REVISED MAPPING OF BEDROCK GEOLOGY ADJOINING THE UTAH FORGE SITE

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Plates 1 & 2

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ABSTRACT

The bedrock of the central Mineral Mountains is dominated by an Oligocene through Miocene intrusive batholith emplaced in older Precambrian metamorphic rocks and a series of Paleozoic sedimentary rocks. Most exposed rocks consist of a variety of granitoid intrusives and a few exposures of related diorites, and adjoining gneiss, schist, and quartzite. All of these rocks are intruded by late-stage dikes that range from felsic to mafic in composition. Paleozoic wall rocks are exposed along the north and southeast parts of the intrusive complex. A significant series of Quaternary rhyolite and tuff, consisting of high-standing domes and drainage-filling flows, occurs across the central Mineral Mountains. The intrusive and metamorphic rocks exposed in the central Mineral Mountains are directly analogous to reservoir rocks at the Utah FORGE site.

Precambrian metamorphic rocks form screens and wall rocks along the western margin of the batholith. These rocks consist primarily of Precambrian banded gneiss (~1720 Ma) and minor associated quartzite and sillimanite schist. Intrusions of Oligocene granodiorite (~ 26 Ma) occur along the western flank and at the northern end of the batholith. Most of the exposed batholith consists of Miocene (~17–18 Ma) intrusions of granitoid rocks that include granite, quartz monzonite, syenite and diorite. The oldest of these rocks is a locally comingled series of hornblende-bearing granite, quartz monzonite, and diorite. Most of this phase of hornblende-bearing intrusives consists of medium- to coarse-grained granite that contains potassium feldspar, quartz, biotite, and hornblende. A series of smaller syenite intrusions occurs along the western flank of the Mineral Mountains. Map relations and chilled margins along contacts indicate the unit was emplaced between 17.5 and 18 Ma. A medium-grained biotite granite makes up most of the eastern part of the batholith. This unit intrudes older hornblende-bearing units forming a large contiguous body in the central Mineral Mountains. A series of late Miocene (~11 Ma) intrusive dikes that consist of granite, porphyritic rhyolite, diabase, and andesite, cross-cut the older intrusive and metamorphic rocks across the range.

INTRODUCTION

This chapter summarizes the revised mapping of the bedrock geology of the central Mineral Mountains adjoining the Utah Frontier Observatory for Research in Geothermal Energy (FORGE) site. The metamorphic and intrusive bedrock exposed in the Mineral Mountains is contiguous and directly analogous to the bedrock at the Utah FORGE site. The proximity and correlation between reservoir and exposed bedrock represents a unique opportunity to study and quantify rocks and processes at outcrop scale that are likely to be observed in the borehole.

This mapping was completed as part of FORGE project phase 2b in 2017. The bedrock geologic map presented in this section is based on the digitized version of Sibbett and Nielson (1980) and the subsequent unit correlations and age information presented by Coleman (1991) and McDowell (2004). Map alterations and adjustments were made based on fieldwork during the summer of 2017.

Previous bedrock mapping includes early work by Sibbett and Nielson (1980), who mapped the entire central Mineral Mountains and defined basic geologic units. Their mapping was completed as part of Department of Energy (DOE)-funded geothermal investigations related to development of the Roosevelt Hot Springs hydrothermal system. Lipman et al. (1978) mapped and subdivided the Quaternary rhyolites of the Mineral Mountains and other nearby extrusive volcanic units. Alienikoff et al. (1987) mapped and subdivided Precambrian metamorphic rocks and intrusive rocks on the northern and western margins of the central Mineral Mountains. Coleman (1991) and Coleman and Walker (1992) present localized detailed mapping and new unit correlations for intrusive rocks of the central Mineral Mountains. McDowell (2004) presents detailed mapping of a strip of bedrock along the western flank of the Mineral Mountains. Regional scale (1:100,000) geologic mapping by Hintze et al. (2003) and Rowley et al. (2005) provide detail on the Paleozoic wall rocks that adjoin the batholith to the north and southeast.

METHODS

Previous bedrock mapping by Sibbett and Nielson (1980) was digitized and turned into a GIS product in spring 2017 and released as a Utah Geological Survey Miscellaneous Publication (Sibbett and Nielson, 2017). This mapping is contiguous across the

Mineral Mountains and the geologic units are accurately described. The mapping of Sibbett and Nielson (2017) was therefore used as the basis for the bedrock geology. Subsequent work by Aleinikoff et al. (1987), Coleman (1991), Coleman and Walker (1992, 1994), and McDowell (2004) has better defined age and lithologic correlations of the bedrock in the Mineral Mountains. These age data and unit correlations were applied to the Sibbett and Nielson (2017) map following the scheme presented by Coleman (1991) (Table 1). The resulting map was edited and checked based on several weeks of fieldwork in the summer of 2017. Plates 1 and 2 present the revised bedrock geology merged with a simplified and expanded version of Quaternary mapping by Knudsen et al. (2019) completed as a part of FORGE project phase 2b. Plate 2 presents a correlation diagram of map units based on the revised bedrock mapping. Map units are described in detail on Plate 2 and a discussion of these units is presented below.

Table 1. *Correlation matrix used to revise bedrock nomenclature for intrusive and metamorphic rocks of the central Mineral Mountains. Correlation largely follows the schema presented by Coleman (1991).*

Coleman (1991) Unit	Age (Ma)	Rock Type	Sibbett and Nielson (2017) Unit	Rock Type
Mpr	11	Porphyritic Rhyolite	Tpr	porphyritic rhyolite dikes
			Trd	rhyolite dikes
Mhd	11	Hornblende Diabase Dikes	Tds	diabase dikes
			Tmd	microdiorite dikes
Mg	11	Granite Dikes	Tgr	granite dikes
Mbg	17	Biotite Granite	Tg	granite
			Tg?	granite?
Mbhs	<18	Biotite-Hornblende Syenite	Ts	syenite
Mbhg	18	Biotite-Hornblende Granite	Tbg	biotite granite
			Tqm	quartz monzonite
Mbhm	18	Biotite-Hornblende Monzonite	Ti	porphyritic quartz monzonite
Mbhd	18	Biotite-Hornblende Diorite	Td	diorite
			gd	biotite granodiorite
			Tdb	diorite breccia
Ohg	26	Hornblende Granodiorite	hd	hornblende granodiorite
			hgn	hornblende gneiss
PCss	1720	Sillimanite Schist	Xs	sillimanite schist
PCq	1720	Quartzite	Xq	quartzite
PCbg	1720	Biotite Gneiss	Xbg	banded gneiss

GEOLOGIC BACKGROUND

The Utah FORGE site is in the eastern Basin and Range Province of south-central Utah. Late Cenozoic unconsolidated deposits in the map area consist of coarse-grained alluvial deposits of late Tertiary to Holocene age, and coarse- and fine-grained lacustrine sediment deposited during at least two Quaternary lake cycles. Quaternary hot-spring deposits are common along the western margin of the Roosevelt geothermal area. Scarps of the Mineral Mountain West, NM, and Opal Mound faults offset pre-Holocene alluvial-fan deposits.

The bedrock in the Mineral Mountains, east of the Utah FORGE site, consists primarily of a Miocene- to Oligocene-age batholith complex and adjoining Precambrian metamorphic and Paleozoic sedimentary wall rocks. Exposures of the batholith cover an area of more than 200 km^2 in the central Mineral Mountains. Precambrian metamorphic rocks form screens and wall rocks along the western margin of the batholith. These rocks consist of Precambrian (~1720 Ma) banded gneiss and associated quartzite and schist (Alienikoff et al., 1987; Coleman, 1991). Small intrusions of Oligocene (~26 Ma) granodiorite occur along the western flank and at the northern end of the batholith. Most of the exposed batholith consists of Miocene (~17–18 Ma) intrusions of granitoid rocks that include granite, quartz monzonite, syenite and diorite. A series of late Miocene (~11 Ma) intrusive dikes that consists of granite, porphyritic rhyolite, diabase, and andesite cross-cut the older intrusive and metamorphic rocks throughout the range. The northern edge of the batholith intrudes Lower and Middle Cambrian quartzite, shale, and limestone (Coleman, 1991; Hintze et al., 2003). The southeast margin of the batholith intrudes upper Paleozoic wall rocks that include sandstone, limestone, dolomite, and shale (Rowley et al., 2005).

Thermochronologic, mineralogic, and textural relations in the batholithic rocks support emplacement at mid-crustal depths greater than 5 km (Nielson et al., 1986; Coleman and Walker, 1992; Coleman et al., 2001). Thermochronology also supports rapid exhumation and cooling of the batholith between 11 and 8 Ma (Coleman et al., 2001). Exhumation was likely localized along regionally extensive detachment faults (Coleman and Walker, 1994). Paleomagnetic data, dike orientations, and fracture data from various phases of the Miocene intrusions support eastward rotation of the Mineral Mountains (Coleman and Walker, 1994; Coleman et al., 2001; Kirby et al., 2017). Exhumation likely followed a rolling hinge model (Buck, 1988) whereby uplift of the igneous bedrock of the Mineral Mountains was accommodated by a combination of fault slip, rotation, and flexural rebound of the footwall of a regional detachment fault (Coleman and Walker, 1994; Coleman et al., 2001).

Volcanism began following or during active exhumation. The oldest extrusive unit is a Miocene (6.2 Ma) porphyritic quartz-latite flow that overlies Tertiary alluvial-fan deposits southwest of the Mineral Mountains. This flow and its relationship with underlying fan deposits provide basic age constraint on basin formation and consequent sedimentation immediately adjoining the Mineral Mountains.

Quaternary volcanism in the central Mineral Mountains began just after 1 Ma with the eruption of several small basaltic cones and flows along the northeastern flank of the Mineral Mountains (Hintze et al., 2003). An extended period of rhyolitic volcanism also began just after 1 Ma and continued to 0.5 Ma (Lipman et al., 1978). Age control on the rhyolites is based on a small number of older K-Ar ages presented by Lipman et al. (1978). These rocks are exposed over an area of more than 50 km^2 and they overlie intrusive and metamorphic rocks and, locally, older alluvial-fan deposits. The mapped rhyolites form a series of at least 10 distinct high-standing domes and related tuffaceous deposits that fill adjoining drainages. The rhyolitic units locally overlie the oldest Quaternary alluvial deposits and constrain the age of the oldest exposed Quaternary deposits to the middle Pleistocene.

GEOLOGY OF THE MINERAL MOUNTAINS BATHOLITH

The Oligocene through Miocene intrusive rocks of the Mineral Mountains batholith, and Precambrian metamorphic rocks, are directly analogous to the rocks beneath the Utah FORGE site. Faults exposed in the Mineral Mountains may be similar to faults encountered at depth in the reservoir rocks of the Utah FORGE site. To facilitate better understanding and correlation of these rocks, and associated faults, across the various FORGE project tasks, the exposed geology of the Mineral Mountains batholith is described in detail below.

Tertiary Intrusive Rocks

Intrusions of Oligocene granodiorite occur along the western flank and at the northern end of the batholith (Plate 1). This granodiorite is coarse- to medium-grained and consists of plagioclase, potassium feldspar, hornblende, quartz, and biotite with accessory minerals including sphene, apatite, magnetite, and thorite. Large hornblende and potassium feldspar crystals up to 1 cm are common. Coleman (1991) and McDowell (2004) note that individual potassium feldspar crystals commonly contain abundant fractures. This unit intrudes Cambrian rocks on the northern end of the batholith and intrudes Precambrian metamorphic rocks along the western flank of the batholith. The granodiorite commonly displays planar foliation. The age of the granodiorite is 26 Ma based on U-Pb zircon analyses of Alienikoff et al. (1987).

Most of the exposed batholith consists of Miocene (~17–18 Ma) intrusions of granitoid rocks that include granite, quartz monzonite, syenite, and diorite. The oldest of these rocks is a locally comingled series of hornblende-bearing granite, quartz monzonite, and diorite. Most of this phase of hornblende-bearing intrusives consists of medium- to coarse-grained granite that contains potassium feldspar, quartz, biotite, and hornblende. The quartz monzonite is medium-grained and porphyritic, and contains large potassium feldspar phenocrysts with plagioclase mantles in a matrix of plagioclase, quartz, biotite, and hornblende (Coleman, 1991). The diorite is medium- to fine-grained and contains plagioclase, potassium feldspar, quartz, biotite, and hornblende. Coleman (1991) states sphene is commonly observed in the core of plagioclase crystals in the diorite. Accessory minerals are similar amongst the hornblende-bearing suite of intrusives and commonly include sphene, apatite, zircon, and magnetite. Mineralogic composition is commonly variable across these units, and where these units are mapped adjoining one another there is locally extensive mixing of the various lithologies on a scale of less than 10 m (Coleman, 1991; McDowell, 2004). The age of the hornblende-bearing monzonite, granite, and diorite is 18 Ma based on U-Pb zircon analyses (Coleman, 1991).

Syenite is mapped as a series of smaller intrusions along the western flank of the Mineral Mountains. The syenite is medium- to coarse-grained and consists primarily of potassium feldspar with lesser amounts of plagioclase, quartz, biotite, and hornblende. Accessory minerals include sphene, magnetite, zircon, and apatite. The syenite has no direct age control. Map relations and chilled margins along contacts indicate the unit is younger than the hornblende-bearing units and older than the biotite granite and was likely emplaced between 17.5 and 18 Ma (Coleman, 1991).

A medium-grained biotite granite makes up most of the eastern part of the batholith. This granite contains potassium feldspar, quartz, plagioclase, and biotite. Accessory minerals include sphene, apatite, zircon, magnetite, and hematite, and locally the granite contains beryl, garnet, and hornblende. This unit intrudes older hornblende-bearing units forming a large contiguous body in the central Mineral Mountains. Coleman (1991) distinguished this unit from slightly older biotite-hornblende granite by the presence of abundant early resorbed quartz, late-stage interstitial quartz, and significantly less hornblende. The age is 17.5 Ma based on U-Pb zircon analyses (Coleman, 1991).

A series of young Miocene (~11 Ma) intrusive dikes that consist of granite, porphyritic rhyolite, diabase, and andesite cross-cut the older intrusive and metamorphic rocks throughout the range. The granite dikes consist of coarse- to fine-grained, typically resistant granite containing quartz, potassium feldspar, plagioclase, and biotite. Accessory minerals include sphene, apatite, and zircon. The unit includes fine-grained and coarse-grained dikes mapped as unit Tgr by Sibbett and Nielson (1980). The granite dikes intrude older rocks along the western flank of the Mineral Mountains. The current map unit correlation yields a wide zone of these dikes north of Negro Mag Wash. Individual dikes may be up to 10 m thick. Age is ~11 Ma based on U-Pb zircon analyses (Coleman and Walker, 1992). Porphyritic rhyolite dikes contain phenocrysts of quartz, potassium feldspar, hornblende, and biotite in a groundmass of potassium feldspar and quartz. Accessory minerals include magnetite and sphene. Porphyritic rhyolite dikes range in thickness from several meters to tens of meters and are oriented from sub-horizontal to sub-vertical. The age of the porphyritic rhyolite is 11 Ma based on data presented by Nielson et al. (1986) and Coleman and Walker (1994). Dark colored, fine-grained, hornblende-bearing diabase dikes contain plagioclase microlites (Sibbett and Nielson, 1980). Accessory minerals include biotite and magnetite. Individual diabase dikes are up to 10 m thick. Diabase dikes commonly co-occur with granite dikes and porphyritic rhyolite dikes and have similar orientations. The diabase dikes have no direct age data. Coleman (1991) and McDowell (2004) correlate this unit with 11 Ma granite dikes and porphyritic rhyolite dikes based on proximity and similar orientations. Porphyritic andesite dikes with phenocrysts of plagioclase and hornblende in a fine-grained glassy groundmass intrude biotite granite on the southeast flank of the Mineral Mountains. Coleman and Walker (1992) give an age of ~11 Ma based on field relations and similar orientations with other dike units.

Select whole-rock geochemical samples from the Mineral Mountains batholith are presented on Plate 2. These data are taken from geochemistry presented by Alienikoff et al. (1987) and Coleman and Walker (1992). For each sample, a map unit based on the available sample location and sample description information was added to the geochemical samples based on the correlation scheme discussed above. A simple total alkali versus silica plot displays significant compositional overlap among geologic units (Plate 2). This plot defines broad zones of geochemistry for the various units and implies that whole-rock geochemistry is variable and not necessarily sufficient to determine geologic map units. This result is broadly consistent with the observable variation in lithology at outcrop scale and the genetic relationships described between the various units (Coleman, 1991; Coleman and Walker, 1992). Alternately, whole-rock geochemistry may be under-characterized by the existing sample data and revised bedrock geology.

Precambrian Metamorphic Rocks

Precambrian metamorphic rocks form screens and wall rocks along the western margin of the batholith. These rocks consist primarily of Precambrian banded gneiss and minor associated quartzite and sillimanite schist (Alienikoff et al., 1987; Coleman, 1991). The banded gneiss consists of light-colored bands of potassium feldspar, quartz, and biotite, and dark-colored bands of biotite, plagioclase, quartz, and hornblende. Gneissic banding is commonly folded and ptygmatic in character. Accessory minerals include rounded zircon and apatite. Muscovite is locally present and useful for distinguishing this unit from the granodiorite. The gneiss also contains no sphene, whereas sphene is common in all younger intrusive units. The age of the gneiss is ~1720 Ma based on U-Pb zircon and Rb-Sr model ages presented by Alienikoff et al. (1987). Nielson et al. (1978) suggest the protolith for the gneiss may be the quartzite and schist associated with the gneiss.

Faults

Previously mapped faults in the bedrock of the Mineral Mountains (Sibbett and Nielson, 2017) consist of structures that range from steeply dipping normal faults along the western margin to gently dipping faults mapped in the central part of the Mineral Mountains. Field examination of the gently dipping faults suggest these features have offsets of less than several meters. The scale of the mapping does not allow depiction of these faults. These gently dipping faults are discussed in greater detail in a companion paper that examines fracturing in the Mineral Mountains (Bartley, 2019). The steeply dipping faults along the western margin of the Mineral Mountains commonly offset Precambrian metamorphic rocks and various intrusive phases. In outcrop these faults commonly contain discrete damage zones and defined fault planes that occur over a width of several meters. Secondary mineralization along the fault planes is common and includes quartz, calcite, and epidote. Observable slickensides indicate dip slip in most cases. Similar steeply dipping faults may exist in the reservoir rocks of the Utah FORGE site.

CONCLUSION

The bedrock of the central Mineral Mountains is dominated by an Oligocene- to Miocene-age batholith emplaced in Precambrian metamorphic rocks and a series of Paleozoic sedimentary rocks. The bedrock of the central Mineral Mountains is directly analogous to reservoir rocks at the Utah FORGE site. Most of the exposed rocks east of the site consist of Miocene (~17–18 Ma) intrusions of granitoid rocks that include granite, quartz monzonite, syenite and diorite. The oldest of these rocks is a locally comingled series of hornblende-bearing granite, quartz monzonite, and diorite. All of these rocks are intruded by late-stage dikes that range from felsic to mafic in composition. A significant series of Quaternary rhyolite and tuff, consisting of high-standing domes and drainage-filling flows, occurs across the central Mineral Mountains. The steeply dipping bedrock faults along the western margin of the Mineral Mountains offset Precambrian metamorphic rocks and various intrusive phases. In outcrop these faults commonly contain discrete damage zones and defined fault planes that occur over a width of several meters. Secondary mineralization along the fault planes is common and includes quartz, calcite, and epidote. Observable slickensides indicate dip slip in most cases. Similar steeply dipping faults may exist in the reservoir rocks of the Utah FORGE site.

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