GEOLOGY OF THE BUTTE NORTH 30' X 60' QUADRANGLE

SOUTHWEST MONTANA

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Introduction and Previous Mapping

The Butte North 30' x 60' quadrangle in southwestern Montana has been subject to extensive geologic research since the 1890s, with detailed U.S. Geological Survey (USGS) investigations beginning over 100 years ago (Weed, 1912). Mineral resource exploration associated with the Butte, Welcome Creek, and Rock Creek mining districts was the focus of early geologic investigations (Weed, 1912; Blackwelder and Atwood, 1917). Geologic mapping efforts in the 1960s and 1970s by the USGS focused on the Boulder Batholith (figs. 1, 2), in part to explore for mineral deposits (Becraft, 1960a,b; Becraft and Pinckney, 1961; Pinckney and Becraft, 1961; Smedes and others, 1962; Ruppel, 1963; Wanek and Barclay, 1966; Protska, 1966; Weeks, 1974; Wallace, 1987). The Montana Bureau of Mines and Geology (MBMG) added quadrangle maps by Derkey and Bartholomew (1988), Derkey and others (1993), and a 1:250,000 compilation by Lewis (1998; fig. 2).

In 2004 the MBMG and the State Mapping Advisory Committee selected the Butte North 30' x 60' quadrangle as a mapping priority because it has world-class ore deposits, is transected by two major transportation corridors, has seen increased development in the valleys, and is within a major Superfund site with ongoing reclamation. STATEMAP-funded mapping at 1:24,000 and 1:50,000 scale over the following years significantly advanced knowledge of structural and igneous geology of the area [Berg, 2004; Berg and Hargrave, 2004; Hargrave and Berg, 2013; Elliott and others, 2013; Scarberry and Elliott, 2016; Scarberry, 2016a,b; Scarberry and others, 2017; Elliott and Lonn, in preparation; Elliott and Scarberry, in preparation; Scarberry, in review (a,b)]. Other important contributions to mapping in the quadrangle include: (1) a geologic hazard assessment at 1:50,000 scale for Silver Bow County (Elliott and McDonald, 2009), (2) three 7.5' quadrangle maps produced as student EDMAP projects (Feeney and others, 2009; Olson and others, 2016, 2017), and (3) a detailed map of the Butte mining district (Houston and Dilles, 2013b).

The Butte North quadrangle lies in a geologically complex area of southwestern Montana. Archean and Paleoproterozoic crystalline basement rock, Mesoproterozoic through Cretaceous metasedimentary and sedimentary rock, Cretaceous through Tertiary intrusive and volcanic rock, and Tertiary and Quaternary valley-fill and surficial deposits are all exposed in the quadrangle. The Late Cretaceous Boulder Batholith and co-magmatic Elkhorn Mountains Volcanic Field, and the Eocene–Oligocene Lowland Creek and Elliston volcanic fields (fig. 1) are the dominant units in the quadrangle. The Boulder Batholith hosts two world-class porphyry Cu-Mo deposits, which are cut by polymetallic lode veins (Weed, 1912; Lund and others, 2002; Houston and Dilles, 2013a,b; Reed and others, 2013; Lund and others, 2018 and references therein).

Cretaceous and older rocks along the western edge of the Butte North quadrangle were deformed and metamorphosed during Sevier/Laramide contraction in late Cretaceous to Paleocene time: however, the large-scale architecture of the quadrangle is dominated by younger extensional structures. The Anaconda Metamorphic Core Complex (AMCC; O'Neill and others, 2004; Foster and others, 2007, 2010; Kalakay and others, 2014) is exposed along the western edge of the quadrangle. A set of shallowly dipping, weakly mylonitic detachment faults extends into the subsurface below the Deer Lodge Valley and probably much farther east (Foster and others, 2010). Detachment faults appear to form the base of valley fill in the Deer Lodge Valley, where six oil and gas exploration wells penetrated thousands of feet of Tertiary sediments and volcanic rocks.

Three of the wells bottomed out in granite, and one intersected granite mylonite at 11,605 ft (3,537 m). Descriptions of the depths, locations, and stratigraphy penetrated by the wells was the subject of the MS thesis of McLeod (1987).

Younger, steeper normal faults bound the valleys. A steep fault is present on the west side of Elk Park, where a primary east-dipping normal fault is paralleled by an antithetic west-dipping normal fault that offsets Quaternary sediments. Scarps on the primary fault are up to 18 m (60 ft) high. Fault scarps on the antithetic west-dipping fault are up to 1.5 m (5 ft) high and offset Quaternary debris flow deposits, indicating that this fault has been active in Quaternary time. Triangular facets and active alluvial fans suggest that faults on the west side of the Deer Lodge Valley and in the Whitetail Valley may be active in Quaternary time. Additional field investigations, supported by high-resolution topographic data, will shed light on the location of faults scarps. No paleoseismic investigations have yet been done in the Butte North 30' x 60' quadrangle, leaving earthquake recurrence intervals and maximum potential earthquakes on Quaternary faults unknown.

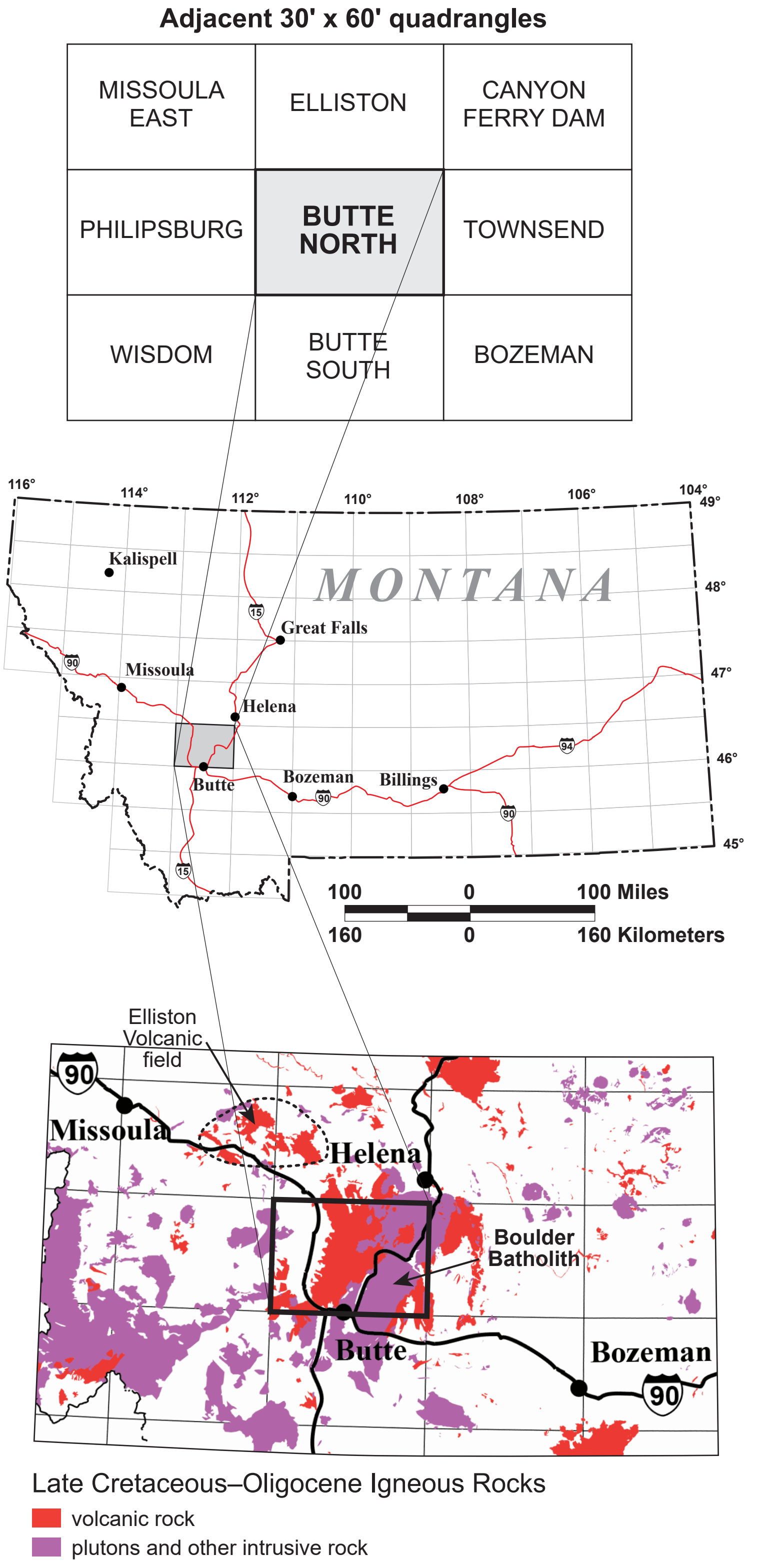
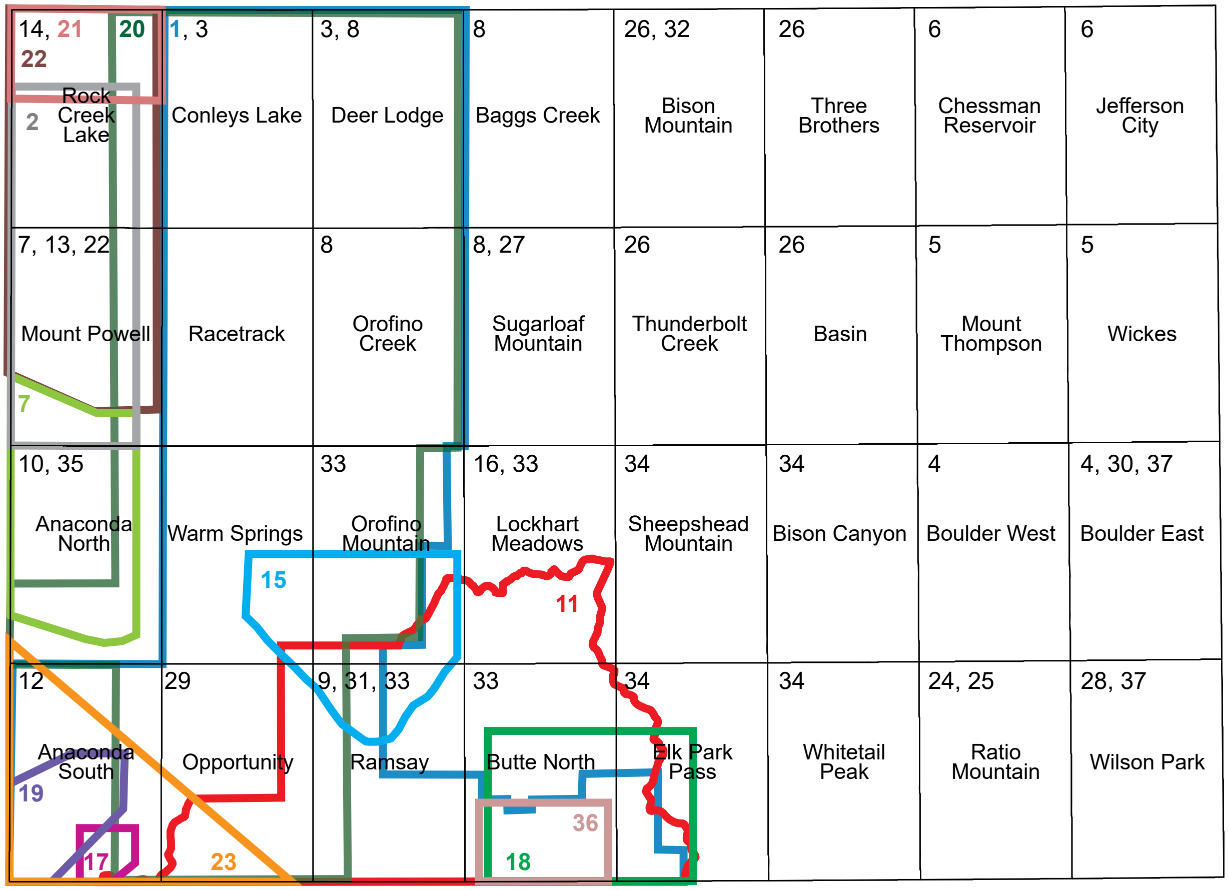


Figure 1. Location of the Butte North quadrangle and the Boulder Batholith.



Entire map covered at 1:250,000 by Lewis (1998) and Wallace (1987)

1. **Berg and Hargrave (2004)**
2. **Allen (1962)**
3. Berg (2004)
4. Becraft and Pinckney (1961)
5. Becraft (1960a), Becraft and others (1963)
6. Becraft (1960b), Becraft and others (1963)
7. **Csejtey (1962)**
8. Derkey and others (1993), Ruppel (1961)
9. Derkey and Bartholomew (1988)
10. Elliott and Lonn (in preparation)
11. **Elliott and McDonald (2009)**
12. Elliott and Scarberry (in preparation)
13. Elliott and others (2013)
14. Feeney and others (2009)
15. **Hargrave (1990)**
16. Hargrave and Berg (2013)
17. **Hastings and Harold (1986)**
18. **Houston and Dilles (2013)**
19. **Iagmin (1972)**
20. **Konizeski and others (1968)**
21. **Loen (1986)**
22. **Mutch (1961)**
23. **Noel (1956)**
24. Olson and others (2016)
25. Pinkney and Becraft (1961)
26. Ruppel (1963)
27. Scarberry (2016a)
28. Scarberry (2016b)
29. Scarberry Elliott (2016)
30. Scarberry and others (2017)
31. Scarberry (in preparation a)
32. Scarberry (in preparation b)
33. Smedes (1968)
34. Smedes and others (1962)
35. Wanek and Barclay (1966)
36. **Weed (1912)**
37. Weeks (1974)

Figure 2. Previous mapping in the Butte North quadrangle.

DESCRIPTION OF MAP UNITS

Anthropogenic units

m	**Land modified during mining and/or reclamation activities.** Includes areas covered by mine tailings, placer workings, open cut mines, and sand and gravel pits.

Sedimentary units

Qal	**Alluvium (Holocene)**—Clay, silt, sand, gravel, and bog deposits produced by or near channels of modern streams. Clasts are generally rounded and well sorted. Includes Qb "bog and swamp" deposits of Ruppel (1963). Thickness generally less than 10 m (33 ft), but locally up to 60 m (200 ft) thick.
Qrg	**Rock glacier (Holocene)**—Angular boulders to cobbles frozen together by ice in lobate deposits. Found on and near Mount Powell, west of the Deer Lodge Valley. Thickness generally less than 10 m (33 ft).
Qls	**Landslide deposit (Holocene)**—Unsorted clay to boulder-sized sediments from mass wasting of surface deposits and/or bedrock. Color and lithology reflects source material. Includes debris flow, mud flow, and earth flow deposits as well as rotational landslides and slumped blocks. Deposits may be stable or unstable. Thickness highly variable depending on size of landslide, but generally less than 10 m (33 ft).
Qc	**Colluvium (Holocene-Pleistocene?)**—Loose unconsolidated deposits of angular to subangular boulders to pebbles. Locally sourced from and deposited on or at the base of slopes. Includes small alluvial channels and sheet wash deposits. Thickness generally less than 10 m (33 ft).
Qac	**Alluvium and colluvium, undifferentiated (Holocene-Pleistocene?)**—Clay, silt, and cobble deposits of modern and ancient rivers and adjacent hillslopes. Clasts are rounded to angular. Thickness generally less than 10 m (33 ft).
Qdf	**Debris flow deposits (Holocene–Pleistocene?)**—Black or gray to brown, poorly sorted, unstratified, matrix-supported pebble to boulder gravel with silty to very coarse sand matrix. Clasts are angular to subround. Identified in Elk Park. Clast compositions are identical to bedrock lithologies immediately west of Elk Park. Age constrained by palynology sample 17EP04. Thickness is up to 100 m (330 ft).
Qat	**Alluvial-terrace deposits (Holocene and Pleistocene)**—Poorly sorted, clay- to gravel-sized sediments derived from Tertiary and older strata on irregularly shaped, unpaired terraces 1–10 m (3–30 ft) above the modern floodplain (Derkey and others, 1993). Thickness generally less than 10 m (33 ft).
Qalo	**Older alluvium (Holocene–Pleistocene)**—Gravel, sand, silt, and clay deposited by rivers and streams with surfaces slightly higher than Qal. Includes sand, silt, clay, and organic matter of floodplain deposits at surface. Older alluvial deposits are only differentiated in Butte, and immediate vicinity. Variable thickness, probably less than 25 m (80 ft).

Qg **Glacial deposits, undifferentiated (Pleistocene)**—Primarily unconsolidated till and outwash. Poorly to well-sorted, angular to rounded clasts of locally sourced material. Clay to boulders up to 3m (10 ft) in diameter. Up to 100 m (330 ft) thick.

Qgo **Glacial outwash (Pleistocene)**—Poorly to well sorted and stratified, unconsolidated, sand to boulder deposits from ancient mountain glaciers. Clasts are typically locally sourced and reflect lithologies along path of glaciers. Up to 25 m (80 ft) thick.

Qgt **Glacial till (Pleistocene)**—Poorly sorted, unconsolidated, silt to boulder-sized clast-supported lateral and ground moraine deposits. Clasts are angular and locally sourced. In the Deer Lodge Valley, may correlate with late Wisconsin glaciation (Berg and Hargrave, 2004). Up to 100 m (330 ft) thick.

Qgoo **Glacial outwash, older (Pleistocene)**—Poorly sorted, subrounded to rounded, unconsolidated sand to boulder gravel. Stratified to poorly stratified, locally sourced deposits were incised during younger glaciation events, and are inset by younger outwash (**Qgo**). In the Deer Lodge Valley, may correlate with the Bull Lake glaciation (Berg and Hargrave, 2004). Up to 30 m (100 ft) thick.

Qgto **Glacial till, older (Pleistocene)**—Poorly sorted, unconsolidated, angular, silt to boulder-sized, clast-supported deposits from mountain glaciers. Typically incised during younger glaciation events, and inset by younger till. In the Deer Lodge Valley, may correlate with the Bull Lake glaciation (Berg and Hargrave, 2004). Up to 100 m (330 ft) thick.

Qaf **Alluvial fan deposits (Quaternary)**—Clay to cobble-sized, angular to subrounded clasts forming broad conical deposits at outlets of mountain streams, or broad sheets where multiple alluvial fans have formed a bajada. May locally contain thin ash deposits. Qaf deposits across the map area do not likely correlate with one another. Unit 'Qsf' of Ruppel (1963). Up to 30 m (100 ft) thick.

Qta **Talus (Quaternary)**—Unconsolidated angular pebbles to boulders of bedrock, forming apron-like deposits below steep slopes. Poorly sorted with clast composition identical to lithologies of adjacent hillslopes. Includes rock fall and rock-slide deposits. Thickness generally less than 10 m (33 ft).

QTtu **Tufa deposits (Tertiary–Quaternary)**—Gray, laminated, calcite and dolomite breccia with scattered pebbles, cobbles, and round quartz grains. Weathered to pale tan. Cobbles are rounded white, pink, and black quartzite, granite, aplite, red feldspathic sandstone and Lowland Creek porphyry (**Tlcp**). Tufa overlies and is younger than Tertiary volcanic rocks and sediments. Found in Sheep Gulch and at the base of Weather Hill, immediately south of the city of Anaconda. 3–10 m (10–30 ft) thick.

QTdf **Debris flow deposits (Tertiary?–Quaternary?)**—Silt to boulder-sized, unconsolidated, unstratified deposits with angular to rounded clasts. Clasts are commonly matrix supported, and angular to subround. Identified at the top and east flank of Bull Mountain. Thickness is less than 10 m (33 ft).

Ts **Sediment and sedimentary rock, undivided (Tertiary)**—Unconsolidated to poorly consolidated clay to cobble-sized deposits with angular to rounded clasts, both locally and distally sourced. Deposits are matrix-supported to clast-supported. Age relative to other Tertiary units unknown.

Tsc **Sixmile Creek Formation (Miocene**)—Youngest sediments of the Bozeman Group. Generally unconsolidated and typically coarse-grained (cobble to boulder gravel), though not exclusively. Overlies the Renova Formation with angular unconformity. Matrix is generally tuffaceous, yellowish gray siltstone. Gravels are matrix- and clast-supported granules to boulders. Clasts may be dominantly angular or dominantly subrounded to well-rounded. The clasts are primarily Belt Supergroup and Boulder Batholith rock, with subordinate locally sourced rocks. Thickness in the Deer Lodge Valley is estimated to be up to ~2,290 m (7,500 ft), based on drillhole data (McLeod, 1987). Differentiated in the eastern Deer Lodge Valley into two members following the stratigraphy of Sears and others (2009):

Tscb **Big Hole River Member**—Well-sorted, clast-supported, coarse sand to boulder gravel with sandy matrix. Clasts are rounded to well-rounded and commonly imbricated. Contains white, gray, pink, and red cobbles of Belt Supergroup quartzite from local and distal sources, and biotite–muscovite granite, lithic sandstone, and schist derived from the footwall of the Anaconda Detachment. Thickness ranges to more than 120 m (395 ft) thick.

Tscs **Sweetwater Creek Member**—Immature silt, sand, and gravel. Poorly lithified, tan to light gray, with ashy matrix. Clasts mostly derived from local granitic and volcanic bedrock. Contains 5- to 60-cm-thick beds of matrix-supported very coarse sand to pebble conglomerate with silty to sandy matrix, interpreted to be debris flow deposits. Includes 0.1- to 3-m-thick beds of clast-supported pebble to cobble conglomerate, with subrounded to rounded clasts of predominantly local affinity. These beds are interpreted to be small to major channels. Commonly includes 10- to 30-cm-thick massive light gray ashy silt to fine sand beds. A thin tuff layer interbedded with fluvial deposits on the east side of the Deer Lodge Valley yielded a maximum U-Pb zircon age of 9.69 ± 0.19 Ma (sample # CE17BN2). Thickness in the Deer Lodge Valley is estimated to be up to ~845 m (2,900 ft) thick from drillhole data (McLeod, 1987). Exposures are up to 360 m (1,200 ft) thick.

Tre **Renova Formation, undivided (Tertiary; Eocene, Oligocene and early Miocene)—** Very pale yellow to tan, massive to weakly fissile, ashy mud with scattered locally derived granules. Near Lost Creek, Tre is mostly white, pale gray, tan, or locally red, tuff-rich, fine-grained fluvial sediments named the Hoodoo Gulch beds by Csejtey (1962). They include poorly exposed quartz and biotite sandstone, silicic shale and siltstone, and unsorted, angular conglomerate with quartz, black chert, quartzite, and feldspar clasts and a fine-grained matrix. Local fissile shales and siltstone contain abundant plant impressions. Csejtey (1962) interpreted the beds to be late Oligocene or early Miocene, but their association with the volcanic rocks suggests that they are Eocene. The Hoodoo beds are more than 180 m (600 ft) thick.

Teeth from a fossil jaw found during this study at N. 46.237342°, W. 112.892327° (NE¼NE¼ sec. 31, T. 6 N., R. 10 W.) were tentatively identified as the last two deciduous premolars and the front half of the first permanent molar of a Mesohippus (Alan Tabrum, Carnegie Museum, written commun.). If the identification is correct, the fossil age is Chadronian or Orellan (late Eocene to earliest Oligocene).

Where possible, the Renova Formation is divided into two members:

Trcp **Cabbage Patch member (Miocene and Oligocene)**—Fine-grained ashy sediments interlayered with well-lithified feldspathic sandstone and conglomerate channel deposits. Sandstone distinctively contains large biotite and muscovite books. Unit also contains gastropod-bearing marlstone, thinly bedded limestone, and local gastropod coquina, shale, and tuffaceous, micaceous siltstone with local lenses of rip-up clast breccia. Carbonate beds are locally silicified to white-weathering, gray porcellanite and variegated chert. Sandstone and conglomerate form resistant, trough cross-bedded lenses with imbricated clasts of subrounded to well-rounded Belt Supergroup feldspathic quartzite mixed with less mature locally derived rocks. The Cabbage Patch member is richly fossiliferous, and has been well-described by Rasmussen (1977), Calede and Rasmussen (2015), and Calede (2016). It has a North American Land Mammal age of Arikareean (29.5–18.5 Ma, Barnosky and others, 2014). A U-Pb detrital zircon analysis for Trcp at Robinson Ridge near the west side of the Butte North quadrangle yielded zircons with concordant ages of ~25 and 26 Ma, and one with a discordant age of 26 Ma, all of which fall within the Arikareean age range. Base not exposed. Thickness over 600 m (2,000 ft).

Trca **Renova Formation, Climbing Arrow Member (Tertiary: Eocene)**—Pale olive and gray bentonitic mudstone, paper shale, lignite, yellowish gray siltstone, subordinate brownish gray sandstone, and gravel/conglomerate lenses. Sandstone dominantly medium- to coarse-grained with quartz, feldspar, biotite, and rhyolite grains. Gravel/conglomerate consists of clast-supported lenses of rounded granules, pebbles, and cobbles of rhyolite porphyry. Bentonitic mudstone typically displays "popcorn" texture and desiccation cracks when dry, and is prone to landslide development. Exposed thickness approximately 180 m (600 ft).

Twv **West Valley breccia (Eocene-Oligocene)**—Sedimentary and tectonic breccia characterized by angular clasts and blocks in an unsorted clastic matrix. Clasts include a wide variety of identifiable Mesoproterozoic, Paleozoic, Mesozoic, and Eocene rock types. Twv is a mélange of tectonic and sedimentary breccias that extends along the Anaconda Detachment from the northwest end of the Deer Lodge Valley into the Big Hole Valley (Elliott 2015, 2017). Named after the West Valley "chaos" described by O'Neill and Lageson (2003), and O'Neill (2005). Thought to be syntectonic with extension of the Anaconda Metamorphic Core Complex, which occurred between 43 and 27 Ma (Foster and others, 2010), therefore ranging from early Eocene to late Oligocene. Estimated to be up to 600 m (2,000 ft) thick.

Tcg **Conglomerate (Eocene?)**—Mixed clast boulder conglomerate and gravel deformed by and in hanging wall of the Anaconda Detachment. On Ballard Hill (northwest corner of map), clasts are dominantly rounded, unsorted, black and gray slate and meta-lithic sandstone from the Kootenai and/or Blackleaf Formations, but include schist, phyllite, clean quartzite, intrusive igneous rocks, and bull quartz. On Bielenberg Ridge (central west part of map), Tcg is unsorted with angular to round cobbles up to 2 m across. Clasts are dominantly lithic sandstone and maroon mudstone, probably Kootenai Formation. Other clasts are porphyritic granite, aplite (some with a cleavage, some without), gray limestone (Madison Group?), coarse crystalline white marble, clean and feldspathic quartzite, and rare vesicular basalt. Where this unit is well exposed on the top of the ridge, a slaty cleavage is persistent across clasts of different size and composition (Elliott and others, 2013), indicating that the unit has been tectonized. Thickness locally greater than 300 m (1,000 ft).

Tlcs **Sediments related to the Lowland Creek volcanics (Paleocene-Eocene)**—Fluvial and lacustrine sediments containing non-volcanic clasts that interlayer with Lowland Creek Volcanic rocks. They are variably lithified, fine- to coarse-grained, clastic sediments and rocks, generally immature, rich in feldspar and quartz crystals as well as lithic clasts. Lithic clasts are volcanic, shale, quartzite, hornfels, lithic sandstone, and sulfides. Locally, clasts have a silvery manganese coating or distinctive chrome-green alteration. Sandstones are locally cross-bedded.

Conglomerate sitting on **Kbkm** hornfels at N. 46.198938° W. 112.931743 (W ½ sec. 12, T. 5 N., R. 11 W.) is represented by cobbles of well-lithified pale tan to buff unsorted conglomerate in the float. Clasts in the conglomerate range from millimeters to 10 cm, and are angular to well-rounded quartzite, lithic sandstone (probably Cretaceous), quartz-eye rhyolite, black hornfels, and volcanogenic quartz, euhedral feldspar and biotite.

Tlcs resting unconformably on **Kbkm** at N. 46.163687° W. 112.932640° (NW1/4 sec. 25, T. 5 N., R. 11 W.) is unsorted sedimentary breccia consisting of gray hornfels, red lithic sandstone, gray limestone, and slate, all of which appear to be locally derived from the underlying Cretaceous rocks and **Tlcr** clasts. The breccia grades upwards into white to pale yellow sandstone with silicic cement and significant volcanic component. Sandstone contains layers of matrix-supported pebble conglomerate dominated by 1- to 2-cm rounded clasts of rhyolite, black shale, limestone, and white quartzite.

Lacustrine deposits occur at the base and around the margins of the 50.0 Ma (Dudas and others, 2010) Hackney lava dome (**Tlca**). They are locally oxidized and altered to palagonite, lack varve sets, and consist almost entirely of altered volcanic material, and perhaps formed in an intra-caldera lake bed or moat (e.g., Gardner and Goff, 1996). The exposed thickness of fine sediment is less than 10 m (33 ft).

Tlcs includes many gravels and conglomerates mapped by Csejtey (1962) and O'Neill (2005) as Anaconda Beds. Tlcs sedimentary breccias are distinguished from **Twv** by the absence of tectonic breccia. Thickness up to 730 m (2,400 ft). Thickest where **Tlc** volcanic rocks pinch out on the west side of the Butte North quadrangle.

This study produced U-Pb detrital zircon spectra from five outcrops. Maximum depositional ages ranging from 52.9 ± 1.8 Ma to 49.97 ± 0.22 Ma make these the oldest dated Cenozoic sediments and sedimentary rocks in western Montana, with a North American Land Mammal age of Wasatchian (Barnosky and others, 2014). The concordant 52.9 ± 1.8 Ma age comes from a rhyolite tuff within coarse fluvial sediments in the middle of the Deer Lodge Valley (sample 16OC07). While it is possible that the tuff is reworked, a general lack of lithic fragments and angularity of mineral grains suggest that it has not been transported. The youngest grains in sample 17DV04 have a mean age of 52.19 ± 0.54 Ma and come from less than a meter above the eroded Cretaceous granite, dating the base of the Lowland Creek sequence there. Two samples of Tlcs were collected on the north side of Anaconda by K. Consentius for palynomorph analysis. The age of one sample is estimated to be Late Eocene to Early Oligocene, while the other had a less diagnostic taxa. The estimated age is younger than 53–48 Ma, the known age of the Lowland Creek volcanic field (Dudas and others, 2010), with which the sediments are interlayered. The sediments appear to have been deposited in a shallow lake and have undergone very little diagenesis.

MzPzsm **Mesozoic and Paleozoic sedimentary rocks, thermally metamorphosed**—hornfelsed strata from contact metamorphism along the margins or within roof pendants of the Boulder Batholith.

Kgs **Golden Spike Formation (Upper Cretaceous: Campanian)**—Alternating volcaniclastic sandstone, non-volcaniclastic pebble conglomerate, siltstone, and mudstone and mélange. Interlayered with aphanitic andesitic lava flows (Gwinn, 1961; Gwinn and Mutch, 1965), and intruded by Late Cretaceous–Paleocene dikes (Sears and others, 2010). Kgs was derived from uplifted sedimentary strata west of the deposit, and coarse to fine epiclastic volcanic debris and lavas from the Elkhorn Mountains Volcanic field, east of the deposit (Gwinn and Mutch, 1965). The nonvolcanic base of the sequence is texturally and compositionally immature conglomerate and sandstone. Gwinn and Mutch (1965) describe “chaos beds” (i.e., mélange) low in the section that contain mixed non-volcanic and volcanic blocks 10–15 m long set in a volcanic matrix. Other clasts include rounded cobbles of Precambrian Belt Supergroup rocks, Paleozoic carbonates, and angular blocks of Mesozoic sandstone and volcanic rocks (Gwinn and Mutch, 1965; Mackie, 1986; Waddell, 1997). Lava flow clasts were introduced by debris flows derived from the Elkhorn Mountains to the east (Sears and others, 2010). Predominately andesitic lavas and flow breccia interbedded with epiclastic volcanic debris forms the top of the sequence in the southeastern part of the exposure. Vuke and others (2007) correlated the Golden Spike Formation with the entire Elkhorn Mountains Volcanic field, yet the Golden Spike Formation lacks pyroclastic debris (Gwinn and Mutch, 1965), suggesting a better correlation with the lower, more effusive, andesitic to dacitic member of the Elkhorn Mountains Volcanic field (**Keml**). Up to 2,000 m (6,600 ft) thick.

Kcc **Carter Creek Formation (Upper Cretaceous)**—Tan to gray and gray-green sandstone, siltstone, shale, and siliceous mudstone. Basal sandstones are thin-bedded to massive with shaly partings, abundant oyster shells, and some chert pebbles. Interbedded siliceous volcanic-rich beds are common in upper 460 m of formation. Thickness 610–762 m (2,000–2,500 ft.). After Gwinn (1960).

Kbl **Blackleaf Formation, undivided (late Lower Cretaceous)**—Fine- to medium-grained quartzose sandstone and quartz-pebble conglomerate along the western flank of the Boulder Batholith. Contact-metamorphic minerals include minor amounts of skarn minerals, suggesting this unit contained carbonate cement. Locally, hematite-rich pods and veins occur. Thickness is more than 60 m (200 ft).

Kblv **Blackleaf Formation, Vaughn Member**—Siltstone, mudstone, and shale with subordinate sandstone, volcaniclastic sandstone, and conglomerate with chert and quartzite pebbles. Sandstone is light gray to yellow brown, commonly with volcanic detritus. Fine-grained layers are yellow brown and dark gray, partly calcareous. Conglomerate occurs as discontinuous lenses up to 6 m (20 ft) thick. Contact metamorphosed to green, black, and brown hornfels, white to green quartzites, and metaconglomerates near contact with granodiorite. Dyman and others (1994) measured a thickness of approximately 483 m (1,585 ft) near Dickie Peak, just off the southwest corner of the map.

Kblf **Blackleaf Formation, Flood Member**—green and gray meta-mudstone, shale, and minor interbeds of siltstone and quartz-rich sandstone. Thickness unknown.

Kbkm **Kootenai and/or Blackleaf Formation, metamorphosed (Cretaceous)**—Fine- to coarse-grained metaclastic rocks that typically have a slaty cleavage and a thermal metamorphic overprint. Outcrops near the mouth of Lost Creek are conglomeratic and probably part of the Kootenai Formation. Dyman and others (1994) identified Cretaceous sedimentary rocks north of Lost Creek as the upper part of the Vaughn Member of the Blackleaf Formation and to an unnamed overlying unit dominated by brown siltstone. Thickness unknown.

Kk **Kootenai Formation (Cretaceous)**—Gray limestone, dark gray, red, and green shale, and siltstone, and coarse- to medium-grained, speckled quartz-chert (salt-and-pepper) sandstone. Near Anaconda, distinguished from other Cretaceous rocks by the presence of gastropod fossils in limestone. Thickness unknown.

KJkem **Kootenai Formation and Ellis Group, metamorphosed (Jurassic and Cretaceous)**—Phyllite, quartzite, marble, and schist that are the metamorphic equivalents of the Kootenai and Ellis sedimentary rocks. Markedly attenuated sequence is exposed in northwest corner of quadrangle.

Jme **Morrison Formation and Ellis Group (Late to Middle Jurassic)**—Recessive succession characterized by a lower portion of thin-bedded, calcite-cemented, lithic arenite, sandy siltstone, siltstone, and shale yielding orange, red, tan, and dark gray, sandy siltstone regolith and an upper portion of thin- to medium-bedded, orange to red quartz arenite, thin-bedded siltstone, shale, and sandy micrite (Mahoney and others, written commun., 2009). Also contains discontinuous beds of light-gray-weathering limestone. Rocks assigned to the Morrison Formation may consist entirely of olive gray and grayish olive mudstone (Ruppel, 1963). Total thickness is around 150 m (490 ft).

Jsw **Swift Formation (Jurassic)**—Medium to light gray, tan and pink chert–clast-rich sandstone with pebble conglomerate lenses and beds. Secondary quartz veins locally make up >50 percent of the rock (Derkey and others, 1993). Thickness undetermined.

PℙMpm **Phosphoria and Quadrant formations and Madison Group, undivided (Permian, Pennsylvanian, Mississippian)**—Includes gray, fine- to medium-grained quartz sandstone; thinly interbedded oolitic phosphatic sandstone, shale and chert; vitreous gray, tan, and rusty orange, fine-grained quartz sandstone; thick to massively bedded, medium to dark gray, fossiliferous limestone (Mahoney, written commun., 2009). Found along center of north edge of quadrangle. Total thickness around 75 m (250 ft).

ℙq **Quadrant Formation (Pennsylvanian)**—Vitreous white, gray, and red quartzite, very clean, very hard. Exposures typically strongly brecciated. Forms resistant ridges. Up to 60 m (200 ft) thick.

MDsm **Sedimentary rock metamorphosed to marble (Mississippian?)**—Massive light-colored limestone and marble derived from Paleozoic carbonate rocks, dominantly the Mission Canyon and Lodgepole Formations. Mylonitized along the Anaconda Detachment. Structural complexity or metamorphism obscure distinctions between formations. In southwest part of quadrangle, fossiliferous Madison Group limestone grades into marble mylonite. Thickness controlled by tectonism.

Ꞓrfm **Hasmark, Silver Hill, and Flathead Formations, metamorphosed, undivided (Cambrian)**—Quartz sandstone of the Flathead Formation, dolomite of the Hasmark Formation, and siltstone and shale of the Silver Hill Formation, poorly exposed on the west edge of the map. Thickness unknown.

Ymim **Missoula Group metamorphosed (Mesoproterozoic)**—Medium-grained pink, gray, and red feldspathic quartzite. Cross-bedded with conglomerate layers containing meta-sandstone cobbles. Thickness unknown.

Ypng **Calc-silicate gneiss, metamorphosed Piegan Group (Mesoproterozoic)**—Interpreted to be metamorphic equivalent of Piegan Group as defined by Winston and others (2006). On the south side of Mount Powell, Ypng is interlayered massive calcite marble and coarse crystalline tremolite, quartz, and dolomite, and is intruded by leucocratic garnet-bearing granite dikes. The compositional layering is isoclinally folded and transposed, and has been refolded into complex two- or three-generation interference patterns. The folds are overprinted by a slaty preferred dimensional orientation fabric oriented 062°/52° SE. This fabric has been subsequently overprinted by NW-trending right-handed ductile shear zones and low-angle top-west shear zones. The long complex deformation history of these rocks suggests that they come from deep within the footwall of the Anaconda Metamorphic Core Complex. At Deer Lodge Mountain, Ypng is composed of argillite and calc-silicate layers millimeters to centimeters thick, with a transposition foliation overprinted by a slaty cleavage. Thickness unknown.

Yra **Ravalli Group (Mesoproterozoic)**—White feldspathic quartzite near the northwest corner of the map. Quartzites are well exposed on the top of a ridge, and abundant primary structures show that the sequence is overturned. Exposed thickness about 350 m (1,100 ft).

Ysq **Schist and quartzite (Mesoproterozoic)**—Gray micaceous quartzite and phyllite, fine-grained, well-sorted, with minor feldspar. The dominant fabric is a transposed foliation of millimeters to centimeters right, dark and light bands with strong mica preferred dimensional orientation, overprinted by crenulation and shear band cleavages. Found on and around Mount Powell. Thickness and protolith unknown.

Igneous Units

The Elliston Volcanic Field

Tr **Rhyolite (Eocene–Oligocene)**—White, gray, red, maroon, dark gray, and black rhyolite tuff, lava, breccia, and vitrophyre. Light pinkish gray to red, flow-banded and porphyritic tuff with abundant fragmented smoky quartz and sanidine phenocrysts (Becraft and others, 1963) is the dominant rock type in the unit. Tuffs are characterized by compacted pumice fragments (fiammé) and rheomorphic flow indicators such as post-crystallization flow-bands and stretching lineations. Lavas are typically flow-banded and associated with autoclastic flow breccia and marginal vitric zones. Conspicuous flow-bands warp around solid fragments of identical composition, which indicates flow after partial crystallization (Becraft and others, 1963) and is consistent with a rheomorphic ignimbrite origin (e.g., Andrews and Branney, 2011). These rhyolite deposits are up to 400 m thick in the northern half of the quadrangle and thin to about 250 m to the west, near Bison Mountain, where sample KCS-16-30 yields a sanidine ^{40}Ar-^{39}Ar age of 37.4 Ma. West of Jefferson City, the rhyolite ignimbrite is 10–20 m thick, poorly to moderately welded, and crystal-rich (30–35 percent sanidine, quartz, biotite, trace plagioclase), with 2–5 volume percent fiammé, and a 1- to 2-m-thick basal vitrophyre (Olson and others, 2017). Moderately welded, crystal-poor rhyolite ignimbrite forms the top 100 m of Orofino Mountain and contains fiammé up to 10 cm long. Phenocrysts comprise ~5 percent of this ignimbrite, and consist of euhedral black quartz, subhedral sanidine, and some embayed quartz megacrysts. The sequence in part correlates with the Elliston volcanic (see location figure on the map) where Mosolf (2015) reported ages of 48 to 30 Ma for a series of rhyolite tuffs and andesite to dacite lavas. Total thickness between 10 and 400 m (30 and 1,300 ft).

The Lowland Creek Volcanic Field

Tlci **Intrusive to subvolcanic dike rocks (Eocene)**—White to gray and light pink, blocky and platy, porphyritic rhyolite to rhyodacite. Dikes contain plagioclase, sanidine, quartz, hornblende, and biotite phenocrysts and less common glass and centimeter-long cubes of partially resorbed and zoned plagioclase xenocrysts. Dikes typically exhibit a sub-vertical foliation defined by compaction features (e.g., fiammé, flow bands, or void). Zones of intense hydrothermal alteration occur within and adjacent to many of the intrusions. Alteration zones are recognized by white to tan, intensely bleached and silicified coarsely porphyritic rocks. Zones of argillic to mildly propylitic alteration occur locally. Tlci occurs at several historic mines in the volcanic field and includes precious-metal ores, rhyolite breccia, and silica veins (Foster and Childs, 1993; Metesh and Scarberry, 2017). Rhyodacite porphyry dikes, mapped as clastic dikes by Ruppel (1963) near Basin, cut the lower tuff (**Tlcl**) along the road between Bernice and the Lowland Creek campground (FR 019) and may be feeder dikes for porphyry lava flows (**Tlcp**; Smedes, 1968). Dike rocks are concentrated and well-exposed near vents for the upper tuff unit (**Tlcu**) near Jefferson City (Olson and others, 2017) and Butte (Houston and Dilles, 2013a,b). Three sets of dikes at the vent near Jefferson City include: (1) crystal-rich rhyolite porphyry with 35 percent plagioclase, quartz, and biotite; (2) crystal-poor dacite with abundant amphibole and lesser amounts of biotite; and (3) crystal-rich dacite with 20–30 percent crystals of plagioclase, quartz, zoned sanidine and anorthoclase, and fine-grained biotite and amphibole. Cross-cutting relationships suggest that the crystal-rich rhyolite dikes are related to the lower tuff (**Tlcl**), whereas the crystal-poor and crystal-rich dacite dikes formed with the upper tuff (**Tlcu**; Olson and others; 2017). Rhyolite dikes up to 60 m wide feed pyroclastic deposits at the Big Butte vent complex on the Montana Tech campus in Butte (Houston and Dilles, 2013a,b). Subvolcanic dikes described north of Butte by Smedes (1968) and Hargrave and Berg (2013) are in part younger than the tuff units (**Tlcl** and **Tlcu**) and may have formed during caldera resurgence. One of these dikes is continuous for nearly a kilometer north of Ramsay, and contains abundant inherited Cretaceous–Archean zircon grains and crystallized at around 51.1 Ma [Scarberry, in review (a)].

Tlca **Andesite–dacite lavas of small "turtle-back" lava dome complexes (Eocene)—**Black, glassy, crystal-poor to aphanitic lava, agglutinate and phreatomagmatic deposits. Tlca is distinguished by its dark color, mafic composition, and geomorphic expression. The best exposure is the Hackney lava dome west of Ramsay, a <1 km^3 lava dome cut by the I-90 corridor [Scarberry, in review (a)]. Here, platy outcrops with subhorizontal and subvertical flow banding suggests subvolcanic exposure of the lava dome. Subaerial deposits of the unit are vesicular with auto-brecciated flow bases and local pillow lavas (Scarberry and others, 2015). A lava dome west of Ramsay overlies rhyodacite porphyry lavas (**Tlcp**), at least locally. Dudas and others (2010) referred to the lava sequence as the "upper lava dacite" and reported a preferred eruption age of about 50 Ma (fig. 2). The exposed thickness is around 100 m (330 ft).

Tlcu **Upper rhyolite ignimbrite and vent complexes (Eocene)—**Dacite to rhyolite welded and air-fall tuff, rhyolite pyroclastic rocks, pyroclastic vent breccia, and phreatomagmatic diatreme breccia deposits (Sillitoe and others, 1985; Houston and Dilles, 2013a,b; Olson and others, 2017). Collectively, Tlcu marks a regional ignimbrite eruption followed by collapse of previously erupted surface rocks into vents at the Big Butte and Spring Gulch complexes, located north of Butte and west of Jefferson City (fig. 1), respectively. South of Anaconda, the upper ignimbrite contains conspicuous subangular to well-rounded quartzite clasts up to 10 cm long that are encased in densely welded tuff. Vent deposits are felsic pyroclastic beds, concentrated dike rocks, and moderately to steeply tilted blocks of older volcanic deposits (e.g., **Tlcp**, **Tlcl**). Vents include the 6 km^2 Big Butte vent complex (Houston and Dilles, 2013a,b) and the 11 km^2 Spring Gulch vent complex. Both vents intrude the Elkhorn Mountains–Boulder Batholith magma system. Pyroclastic breccia in the Big Butte vent complex consists of angular blocks (< 1 to 30 m wide) of granite (**Kg**), aplite (**Ka**), rhyolite ignimbrite (**Tlcl**), and rhyodacite porphyry lavas (**Tlcp**) in a poorly welded matrix of pyroclastic rhyolite (Houston and Dilles, 2013a). The Spring Gulch vent complex has red-brown to tan, welded dacite and air-fall tuff exposed mainly on the vent margins. The tuffs contain 30–35 percent broken plagioclase, biotite, hornblende and quartz crystals, and fiammé. Polylithic breccia clasts up to 1 m in diameter occur towards the base of the deposit (Olson and others, 2017). Gray breccia locally forms prominent outcrops with abundant (20–40 percent) angular fragments of dacite and lesser amounts of granite (**Kg**) and rocks from the roof pendant of the Elkhorn Mountains volcanic field (units **Kemm** and **Kemu**). Diatreme breccia in the unit at the Montana Tunnels mine produced Au (Sillitoe and others, 1985). The diatreme breccia contains up to 30% of polylithic, subangular to well-rounded clasts of rocks from the Boulder Batholith, the Elkhorn Mountains Volcanic field, and the Lowland Creek Volcanic field. The early intra-caldera dacite tuff and the late cross-cutting crystal-rich dacite dikes both crystallized at about 51.9 Ma (Olson and others, 2017), which suggests that the Spring Gulch vent complex formed rapidly The Big Butte vent complex also formed at 51.9 Ma (Dudas and others, 2010; Houston and Dilles, 2013a). A sample of Tlcu (CE16AN1) from the north side of the Lost Creek Valley on the west side of the Butte North quadrangle yielded a detrital zircon age spectrum with a mean age of 51.84 ± 0.70 for the youngest zircons. Thicknesses vary from about 10 m to 100 m (33–330 ft) thick.

Tlcp **Rhyodacite porphyry lava flows (Eocene)**—Dark gray and maroon flows with plagioclase crystals commonly larger than 5 mm. Other phenocrysts include biotite, hornblende, and quartz in a devitrified and oxidized groundmass. Tlcp is distinguished by a flow-banded texture and spatial association with breccia (**Tlcb**) and vitrophyre (**Tlcv**) of the same composition. Lava above **Tlcb** is platy and crystal-poor (10–15 percent) with near-planar flow bands and similarly oriented lithophysal laminations. Highly contorted flow banding occurs in the upper parts of individual lava flows. Vitrophyre (**Tlcv**) marks the quenched outer margins of the lavas. All of these features are exposed in outcrops north of I-90 at Ramsay [Scarberry, in review (a)]. Reported ages for the unit range from about 52.9 to 51.8 Ma (Dudas and others, 2010; Scarberry and Elliott, 2016). Tlcp lavas are interstratified with **Tlcl** and **Tlcu** and are interpreted here to represent intercaldera lava sequences that filled NE-trending grabens or half-grabens within the volcanic field. Total thickness 350 m to 500 m (1,150–1,640 ft).

Tlcb **Volcanic breccia (Eocene)**—White to salmon pink and red, locally dark greenish gray, predominately autoclastic breccia that forms the tops and bottoms of rhyodacite porphyry lavas (**Tlcp**) and vitrophyre (**Tlcv**). Generally monolithologic, matrix- and clast-supported, and variably indurated. Excellent outcrops of breccia at the base of the lava sequence occur along Silver Bow Creek where white to salmon pink and red, oxidized, poorly indurated and matrix-supported block and ash deposits transition up section to massive, clast-supported, autoclastic breccia with blocks as wide as 3 m (Scarberry and Elliott, 2016). Tlcb is locally (1) flow-banded blocks of rhyodacite or vitrophyre in a lava or glassy matrix; (2) 5–10 m thick bands of monolithologic rhyolite breccia that area fused where they contact Tlcp, and likely formed via convection of superheated steam at the edges of lava flows (e.g., Christiansen and Lipman, 1966), which fused **Tlcl** talus perhaps adjacent to fault scarps; (3) small volumes of monolithic clast-supported and intensely silicified fissure breccia related to the Hackney lava dome complex (Scarberry and others, 2015); and (4) dark greenish gray, poorly sorted, fine-grained breccia and coarse-grained sandstone described by Ruppel (1963) east of Cliff Mountain. Clasts in the 150-m-thick breccia deposit are angular fragments of Cretaceous and Eocene volcanic rocks. Thickness is highly variable up to 150 m (500 ft).

Tlcv **Vitrophyre (Eocene)—**Black vitrophyre primarily related to **Tlcp**. Contains abundant plagioclase phenocrysts and sparse biotite. The unit is exposed at, or near, the base and margins of **Tlcp** and is a facies of the same volcanic pulse. Derkey and Bartholomew (1988) mapped the unit as rhyodacite welded tuff (their unit Trdp). Exposures of the unit are typically <20 m (65) thick. Tlcv is over 100 m (330 ft) thick where it is brecciated and in contact with **Tlcl** north of I-90 near Ramsay.

Tlcl **Lower rhyolite ignimbrite (Eocene)—**White and gray, lithic- and crystal-rich, variably welded ignimbrite. With three distinct, mutually gradational horizons. The bottom 80 m (260 ft) consists of non-welded, pumice- and lithic- and biotite-rich dacite and is exposed north and west of Butte, where it overlies micaceous mudstones and siltstones that grade upward to coarse feldspathic sandstones, tuffaceous sandstones, and silicified–conglomerate [Houston and Dilles, 2013a; Scarberry, in review (a)]. The overlying 150 m (500 ft) of the section is non-welded air-fall and base surge deposits with sparse, thin, laminar, and densely welded tuff interbeds. The uppermost 70 m (230 ft) consists of moderately to densely welded rhyolite tuff with a compaction foliation defined by flattened pumice. Gas escape voids that formed during vapor-phase crystallization in poorly welded tuff outcrops are also flattened. North of I-90 near Ramsay, dislodged blocks of the unit exhibit chaotic compaction orientations, suggesting they are megabreccia blocks formed during caldera collapse (Scarberry and others, 2015). The ignimbrite is up to 300 m (1,000 ft) thick and has an age of about 52.9 Ma (Dudas and others, 2010). Tlcl was deposited on a surface of low-relief, and near Butte contains up to 13 cooling units marked by distinct welding breaks (Houston and Dilles, 2013a).

Tlcr **Rhyolite ignimbrite, undifferentiated (Eocene)—**The two rhyolite tuff sequences in the volcanic field are difficult to distinguish mineralogically and geochemically (Dudas and others, 2010). Deposits that make up Tlcr may consist of the 52.9 Ma lower rhyolite ignimbrite (**Tlcl**), the 51.9 upper rhyolite ignimbrite (**Tlcu**), or a combination of both sequences (Dudas and others, 2010; Olson and others, 2017).

Anaconda Metamorphic Complex Plutonic Suite

Tgbm **Granite, biotite–muscovite (Eocene)—**Fine- to medium-grained two-mica granite, dacite, and granodiorite of the Hearst Lake suite. Generally porphyritic. Mylonitic foliation is present within and adjacent to the Anaconda Detachment Fault. Foster and others (2007) report a U-Pb crystallization age of 53 ± 1 Ma for a related granodiorite. Foster and others (2010) report ^{40}Ar/^{39}Ar cooling ages between 39 and 41 Ma for two-mica granite mylonites.

Tgt **Biotite granite of the Lost Creek Stock (Eocene?)—**Red to gray, biotite monzogranite of the Lost Creek stock (Winegar, 1971). The body contains bands of dark-colored mylonite, ultramylonite, and cataclasite, and is locally strongly brecciated. Foster and others (2010) established a biotite age of 38.8 ± 1.4 Ma for a mylonitic biotite granodiorite at 46.197004° N, 112.986360° W (E½ SW¼ sec. 9 T. 5 N., R. 11 W.), believed to be a phase of the same stock. Kalakay and others (2014) interpret the biotite age to be much younger than the crystallization age of the pluton, and to reflect the timing of tectonic exhumation of the footwall of the Anaconda Detachment.

TKdi **Diorite of the Mount Powell Batholith (Cretaceous?–Tertiary)**—Fine- to coarse-grained, layered to massive, hornblende–plagioclase diorite. Locally intrudes the Mount Powell Batholith, suggesting it is mostly, if not all, Tertiary.

TKg **Mount Powell Batholith (Late Cretaceous to Paleocene)—**Suite of Late Cretaceous to Paleocene monzogranitic to monzodioritic plutons, sills, and dikes. Includes potassium feldspar porphyritic muscovite–it's biotite granite, garnet-bearing aplite, and pegmatite. Zones within the batholith contain sheets of metamorphic rocks such as strongly foliated quartz–chlorite–biotite phyllite, quartz–muscovite schist, and quartz–feldspar–chlorite–epidote gneiss. The schistose rocks appear to have sedimentary protoliths and the gneisses appear to have intrusive igneous protoliths. Many of these rock types were mapped by Mutch (1960, 1961) as "altered diorite." The metamorphic rocks appear to have been strongly deformed prior to inclusion in the batholith.

Eight apatite fission track dates from the Mount Powell Batholith have an average age of 62.1 Ma (Baty, 1973). Marvin and others (1989) report K/Ar dates of 61.5 ± 1.0 Ma for biotite and 59.7 ± 1.4 Ma for muscovite from a sample of granite from the Mount Powell Batholith just west of the Mount Powell 7.5' quadrangle along Racetrack Creek. Grice (2006) reports an ^{40}Ar/^{39}Ar mica cooling age closer to 68 Ma based on slightly discordant biotite and muscovite plateaus. Naibert and others (2010) conclude that the emplacement age of the Batholith is younger than or equal to the youngest biotite age (65.4 Ma) of the adjacent Philipsburg Batholith. Given the variety of intrusive phases within the Mount Powell Batholith, it seems likely that it was intruded in stages that ranged between late Cretaceous and early Tertiary times. The batholith was probably crystallized by Eocene times because it was affected by top-east mylonitization along the Anaconda Detachment.

The batholith contains inherited zircons with ages between 1.63 and 2.47 Ga (Foster and others, 2006), indicating the presence of Paleoproterozoic rocks in the magmatic source area. Foster and others (2006) include the batholith in their Selway basement terrane, which bounds the west side of the Great Falls Tectonic Zone.

Kgd **Foliated granodiorite (Cretaceous)**—Hornblende granodiorite with well-developed mylonitic fabrics. Shallowly dipping, top-to-the-west S-C fabrics and shear bands are locally overprinted by top-east shear indicators that are congruent with top-east mylonitic foliation in the Mount Powell Batholith (**TKg**). Dikes and sills of **TKg** cut the mylonite, showing that west-directed shear in **Kgd** occurred before intrusion of the batholith. **Kgd** and **TKg** were both subjected to top-east shear during extension of the Anaconda Metamorphic Core Complex (O'Neill and others, 2004; Foster and others, 2010). Hawley (1974) named the Cretaceous granodiorite the Racetrack Pluton but included rocks that are tectonically and lithologically distinct (Elliott and others, 2013).

Boulder Batholith [see du Bray and others (2009) and du Bray and others (2012) for detailed descriptions and analyses of the Boulder Batholith]

Ka **Aplite and alaskite, alaskite porphyry, pegmatite, and other felsic intrusive rocks (Late Cretaceous)—**Light tan, sheet-like bodies that locally appear bedded but lack volcanic or sedimentary structures. Typically fine-grained with a sugary and equigranular, granophyric texture but locally moderately coarse. Minerals include 5 to 10 percent biotite and near equal amounts of quartz and K-feldspar and plagioclase. Includes small masses of pegmatite with radiating tourmaline crystals, potassium feldspar, and plagioclase. Aplite on the west side of the Boulder Batholith, north of Butte, is about 75 Ma (Korzeb and Scarberry, 2018).

Kg **Granite of the Boulder Batholith, undivided (Late Cretaceous)—**Light to medium gray, or light brownish with a hint of pink. Massive jointed outcrops that form the Butte pluton, which is the principal pluton, by volume, of the Boulder Batholith. Coarse, medium, and fine varieties occur and exhibit normal-zoned plagioclase (45–50 percent), orthoclase (20–30 percent), and quartz (5–10 percent; Berg and Hargrave, 2004). Contains accessory amounts of sphene, apatite, magnetite, and rare zircon (Weeks, 1974). Hornblende and biotite generally make up 15–20 percent of the rock and occur at a 1:1 to 1:2 ratio. The mafic minerals are largely altered to chlorite and epidote. Accessory minerals include apatite, chlorite, epidote, magnetite, sphene, and zircon (Ruppel, 1963). The Butte pluton formed between 76.3 and 74.5 Ma and is cut by 75.1 to 73.8 Ma Pb-Zn-Ag veins (Lund and others, 2002).

Kdi **Diorite (Late Cretaceous)—**Medium gray to dark greenish gray or greenish gray, fine- to medium-grained porphyritic to seriate-textured diorite dikes, sills, and plugs. Contain 15–20 percent phenocrysts of pyroxene, hornblende, biotite, and plagioclase in a fine-grained groundmass of plagioclase and pyroxene (Olson and others, 2016). Includes a 500 m (1, 600 ft) wide monzodiorite stock that intrudes the lower and middle members of the Elkhorn Mountains Volcanic field (**Keml** and **Kemm**) in the eastern flank of the Boulder Batholith (Olson and others, 2016). Good exposures of the unit occur east of Deer Lodge, where diorite intrusions form a series of aligned rock towers mantled by fissure breccia (Scarberry, 2016a). In part, the diorite intrusions represent intrusive equivalents to the lower member of the Elkhorn Mountains Volcanic field (**Keml**) and pre-date granitic rocks of the Boulder Batholith (Kg). Reported ages for the unit range from about 80 to 77 Ma (Olson and others, 2016; Scarberry, 2016b; Korzeb and others, 2018).

Kgi **Gabbro (Late Cretaceous)—**Medium to dark gray and coarsely porphyritic, with plagioclase (labradorite), hornblende and pyroxene (augite) phenocrysts that range from about 2 mm up to 3 cm in length. Kgi cuts the lower and middle members of the Elkhorn Mountains Volcanic field (**Keml** and **Kemm**) in both the western and eastern flanks of the Boulder Batholith. A gabbroic sill that cuts **Keml** in the Little Blackfoot River drainage on the western side of the Boulder Batholith has an age of about 82 Ma. On the eastern flank of the batholith, Kgi includes subvolcanic alkalic basaltic dikes and olivine- and biotite-bearing lamprophyre dikes (Prostka, 1966; Weeks, 1974; DeWitt and others, 1996; Olson and others, 2016). The best exposure of these rocks is along the eastern flank of the Boulder Batholith, and particularly on the west side of Bull Mountain where a mafic laccolith at least 600 m (2,000 ft) thick intrudes the middle member of the Elkhorn Mountains Volcanic field (**Kemm**; Scarberry, 2016b). The laccolith is compositionally layered with diorite at the base and gabbro forming the main body of the intrusion. Kgi contains euhedral pyroxene up to 4 mm in length, olivine, and partially resorbed felsic crystalline igneous xenoliths that are >10 cm long. The laccolith could be similar in age to a nearby diorite sill that formed around 79 Ma (Scarberry, 2016b), and is younger than the middle member of the Elkhorn Mountains Volcanic field (**Kemm**), which is about 81 Ma in the region (Olson and others, 2016).

Kqp **Quartz porphyry (Late Cretaceous)**—Blocky and jointed brown granitic rocks that contain conspicuous 2-4 mm, round quartz "eyes," potassium feldspar, and biotite. Kqp dikes or plugs occur in the main roof pendant to the Boulder Batholith near Jefferson City and along the eastern flank of the Boulder Batholith near Boulder. Kqp intrusions near Jefferson City exhibit granophyric and graphic textures and consist of 50–60 percent phenocrysts and 40–50 percent interstitial quartz and K-feldspar (Olson and others, 2016). The intrusions are dated at about 83 Ma near Jefferson City (Olson and others, 2017) and 80 Ma near Boulder (Scarberry and others, 2017).

The Elkhorn Mountains Volcanic Field

Kemu **Elkhorn Mountains Volcanics, upper member (Late Cretaceous)**—Dark gray to green, bedded and water-laid tuff, andesitic epiclastic volcanic rocks, and well-bedded dark gray andesitic tuffs, tuffaceous sandstone, and lapilli tuff with fine-grained crystal tuff interbeds (Becraft and others, 1963; Smedes, 1966). Laterally discontinuous dark gray ignimbrite deposits are interbedded with thinly bedded dark gray, reddish-brown, or dark green volcanic sandstone and siltstone (Olson and others, 2017). The ignimbrites locally contain up to 5 percent, 3- to 5-cm-long fiammé and have a vitroclastic texture (Olson and others, 2017). Scarberry (2016b) assigned a 75-m-thick (250 ft) sequence of rocks on Bull Mountain near the eastern flank of the Boulder Batholith to Kemu. The rocks on Bull Mountain are dark gray to light green water-lain andesitic tuffs, volcaniclastic sedimentary rocks, banded chert, and rheomorphic andesitic ignimbrites. Most of the mafic minerals are altered to chlorite with lesser epidote. Kemu is best exposed in roof pendants in the Boulder Batholith between Butte and Helena. There are no radiometric age data, but in the main roof pendant, near Jefferson City, upper member volcanic sandstones are cross-cut by an 83.2 ± 1.9 Ma quartz porphyry intrusion (**Kqp**; Olson and others, 2017). The upper member has a maximum thickness of 600 m (2,000 ft; Becraft and others, 1963; Olson and others, 2017).

Kemm **Elkhorn Mountains Volcanics, middle member (Late Cretaceous)**—Tan, gray to light green, andesitic breccia, tuff, and at least seven welded rhyolite ignimbrites intercalated with epiclastic volcanic debris from the lower member of the volcanic field. Hematite, chlorite, and epidote alteration add red and green tones to the rocks. Flattened and stretched pumice fragments are characteristic of the ignimbrite deposits. In the Little Blackfoot River drainage, on the northwest flank of the Boulder Batholith, Kemm is about 550 m (1, 800 ft) thick and consists of greenish gray to black, moderately welded, basaltic andesitic–dacite breccia, tuff, and debris flow deposits [Scarberry, in review (b)]. Breccia clasts range from about 1 mm to 5 cm long and locally include sand–pebble-sized, reworked fluvial clasts. Andesitic tuff overlying the breccia is welded near its base, contains prominent flattened pumice 7–10 cm long, and is crystal-rich, with about 30 percent millimeter-long broken plagioclase crystals and 5 percent altered mafic minerals. East of Deer Lodge, Kemm is up to 1, 400 m and consists of tuff breccia, debris flows, and variably welded rhyolite ignimbrites. The breccia is heterolithic and contains clasts of **Keml** andesite–dacite volcanic rocks, equivalent intrusive compositions, and metasedimentary rocks. Blocks in clast-supported breccia are 10–30 m wide at Cliff Mountain, suggesting that the deposit formed during caldera vent collapse (Scarberry, 2016a). Moderately to densely welded rhyolite ignimbrites overlie and are interstratified with the breccia deposits. The massive cliff-forming ignimbrites contain 1- to 5-cm-long fiammé and 0.5- to 2.0-mm-long shattered plagioclase crystals. Olson and others (2016) and Scarberry and others (2017) correlate three middle member rhyolite ignimbrites along the east flank of the Boulder Batholith using the stratigraphic nomenclature of Prostka (1966). The ignimbrite sheets are each 100 to 300 m thick, rheomorphic, vitroclastic, crystal-rich (30 percent) and crystal-poor (10 percent), and contain stretched pumice with length:width ratios of up to 100:1 (Olson and others, 2016; Scarberry and others, 2017). Radiometric ages for the middle member rhyolite tuffs range from about 84 Ma to 77 Ma. The ignimbrites appear to be younger on the north and west side of the Boulder Batholith (Ihinger and others, 2011; Olson and others, 2017; Korzeb and others, 2018) than on the southeast between Boulder and Whitehall (Olson and others, 2016). The middle member of the volcanic field averages 1,650 m (5,400 ft) thick.

Keml **Elkhorn Mountains Volcanics, lower member (Late Cretaceous)—**Dark brown to greenish gray, basaltic to andesitic lavas, and white to medium gray, purple, and green dacitic lavas and domes that are predominantly structureless but locally flow-banded and brecciated. Smaller amounts of vitrophyre, autoclastic breccia, and pyroclastic and epiclastic volcanic deposits also occur. The basaltic to andesitic lavas commonly form steep, resistant hillslopes. Phenocrysts in these lavas include 30–40 percent plagioclase, 1–3 mm long, and 5–10 percent pyroxene 3–5 mm long. Sparse, sub-millimeter, olivine that has altered to fibrous amphibole or antigorite was noted by Robertson (1953). Accessory minerals include magnetite and apatite. Amygdaloidal layers and autoclastic breccia along flow margins are common distinguishing features of the basaltic to andesitic lavas. The rocks are chalky white and appear bleached where they are intruded by Boulder Batholith granite (Kg). Dacitic lavas are coarsely porphyritic (30–35 percent crystals) to fine-grained (<10 percent crystals) and locally form domes due to their high viscosity relative to the basaltic to andesitic lavas. Phenocrysts include plagioclase, augite, hornblende, and minor biotite and Fe-Ti oxides. Autoclastic breccia, characterized by subangular dacite clasts in a dacite lava matrix, and ramp structures establish an extrusive origin for the lavas and domes. Dacite lavas and domes often transition laterally to subrounded dacitic conglomerates, sands, and muds. Plagioclase is typically 1–3 mm long and euhedral in the dacitic lavas and domes, and appear broken and abraded in the dacitic volcanogenic sediments. Radiometric ages of the middle member rhyolite ignimbrites constrain the age of the lower member to older than about 80 Ma on the west flank of the Boulder Batholith (Korzeb and others, 2018; Scarberry, 2016a) and older than about 85 Ma on its southeastern flank (Olson and others, 2016). The best exposures of basaltic to andesitic lavas occur east of Deer Lodge in the Emery mining district, where they are at least 200 m (660 ft) thick and cut by gold-bearing quartz veins (Derkey and others, 1993; Scarberry, 2016a; Korzeb and others, 2018). The best exposure of dacitic lavas and domes occurs near Ratio Mountain, where the sequence is about 600 m (1,970 ft) thick (Prostka, 1966; Olson and others, 2016). The unit averages about 650 m (2,100 ft) thick regionally (Smedes, 1966).

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