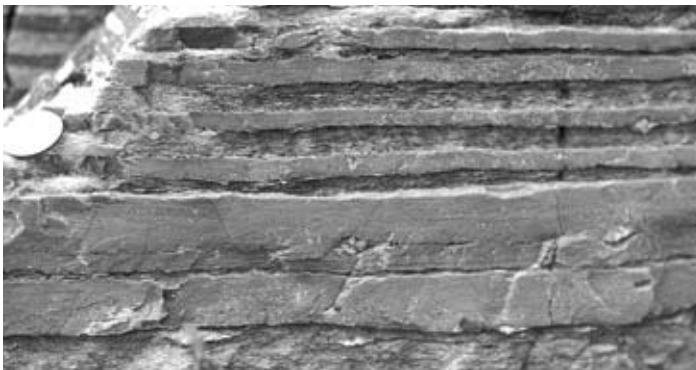


Geologist standing in front of 1- to 1.5-m-thick layer of lit-par-lit injection gneiss. This face is freshly exposed in a building stone quarry. The injection gneiss layer conformably overlies a 1.5-m-thick layer of mylonitized quartzite. Middle Mountain, south-central Idaho.

continuity of each granitic layer or sill throughout the 328-feet (100-m) length of the exposure with little or no variation in the thickness.



Lit-par-lit gneiss with thick felsic layer; however, note the faint foliation planes spaced about 1 cm apart throughout the thick felsic layer. Dark layers are quartzite. Middle Mountain, south-central Idaho.



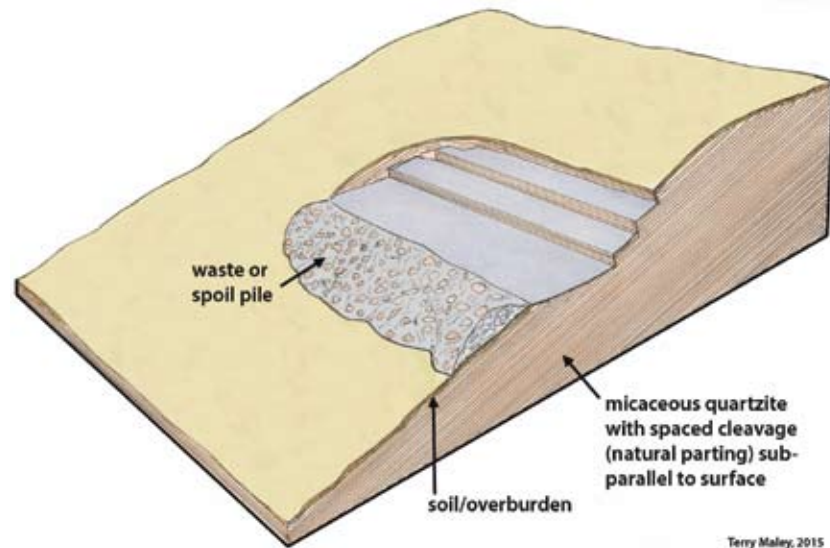
Lit-par-lit gneiss formed by thin parallel sheets of granitic material intruded along the cleavage planes of the quartzite. Note that the quartzite layers are more resistant to weathering than the granitic layers. The biotite grains in the granitic rock are parallel to the cleavage of the quartzite. Middle Mountain, south-central Idaho.

Building Stone Quarries

In south-central Idaho a very unusual rock is mined from a group of quarries situated on the west flank of Middle Mountain. This mountain, which terminates several miles south of the town of Oakley, has the appearance of a tilted fault block with a gentle slope on the west side and steep slope on the east side. In the vicinity of the stone quarries, the crest of Middle Mountain reaches an elevation 8457 feet (2578 m). The quarries are situated about half way up the west flank



Looking north at typical Quarry on the west side of Middle Mountain. Note that the pallets have plates of quartzite stacked both vertically and horizontally. The large plates must be packed vertically to avoid damage during shipping.



Terry Malley, 2015

Block diagram showing platy quartzite quarry. The fact that the spaced cleavage is approximately parallel to the surface is an important advantage in mining the stone.

of Middle Mountain at an elevation ranging from 6000 to 7500 feet (1830 to 2286 m). This rock is unusual because it can be split into large flat plates up to 8 feet (2.4 m) in diameter and less than one-half-inch (1 cm) thick. Geologists call this stone a micaceous quartzite because it is composed primarily of quartzite (silica) and muscovite mica.

Marketing History. The micaceous quartzite, sold under several different trade names, has been mined and sold in significant quantities since 1948. By the middle 1950s, this quartzite was well known by the stone industry throughout the United States. A national market was quickly established because it was much thinner than competing stone veneers. A ton



Quarry where quartzite is easily split along spaced cleavage. Note the large muscovite mica grains exposed on the well-defined cleavage surfaces. The cleavage is consistently spaced at 1 to 2 cm throughout the exposure. The cleavage is exceptionally well developed where parallel to bedding. Middle Mountain, south-central Idaho.



Large, flat plates of quartzite up to 3 m in diameter and approximately 1.5 cm thick ready for shipment; plates are stacked vertically to minimize breaking. This quartzite has a global market for veneer building stone. Middle Mountain, south-central Idaho.

of quartzite from Middle Mountain could cover 150 to 300 square feet (13.5 to 37 m²); most competing stone veneers would typically cover less than 80 square feet (7.2 m²) per ton. This superiority in coverage as well as durability and range of colors played a significant role in the stone's penetration of Canadian and European markets by the early 1970s. In Idaho, the quartzite veneer is commonly used to pave entryways, to cover fireplaces, and to cover the exterior of homes.

Spacing between the foliation planes of parting is very consistent, averaging about 0.75 of an inch (2.5 cm), but ranging from 0.25 to 4 inches (0.6 to 10 cm). The foliation planes also tend to be flat, except at localized areas. Geologists refer to this type of foliation as spaced cleavage.

Extraction at the Quarry. Large plates are removed from the outcrop using only small hand tools such as pry bars, hammers and chisels. Typically, the plates are removed from the underlying rock by driving a chisel in along the thin mica-rich layers (foliation). Once split free from its source, an individual plate may be shaped on the edges. The workers sort each plate by color and size and then place it in one of the several pallets kept within several feet of the working face of the quarry. The largest plates are packed vertically to prevent breakage during handling and transportation; all other sizes are packed horizontally. When the pallet is filled, it weighs almost 2 tons.



Truck hauling pallets of platy quartzite building stone from the quarry. Plates up to 8 feet in diameter can be transported if they are stacked vertically.