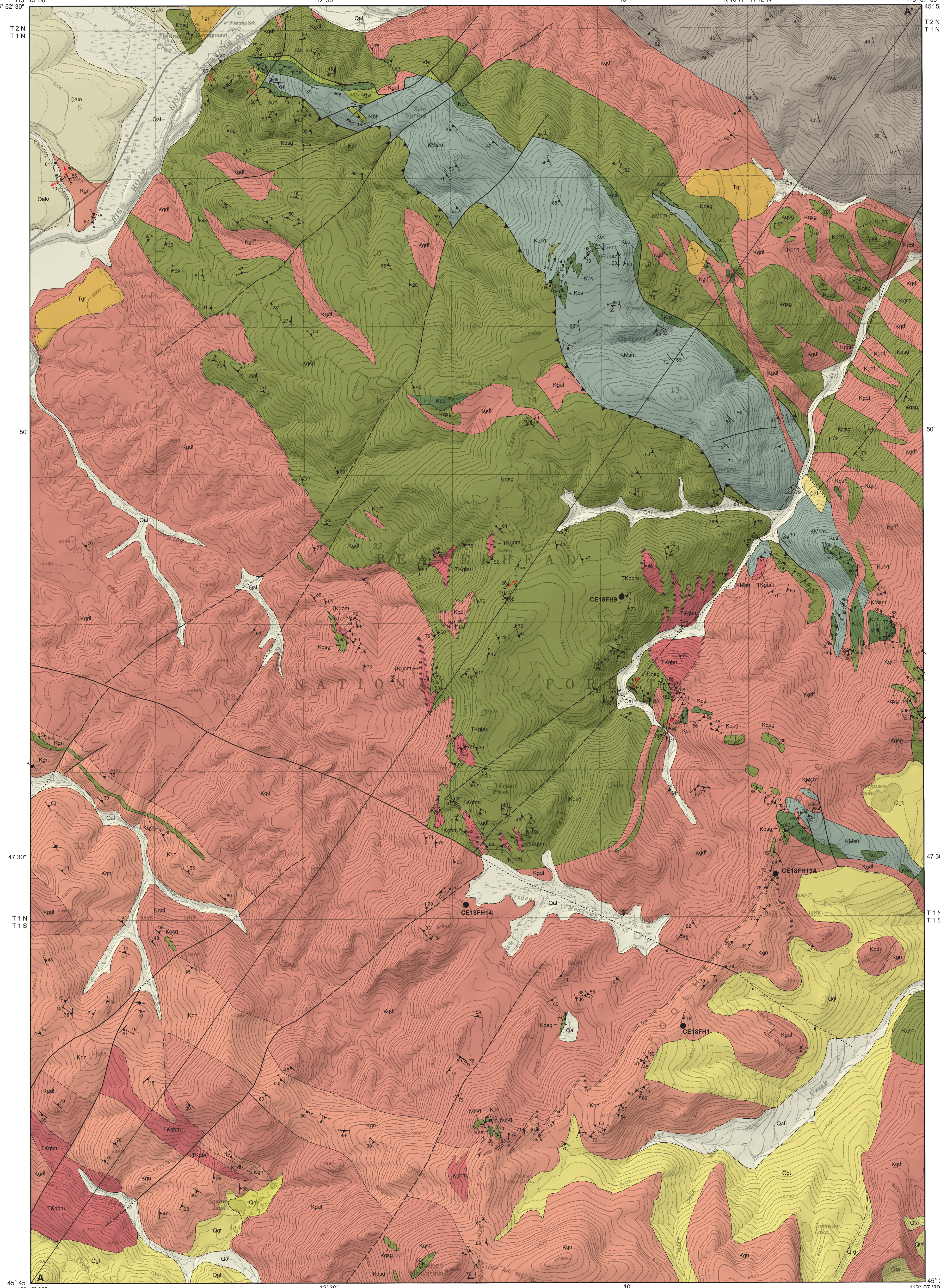


Base map produced by the United States Geological Survey
Foolhen Mountain1:24,000-scale quadrangle map
Control by: USGS and NOS/NOAA
Compiled from aerial photographs taken 1955
Field checked: 1962
Projection: Polyconic
Grid:1000 meter Universal Transverse Mercator Zone 12
UTM grid declination: 1°34' West
1988 Magnetic North Declination: 16.5° East
Vertical Datum: National Geodetic Vertical Datum of 1929
Horizontal Datum: 1927 North American Datum

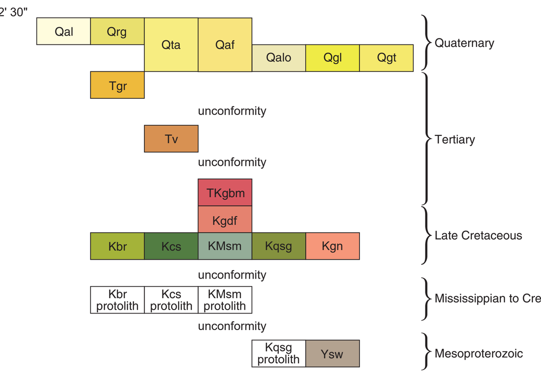
Shaded relief created from 10 meter digital elevation model from U.S. Geological Survey National Elevation Dataset.

UTM GRID AND 2017 MAGNETIC NORTH DECLINATION AT CENTER OF SHEET
1° 34´ 28 MILS
12° 52´ 229 MILS

SCALE 1:24,000
CONTOUR INTERVAL 40 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

Maps may be obtained from:
Publications Office
Montana Bureau of Mines and Geology
1300 West Park Street
Butte, Montana 59701-8997
Phone: (406) 496-4174
http://mbmg.mtech.edu

CORRELATION DIAGRAM



MAP SYMBOLS

- Contact: dashed where approximately located
- Gradational contact
- Fault: dashed where approximately located, dotted where concealed, bar and ball on downthrown block
- Reverse or thrust fault: dashed where approximately located; dotted where concealed, teeth on upthrown block
- Bedding, showing strike and dip
- Overturned bedding, showing strike and dip
- Upright bedding where tops are known, showing strike and dip
- Gneissic layering, showing strike and dip
- Vertical or near-vertical gneissic layering, showing strike
- Foliation defined by preferred dimensional orientation of grains, showing strike and dip
- Vertical foliation defined by preferred dimensional orientation of grains, showing strike
- Schistosity, showing strike and dip
- Overprinting foliation (local S2), showing strike and dip
- Disjunctive (spaced) cleavage, showing strike and dip
- Crenulation fabric, showing strike and dip
- Mylonitic foliation, showing strike and dip
- Mylonitic foliation with stretching lineation, showing strike and dip of foliation and plunge and trend of lineation
- Generic lineation, showing plunge and trend
- Slickenlines, showing plunge and trend
- Elongate clasts in conglomerate, showing plunge and trend
- Mineral lineation, showing plunge and trend
- Intersection lineation, showing plunge and trend
- Axis of minor fold or crenulations, showing plunge and trend
- Axis of symmetric minor fold, showing plunge and trend
- Axis of S-fold, showing plunge and trend
- Sample points

INTRODUCTION

The Foolhen Mountain 7.5' quadrangle map continues detailed geologic mapping in the Wisdom 30' x 60' quadrangle, a long-term Montana STATEMAP goal to fill gaps remaining in 1:100,000-scale geological coverage of Montana. The Foolhen Mountain quadrangle is unlike much of southwestern Montana in that it is underlain by high-grade metamorphic rock and migmatite, and therefore requires attention to metamorphic series more than stratigraphic sequence. This is one of the MBMG's few attempts at mapping the migmatites and high-grade metamorphic rocks of the West Pioneers, so our units and interpretations are tentative and will guide further mapping.

Geologic overview

Foolhen Mountain is in the West Pioneer Mountains (fig. 1), where two structural provinces overlap: Cordilleran fold and thrust belt structures intruded by the Cretaceous Pioneer Batholith, which characterizes the East Pioneer Mountains, and the Eocene–Oligocene Anaconda Metamorphic Core Complex (AMCC)(O'Neill and others, 2004; Foster and others, 2010), which dominates the Anaconda Range to the north. The two provinces are reflected in the West Pioneer Mountains as deeper parts of a fold and thrust belt that has been intruded by orogenic granitoids and then extended in the hangingwall of the low-angle Anaconda Detachment.

Alternating, northwest-striking bands of granitoid, granitoid gneiss, migmatite, and amphibolite facies metasediment define the dominant structural fabric of the quadrangle. The protoliths are presumably Proterozoic and Phanerozoic rocks, based on correlations with lower grade units in the adjacent 7.5' quadrangles (see previous mapping figure). Within the Foolhen Mountain quadrangle, metamorphic grade and degree of partial melting increase southwestward and the contact between migmatites and granodiorite is gradational. Sedimentary structures can be identified in the feldspathic quartzites (Ysw) in the northeast corner of the Foolhen Mountain quadrangle and some original bedding can be identified in the probable Phanerozoic sediments (KMsm), but secondary fabrics and structures dominate everywhere else.

Truckle (1988) mapped a sedimentary stratigraphy within KMsm, but we found that strain within that package is too intense to trace units laterally for any significant distance. Shear zones and isoclinal folds in bedding as well as metamorphic layering within the KMsm package indicate a complex internal structure that will require more detailed mapping to disentangle. Quartzite pebble conglomerates are locally identifiable in spite of considerable strain (fig. 2).

The northwest grain of the Foolhen Mountain quadrangle is continuous with very tight northwest-striking synforms in the east-adjacent Dickie Hills quadrangle (Lonn and McDonald, 2004), synforms that have Mesoproterozoic limbs and Phanerozoic cores as young as early Cretaceous. In the northeast-adjacent Lincoln Gulch quadrangle, the northwest-striking folds overprint the Johnson Thrust that placed Mesoproterozoic quartzite over Phanerozoic rocks in Cretaceous time (McDonald, 2011; Elliott, 2017).

The southeast corner of the Foolhen Mountain quadrangle has a north–northeast grain that mirrors the dominant trend of the fold and thrust belt of the East Pioneer Range. Pole plots of bedding, foliations, and fold axes measured in the quadrangle (fig. 3) grossly reflect folding about a southeast-plunging fold axis. This overall structural pattern does not reflect the multiple generations of folds and foliations present at the outcrop scale, and the relative ages of the large- and small-scale structures are not clear. In the Foolhen Mountain quadrangle, the north–northeast-striking gneissic foliations that dominate the southeast corner of the map appear to be overprinted and transposed into the east–southeast fabric that dominates the rest of the quadrangle (fig. 4). In the northeast-adjacent Lincoln Gulch quadrangle, the east–southeast fabric, represented by steep axial planes, appears to be overprinted by north- and northeast-striking folds (Elliott, 2017).

The steep 045°- to 050°-striking faults that cut across bedrock may be related to extension on the Anaconda Detachment. They are 5–10° oblique to the strike of the Anaconda Detachment in the Big Hole valley (figs. 1, 3), and perpendicular to the measured extension direction on the detachment (Elliott and Lonn, in review; Howlett and others, 2020). The youngest structure in the quadrangle is a roughly 115°-striking brittle fault that has a small down-to-the-south offset.

Future mapping in the 7.5' quadrangles south and west of Foolhen Mountain will focus on distinguishing between igneous protoliths, on overprinting relationships between foliations, structures, and metamorphic minerals, and on the mechanisms and structures that brought rocks from the middle crust to the surface in the West Pioneers.

Figure 2. Highly strained and metamorphosed conglomerate in KMsm near Calvert Hill. Pencil is approximately 15 cm long.

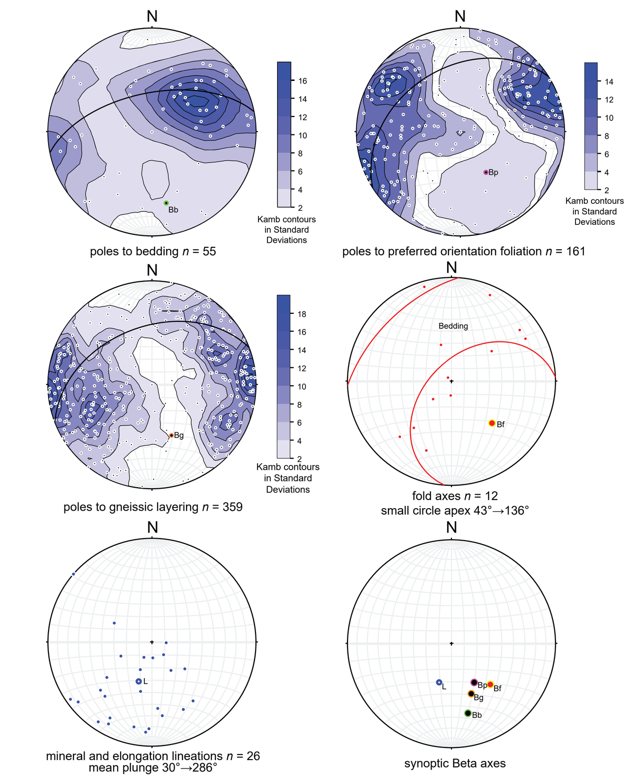


Figure 3. Equal area, lower hemisphere stereonet plots of orientation data from the Foolhen Mountain quadrangle. The synoptic plot in the lower right shows the fold axes (B) as determined from poles to bedding (Bb), poles to preferred dimensional orientation foliations (Bp), poles to gneissic foliation (Bg), and the apex of the small circle distribution of outcrop-scale fold axes (Bf). The center of the lineation distribution is marked as "L." All data point to a map-scale structure that plunges moderately towards the southeast.

Figure 4. Evidence of transposition in Kgn with a probably igneous protolith. A lozenge with gneissic layering parallel to the top edge of the photo is preserved within gneissic layering that is parallel to the sides of the photo.

Figure 5. Two-mica granite gneiss from an inclusion within Kqsg.

Figure 7. Interlayered calcsilicate and marble inclusion within KMsm.

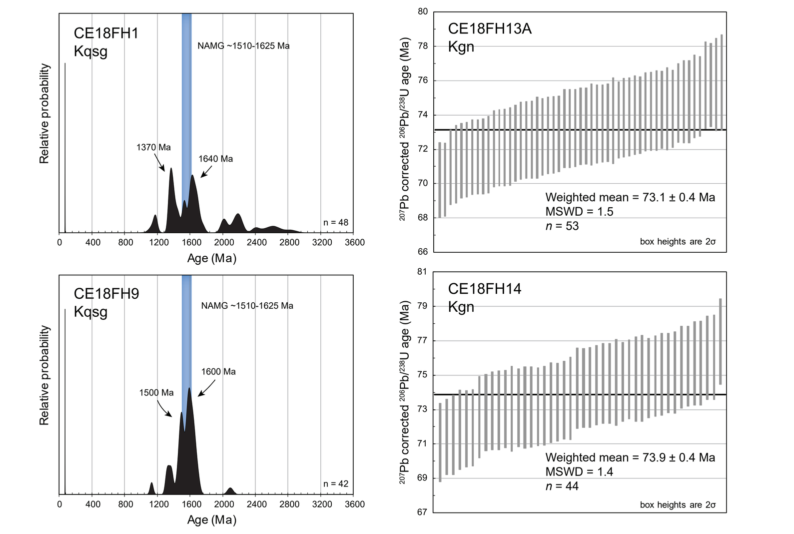


Figure 6. U-Pb age spectra for detrital zircons from Kqsg samples (left) and weighted mean ages for Kgn samples (right). Analytical procedures are described below. NAMG, North American Magmatic Gap; MSWD, Mean Square Weighted Deviation.

LA-ICPMS methods

Zircon was separated from 1–2 kg of sample using standard density and magnetic separation techniques at the MBMG mineral separation laboratory. For igneous rocks, approximately 100–200 representative zircon grains were hand selected from each sample and set in a 2.5-cm epoxy grain mount. For metamorphic rocks, an unbiased split of ~1,000 zircon grains from each sample was set in an epoxy grain mount. Zircon crystal structure and inheritance were assessed by scanning election microscopy cathodoluminescence at the Montana Technological University. Laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) of the samples was then performed by Jesse Mosolf, MBMG, at the University of California Geochronology Center, Santa Barbara. Approximately 60 zircon grains from each sample were analyzed. Figure 6 reports ^{207}Pb corrected $^{206}Pb/^{238}U$ ages for igneous samples, and $^{206}Pb/^{238}U$ (<1,400 Ma) and $^{207}Pb/^{206}Pb$ (>1,400 Ma) age distributions for metamorphic rocks. Appendix A (available online with this publication) summarizes all LA-ICPMS data collected in this study.

Figure 8. Granodioritic gneiss with salmon-colored neosome segregations forming a new foliation that is parallel to the pencil. Pencil is 8 mm across.

UNIT DESCRIPTIONS

Qal **Alluvium (Holocene)**—Modern stream and floodplain deposits. Thickness as much as 40 m (130 ft).

Qrg **Rock glacier (Holocene)**—Angular boulders to cobbles frozen together by ice in lobate deposits. Found in the southeastern corner of the map. Thickness generally less than 10 m (33 ft).

Qta **Talus (Holocene–Pleistocene)**—Angular and subangular cobble- to boulder-size clasts at the base of steep valley walls or cliffs. Thickness probably less than 30 m (100 ft).

Qaf **Alluvial fan deposits (Holocene–Pleistocene)**—Angular to subrounded, unsorted, cobble to boulder gravel fans. Thickness probably less than 10 m (33 ft).

Qalo **Alluvium, older (Pleistocene)**—Moderately to well-sorted cobble gravel, sand, and silt layers forming dissected terraces traced from the northwest-adjacent Long Peak quadrangle (Elliott and Lonn, in review). Thickness 2–10 m (9–33 ft).

Qgl **Glacial lake deposits (Pleistocene)**—Fine-grained lacustrine deposits in the southwest corner of the map. Thickness unknown.

Qgt **Glacial till (Pleistocene)**—Unsorted clay to boulder deposits in lateral, ground, and medial moraines. Characterized by hummocky terrain scattered with large subangular to subrounded boulders. Thickness may be as much as 120 m (400 ft).

Tgr **Gravel (Tertiary)**—Poorly exposed gravel with subrounded quartzite pebbles and cobbles and subangular quartzite boulders in a silty matrix. In the northeastern part of the map, Tgr probably represents debris flow deposits. Truckle (1988) mapped Tgr as glacial till, but it is continuous with known Tertiary gravels in adjacent quadrangles. Tgr near the northwest corner of the map along the Big Hole River is boulder and cobble gravel dominated by rounded to very well-rounded quartzite clasts. It closely resembles the Miocene Sixmile Creek Formation in the north-adjacent Lower Seymour Lake quadrangle (Elliott, 2015). Thickness less than 65 m (220 ft).

Tv **Volcanic rock (Tertiary?)**—One very small exposure of undated, fine-grained, pink, igneous rock with 1–3 mm phenocrysts of glassy, white plagioclase. Fragmental texture with flattened pumice suggests an extrusive origin. Truckle (1988) mapped Tv as an andesite dike. Located in the northwestern corner of the map.

TKgbm **Granite, two mica (Cretaceous–Paleocene–Oligocene?)**—Medium- to coarse-grained, porphyritic, biotite–muscovite granite. Light gray to very pale pink. Mostly massive, but weakly foliated along Bryant Creek. Where it forms inclusions in Kqsg, it can be massive to strongly deformed and gneissic (fig. 5, contorted TKgbm gneiss). Contains mafic inclusions up to 5 m across. TKgbm is the Bryant Creek granite of Truckle (1988) and TKg of Ruppel and others (1993). Other two-mica granites in the region have crystallization and cooling ages that vary between about 65 and 39 Ma (Snee, 1982; Desmarais, 1983; Zen, 1988; Wallace and others, 1992; Ruppel and others, 1993; Foster and others, 2007, 2010; Howlett and others, 2020).

Ruppel and others (1993) correlate TKgbm with the Clifford Creek Granite of Zen (1988) who reports 64.6 ± 2.1 Ma and 64.9 ± 2.2 Ma K-Ar ages for biotite and an $^{40}Ar/^{39}Ar$ biotite age of 65.6 ± 1.4 Ma. Snee (1982) reports a muscovite cooling age of 63.9 ± 0.8 Ma and a biotite cooling age of 61.3 ± 0.6 Ma for a small two-mica pluton in the southwest-adjacent Proposal Rock quadrangle. Snee (1982) prefers an emplacement age of about 65 Ma but acknowledges that it could be as old as 72 Ma.

Two-mica granites are abundant in the footwall of the AMCC, and have K-Ar ages between 54 and 49 Ma (Wallace and others, 1992); $^{40}Ar/^{39}Ar$ cooling ages between 39 and 41 Ma for mylonites (Foster and others, 2010); and an $^{40}Ar/^{39}Ar$ biotite age of 53 ± 0.6 Ma for a related granodiorite (Foster and others, 2007). The two-mica Chief Joseph pluton in the western AMCC has Paleocene and Eocene $^{40}Ar/^{39}Ar$ cooling ages (Desmarais, 1983; Foster and others, 2010), and monazite U-Pb lower intercept age of 58 Ma (Desmarais, 1983). Howlett and others (2020) found U-Pb zircon ages around 60 Ma on TKgbm near Pintler Lake.

Kgdf **Granodiorite, foliated (Cretaceous)**—Gray, medium- to coarse-grained granular to porphyritic granodiorite and tonalite containing 5–35 percent biotite, hornblende, or biotite and hornblende and 5–56 percent potassium feldspar (Truckle, 1988). Hornblende appears to increase in abundance towards the south. Varies from massive with no foliation, to weakly foliated (preferred dimensional orientation fabric), to strongly gneissic. Named the Foolhen Mountain tonalite (Kf) by Snee (1982) and Truckle (1988), the tonalite of Foolhen Ridge (Kfn) by Berger and others (1983), and Kgtd granodiorite, tonalite, and quartz diorite by Ruppel and others (1993). Contains numerous light gray, fine-grained aplite dikes with up to 15 percent plagioclase and 5 percent biotite. Also contains metasedimentary inclusions of all sizes, from hand sample to map scale. In the east side of the map, large inclusions contain compositional layering and/or preferred orientation foliations at a high angle to the fabric in the enclosing granodiorite. In the western part of the map, foliations are commonly, but not everywhere, subparallel to contacts.

Snee (1982) did not find a crystallization age, but proposed an emplacement age of about 77 Ma for the Foolhen tonalite, with biotite $^{40}Ar/^{39}Ar$ cooling ages decreasing westward from 69 to 65 Ma. Roe (2010) obtained a U-Pb zircon age of 71.8 ± 2.0 Ma for a sample from Chalk Bluff in the west-adjacent Pine Hill quadrangle. Zircons from a biotite-rich, unfoliated sample of Kgdf have a U-Pb age of 73.89 ± 0.39 Ma (fig. 6, sample CE18FH14). At Chalk Bluff, the contact with metasedimentary rocks is gradational and not parallel to gneissosity, suggesting that the contact is tightly folded and that the compositional layering is axial planar to the folds. Alternately, it is possible that the metasedimentary rocks and granodiorite were interleaved before deformation.

Many metasedimentary inclusions in Kgdf that are large enough to show on the map locally contain primary structures, like bedding, but are mostly intensely foliated. The internal foliations are commonly at a high angle to the fabric in the enclosing granodiorite. This indicates that the sedimentary protoliths were strongly deformed prior to intrusion of Kgdf.

Kbr **Quartz breccia (Cretaceous?)**—Black and white mottled quartz-rich cataclasite. Appears to be hydrothermally altered fault breccia along the northern edge of the large KMsm belt in the northern half of the map. The presence of Kbr and mylonitized marble along the KMsm/Kqsg contact suggests that it is a fault.

Kcs **Calcsilicate and marble (Cretaceous metamorphic age)**—Light to dark gray, mostly coarse-grained marble with varying amounts of silicate minerals, including epidote, garnet, scheelite, and a wide variety of skarn minerals (Truckle, 1988; Messenger, 2016). Outcrop-scale textures can be mylonitic, brecciated, gneissic (fig. 7), or massive. The protoliths may have been Madison Group and/or Kootenai Formation carbonates, (Truckle, 1988), but Mesoproterozoic origins have also been proposed (Messenger, 2016). Kcs is here labelled Cretaceous to reflect the age of metamorphism. Kcs hosts the Calvert tungsten skarn deposit as well as other skarn prospects throughout the quadrangle.

KMsm **Metasedimentary rocks (Mississippian through Cretaceous, Cretaceous metamorphic age)**—Layered, folded, severely deformed rock with rare recognizable primary structures. Includes metamorphosed sandstone, conglomerate, and quartzite. Truckle (1988) mapped these as formations in the regional Phanerozoic stratigraphy but our mapping suggests that while Phanerozoic protoliths are possibly identifiable in some cases (e.g., dense, purple quartzite with apatite nodules might be metamorphosed Phosphoria Formation), stratigraphic relationships are not retained. Messenger (2016) interpreted the protolith of the carbonates that host the Calvert tungsten deposit as Pennsylvanian. We interpret KMsm to be in fault contact with Kqsg and intruded by Kgdf.

Kqsg **Quartzite, schist, and migmatite gneiss (Cretaceous metamorphic age)**—Fine- to medium-grained amphibolite–facies quartz–potassium feldspar–plagioclase–muscovite–biotite–sillimanite metasedimentary gneiss and schist that is commonly migmatitic. Metasediments vary from quartzose to feldspathic. Truckle (1988) recognized that there are two generations of sillimanite, one that is deformed (overprinted by a foliation), and one that is randomly oriented in the hinges of folds. Migmatite neosome is fine- to medium-grained biotite–mica granite locally injected or segregated in foliation-parallel sheets (lit-par-lit), locally segregated as blobs in fold hinges, and locally parallel to the axial plane of folds (fig. 8). Migmatization increases towards contact with Kgdf, which is gradational; there are inclusions of Kqsg in the granodiorite as well as inclusions of granodiorite in the metasediments. Kqsg is complexly deformed, with several fold generations.

Mapped by Truckle (1988) and Berger and others (1983) as Paleoproterozoic metamorphic rock, but Ruppel and others (1993) reinterpreted this unit as metamorphosed Mesoproterozoic Belt Supergroup. We concur, and would correlate this package with the thick quartzite units of the Lemhi subbasin, upper Belt Supergroup (Burmester and others, 2016). However, U-Pb zircon age spectra for a garnet-bearing, feldspathic Kqsg metaquartzite inclusion in Kgn (CE18FH1) and a Kqsg migmatitic quartz–feldspar–muscovite–biotite–sillimanite gneiss (CE18FH9) are shown in figure 6. While the ages fall within the expected range for upper Belt rocks, the presence of North American magmatic gap (NAMG) grains and lack of 1,700–1,800 Ma grains are unusual. Variations in age distribution may reflect input of local sources, and more work will need to be done before a full understanding is reached.

Kgn **Gneiss complex (Cretaceous)**—Quartz–feldspar–biotite–cordierite mixed hornblende granodiorite and metasedimentary gneiss. Typically gray and very fine-grained, with evidence of transposition (figs. 4, 8). Locally, the preferred dimensional orientation of hornblende grains defines a strong lineation. Less deformed zones show granodiorite intruded into metasandstone as well as metasandstone inclusions within granodiorite gneiss. Kgn is intruded by, and older than, Kgdf. Metasedimentary protoliths are uncertain, and could be any age from Mesoproterozoic to Mesozoic. Kgn is equivalent to Xm of Berger and others (1983) who interpreted the unit to be Paleoproterozoic basement gneiss. Ruppel and others (1993) reinterpreted the unit as metamorphosed Cretaceous igneous rock (Khbg). Zircons from a sample of fine-grained Kgn yield weighted mean U-Pb ages of 73.1 ± 0.40 Ma (fig. 6, sample CE18FH13A).

Ysw **Quartzite (Mesoproterozoic?)**—Light gray, poorly sorted, fine- to coarse-grained feldspathic quartzite and pebble conglomerate. Metamorphic grade and deformation intensity increase from northeast to southwest. At the north edge of the map, primary structures are abundant, and the quartzites can confidently be traced to well-exposed Mesoproterozoic rocks in the north-adjacent Lincoln Gulch quadrangle (Elliott, 2017), and northeast-adjacent Dickie Peak quadrangle (McDonald, 2011). Bed thicknesses range from 0.2 to 1.0 m. Contains obvious chalky white feldspar grains, large trough cross beds, detrital muscovite, and metamorphic biotite along bedding planes. Contains lenses and intervals of conglomerate with round pebbles up to 2 cm. Clasts are fine-grained quartzite, angular granules, and small pebbles of feldspar and quartz, suggesting at least two source areas. Rare thin argillite beds typically contain desiccation cracks. Three slabbed and stained samples contained 20–25 percent potassium feldspar, and 15–20 percent plagioclase. The coarse grains and high potassium feldspar content relative to plagioclase support correlation with the Swauger Formation of the Lemhi subbasin strata in the upper Belt Supergroup (Burmester and others, 2016). Deformation precludes thickness estimates, but the unit is at least 1,600 m (5,250 ft) thick in the nearby Wise River valley (Calbeck, 1975; Lonn and Elliott, 2017). Unit is equivalent to pCm2 and pCm3 of Truckle (1988) and Ym of Ruppel and others (1993).

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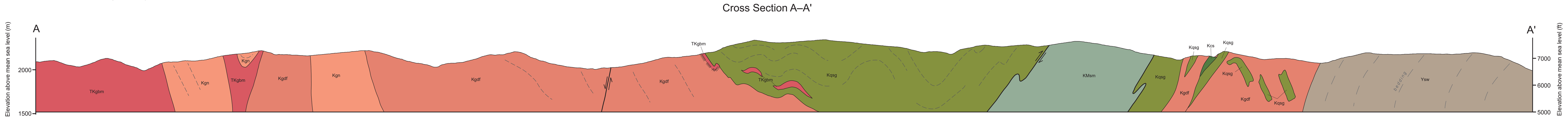
Cross Section A–A'



No vertical exaggeration
Surficial units not shown
Foliation trends

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feet 0 1000 2000 3000 4000 5000 6000 7000 8000 9000 10,000
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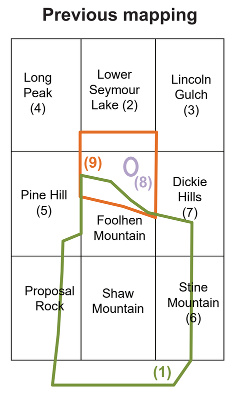
Previous mapping



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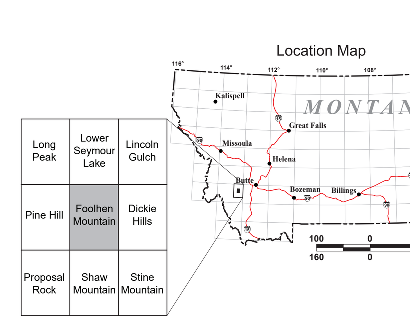
Location Map



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Map layout: Susan Smith, MBMG. Editing: Susan Barth, MBMG.

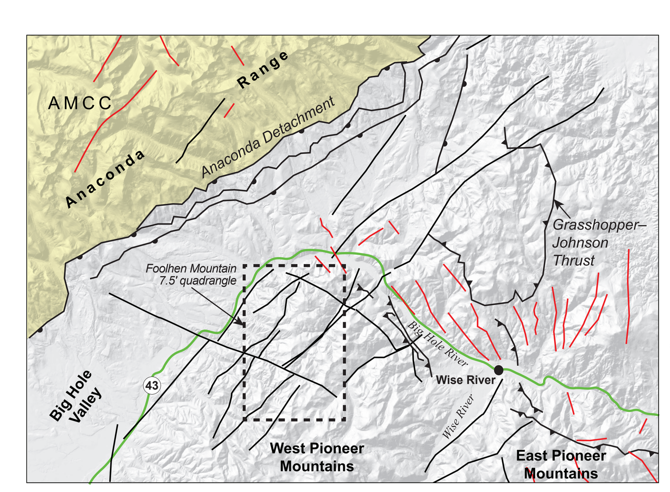

Figure 1. Regional structures. Overlain on same DEM/hillshade as the geologic map.

Geologic Map 79

Geologic Map of the Foolhen Mountain 7.5' Quadrangle, Beaverhead County, Montana

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