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View west at the geosite, within the selvage-joint phase of The Three Peaks intrusion. For scale, a rock hammer is near the base of the cliff, left of center and above the shadows on the left.

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A Site Bearing on the Origin of Iron Deposits in the Iron Springs Mining District, Iron County, Utah

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ABSTRACT

The discovery of the origin of iron in the Iron Springs mining district of southwestern Utah is a story of unconventional thinking based on detailed geologic mapping. This district, for many years the largest iron producer in the West, owes its resources to emplacement of three Miocene laccoliths of quartz monzonite porphyry. A visit to the geosite, in the outer part of one of them, The Three Peaks laccolith, reveals evidence of magma emplacement and mineralization of the overlying host rock. This outcrop formed by upward and outward bulging during intrusion of a rapidly congealing, crystal-rich magma. The pluton was emplaced remarkably close to the surface, about 1.2 miles (2 km) depth, and the ferromagnesian phenocrysts became unstable and broke down (deuteric alteration), releasing iron molecules into the hydrothermal solutions. As the magma solidified, subvertical extension joints formed. The radial joints in particular, oriented perpendicular to the intrusive contacts, allowed the iron-rich solutions to escape into the concordant upper contact of a pure limestone about 280 feet (85 m) thick. This limestone is the Co-op Creek Limestone Member of the Carmel Formation (Middle Jurassic). The joints tapped the solidifying crystal mush adjacent to the joints. The iron in the solutions replaced some or most of the Co-op Creek Limestone Member, creating huge ore bodies of hematite.

INTRODUCTION

The Iron Springs mining district in southwestern Utah was for many years the largest iron district in the western U.S.A. Mining began with the Utah pioneers and in fact was the reason for establishing Cedar City, which is about 10 miles east of the district (figure 1), but production then was insignificant. Mining began in earnest in 1923, but iron production climbed spectacularly during World War II (Bullock, 1970) and therefore the district was strategically important for the allies. At that time, as part of the war effort that involved most U.S. adults in some form or other, the geology of the district was studied through detailed geologic mapping and aeromagnetic surveys (by magnetometers in aircraft), and ore bodies were identified and mined. Ore was shipped by train to blast furnaces that were built at Geneva, Utah (west of Provo) and at Pueblo, Colorado. Mining continued at high production after the war, with a spurt during the Korean War, and on through the 1980s (MacDonald, 1991), closing in the mid-1990s. During this time, iron mining and businesses that depended upon it were important employers in Cedar

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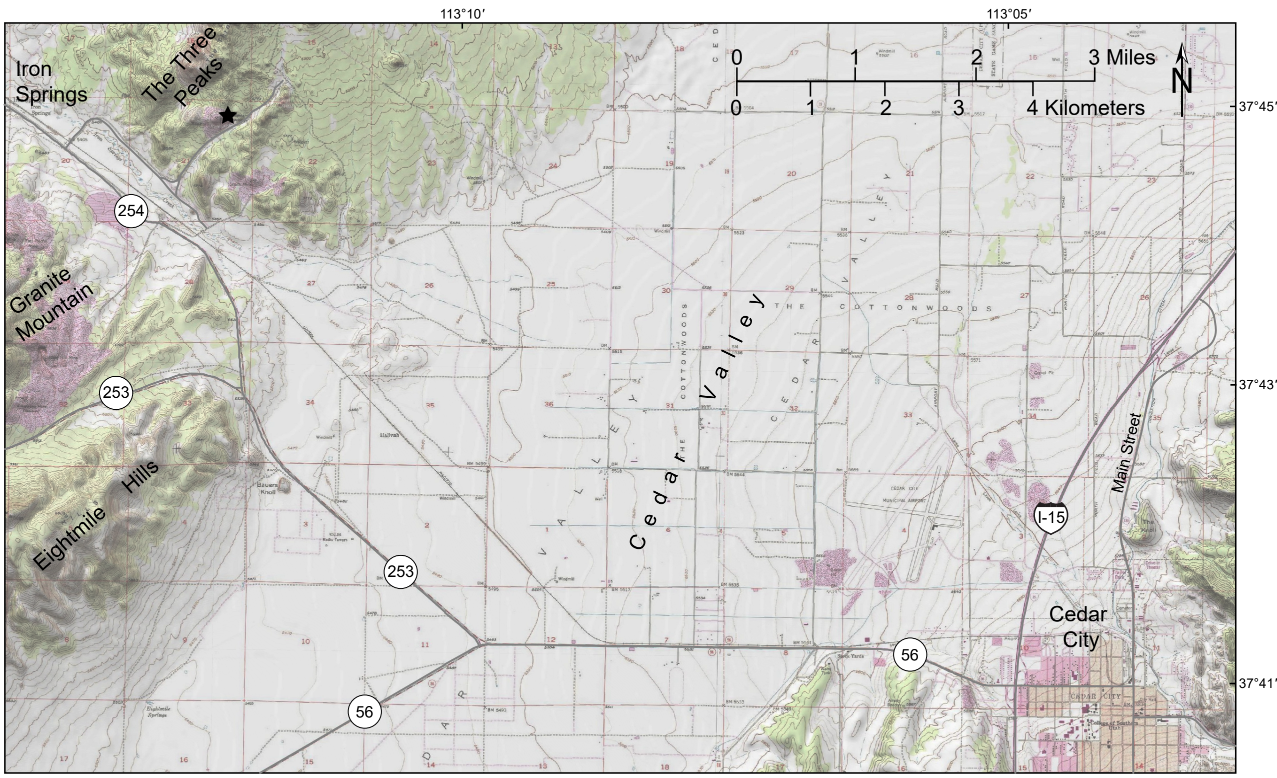

Figure 1. Location map of the Cedar City to The Three Peaks area, Iron County, Utah. The geosite is marked by a star. On the trip to the geosite, just before the turn to the Cedar City landfill, you will drive past a low barren hill just east of two former mine buildings (Utah Construction) that contains a spectacular angular unconformity. An unconformity is a surface of erosion, here beveled by stream erosion. When bedded sedimentary rocks below an unconformity have a steeper dip than the beds above the unconformity, it is an angular unconformity, for those strata were deformed before being eroded to a flat surface, then the beds above them were deposited on the surface. The rocks below this unconformity are steeply west-southwest-dipping tan sandstone of the Iron Springs Formation, deformed during thrusting. The rocks above the unconformity are more gently south-dipping pink conglomerate of the Claron Formation, concordantly dipping off The Three Peaks intrusion to the north. The erosion to form the unconformity took place sometime between Late Cretaceous (about 100- to 66-Ma) and early Eocene (56- to 34-Ma) time, a span of at least 30 million years. Paved Utah Highway 254, which you will follow through Iron Springs gap and past the angular unconformity, follows the Old Spanish Trail, partly chosen to go here because it allowed the travelers to stop at Iron Springs (labeled). Later, the springs were a watering hole for herds of cattle driven west during the mid- to late-1800s to Pioche and other mining districts to the west. The springs are a half mile (0.8 km) west of our geosite turnoff, where some buildings may be seen. Beyond the springs, and where Highway 254 is going, is a complex of white buildings in the distance known as WECCO (Western Electro-Chemical Co.), a plant that manufactures ammonium perchlorate, a component of solid-rocket fuel. This plant is a renamed version of the PEPCON plant in the suburb of Henderson, Nevada, that blew up in 1988, killing one and injuring 326 persons. For our geosite, turn northeast off the highway and cross the railroad tracks and Iron Springs Wash.

City. Mining resumed in 2010 with ore extracted from the Comstock/Mountain Lion ore bodies on northeastern Iron Mountain and shipped to China, but closed again in 2014 due to a drop in metal prices; the mine has since reopened.

This geosite is on the southwestern side of The Three Peaks intrusion, one of three mineralized plutons in the Iron Springs district. The site is significant because it illustrates how careful field observation in the course of detailed geologic mapping explained how these huge iron-ore deposits probably formed. As intruding crystal-rich magma solidified, extension joints formed to allow upward passage of iron-rich solutions derived from the breaking down (deuteric alteration) of iron-bearing mineral crystals. These solutions passed outward from the intrusive contacts to form replacement iron bodies in adjacent limestone strata. The results of deuteric alteration, explained below, are visible at the geosite.

The Iron Springs mining district occurs along the Iron Axis, a northeast-trending string of igneous plutons of Miocene age. Three of these (The Three Peaks, Granite Mountain, and Iron Mountain intrusions) were mineralized, forming the district (Mackin, 1947b, 1954, 1960, 1968; Blank and Mackin, 1967; Bullock, 1970; Rowley and Barker, 1978; Barker, 1995; Rowley and others, 2006; Hacker and others, 2002, 2007). The plutons of the Iron Axis are concordant (intrusive contacts are parallel to the bedding of sedimentary country rocks), many of them demonstrably laccoliths. Laccolithic plutons have upward-convex roofs and flat basal floors. Other workers in the district disputed the laccolith idea. Instead, while acknowledging that the roof was concordant, they argued that the lower part of the intrusion was a stock or plug whose contacts continued downward vertically. Bullock (1970) was particularly adamant in urging such a model. His reason, as with others, was that he could not see how huge hematite ore bodies could result from a laccolith. Evidence from later mapping of the plutons of the Iron Axis (e.g., Blank and others, 1992; Hacker, 1998; Hacker and others, 1996, 2002, 2005, 2007) disclosed more laccolith floors. Additionally, a petroleum exploration drill hole was spudded in the Iron Springs Formation west of the exposed part of The Three Peaks intrusion and passed entirely through the intrusion (a thickness of 2586 feet, or 788 m) and into a floor of the Carmel Formation and Navajo Sandstone, demonstrating a laccolith origin (Van Kooten, 1988).

Huge stratabound ore bodies of mostly hematite occur sporadically around the intrusive margins of the three plutons. The hematite replaced, volume for volume, limestone of the Carmel Formation (Jurassic) that is essentially adjacent to the intrusive contacts. The ore was mined by steam shovels in open pits, and some of the huge holes that remain now on the eastern side of Granite Mountain are ignominiously being filled in by Cedar City's garbage, as landfills (figure 2). Magnetite, a

Figure 2. View north into the Armstrong pit at Granite Mountain, now the site of the Cedar City landfill. Note the warped, near-vertical Iron Springs strata in the pit wall on right (east); the Granite Peak intrusion forms the left (west) wall of the pit. The Three Peaks is visible in the distance. Photo courtesy of Tyler Knudsen.

higher grade of iron ore but more difficult to smelt, also was mined, but a much smaller volume. The magnetite occurs in "veins" or "dikes," as much as 10 feet wide, within the plutons.

Most information on the ore deposits of the Iron Springs district during World War II came from plane-table mapping (at scales of 1:1200 to 1:4800, including the topography inasmuch as no detailed topographic maps existed at the time) and related field and laboratory studies by J. Hoover Mackin. Mackin was a Professor in the Department of Geology at the University of Washington before and after the war, but during the war was employed by the U.S. Geological Survey (USGS). Magnetometer surveys and diamond drilling accompanied the mapping, as he and assistants worked closely with economic geologists, geophysicists, and drillers employed by the U.S. Bureau of Mines and by the three mining companies in the district, U.S. Steel, CF&I Steel, and Utah Construction and Mining. After the war, Mackin published his scientific conclusions. These included geologic maps, aeromagnetic surveys, and summary reports on the district, as well as reports on more regional aspects that resulted from his discoveries during his war efforts, such as structural geology and the volcanic rocks. Back at the University of Washington, and later when he was hired by the University of Texas, Mackin enlisted the aid of his graduate students in at least a dozen masters and doctorate studies of the geology of areas in and extending outward from the district. Rowley was Mackin's last graduate student to finish his studies before Mackin died in 1968. Best known as a geomorphologist, Mackin in fact was a genius and a great field geologist, whose sense of humor and larger-than-life personality helped make him the best teacher Rowley and virtually all other students who took his classes ever had. He received many awards and was a member of the National Academy of Sciences, but tragically he died early (not yet 63 years old) of a bad heart valve (Anderson and others, 2001). He was a generalist who did his best thinking in the field, but hardly an expert on mineral deposits. His brain and mapping skills nonetheless led to an innovative hypothesis for the origin of the ore deposits at Iron Springs. Then he reached out to collaborators who were excellent economic geologists and petrologists, and with their counsel he refined his ideas. Much of the evidence for his hypothesis on the origin of the iron deposits came from The Three Peaks intrusion, although it had the fewest ore bodies, and the geosite is here. Mackin's hypothesis was given in abstracts in 1946-1948 (Mackin, 1946, 1947a; Mackin and Switzer, 1948), a remarkably perceptive report in 1947 (Mackin, 1947b), the expanded text of his Granite Mountain map (Mackin, 1954), and a short paper in 1960, this last one with a junior author who was an outstanding economic geologist (Mackin and Ingerson, 1960). Mackin called it the deuteric-release hypothesis. Harold L. James, a friend and equally renowned (member of the National Academy of Sciences, a Chief Geologist of the USGS) economic geologist, stated in his memorial to Mackin that this hypothesis was "one of the finest contributions to the science of ore deposits of the past three decades" (James, 1974). It was not until much later (1995) that Daniel S. Barker, a young Professor at the University of Texas, was able to put together the geochemistry that made Mackin's hypothesis a likely explanation. Barker took such a long time because he feared that he could not be objective, for he not only loved Mackin as we did but he married Barbara, Mackin's beautiful daughter!

LOCATION

The geosite is in the southwestern part of The Three Peaks pluton, at the northern edge of the Cedar City NW 7.5-minute quadrangle, west of Cedar City, Iron County, Utah. The coordinates are: 37°44'53" N., 113°12' 01.32" W. A word of warning about the geosite—after a significant rainfall, the dirt road that allows the final access to the site is likely to become a mudhole. A four-wheel drive vehicle may be necessary to reach the site and even such a vehicle might not be good enough!Past these mudholes and after the dirt road swings north, you will go past some blocky outcrops, first on the left, then on the right, of the peripheral shell of The Three Peaks pluton. This fresh, hard, fine-grained igneous rock is the chilled margin of the once intruding, semi-molten pluton. From these outcrops it is 0.7 miles (1.1 km) farther north to the geosite. Before you reach it, you will pass mine dumps and two mine roads that head west to the Great Western mine, a shallow pit that mined a northeast-trending "dike," about 10 feet (3 m) wide, of magnetite. If you look south just before you reach the geosite, you will have a good view of Granite Mountain and big pits that were mined for iron at the intrusive contact (figure 3). A geologic map and stratigraphic column of the area is shown by figures 4 and 5.

GEOLOGIC SETTING

The Iron Springs mining district is in the Great Basin, a physiographic province west of the stable Colorado Plateau and making up the western half of Utah and all of Nevada. The Great Basin was formed starting about 20 million years ago, when east-west regional extension (pulling apart in an east-west direction) created north-trending basin-range normal faults that broke the Earth's crust into north-trending ranges and alternating north-trending basins. Most basin-range deformation, however, has taken place since about 10 million years ago, when the present topography began to be created (Anderson and Mehnert, 1979; Rowley and others, 1979, 1981, 2006; Rowley, 1998; Hurlow, 2002). The great north-trending Hurricane fault, which passes through the eastern edges of Cedar City and creates the Hurricane Cliffs south of Cedar City, marks the boundary between the Great Basin and Colorado Plateau. It is

Figure 3. View south from the geosite toward the Granite Mountain pluton and the mined pits that surround it.

a normal fault with vertical, down-to-the-west displacement of at least 6000 feet (1800 m) (Hurlow, 2002). Cedar basin west of it is a typical north-trending basin, whereas the hills and mountains of, and south of, the Iron Springs district can be looked upon in aggregate as a typical north-trending range. A down-to-the-east normal fault zone that forms the western margin of Cedar basin chopped off the eastern side of The Three Peaks pluton and dropped it down so that it is now concealed beneath basin-fill sediments.

The oldest rock unit exposed in the Iron Springs district is the Manganese Wash Member of the Temple Cap Formation of Early Jurassic age, an olive-colored sandstone and siltstone no more than 50 feet (15 m) thick. It exhibits hornfels-grade contact metamorphism in the district because it is in contact with the intrusions. The unit was originally assigned as the basal siltstone member of the Carmel Formation (Mackin, 1947, 1954), but was reassigned following Sprinkel and others (2009, 2011) and Doelling and others (2013). Regionally, Temple Cap strata unconformably overlie Lower Jurassic Navajo Sandstone, a massive pink eolian (from sand dunes) sandstone about 2000 (600 m) feet thick. The Middle Jurassic Carmel Formation, which overlies the Temple Cap and is marine, consists of a lower Co-op Creek Limestone Member about 280 feet (85 m) thick and an upper Crystal Creek Member about 200 feet (60 m) thick; upper members of the Carmel are cut out under the Cretaceous unconformity (Knudsen and Biek, 2014). The Co-op Creek Member was mineralized, whereas the Crystal Creek Member, a sandstone, was not. Overlying rocks include the enigmatic Marshall Creek Breccia (a possible sedimentary breccia) overlain by the Upper Cretaceous Iron Springs Formation, about 3000 feet (1000 m) of mostly non-marine tan mudstone and sandstone and subordinate limestone, conglomerate, and coal. Iron Springs strata are in turn overlain by the Eocene Claron Formation, generally pink in its lower part and white in its upper part, consisting of mostly fluvial but locally lacustrine mudstone, sandstone, limestone, and conglomerate almost 2000 feet (600 m) thick; Claron strata are unusual in that they are mostly altered into a stacked sequence of paleosols (fossil soils). A series of volcanic rocks of Oligocene and Miocene age, virtually all ash-flow tuffs that erupted from calderas in the Great Basin, are almost 1500 feet (500 m) thick. All these rocks predated emplacement of the laccoliths and represent a total cover of only about 1.2 miles (2 km), so the laccoliths were intruded remarkably close to the surface.

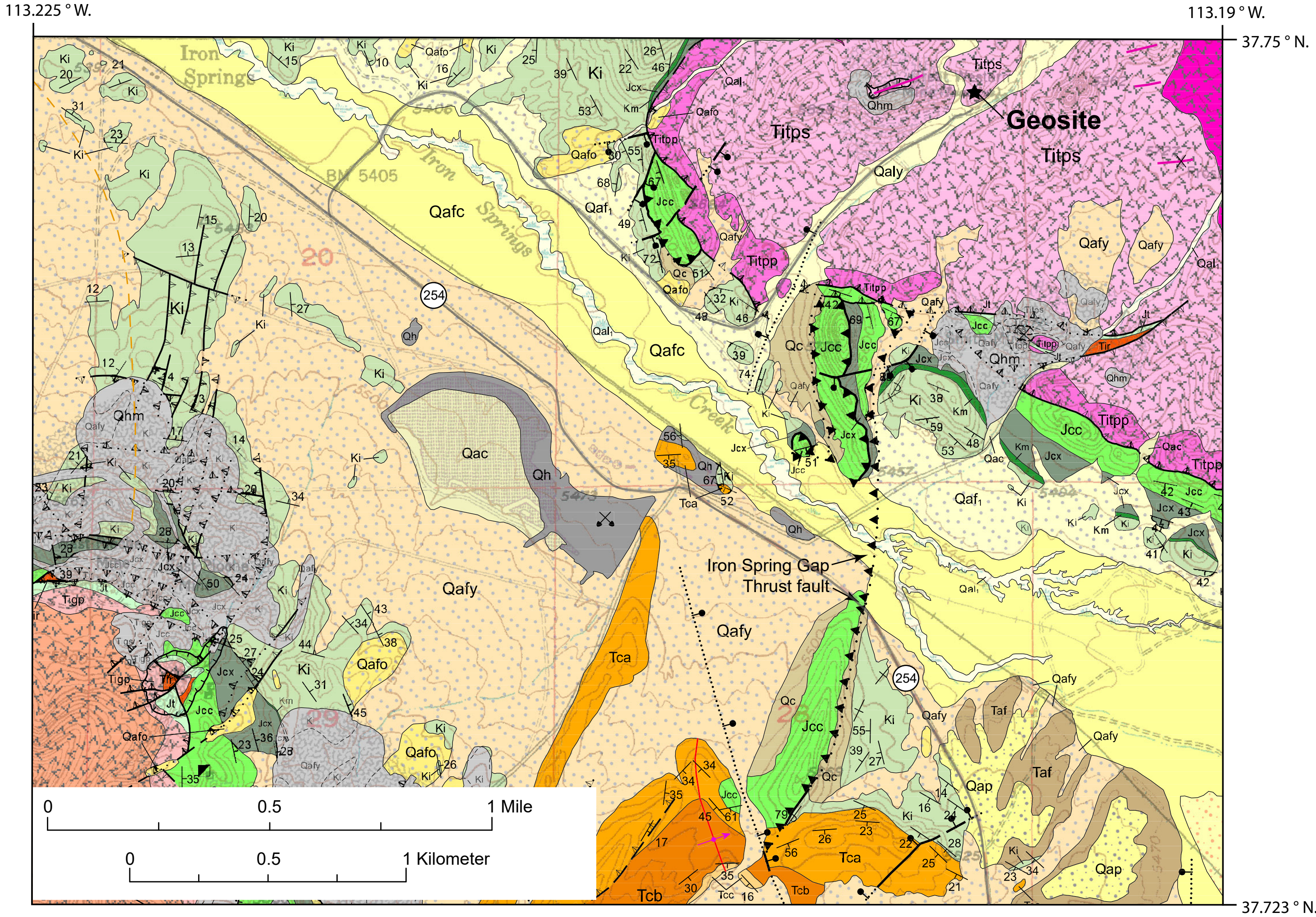

Figure 4. Geologic map of the southern part of The Three Peaks intrusion and adjacent places, Iron County, Utah. The geosite is marked by a star. See figure 5 for map units. Gray areas show mined or disturbed ground with underlying geology from Mackin and others (1976) and Mackin and Rowley (1976). Modified from Knudsen and Biek (2014).

The laccoliths of the Iron Axis rose above a large source batholith at depth, guided by the Iron Springs Gap thrust, one of the main Late Cretaceous to Paleocene Sevier thrust faults in southwestern Utah. In the district, the thrust places Jurassic Temple Cap and Carmel strata over Cretaceous Iron Springs strata and provided a pathway for magma to migrate through the massive Navajo Sandstone. The laccoliths are 22 to 20 million years old, slightly predating initiation of basin-range tectonism (Hacker, 1998; Rowley, 1998; Hacker and others, 2002, 2007; Rowley and others, 2006). As magma rose along the thrust fault it intruded beneath the Manganese Wash Member, then bulged it, the Carmel, and overlying rocks upward to form laccoliths (figure 6). The floor of the laccolith is largely the contact with the underlying Navajo. Each pulse of the laccolith magma (a liquid mush containing solid minerals that had crystallized) pushed up overlying rocks. Shallow intrusions such as this are called hypabyssal, and are common in mining districts in the West.

Emplacement of Iron Springs intrusions was remarkably rapid, such that the slab of Temple Cap and younger strata bulged faster than streams could erode them, and the slab grew rapidly into mountains with considerable relief. Inasmuch as some of these rocks were unstable mudstones (in the Iron Springs Formation) to begin with, the result of the growth of many of these mountains was gravity slides that resulted from

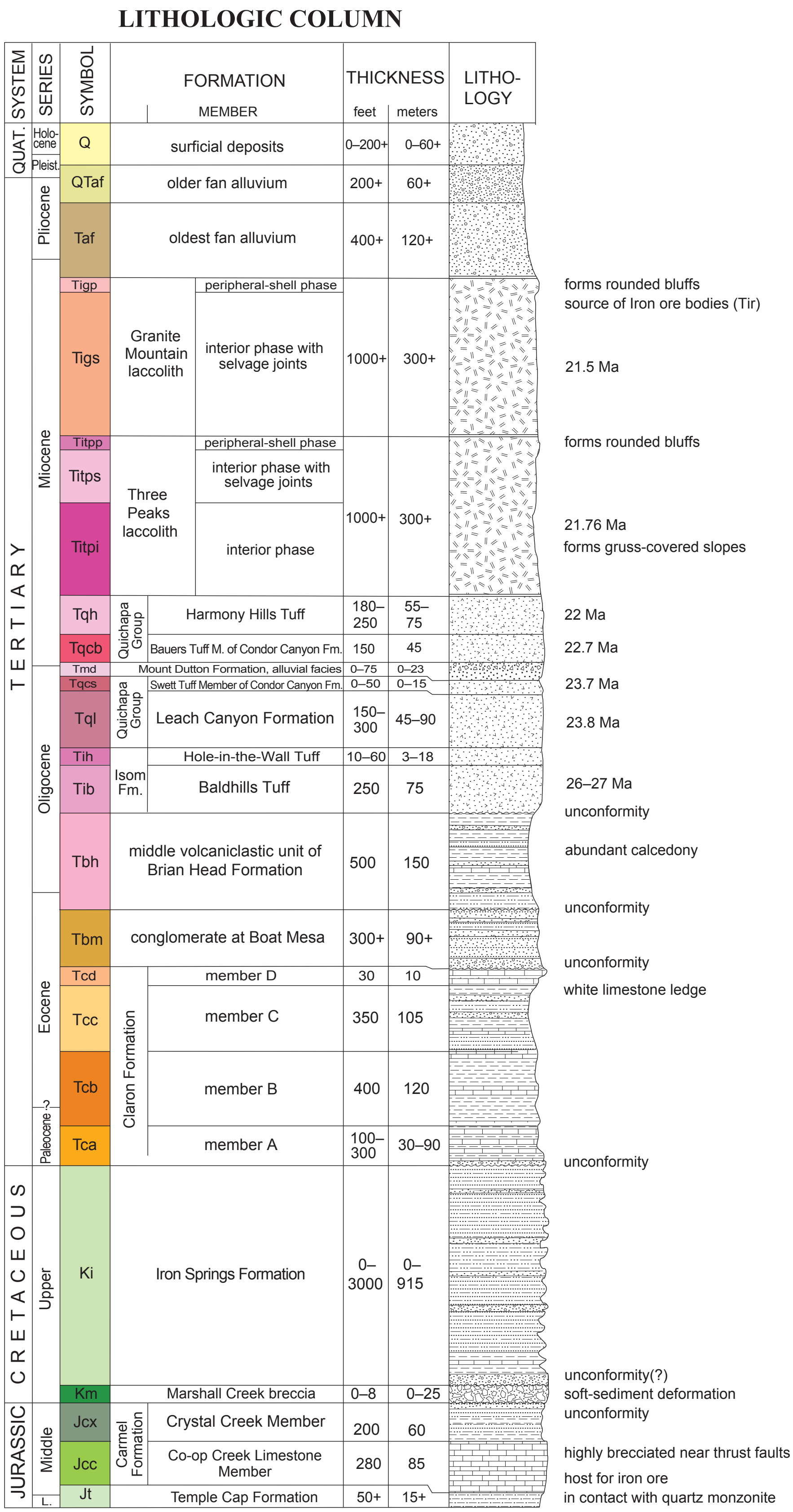

Figure 5. Stratigraphic column showing rock units in the geosite area. From Knudsen and Biek (2014).

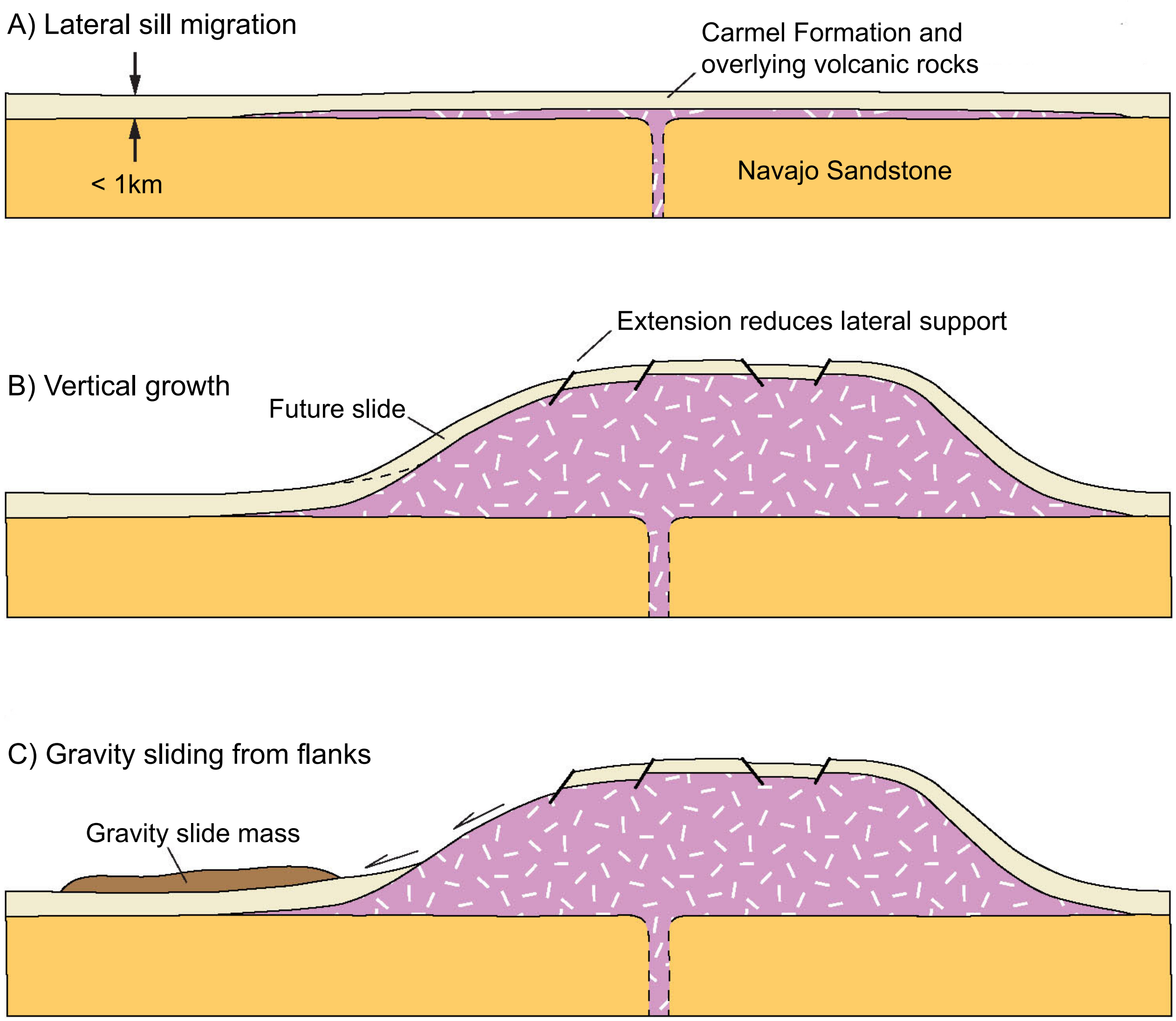

Figure 6. Schematic diagram illustrating growth of a typical laccolith. (A) Initial lateral migration of a sill within the Carmel Formation to its fullest extent at a relatively shallow depth, (B) vertical growth of the laccolith by continued injection of magma, and (C) gravity sliding of oversteepened flanks. Modified from Willis (2002) and Hacker and others (2002).

failure of mudstone beds in the flanks of the laccoliths. The Iron Mountain intrusion, in fact, shed gravity slides at least 4 miles (6.5 km) to the south and southeast (Mackin, 1960; Blank and Mackin, 1967; Hacker, 1998; Hacker and others, 1996, 2002, 2007; Rowley and others, 2006). The Granite Mountain laccolith, immediately south of The Three Peaks, also produced a small gravity slide off its southeastern flank (Knudsen and Biek, 2014). For some intrusions, although not the three mineralized ones, gravity slides took off part of the cover rocks to breach the upward moving, partly molten intrusion (Hacker, 1998; Hacker and others, 2002, 2007), like popping the cork on a bottle of champagne and much like the gravity slide ("the bulge") on the northern flank of Mount St. Helens, Washington, whose failure in 1980 was triggered by an earthquake, resulting in the May 18 eruption.

In his detailed mapping of The Three Peaks pluton, Mackin (1947b) paid particular attention to the joints within the intrusive rocks, and their comparison to flow foliation in the rock. He realized very quickly that joints were part of the story on how the hematite and magnetite ore bodies formed. The flow foliation, identified by the pattern of the phenocrysts in the rock, told him the directions that the crystal mush moved as it pushed upward and outward against the country rocks. When used in conjunction with careful mapping of the intrusive contacts, he identified not only bulges and folds of semi-solid magma at the contact but also places where the contacts were broken by this outward movement along intrusive faults. The flowage of the magma controlled the development of extension joints, and the tighter the folded magma, the more gaping were the joints. As in most plutons, joints were of three types based on their trend: (1) radial to a central part of the pluton (that is, perpendicular to the intrusive contacts), (2) concentric to the contact, and (3) oblique. These joints were extension joints, subvertical and widest (open) near intrusive contacts and tapered and terminating downward into the pluton. The joints related directly to the flow foliation, indicating that they were extending as the crystal mush was flowing. In other words, the joints developed as the intrusive mass was solidifying but being pushed by younger magma pulses coming up the laccolith feeder. The higher the angle of the flow foliation, the more the magma was pushing outward against the intrusive contact and the more open were the extension joints. Of course, as the upper convex surface of the laccolith was growing and moving upward, closer to the surface, the upper parts of the molten mass expanded as the lithostatic pressure decreased.

Most plutons in the Iron Axis have three lithologic phases whose mapping suggested the deuteric-release hypothesis to Mackin (Mackin, 1947b, 1954, 1960, 1968; Mackin and Ingerson, 1960; Mackin and others, 1976; Mackin and Rowley, 1976; Rowley and Barker, 1978; Barker, 1995; Rowley and others, 2006). These phases, from intrusive margin to interior, were the thin (less than 100 yards [30 m]) peripheral-shell phase, the selvage-joint phase, and the interior phase. Chemically and petrologically, however, all phases are quartz monzonite porphyry (phenocrysts of plagioclase and quartz and ferromagnesian minerals in a fine-grained crystalline mass), a rock type common in mineralized Tertiary plutons.

The peripheral shell consists of resistant, fresh, fine-grained rock that represents the chilled margin of the pluton, whereby the semi-molten rock rapidly froze (consolidated) against the cool country rocks of the Temple Cap and Carmel Formations. In contrast, the interior phase is altered coarse-grained rock, easily eroded to lowlands. Here magmatic water (deuteric solutions) within the crystal mush altered the rock, in other words the mush "stewed in its own juices" and the phenocryst minerals broke down into alteration clays and other secondary minerals. At the shallow level in the crust where they had been emplaced, the rock was unstable because it had originated and partly crystallized under deeper and hotter conditions in the source batholith.

The selvage-joint phase is the interesting phase, for its story relates to the joint study. The word selvage comes from a border on a piece of cloth that is finished so as to prevent unraveling. Rock selvages are the borders of the extension joints, averaging about 2.5 inches (6 cm) wide on each side, containing rock that is deuterically altered (a reaction between primary magmatic rock and water-rich solutions that separate from the magma during late-stage cooling). Farther away from the joints, however, the rock is fresh. Selvage rock resembles that of all the interior phase. Chemical analyses of the selvages shows that the rocks are depleted in iron by about 30 percent when compared with fresh rock inward from selvages, from peripheral shell rock, and—perhaps unexpectedly—from interior rock. Furthermore, the extension joints in the selvage-joint phase contain magnetite crystals or crusts, giving Mackin the idea of where the iron-rich solutions or gases went (both liquids and gases are possible)! In places, closer to the intrusive contacts, where the magnetite "veins" were as much as 10 feet (3 m) wide, the extension joint opened progressively wider and wider with time, each time producing a magnetite coating. Iron-rich solutions came from the breakdown (deuteric alteration) of ferromagnesian phenocrysts, especially biotite but also hornblende and pyroxene, in the solidifying crystalline mush of the selvage-joint phase. The extension joints, especially the radial joints, provided the avenue for escape upward of the iron solutions. In contrast, joints were poorly developed and much less common in the interior phase, and none contained selvages, so here the rocks entirely altered in place, contributing no iron to the ore bodies.

Intrusive faults formed where the outward and upward pressure broke the rocks above rather than folding them. Many of these faults are reverse faults that dip inward into the pluton and provide a way that inward parts of the pluton push upward and flare outward. Intrusive faults are important because they tapped the extension joints and provided the main escape for the solutions through the peripheral shell, which congealed rapidly and was largely solid while the rest of the pluton was a crystal mush. In fact, mapping showed that many of the ore bodies are found adjacent to intrusive faults. The largest ore body that was mined in the district was the Comstock body within the Iron Mountain intrusion, where intrusive faults created a graben of limestone that dropped into the crystal mush. Once the iron solutions escaped the peripheral shell, they replaced the nearly adjacent Carmel limestone.

A calculation of volumes of selvage rock indicated that all the huge hematite ore bodies could be accounted for as coming from selvage rock. The Three Peaks pluton had far fewer mineable hematite bodies because its roof was relatively flat (as indicated by flow foliation), whereas the roof of the Granite Mountain pluton arched much more and hematite ore bodies surround parts of the intrusive contact. In the same way that a plate of plexiglass has more and larger extension cracks (and failure, the equivalent of intrusive faults) the more it is bent, greater arching of the solidifying magma produced more and larger extension joints. The Iron Mountain pluton, which has still higher structural relief (uplift and arching), contains the largest ore bodies in the district because its roof was especially peaked and bulged, and large intrusive faults cut pluton margins. Furthermore, no interior phase is exposed in these two plutons; nearly the entire exposed volume of the plutons is selvage-joint phase.

THE SITE ITSELF

As one stands in the dirt road, facing west at the geosite, you will see a cliff of light-gray selvage-joint-phase plutonic rock at least 50 feet (15 m) high (figure 7). It is cut by many vertical joints that trend west, the radial joints. Such a high concentration of joints characterizes the selvage-joint phase. Close inspection reveals that light-green altered rock lines both sides of each joint. These are the selvages, with the light-green color coming from altered ferromagnesian minerals. Yet inward from the selvages, the ferromagnesian minerals are fresh. Most of the joints are lined with magnetite crystals. If you walk up into the saddle just north of the cliff face, you will see a magnetite "dike" about a foot wide. It grew incrementally from the edge to the middle as the joint opened up periodically due to new pulses of upward- or outward-pushing crystal mush, and each time iron-bearing solutions moved vertically and laterally toward the intrusive contacts. Pale-yellow crystals of apatite, whose long axis is horizontal and normal to the controlling extension joint, are apparent. The top of the dike contains a fuzz of tiny magnetite fragments magnetically attached; the upper part of the dike is a natural magnet, called lodestone, due to lightning strikes (you may know that magnetite is high in iron and is attracted to a magnet, but it does not attract iron by itself; an external energy source, such as lightening, is needed to align its molecules to make it into a magnet).

This geosite is significant because it illustrates how careful field observation in the course of detailed geologic mapping resulted in a logical explanation of how huge, economically important iron-ore deposits likely formed. The deuteric-release hypothesis should be an idea that geologists carry around in their heads when they study other ore deposits of iron and other metals adjacent to other hypabyssal intrusions.

ACKNOWLEDGMENTS

Early visits by the senior author to the outcrops making up the geosite discussed here were done with Hoover Mackin, Paul L. Williams, John J. Anderson, and Dan Barker. These mentors used it as a focal point to start a wide-ranging discussion on the origin of the iron deposits, for which we thank them. We later reciprocated when we brought many students and others to the geosite over many years. We are grateful to Grant Willis and Mike Hylland (UGS) and Kimm Harty (UGS retired) for technical review of this manuscript, and Lori Douglas (UGS) for drafting the figures.

Figure 7. View west at the geosite, within the selvage-joint phase of The Three Peaks intrusion. For scale, a rock hammer is near the base of the cliff, left of center and above the shadows on the left.

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