GEOLOGIC MAP OF THE ELLISTON 30′ X 60′ QUADRANGLE, WEST-CENTRAL MONTANA

Catherine McDonald, Jesse G. Mosolf, Susan M. Vuke, and Jeffrey D. Lonn

Partial support has been provided by the STATEMAP component of the National Cooperative Geologic Mapping Program of the U.S. Geological Survey under Contract G14AC00221.

Montana Bureau of Mines and Geology

Cover image: Eocene rhyolite lava and tuff exposed near the summit of Crater Mountain, southeast of Lincoln, Montana. Photo by Jesse Mosolf.

GEOLOGIC MAP OF THE ELLISTON 30′ x 60′ QUADRANGLE, WEST-CENTRAL MONTANA

Catherine McDonald, Jesse G. Mosolf, Susan M. Vuke, and Jeffrey D. Lonn

March 2020

Partial support has been provided by the STATEMAP component of the National Cooperative Geologic Mapping Program of the U.S. Geological Survey under Contract G14AC00221.

Montana Bureau of Mines and Geology

CONTENTS

FIGURES

TABLES

INTRODUCTION

The geologic map of the Elliston 30′ x 60′ quadrangle (plate 1) encompasses a geologically complex and seismically active part of west-central Montana. The quadrangle is located within the eastern part of the Lewis and Clark Fault Zone near the leading edge of the Cordilleran fold-thrust belt (fig. 1). It is underlain by Mesoproterozoic through Cretaceous sedimentary rocks, widespread Cretaceous and Tertiary volcanic rocks, Neoproterozoic sills, numerous Cretaceous and Tertiary intrusions, and Tertiary and Quaternary sedimentary deposits. The topography is dominated by generally northwest–southeast-trending mountain ranges and intervening valleys. The Continental Divide transects the central part of the quadrangle and separates the Clark Fork and Blackfoot River drainages in the west from tributaries of the Missouri River in the east (fig. 2). Helena, the capital of Montana, is located in the southeast corner of the quadrangle.

The geologic map was partially funded by the U.S. Geological Survey (USGS) STATEMAP program. In addition to completing the 1:100,000-scale map, a major focus was to develop a volcanic stratigraphy for the Tertiary volcanic rocks exposed in the quadrangle. Geochronological and geochemical analyses were performed on nearly 90 samples to aid the mapping and correlation of volcanic units throughout the Elliston quadrangle. Age and geochemical results are summarized in the following sections and figures; the data are provided in appendices A and B.

A summary of the geology of the Elliston quadrangle is provided below, followed by detailed descriptions of the 114 map units recognized in the map area.

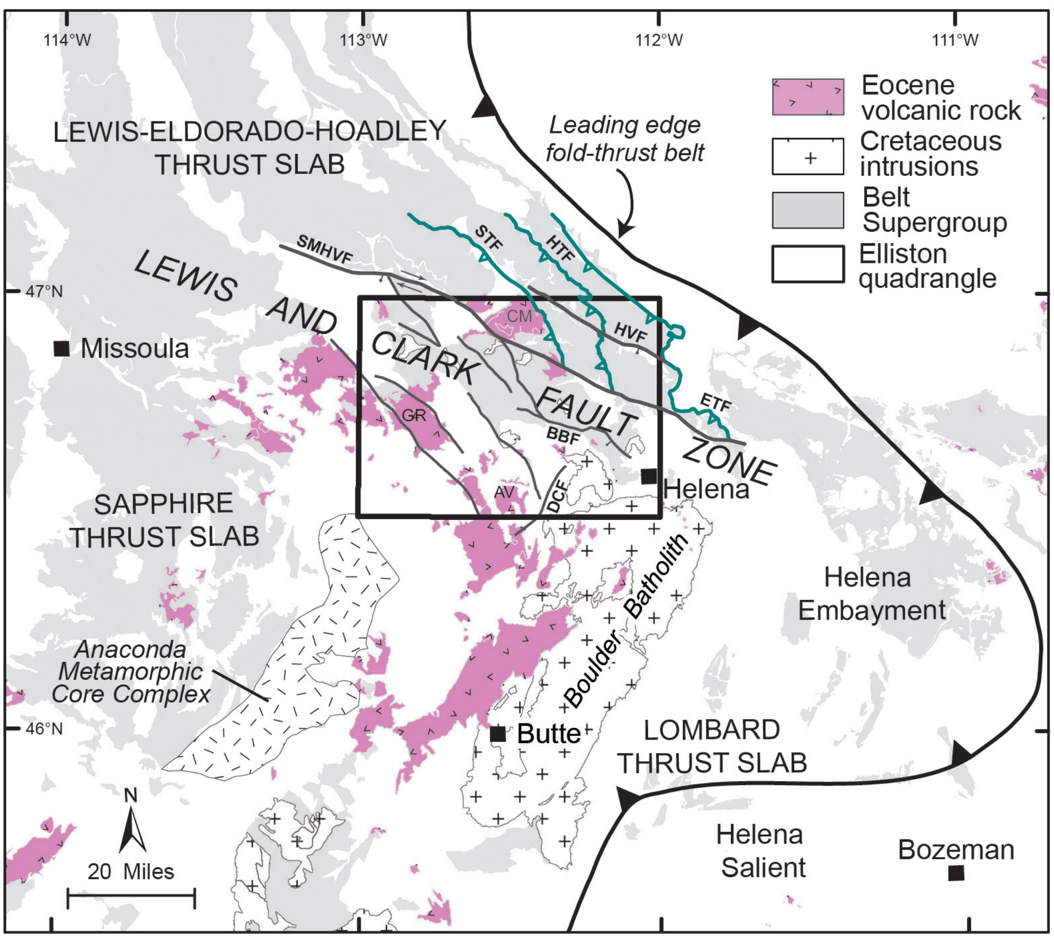


Figure 1. Regional geologic setting of the Elliston 30′ x 60′ quadrangle. The major faults of the Lewis and Clark Fault Zone (LCFZ) and the Lewis–Eldorado–Hoadley thrust slab are shown. The major thrust faults (green) are the Scapegoat (STF), Hoadley (HTF), and Eldorado (ETF) thrusts. These thrusts terminate or are cut by high-angle faults along the LCFZ, including the St. Mary's–Helena Valley Fault (SMHVF) and the Hilger Valley Fault (HVF). Other prominent high-angle faults in the quadrangle include the Bald Butte Fault (BBF) and the Dog Creek Fault (DCF). The main Eocene volcanic fields are the Avon (AV), Garnet Range (GR), and Crater Mountain (CM).

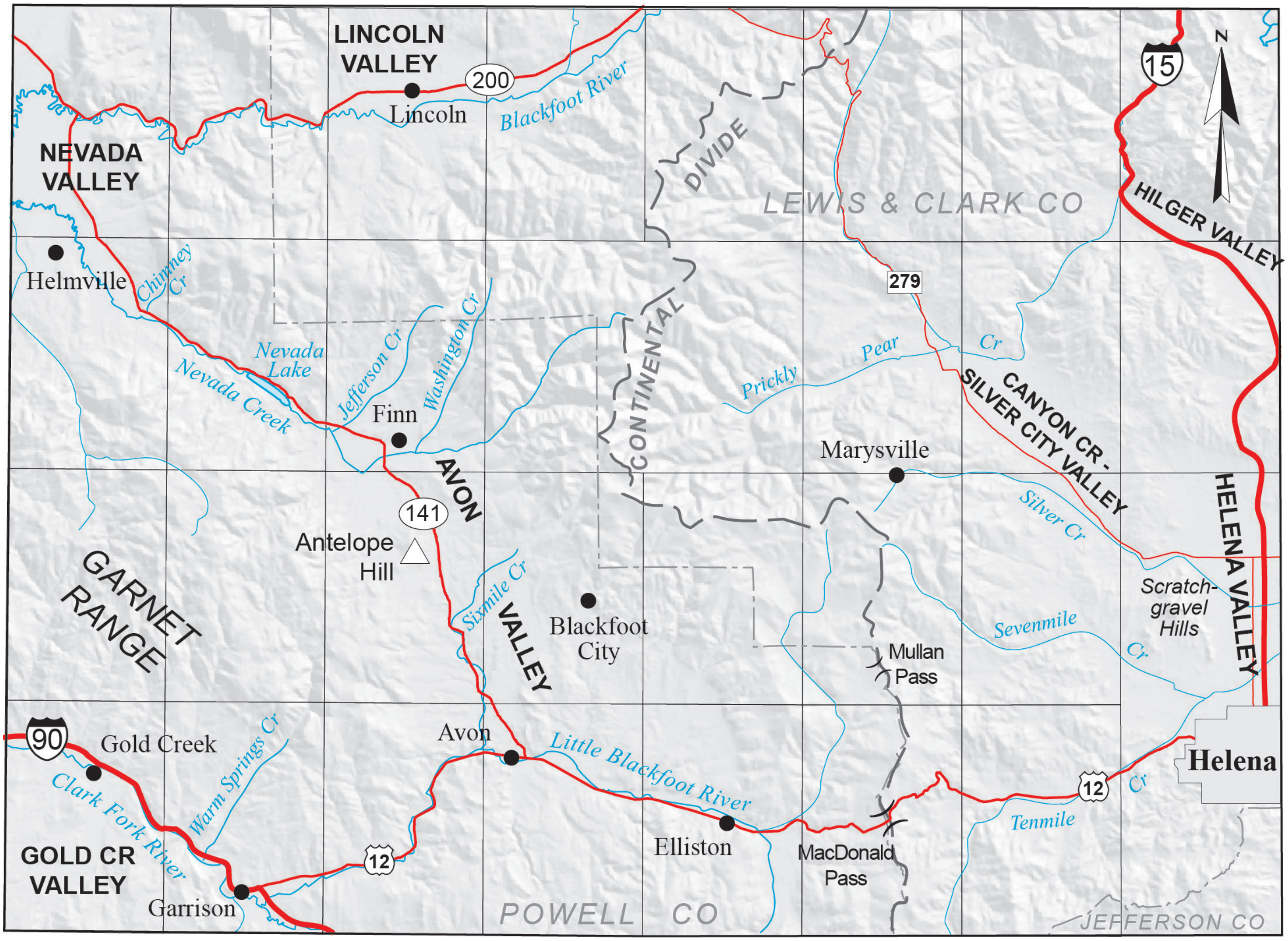


Figure 2. Physiographic map for the Elliston 30′ x 60′ quadrangle.

MESOPROTEROZOIC METASEDIMENTARY ROCKS

Mesoproterozoic metasedimentary rocks of the Belt Supergroup are the oldest exposed rocks in the Elliston quadrangle. These rocks were deposited ca. ~1,500–1,370 Ma (Evans and others, 2000) in an eastern-extending arm of the Belt Basin (Harrison, 1972), spatially coincident with the Helena Embayment (fig. 1). The Belt metasedimentary rocks are widespread in the north half of the quadrangle where they form a thick (about 8,000 m; 26,250 ft) sequence that includes formations from all the major Belt subdivisions including, from oldest to youngest, the informal "lower" Belt (Ross, 1963), and overlying Ravalli, Piegan, and Missoula Groups.

The Greyson Formation is the oldest Belt unit in the quadrangle and is part of the informal lower Belt. The Greyson consists of siltite, argillite, and interbedded quartzite interpreted as shallow shelf deposits that record a prolonged transition from a subtidal, basin-like environment to a shallow water/subaerial environment of the overlying Spokane Formation (Adam and others, 2016). The Spokane and Empire Formations of the Ravalli Group are dominantly fine-grained, thin-bedded argillites and siltites most likely deposited on periodically exposed mudflats where the distal margins of immense eastward-sloping alluvial megafans encountered the Belt Sea (Winston and Link, 1993; Winston, 2013).

The Piegan Group, often referred to as the "middle Belt carbonate," overlies the Ravalli Group and includes the Helena and overlying Wallace Formations. The dominant lithologies are dolomitic limestone, limestone, calcareous siltite, dark gray argillite, and minor fine-grained quartzite. Both the Helena and Wallace Formations are characterized by fining and thinning upward depositional cycles. The Piegan Group strata record expansion and deepening of the Belt Basin, although it was still shallow enough that storm waves could rework the bottom sediments (Winston, 1986a). The Missoula Group (Snowslip, Shepard, Mount Shields, Bonner, and McNamara Formations) are the youngest Belt strata in the quadrangle and consist of alternating sandy and muddy units. The sandier units were deposited on vast northward-sloping alluvial megafans and flats while muddier units formed in a shallow ephemeral sea distal to the megafans (Winston and Sears, 2013).

PALEOZOIC AND MESOZOIC SEDIMENTARY ROCKS

Folded and faulted Paleozoic and Mesozoic sedimentary rocks are exposed in the southern part and northeast corner of the Elliston quadrangle. The oldest Paleozoic strata are Cambrian marine sediments that unconformably overlie Mesoproterozoic Belt rocks. Silurian and Ordovician strata are absent. Devonian through Permian formations include both carbonate and siliciclastic units deposited in shallow marine and marginal marine settings. Mesozoic rocks include Jurassic and Cretaceous marine and non-marine sedimentary units deposited in the foreland of the Cordilleran fold-thrust belt. In the southwestern part of the quadrangle, Cretaceous sediments of Colorado Group (Blackleaf through Carter Creek Formations) formed in the Garrison Depression, a presumably deep basin that accommodated the thickest accumulation (3,000 to 4,500 m; 9,850 to 14,765 ft) of Colorado Group strata in Montana (Gwinn, 1960; O'Brien, 2000). The Colorado Group thins to about 410 m (1,350 ft) in the northeast part of the quadrangle (Bregman, 1981).

INTRUSIVE ROCKS

The oldest intrusive rocks in the Elliston quadrangle are Neoproterozoic diorite and gabbro sills that intruded metasedimentary rocks of the Belt Supergroup. These mafic sills are thought to be part of the Gunbarrel mafic magmatic event, the largest identified mafic dike swarm along the Neoproterozoic margin of the Laurentian craton (Harlan and others, 2003). A diorite sill in the Lewis and Clark Range north of the Elliston quadrangle yielded a K-Ar age of 750 ± 25 Ma (Mudge and others, 1968). Several diorite sills and dikes in the east-adjacent Canyon Ferry Dam 30′ x 60′ quadrangle have reported K-Ar ages of 826 ± 41 Ma to 741.3 ± 32.2 Ma (Reynolds and Brandt, 2005).

The most extensive intrusive units are Late Cretaceous plutonic rocks associated with the Boulder Batholith. These plutons were emplaced ca. ~82–73 Ma (du Bray and others, 2012 and references therein; Olson and others, 2017) into Mesoproterozoic to Mesozoic sedimentary and volcanic rocks, including those of the cogenetic Late Cretaceous Elkhorn Mountains Volcanics. Boulder Batholith magmatism began with intrusion of mafic to intermediate plutons and later granitic and felsic phases (Smedes and others, 1973; Lund and others, 2002). Small gabbroic intrusions near the head of Washington Creek on the east side of the Avon Valley and granodiorites forming the Unionville, Marysville, Scratchgravel Hills, Blackfoot City, Granite Butte, Dalton Mountain, and Ogden Mountain plutons and stocks are associated with the earlier phase of magmatism, with radiometric ages spanning ca. ~81–74 Ma (Schmidt and others, 1994; Lund and others, 2002; du Bray and others, 2012). The Butte Granite, along the southeastern border of the map, crystallized ca. ~76.7 –74.7 Ma (du Bray and others, 2012) and is part of the later, main phase magmatism. In the southern part of the quadrangle, a swarm of Late Cretaceous high-K basaltic and dioritic dikes and sills (Kbd on map) cut the Golden Spike Formation, Elkhorn Mountains Volcanics, and underlying Paleozoic and Mesozoic formations (Mutch, 1961; Gwinn and Mutch, 1965; Sears and others, 1998; Kunz, 2003). One of the sills, located just west of the Elliston quadrangle, yielded a $^{40}Ar/^{39}Ar$ date of 75.9 ± 1.2 Ma (Sears and others, 1998).

Tertiary subvolcanic intrusions exhibit a wide age and compositional array spanning Eocene rhyolitic plugs to mafic stocks. A porphyritic trachydacite dike (51.5 ± 0.3 Ma) cross-cuts the Gravely Mountain Syncline in the southern corner of the map area and is the oldest Tertiary intrusion identified in this study, preceding the oldest Eocene volcanic unit dated in the map area by ~3.3 m.y. This dike is compositionally similar to nearby porphyritic lavas and likely a precursor to Eocene volcanism in the Elliston area. The trachydacitic Silver Bell Stock is the largest Tertiary intrusive complex identified in the quadrangle and yielded U-Pb zircon ages of 47.9 ± 0.2 Ma and 48.0 ± 0.2 Ma. Chemical data highlight compositional similarities between the Silver Bell Stock and contemporaneous lavas, indicating a shared petrogenetic origin.

A trachyandesite intrusion (Tbai; 30.1 ± 0.2 Ma) is the youngest dated Tertiary intrusion, and is likely associated with late Eocene to early Oligocene basaltic volcanism in the Elliston region.

VOLCANIC ROCKS

Volcanogenic rocks occur throughout the Elliston quadrangle that record punctuated episodes of Late Cretaceous and Eocene–Oligocene volcanism. These pulses span major changes in the Elliston region's tectonic development as Late Cretaceous–Paleocene transpressive shortening transitioned to transtensive crustal deformation.

Late Cretaceous Volcanic Units

Late Cretaceous magmatism and associated sedimentation were contemporaneous with transpressional crustal shortening in the Elliston region (Sears and Hendrix, 2004). Volcanogenic units exposed in the Elliston quadrangle include the Golden Spike Formation, the Elkhorn Mountains Volcanics, and the Two Medicine Formation. The Elkhorn Mountains Volcanics and Golden Spike Formation occur only in the southern part of the quadrangle where they rest unconformably on Paleozoic through Late Cretaceous units. Radiometric ages and field relationships suggest these units were comagmatic with the Boulder Batholith (Smedes, 1966; Lipman, 1984; Scarberry and others, 2019a,b). The base of the Elkhorn Mountains Volcanics is composed of andesitic lava flows, ignimbrites, and minor volcaniclastic intervals (Peterson, 1985), whereas the younger units are dominated by crystal-rich ash flows intercalated with dacite porphyry flow–dome complexes (Derkey and others, 2004; Berg, 2009; Scarberry and others, 2019c). The Golden Spike Formation consists of alternating andesitic flows and tuffs; volcaniclastic sandstone and diamictite; and non-volcaniclastic pebble conglomerate, siltstone, and mudstone (Gwinn, 1961; Gwinn and Mutch, 1965). These accumulations appear to intertongue with the volcanic units of the Elkhorn Mountains Volcanics east of Garrison (fig. 2). Volcanic and volcaniclastic rocks composing the Two Medicine Formation occur only in the northeast corner of the Elliston quadrangle, where they are deformed by the Eldorado Thrust and related contractional structures.

Published radiometric age data are sparse for Late Cretaceous volcanogenic units in the Elliston quadrangle, but a suite of U-Pb ages obtained from the Elkhorn Mountains Volcanics outside the Elliston quadrangle range from approximately 84 to 74 Ma (Ihinger and others, 2011; Scarberry and Yakovlev, 2019; Scarberry and others, 2019c).

Tertiary Volcanic Units

Tertiary volcanic deposits in the Elliston quadrangle comprise Eocene, high-K, calc-alkaline lavas and tuffs erupted ca. ~48–39 Ma, with associated subvolcanic intrusions forming as early as ~51.5 Ma (fig. 3, table 1). This flare-up in magmatism appears to have been contemporaneous with the tectonomagmatic development of the nearby Anaconda Metamorphic Core Complex (53–39 Ma; Foster and others, 2010; Scarberry and others, 2019c). Eocene high-K magmatism was followed by the eruption of alkaline melts during the late Eocene to Oligocene (~37.3–30.0 Ma; Reynolds, written commun., 2015), perhaps reflecting sustained, long-duration crustal extension in the Elliston region.

Eocene–Oligocene volcanic rocks in the Elliston quadrangle are best preserved in the Avon, Garnet Range, and Crater Mountain volcanic fields where they unconformably rest on faulted and folded Mesoproterozoic through Late Cretaceous rocks (plate 1; fig. 4). These magmatic centers share a volcanic stratigraphy that can be mapped and correlated throughout the Elliston quadrangle (Callmeyer, 1984; Trombetta, 1987; Parker, 1995; Mosolf, 2016; Mosolf and Vuke, 2017). The Eocene–Oligocene volcanic deposits exceed a composite thickness of ~1 km and record three distinct eruptive sequences ca. ~48.2–45.9 Ma; ~40.9–39.3 Ma; and ~37.3–30.1 Ma.

The oldest Tertiary volcanic rocks in the map area comprise widespread aphanitic to porphyritic dacite/trachydacite–trachyandesite flows (~48.2–45.9 Ma, and younger) intercalated with minor rhyolite lavas (46.0 Ma) and ash flow–airfall tuffs (e.g., ES-05, ~47.4 Ma). Associated vent complexes are difficult to identify in the field, but all of these units likely erupted from multiple vents or fissures formed within northwest-striking shear zones, forming dome complexes locally.

The younger Eocene volcanic sequence is composed of rhyolite lava and pyroclastic tuff deposits erupted ca. ~40.9–39.3 Ma. These volcanogenic units erupted from at least two major vent complexes located in the Avon and Crater Mountain Volcanic

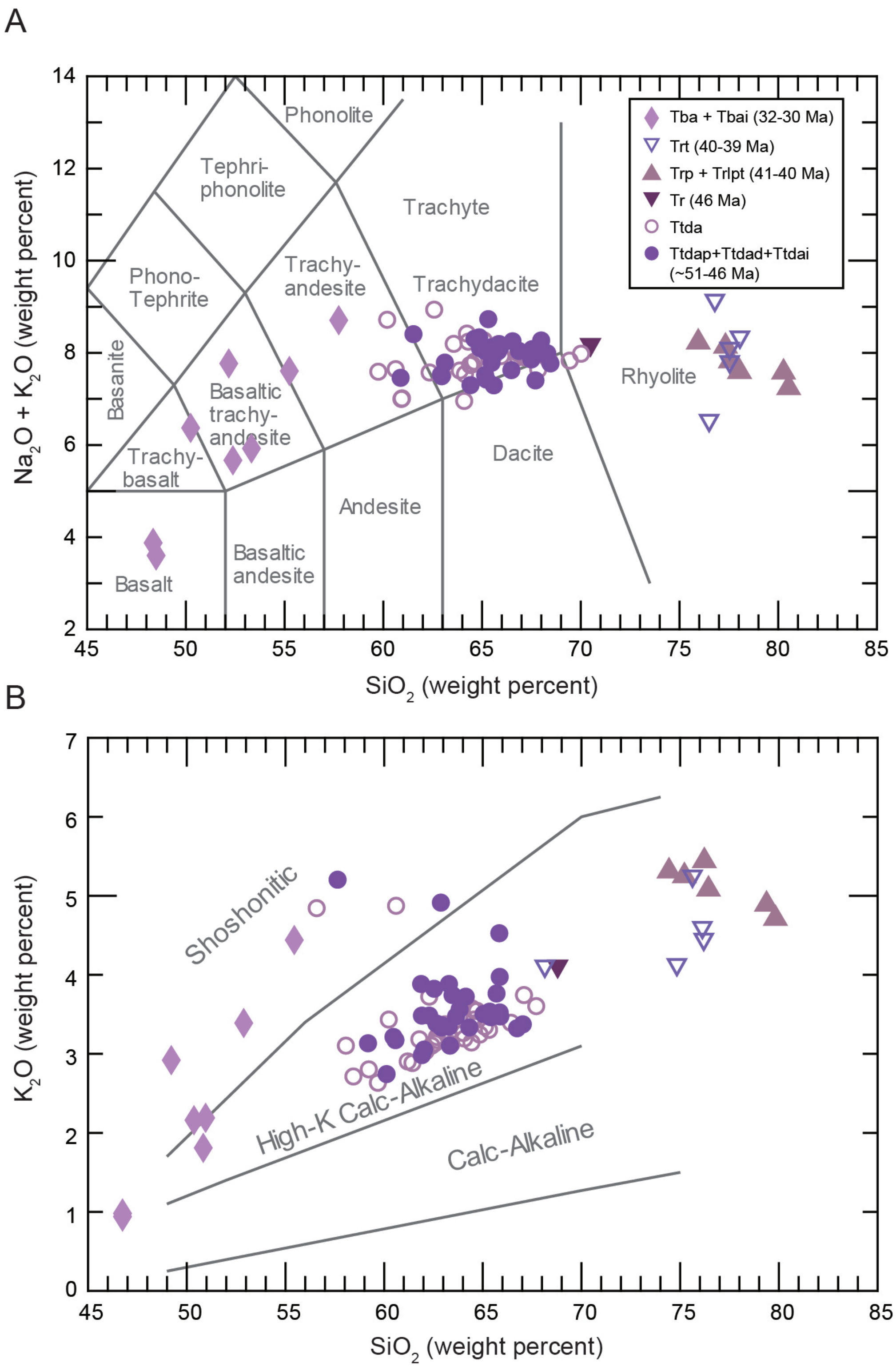


Figure 3. Whole-rock geochemical data from the Tertiary volcanic and intrusive units. (A) Total alkali silica diagram after Le Bas and others, 1986. (B) Alkaline discrimination diagram after Peccerillo and Taylor, 1976. The legend is shared by both diagrams.

Fields. In the Crater Mountain Volcanic Field, widespread pyroclastic accumulations flanking the modern Blackfoot River represent a caldera-forming eruption ca. ~40 Ma; rhyolite lava and tuff exposed by a landslide cutting the southwestern flank of Crater Mountain may preserve a vent associated with this caldera complex. Extensive rhyolite lava flows in the Avon Volcanic Field represent another major rhyolite vent complex in the Elliston quadrangle that formed ca. ~39 Ma. The volcanic facies and stratigraphic architecture expected of a caldera-forming eruption are not evident, however, indicating that rhyolite melts were erupted as flow–dome complexes that were not associated with a caldera.

Late Eocene to early Oligocene alkaline mafic lavas and intrusions (~37.3–30.1 Ma) are the youngest volcanic rocks mapped in the Elliston quadrangle, and appear to be sparser and volumetrically lesser than the older Eocene volcanogenic deposits. The alkaline units typically occur at lower elevations within or near the margins of tectonic basins where they are locally intercalated with sedimentary accumulations of the Renova Formation.

Table 1. U-Pb zircon LA-ICP-MS geochronology.

Sample	Lithology	Unit	Latitude (°N)	Longitude (°W)	# of Spot Analyses[a]	Age (Ma)	2σ	MSWD
ES-04*	Trachyandesite intrusion	Tbai	46.659	112.715	20	30.1	0.2	0.62
ES-46	Rhyolite tuff	Trt	46.934	112.445	25	39.3	0.3	0.33
ES-44	Rhyolite tuff	Trt	46.928	112.509	58	39.7	0.2	0.51
ES-43	Rhyolite tuff	Trt	46.927	112.509	29	39.8	0.2	0.41
ES-72	Rhyolite porphyry	Trp	46.548	112.637	24	39.8	0.2	0.96
ES-75	Rhyolite porphyry	Trp	46.604	112.658	23	40.0	0.2	0.28
ES-26	Rhyolite tuff	Trlpt	46.597	112.633	30	40.7	0.2	0.70
ES-28	Rhyolite porphyry	Trp	46.595	112.579	29	40.9	0.2	0.71
ES-14§	Trachydacite porphyry	Ttdap	46.751	112.782	24	45.9	0.3	0.37
ES-06*	Rhyolite dome(?)	Tr	46.713	112.737	33	46.0	0.3	0.84
ES-47#	Trachydacite porphyry	Ttdap	46.702	112.802	18	46.3	0.3	0.86
ES-20§	Trachydacite porphyry	Ttdap	46.772	112.840	38	46.5	0.2	0.69
ES-07#	Trachydacite porphyry	Ttdap	46.703	112.762	31	46.8	0.3	0.86
ES-61#	Dacite porphyry	Ttdap	46.721	112.787	24	46.8	0.3	0.59
ES-12§	Trachydacite porphyry	Ttdap	46.807	112.758	27	47.1	0.3	0.29
ES-50#	Trachydacite porphyry	Ttdap	46.684	112.809	15	47.1	0.4	0.85
ES-40#	Trachydacite porphyry	Ttdap	46.703	112.834	32	47.2	0.3	0.65
ES-05*	Dacitic tuff	Tdat	46.666	112.739	35	47.4	0.3	0.79
ES-41	Trachydacite porphyry	Ttdap	46.917	112.498	31	47.4	0.3	0.66
ES-24#	Trachydacite porphyry	Ttdap	46.660	112.775	24	47.5	0.3	0.50
ES-18†	Trachydacite porphyry	Ttdap	46.829	112.730	37	47.6	0.3	0.55
ES-80	Trachydacite intrusion	Ttdai	46.907	112.483	38	47.9	0.2	0.75
ES-79	Trachydacite intrusion	Ttdai	46.891	112.549	22	48.0	0.2	0.57
ES-55	Trachydacite porphyry	Ttdap	46.979	112.495	23	48.1	0.3	0.70
ES-64	Trachydacite porphyry	Ttdap	46.968	112.533	39	48.2	0.2	1.03
ES-01*	Trachydacite dike	Ttdad	46.640	112.717	21	51.5	0.3	0.76

Note. Reported ages are the weighted mean of the ^{207}Pb corrected ^{206}Pb/^{238}U ages obtained for each sample. MSWD is the mean Mean Square Weighted Deviation. Zircon separates were prepared at MBMG and analyzed at the University of California, Santa Barbara. Latitudes and longitudes are in the 1984 World Geodetic Survey (WGS84) datum.

[a]Number of spot analyses used to calculate weighted mean age.

#Ages recalculated from Mosolf (2016).

§Ages recalculated from McDonald and Mosolf (2016).

†Ages recalculated from McDonald and others (2016).

*Ages recalculated from Mosolf and Vuke (2017).

TERTIARY SEDIMENTARY DEPOSITS

Tertiary sedimentary deposits underlie the major valleys in the Elliston quadrangle and occur as isolated deposits in the Garnet Range and in the Mullan Pass area north of the town of Elliston (fig. 2). The stratigraphy of the Tertiary sedimentary deposits is similar to that in other western Montana valleys, with Paleogene or early Neogene Renova Formation unconformably overlain by Neogene Sixmile Creek Formation. Vertebrate fossils (Konizeski, 1961, 1965; Rasmussen, 1977; Trombetta and Berg, 2012) and stratigraphic position of the deposits relative to volcanic rocks in the quadrangle indicate age equivalence to similar Tertiary sediments in other western Montana valleys.

The oldest exposed Tertiary sedimentary rocks in the Elliston quadrangle are within the Eocene Climbing Arrow Member of the lower Renova Formation. The Climbing Arrow is dominantly bentonitic mudstone and pebble beds with subordinate carbonaceous shale and lignite deposited in fluvial and associated floodplain, swamp, and lacustrine environments. Volcanic ash devitrification resulted in the widespread

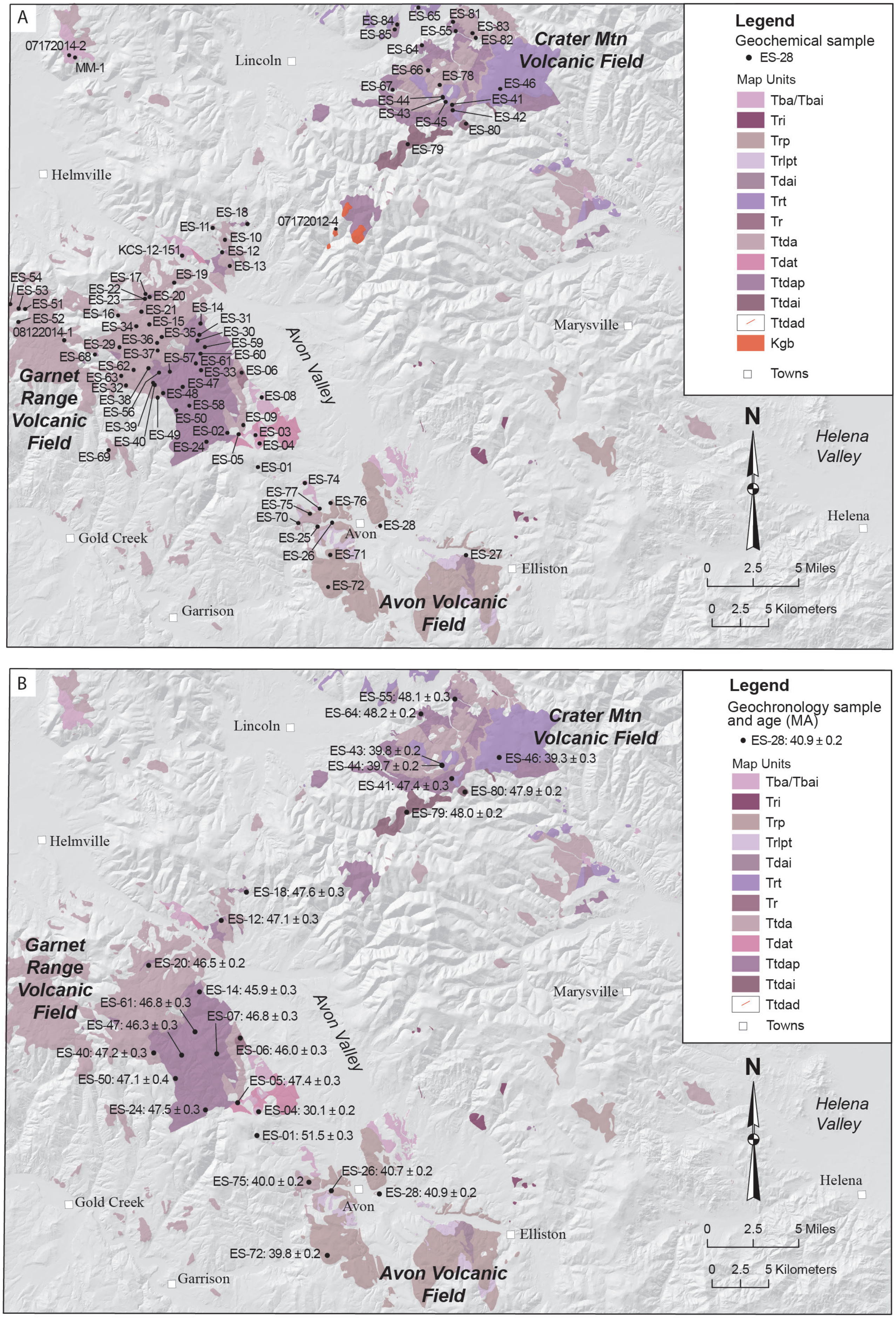


Figure 4. Simplified geologic map showing sample locations for (A) whole-rock geochemical analyses and (B) U-Pb zircon ages.

bentonitic mudstones characteristic of the member. Local paper shales were deposited in lacustrine environments and may be rich in plant and animal fossils including fish scales. The Climbing Arrow Member is equivalent to the Douglass Creek beds, named for Douglas Creek in the Helmville area (Konizeski, 1961, 1965), and to the Blackfoot City beds in the Avon area (Loen, 1990).

The Oligocene to Miocene Cabbage Patch beds (Konizeski and Donohoe, 1958) of the upper Renova Formation (Rasmussen, 1989) are best exposed on Antelope Hill in the central Avon Valley (fig. 2), where they overlie the Climbing Arrow Member, and in the Gold Creek area, where they are overlain by Sixmile Creek Formation equivalents (Loen, 1986). The Cabbage Patch beds consist primarily of siltstone with fluvial sandstone lenses, marlstone, limestone, local gastropod coquina, ash, and porcellanite. Although deposited in basin environments similar to those of the Climbing Arrow Member, the Cabbage Patch beds in the Elliston quadrangle do not contain the extensive bentonitic mudstones of the Climbing Arrow Member and do not include coal.

Isolated exposures of lacustrine Cabbage Patch beds in the Garnet Range are similar to deposits in the adjacent Avon and Nevada Valleys. Likewise, lignitic Climbing Arrow Member sediments are preserved at Mullan Pass and in the Avon Valley. The similarity of these lowland deposits in the present-day mountains and valleys suggests that the ranges were not positive elements at the time of deposition.

A widespread middle Miocene unconformity, recognized in other western Montana valleys, separates the Renova Formation from the overlying, coarser-grained Sixmile Creek Formation. The Sixmile Creek Formation is composed of tuffaceous siltstone with abundant local to laterally persistent, mostly matrix-supported, granule to boulder lenses deposited in fluvial and alluvial environments. It is lithologically similar to the Sixmile Creek Formation in the Drummond and Townsend Valleys, southwest and southeast, respectively, of the Elliston quadrangle.

An extensive, matrix-supported gravel with abundant subangular to subrounded boulders (map unit Tbgr) is preserved along range-front faults on the northeast side of the Avon Valley, the southwest side of the Nevada Valley, and as higher remnants on mountain flanks. Loen (l990) suggested a late Miocene (?) age for the deposits in the Blackfoot City area and interpreted them as alluvial fans. Channel deposits within these fans have been mined for placer gold.

QUATERNARY DEPOSITS

Most Quaternary deposits in the Elliston quadrangle are in the Cenozoic valleys. Surficial deposits in the Helena and other eastern valleys (fig. 2) are dominantly silt, sand, and gravel deposited on alluvial plains and pediments, and as alluvial fans. Glacial deposits associated with Pinedale and Bull Lake (?) ice caps occur in the Lincoln and northern Nevada Valleys in the northern part of the quadrangle, and the upper Little Blackfoot River drainage near the southern border of the quadrangle (Ruppel, 1963; Witkind and Weber, 1982; Wittkop, 2009). Remnants of mountain glacial deposits occur along the Continental Divide between MacDonald Pass and the Lincoln Valley. A dissected outwash fan covers a large area of the central Avon Valley, and glacial outwash underlies part of the Tenmile Creek drainage. Glacial deposits are also present in the Gold Creek Valley in the southwestern corner of the quadrangle.

Pediments are well developed on Tertiary deposits in the Avon, southern Nevada, and Gold Creek Valleys where they are mantled with gravel, lag, and regolith deposits. Numerous landslide deposits occur in the western part of the quadrangle, most of which developed in the Renova Formation and Tertiary volcanic deposits.

STRUCTURAL GEOLOGY AND TECTONICS

The dominantly northwest-striking structural grain evident in the south and west parts of the quadrangle reflects a complex tectonic history associated with the long-lived Lewis and Clark Fault Zone (LCFZ), a major system of crustal-scale faults that cut obliquely across the northern Cordillera (Sears and Hendrix, 2004). Tectonism associated with the LCFZ has been varied and episodic from the Mesoproterozoic to the Holocene, recording intermittent periods of extensional, transpressional, and transtensional faulting (Wallace and others, 1990; Sears and Hendrix, 2004; Reynolds and Brandt, 2005; Foster and others, 2007). The St. Mary's–Helena Valley Fault Zone in the northeast part of the quadrangle generally defines the northern boundary of the LCFZ. Its southern boundary is defined by strike-slip faults that splay southward from the LCFZ and terminate as dip-slip faults (Reynolds, 1979). The more northerly striking structural grain in the northeast corner of the quadrangle reflects Cordillera fold-thrust belt structures associated with the Lewis–Eldorado–Hoadley (LEH) thrust slab.

The oldest evidence of deformation in the Elliston quadrangle is preserved by metasediments of the Belt Supergroup. The Middle Cambrian Flathead Formation unconformably overlies the McNamara Formation (upper Missoula Group) in the western part of the quadrangle, but overlies the Snowslip Formation (lower Missoula Group) in the southeastern part, and the Spokane Formation (Ravalli Group) in the northeastern part. This unconformity documents regional-scale deformation of the Belt strata prior to the Middle Cambrian, possibly in Mesoproterozoic to Early Cambrian time. Mafic sills that intruded the Belt sediments ca. ~780–750 Ma (Mudge and others, 1982; Burtis and others, 2007) in the northeast part of the quadrangle may have been coeval with this deformation. In the southeastern part of the quadrangle, abrupt thickness changes in Missoula Group strata may reflect Mesoproterozoic deformation. Winston (1986b) proposed that an east–west-striking, down-to-the-north Mesoproterozoic growth fault, the Garnet Line, could explain the southward thinning of the Shepard Formation. The thickness changes are most apparent across the Cherry Creek Fault (Berg and Lonn, 2011; Lonn, 2015), located southwest of the Scratchgravel Hills Stock near Helena.

Late Cretaceous–Paleocene(?) deformation in the Elliston quadrangle produced major transpressive structures including northwest-trending, oblique-slip thrust and reverse faults, and south–southeast-plunging, upright folds (e.g., the Black Mountain and Carter Creek synclines, and Garrison Anticline). These transpressive structures are interpreted to represent a shear zone that accommodated differential rotation between the LEH thrust slab to the north and the Sapphire–Lombard thrust slab to the south (fig. 1; Mudge and Earhart, 1983; Sears and Hendrix, 2004). The kinematics of local transpressive shortening are constrained by deformation of the syntectonic Campanian Golden Spike Formation, and by the emplacement and subsequent folding of Cretaceous mafic dikes. The Golden Spike Formation rests on an unconformity that cuts transpressive folds in the Elliston area, and is folded by a syncline that is cut by a second progressive angular unconformity east of Garrison. These structural relationships indicate local transpressive structures were coeval with the deposition of the Golden Spike Formation ca. ~88–83 Ma (Sears and Hendrix, 2004). The Carter Creek Syncline is cored by Late Cretaceous sedimentary rocks and is intruded by a swarm of mafic dikes and sills that are folded (75.9 ± 1.2 Ma; Sears and others, 1998; Kunz, 2003), therefore signifying that transpressive deformation continued until at least ~76 Ma.

The Late Cretaceous and Early Paleocene Eldorado, Hoadley, and Scapegoat Thrust Faults and associated folds mapped in the northeast corner of the quadrangle are part of the LEH thrust slab (fig. 1). The Eldorado Thrust Fault carries Mesoproterozoic rocks of the Greyson and Spokane Formations eastward over folds and imbricate thrust faults deforming Late Cretaceous volcanogenic units of the Two Medicine Formation (Mudge, 1970). West of the Eldorado Thrust Fault, the Scapegoat and Hoadley Thrust Faults place the Greyson Formation over the Spokane Formation. The Hoadley Thrust Fault is cut by the Hilger Valley Normal Fault; all three thrust faults terminate against the St. Mary's–Helena Valley Fault Zone.

Late Cretaceous transpressive shortening in the Elliston quadrangle was followed by transtensive deformation across the LCFZ. Transtensive structures mapped in the Elliston quadrangle include dominantly northwest- and northeast-striking, dip-slip, oblique-slip, and strike-slip faults that overprint the older transpressive structures; the St. Mary's–Helena Valley Fault is the most prominent transtensive fault. Transtensive deformation in the Elliston area was likely contemporaneous with Eocene volcanism and the development of the nearby Anaconda metamorphic core complex (~53–39 Ma; e.g., Foster and others, 2010). Following Eocene volcanism, a broad depositional basin with minor internal faulting developed in the Elliston region that accommodated fine-grained basin deposits of the Renova Formation and intercalated mafic lava flows and associated intrusions. A regional mid-Miocene unconformity separating the Renova Formation from the overlying Sixmile Creek Formation marks the start of the tectonic segmentation of the basin into major fault-bounded valleys including the Avon, Nevada, Lincoln, Canyon Creek–Silver City, Hilger, and Helena Valleys (fig. 2). These valleys are likely underlain by pull-apart basins formed no later than Miocene time (Reynolds, 1979).

Recent seismicity indicates that many faults in the Elliston area are still active, with more than half of all focal mechanisms indicating dextral strike- and oblique-slip motions (Stickney, 2015).

METHODS

Geochronology and Geochemistry

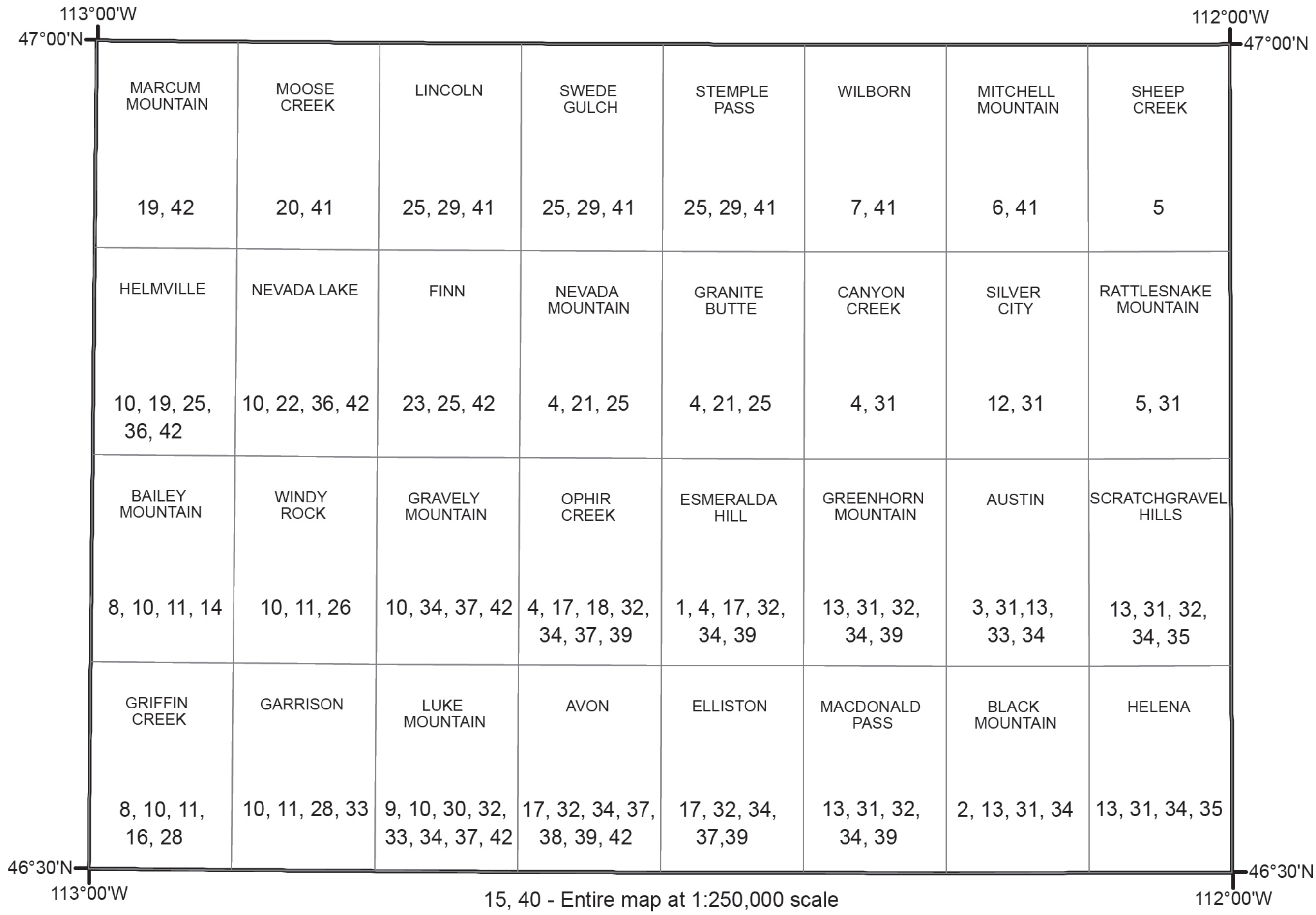
Twenty-six U-Pb zircon ages and 87 whole-rock geochemical analyses aided the geologic mapping of Tertiary volcanic and intrusive rocks in the Elliston quadrangle. The zircon separates were prepared at the MBMG Mineral Separation Laboratory and analyzed by Laser Ablation Inductively Coupled Mass Spectrometry (LA-ICP-MS) at the University of California, Santa Barbara. Major and trace element concentrations in whole-rock samples were measured by X-ray fluorescence (XRF) and inductively coupled plasma mass spectrometry (ICP-MS) at the Washington State University Peter Hooper Geoanalytical Laboratory, Pullman. Analytical results are provided in appendices A and B, and table 1. Sample locations are shown on the geologic map (plate 1) and in figure 4.

Sources of Mapping

The geologic map of the Elliston 30′ x 60′ quadrangle is the result of several years of new 1:24,000-scale mapping by the MBMG and compilation of numerous existing maps. Figure 5 shows the published geologic maps used to complete the map. Other sources of data include unpublished maps of historical placer deposits (R. McCulloch, MBMG retired), mineral exploration projects (B. Cox, exploration geologist, Missoula, MT), and maps and reports from the MBMG Mining Archives collection. Quaternary alluvial deposits along stream bottoms were delineated using aerial photographs (U.S. Department of Agriculture 2009 NAPP imagery) and may not always align with the streams shown on the topographic basemap (USGS 1:100,000-scale Elliston quadrangle, 1972, photoinspected 1990).

ACKNOWLEDGMENTS

The authors gratefully acknowledge the cooperation of numerous landowners who provided access to their land, particularly those in the Avon, Helmville, and Lincoln Valleys. Martin Bregman mapped two 1:24,000-scale maps in the northeast part of the quadrangle (Bregman, 2015, 2017) during the course of our work that were directly incorporated into the Elliston map. Gareth Seward and Andrew Kylander-Clark graciously assisted SEM-CL and LA-ICP-MS work at the University of California Geochronology Center. Scott Boroughs directed geochemical analyses at the Washington State University Peter Hooper Geoanalytical Laboratory. Technical reviews of the map and associated data by MBMG staff and Reed Lewis, Idaho Geological Survey, provided helpful comments and suggestions that significantly improved the quality and presentation of the geologic information. Mapping and compilation were supported by the U.S. Geological Survey STATEMAP program (contract G14AC00221). Editing by Susan Barth, MBMG.



1. Balgord and others (2010)
2. Berg (2009)
3. Berg and Lonn (2011)
4. Bierwagen (1964)
5. Bregman (1981)
6. Bregman (2015)
7. Bregman (2017)
8. Brooks and Sears (2009)
9. Callmeyer (1984)
10. French (1979)
11. Gwinn (1961)
12. Hargrave and others (2011)
13. Knopf (1963)
14. Krause (1964)
15. Lewis (1998)
16. Loen (1986)
17. Loen (1990)
18. Lonn and Vuke (2015)
19. McCune and Hendrix (2009)
20. McDonald (2017)
21. McDonald and Lonn (2015)
22. McDonald and Mosolf (2016)
23. McDonald and others (2016)
24. McDonald and Vuke (2017)
25. Melson (1964)
26. Mosolf (2016)
27. Mosolf and Vuke (2017)
28. Mutch (1961)
29. Parker (1995)
30. Peterson (1985)
31. Reynolds (2000)
32. Schmidt and others (1994)
33. Sears and others (2000)
34. Smedes and others (1988)
35. Stickney and Vuke (2017)
36. Stout (1949)
37. Trombetta (1987)
38. Trombetta and Berg (2012)
39. Walker (1967)
40. Wallace and others (1987)
41. Whipple and others (1987)
42. Witkind and Weber (1982)

Figure 5. Index to major sources of geologic information incorporated into the Elliston 30′ x 60′ quadrangle.

DESCRIPTION OF MAP UNITS

Sediments and rock in the Elliston 30′ x 60′ quadrangle are assigned to 113 map units on the basis of rock or sediment type and age. Igneous rocks are classified using the International Union of Geological Sciences nomenclature (Le Bas and Streckeisen, 1991). Minerals in igneous rock units are listed in order of decreasing abundance. For the most part, the stratigraphy for Mesoproterozoic through Mesozoic sedimentary units follows that of Schmidt and others (1994). Exceptions include Piegan Group (Helena and Wallace Formations) in place of Helena Formation and Pilgrim Formation in place of Hasmark Formation. The stratigraphy for the Tertiary volcanic rocks generally follows that of Parker (1995), Callmeyer (1984), and Trombetta (1987) for the Garnet Range, Crater Mountain, and Avon Volcanic Fields, respectively. The Paleogene Cabbage Patch beds and Climbing Arrow Member of the Renova Formation were identified based on lithologic and paleontologic correlation with nearby areas of known occurrence. Grain size classification of unconsolidated and consolidated sediment is based on the Wentworth scale (Lane, 1947).

QUATERNARY AND TERTIARY SEDIMENTARY DEPOSITS

Qal Alluvium (Quaternary: Holocene)— Gravel, sand, silt, and clay along modern streams and tributaries. Clasts are generally rounded to subrounded, cobble size and smaller, but boulders also present. Thickness generally less than 10 m (33 ft).

Qaf Alluvial fan deposit (Quaternary: Holocene)—Gravel, sand, silt, and clay in fan-shaped deposits. Degree of sorting and rounding of clasts and geomorphic form varies widely depending on drainage area above fan. Larger clasts both matrix- and clast-supported. Coarse clast size dominantly cobbles, but also includes boulders and pebbles. Thickness generally less than 15 m (50 ft).

Qpa Paludal deposit (Quaternary: Holocene)— Argillaceous silt, sand, and organic matter deposited in pond or marsh environments associated with floodplain deposits along streams. Thickness probably less than 5 m (15 ft).

Qc Colluvium (Quaternary: Holocene)—Locally derived, unconsolidated, angular, coarse gravel deposits along and at the base of hillslopes. Thickness generally less than 20 m (65 ft).

Qac Alluvium and colluvium (Quaternary: Holocene)—Silt, sand, granules, and pebbles deposited on slopes by sheetwash alluvium incorporated with locally derived fine-grained colluvium. Thickness generally less than 8 m (20 ft).

Qap Alluvial plain deposit (Quaternary: Holocene)—Moderately sorted, pebble to cobble gravel in a light gray to light brown silt and sand matrix. Clasts are well rounded to subrounded, and generally smaller and better sorted toward the valley. Difficult to distinguish from underlying deposits so thickness not known.

Qdf Debris flow deposit (Quaternary: Holocene and Pleistocene?)—Matrix-supported deposit of locally derived rock. Matrix is fine-grained, clasts are generally subangular and angular ranging from granule to boulder size. Thickness generally less than 20 m (75 ft).

Qat Alluvial terrace deposit (Quaternary: Holocene and Pleistocene)—Fluvial deposits above modern river and stream levels.

Little Prickly Pear Creek/Missouri River/Holter Lake area in the northeastern corner of the quadrangle: unconsolidated, poorly sorted, subrounded and rounded, cobble and pebble gravel; subordinate sand and silt. Thickness less than 4.5 m (15 ft).

Blackfoot City area (Avon Valley): Isolated, coarse-grained, clast-supported stream deposits on terraces at elevations higher than modern streams. Locally cemented; contains gold placers in some locations (Schmidt and others, 1994). Thickness probably less than 8 m (20 ft).

Qpg Pediment gravel (Quaternary: Holocene and Pleistocene)—Deposits of brown, tan, and gray, poorly sorted, unstratified, pebble lag gravel with sandy silt matrix that overlies pediment surfaces. Subrounded to subangular gravel clasts reflect local upslope bedrock lithologies along the margin of the Helena Valley. Thickness 1–2 m (3–6 ft), locally as much as 5 m (16 ft).

Qm Mantle (Quaternary: Holocene and Pleistocene)—Deposits that overlie pediment surfaces and include sheetwash alluvium, fine-grained colluvium, regolith, and pebble, cobble, and small boulder lags from older debris-flow deposits. Thickness generally less than 6 m (20 ft).

Qls Landslide deposit (Quaternary: Holocene or Pleistocene)—Mass-wasting deposit of sediment or rock that detached from its source and slid downslope through rotation or translation. Deposits typically exhibit hummocky topography below a prominent or subdued landslide scarp. The bentonitic Climbing Arrow Member (Trca), the Cabbage Patch member (Trcp), and volcanic deposits are particularly prone to developing landslide deposits. Thickness generally less than 60 m (200 ft).

Qtr Travertine (Holocene and Pleistocene?)—Coarsely crystalline, calcium carbonate beds 3–50 cm (1–20 in) thick that are commonly disturbed/chaotic. Carbonate beds form a large mound in the upper Warm Springs drainage of the Garnet Range, concealing a northeast-striking fault. Major carbonate deposition is no longer active and many of the larger deposits are now karst forming.

Qapo Alluvial plain deposit, older than Qap (Quaternary: Holocene and Pleistocene)—Moderately sorted, cobble to pebble gravel in a light brown silt and sand matrix. Clasts well-rounded to subrounded, generally better sorted toward the valley. Contains sand lenses as much as 30 cm (1 ft) thick. Approximately 40–50 percent of granitic clasts are weathered and decomposed. Thickness probably less than 30 m (100 ft).

Qalo Alluvium, older than Qal (Quaternary: Holocene? and Pleistocene)—Fluvial gravel primarily in the Avon and Nevada Valleys in wider channels than the present-day underfit streams occupy. Clasts are generally rounded to subrounded and cobble size and smaller, but boulders also present. Thickness not known.

Qlso **Landslide deposit, older than Qls (Pleistocene)**—Mass-wasting deposits of rotated or chaotic beds that slid downslope. Subdued geomorphic expression suggests that deposits are older than Qls. Exposed along northwest side of Avon Valley. Thickness not known.

Qbgr Boulder gravel (Quaternary: Holocene? and Pleistocene)—

Avon Valley: Unconsolidated deposits reworked from Tbgr on slopes below the source deposits. Composed of weakly stratified, rounded pebbles and cobbles set in a granule and coarse-grained sand matrix. Thickness less than 20 m (70 ft).

Helena Valley: Weakly stratified, poorly sorted, pebble to boulder gravel in a grayish brown to yellowish light gray clay-rich and silty sand matrix. Clasts well rounded to subrounded and as much as 2 m in diameter with a median size of 2–5 cm. Clasts of granitic composition decomposed in place. Thickness probably less than 15 m (50 ft).

Qg Glacial deposit (Quaternary: Pleistocene)—Unconsolidated, locally derived remnants of mountain glacial till and outwash deposits on either side of the Continental Divide between MacDonald Pass and Lincoln Valley. Till is poorly sorted to unsorted fine-grained sediment to boulders up to several meters in diameter. Thickness generally less than 45 m (150 ft).

Qgo Glacial outwash (Quaternary: Pleistocene)—

Nevada and Lincoln Valleys: Light brown to brown deposits of silt, sand, granules, pebbles, and cobbles with scattered angular to rounded boulders 0.3 to 1 m (1–3 ft) in diameter. Clasts are dominantly rounded and subordinately subrounded. Composition dominantly quartzite, but also includes argillite and igneous clasts. After Witkind and Weber (1982).

Gold Creek Valley: Clast-supported channel gravel typically with over 90 percent granodiorite and less than 10 percent quartzite clasts (Loen, 1986).

Avon Valley: Well-stratified, moderately well-sorted deposit of silt, sand, and gravel (Loen, 1990) along Sixmile Creek that represent the terminus of a large glacial outwash fan about 6.5 km (4 mi) long. Dominantly clast-supported, reworked subrounded iron-stained pebbles and cobbles.

Tenmile Creek Valley west of Helena: Poorly sorted, unconsolidated gravel with granitic boulders as large as 1.2 m (4 ft) in maximum dimension. Boulders decrease in size to the east, and form low, east-trending ridges (Berg, 2009).

Qgt Glacial till (Quaternary: Pleistocene)— *Nevada and Lincoln Valleys:* Light brown, brown, and reddish brown mixture of granules, pebbles, cobbles, and boulders in a sandy to silty matrix that locally is clay-rich and dense. The dominant clast lithologies are quartzite and argillite that can occur as erratics. Locally forms knob-and-kettle topography. After Witkind and Weber (1982).

Qgl Glacial lake deposit (Quaternary: Pleistocene)—Holter Lake area: Light grayish yellow, light gray, and light brown, thin- and medium-bedded silt, clay, and sand with clay in dark and light brown thin laminae that are likely varves (Bregman, 1981). Thickness probably less than 15 m (50 ft).

QTm Mantle, older than Qm (Quaternary and Tertiary)—Boulder-dominated deposits on slopes. Deposits originated along the range-front fault on the northeast side of the Avon Valley. Upslope bedrock on the footwall block is generally, but not always, the source of the deposits. Thickness less than 15 m (50 ft).

QTgr Gravel (Quaternary or Tertiary)—Poorly sorted, matrix-supported gravel with considerable dark brown clay. Contains cobbles of pale green siltite of the Belt Supergroup and less abundant white quartzite, hornfels, and marble. Granitic clasts are not apparent. Mined locally for gold (Berg, 2009). Thickness at least 30 ft (10 m).

QTdf Debris-flow deposit (Quaternary: Pleistocene, or Tertiary: Pliocene?)—Matrix-supported deposit with clasts of upslope-derived volcanic rock and sparse sedimentary rock. Clasts range from granules to boulders. Geomorphic expression suggests that these deposits are older than Qdf. Thickness less than 30 m (100 ft).

Tgr Gravel (Tertiary)—Isolated gravel deposits with rounded to subangular pebbles, cobbles, and boulders at elevations above modern streams. Highest elevation deposits are lags of scattered cobbles and boulders that typically lack Belt Supergroup lithologies. The lowermost gravel contains Belt clasts and may be contemporaneous with Tbgr alluvial fan deposits along the northeast Avon Valley range-front fault. Thickness variable.

Tbgr Boulder gravel (Tertiary)—Dominantly matrix-supported, but locally clast-supported deposit that occurs primarily adjacent to the range-front fault on the northeast side of the Avon Valley, and along the valley to the west and southwest of Nevada Lake Reservoir. Clasts range from pebble to large boulder size in clay/silt/sand matrix or are preserved as lag deposits. Clasts are dominantly Belt Supergroup quartzite with subordinate volcanic and plutonic rock. Matrix in many places includes reworked Climbing Arrow Member of Renova Formation (Trca). The age of the deposit has been interpreted as Miocene (?) (Loen, 1990; Schmidt and others, 1994) and it contains placer gold (Loen, 1990). Thickness as much as 300 m (985 ft).

Tsc Sixmile Creek Formation (Tertiary: Miocene)—Tuffaceous, yellowish gray siltstone with abundant local and laterally persistent lenses of matrix-supported to subordinate clast-supported granules to boulders. Lenses may contain angular clasts or subrounded to well-rounded clasts. The clasts are primarily Belt Supergroup rock, subordinate volcanic and plutonic rock in the Helmville area, dominantly Quadrant Formation in the Gold Creek area (Loen, 1986), and dominantly volcanic rock south of Avon. A distinctive zone of lenses with well-rounded Belt quartzite cobbles to small boulders extends from Chimney Creek to the Blackfoot River in the northwestern part of the quadrangle. Exposed thickness of the Sixmile Creek Formation is approximately 60 m (200 ft) in the Helmville area, and 145 m (480 ft) in the Gold Creek area.

Tj Jasperoid (Tertiary?)—Light gray to red, dense, silicified breccia containing angular clasts in a jasperoid matrix. The protolith of breccia clasts is difficult to discern, but is most likely limestone derived from the Paleozoic units. The most prominent exposures of jasperoid occur along an unnamed northwest-striking fault in the Garnet Range, approximately 17.5 km

(11 mi) northeast of the town of Garrison in southwest corner of map (fig. 2 and plate 1).

Tbr **Breccia (Tertiary)—**Sedimentary breccia consisting of angular cobble to boulder size, medium- to coarse-grained quartzite clasts derived from the Mesoproterozoic Bonner or Mount Shields Formations. Breccia is lithified and locally has a clay-rich matrix. Located on the bench immediately north of Nevada Lake Reservoir in the northwest part of the quadrangle. May have formed as a colluvial wedge along the footwall of nearby faults. Thickness less than 75 m (250 ft).

Trcp **Renova Formation, Cabbage Patch member (Tertiary: Miocene and Oligocene)—** *Antelope Hill area:* Gastropod-bearing marlstone, thinly bedded limestone, and local gastropod coquina that in many places overlies a coarse-grained arkosic sandstone with plant impressions, petrified wood, and associated shale or tuffaceous, micaceous siltstone with local lenses of rip-up clast breccia. Sandstone contains lenses of pebble conglomerate with rounded to subrounded clasts. Carbonate beds are locally silicified to white-weathering, gray porcellanite and variegated chert. Faint outlines of gastropods are discernible in recrystallized limestone along the crest of Antelope Hill. The Cabbage Patch member overlies volcanic rock in the lower parts of the Garnet Range, but in most places it occurs as float that may represent a lag deposit. Silicified beds on Antelope and Rhine Hills in the north-central part of the map area were quarried by native people for projectile point material. This material, with the archaeological name Avon chert, has a distinctive LA-ICP-MS signature. Avon chert artifacts are found in places as far-removed as Illinois (Roll and others, 2005). Includes rounded rip-up clasts on Rhine Hill where unit is also brecciated. In the Gold Creek area, the unit contains more tuffaceous siltstone and mudstone than on Antelope Hill. Thickness is approximately 610 m (2,000 ft).

Trca **Renova Formation, Climbing Arrow Member (Tertiary: Eocene)—**Pale olive, light olive gray, moderate olive brown, and medium light 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. West of Finn and east of Jefferson Creek, fish scales occur in platy siltstone and paper shale beds in a road cut along Highway 141. Bentonitic mudstone typically displays “popcorn” texture and desiccation cracks when dry, and is prone to mass wasting. Near-surface groundwater in NW¼ sec. 9, and NW¼ sec. 22, T. 12 N., R. 9 W. and several other localities is concealed by thin crusts of Climbing Arrow Member. Unit referred to as Blackfoot City beds (Loen, 1989) and Douglass Creek beds (Konizeski, 1961, 1965). Exposed thickness approximately 180 m (600 ft).

TERTIARY AND CRETACEOUS VOLCANIC AND PLUTONIC ROCKS

Tba/Tbai **Basalt, trachybasalt, basaltic trachyandesite, and trachyandesite flows; undivided (Tertiary: Eocene–Oligocene)—**Mafic lava flows (Tba) and intrusions (Tbai) that are light brown to dark gray, and weather to angular blocks. Some lava flows contain distinct zones of vesicles, columnar jointing, and autobreccia. Typically aphanitic to slightly porphyritic, containing phenocrysts of plagioclase, clinopyroxene, orthopyroxene, biotite, olivine, or resorbed quartz. The groundmass consists mainly of plagioclase microlites, but also includes pyroxenes, biotite, and Fe-oxides. A small trachyandesite stock (Tbai), located in the southern part of Garnet Range Volcanic Field, yielded a U-Pb zircon age of 30.1 ± 0.2 Ma. A basaltic lava near Nevada Lake yielded a K-Ar age of 32.3 ± 0.17 Ma (Reynolds, written commun., 2015). Other mafic flows in the region yielded K-Ar ages as old as 37.3 Ma (Reynolds, written commun., 2015). Lava flows are up to ~120 m (400 ft) thick.

Tvs **Volcaniclastic sediment (Tertiary)—**Poorly consolidated deposits of volcaniclastic conglomerate and sandstone with interbeds of siltstone, mudstone, and claystone. Sandstone deposits are yellowish gray and massive, containing sparse subrounded quartz and feldspar grains in a matrix of reworked ash and glass shards. Conglomerate deposits consist of well-rounded boulders or cobbles mainly derived from Eocene rhyolite. Conglomerate deposits exhibit crude normal grading, can be well imbricated, and locally grade into coarse-grained sandstone deposits. Volcaniclastic deposits are prone to mass wasting. Best exposed north of the Blackfoot River and east of Lincoln where they rest on pyroclastic deposits (Trt). As thick as ~170 m (558 ft).

Tsi **Sinter (Tertiary)**—White, thinly banded siliceous sinter or colloform chalcedony that exhibits planar to wavy, yellowish brown iron oxide laminae that range in thickness from 2 to 10 mm (Parker, 1995). Commonly associated with ash flow deposits (Trt) in the Crater Mountain Volcanic Field. Thickness and age unknown.

Tri **Rhyolite intrusions (Tertiary: Eocene)**—Light gray to light brown, non-foliated, porphyritic plugs, dikes, and sills. Rhyolite intrusions are both texturally and compositionally similar to rhyolite tuff (Trt) and contain 10–40 percent phenocrysts of sanidine and quartz. After Schmidt and others (1994).

Trt **Rhyolite tuff (Tertiary: Eocene)**—Weakly to densely welded rhyolite tuff deposits containing phenocrysts of sanidine, smoky quartz, and rare biotite books. Quartz crystals are typically broken and deeply embayed. Pumice lapilli compose 10–25 percent of the rock and occur as fiamme in zones of dense welding. Tuff deposits contain 10–30 percent subangular lithic fragments that are mostly derived from the Belt Supergroup, but also include porphyritic and aphanitic fragments from the underlying Eocene volcanic rocks. Dense welding is generally observed in the lower part of ash flows. Unwelded ash and breccia intervals exhibit planar and low-angle cross-laminated beds and reverse grading, and are interpreted to be pyroclastic surge deposits (e.g., Fisher and Schmincke, 1984; Cas and Wright, 1987). Devitrification of tuff deposits varies from incipient to complete. Locally abundant lithophysae near the base of ash flow deposits are up to 60 cm in diameter. Tuff accumulations near the summit of Crater Mountain are intercalated with a dark weathering body of crystallized rhyolite, perhaps representing a volcanic plug or dome. U-Pb zircon ages range from 39.8 ± 0.2 Ma to 39.3 ± 0.3 Ma. As thick as ~400 m (1,300 ft).

Tdai **Dacite intrusive dome (Tertiary: Eocene)**—Exogenous dome that intrudes and is overlain by porphyritic rhyolite lavas (Trp). Dacite is gray to black weathering and generally fine-grained with sparse phenocrysts (<5 percent) of quartz, sanidine, oligoclase, hypersthene, and augite. Exhibits prominent columnar jointing and vertical igneous foliations. Best exposed along Highway 12 between Avon and Elliston. Absolute age unknown. As thick as 120 m (400 ft).

Trp **Rhyolite porphyry (Tertiary: Eocene)**—Porphyritic rhyolite lava flows are mostly gray, white, tan, red and/or purple weathering. Centimeter- to meter-scale flow foliations commonly give rhyolite outcrops a flaggy or blocky weathering characteristic. Phenocrysts compose up to 30 percent of the rock and include quartz, sanidine, oligoclase, biotite, and amphibole in a matrix of glass, clay, and cryptocrystalline material. Devitrification of the matrix varies from none to complete. Lithophysae up to 10 cm in diameter are locally abundant and typically eroded and partially filled with chalcedony. Discontinuous zones of vitrophyre and autobreccia separate individual flows. U-Pb zircon ages range from 40.9 ± 0.2 Ma to 39.8 ± 0.2 Ma. Rhyolite lavas are best exposed near the town of Avon in the southern part of the quadrangle. Thickness as much as 550 m (1,800 ft).

Trlpt **Rhyolite lithic-pumice tuff (Tertiary: Eocene)**–Unwelded to densely welded rhyolitic tuff containing ~5–15 percent lithic clasts and pumice lapilli; and ~5–10 percent crystals and crystal fragments of quartz, sanidine, oligoclase, biotite, amphibole, and opaque minerals. Lithic clasts comprise rhyolite and sandstone fragments; intervals of dense welding are often characterized by black fiamme. The matrix consists of glass shards, pumice fragments, and clay. Tuff deposits are generally intercalated with rhyolite lava flows (Trp), and are brecciated locally. A sample collected along Highway 12 yielded a U-Pb age of 40.7 ± 0.2 Ma. Thickness as much as 200 m (650 ft).

Tr Rhyolite flow or dome (Tertiary: Eocene)—Porphyritic rhyolite with distinct red, white, and green flow bands 2–20 mm thick; brecciated locally. Contains crystals of subhedral plagioclase, amphibole, biotite, and rare quartz that are set in an aphanitic groundmass of devitrified glass and flow-aligned microcrystals of euhedral plagioclase, hornblende, and biotite. Possibly formed as a lava dome or plug. Occurs near Davis Creek on the west side of the Avon Valley where it overlies or intrudes Eocene lava flows (Ttda). This unit yielded a U-Pb zircon age of 46.0 ± 0.3 Ma. As thick as 600 m (1,970 ft).

Ttda Trachydacite and trachyandesite flows (Tertiary: Eocene)—Dark gray and dark greenish gray, aphanitic to weakly porphyritic trachydacite and trachyandesite flows. Lava flows are commonly flow banded and form flaggy, angular talus, often with red iron oxide stain on parting surfaces. In thin section, aphanitic lavas exhibit a strong trachytic texture consisting mainly of plagioclase microcrystals, but also include subordinate pyroxene, magnetite, and volcanic glass. Porphyritic flows contain <10–15 percent phenocrysts of plagioclase, amphibole, and occasional biotite. As thick as ~500 m (1,640 ft).

Tdat Dacite tuff (Tertiary: Eocene)—Massive or flow-banded variably silicified dacite tuff that contains phenocrysts of plagioclase, quartz, biotite, and amphibole. The groundmass is almost entirely devitrified glass with some magnetite. Pumice lapilli occur locally and account for up to ~50 percent of the rock. Fine-grained intervals contain preserved plant and wood fragments, and are possibly water-lain. Poorly exposed and therefore often distinguished by flaggy chips that are weathered to white, yellow, and orange. A U-Pb zircon age of 47.4 ± 0.3 Ma was obtained for this unit. As thick as 150 m (490 ft).

Ttdap Trachydacite/dacite to trachyandesite porphyry lavas (Tertiary: Eocene)—Gray-, green-, and red-weathering porphyritic trachydacite/dacite to trachyandesite lava flows containing subhedral to euhedral phenocrysts of plagioclase (up to ~5 mm) and minor amounts of amphibole, biotite, and quartz. The aphanitic groundmass commonly has a trachytic texture and consists mainly of aligned microlaths of plagioclase, but also includes amphibole, biotite, and magnetite. Thick carapaces of autobreccia several meters thick typically envelop the coherent interiors of individual lava flows. Commonly weathers to blocks or plates, with some outcrops forming hoodoos or spires. Locally gradational with aphanitic flows (Tdat). U-Pb zircon ages span 48.2 ± 0.2 to 45.9 ± 0.3 Ma. As thick as 600 m (1,970 ft).

Ttdai Trachydacite intrusions (Tertiary: Eocene)—Phaneritic to porphyritic trachydacite intrusions composed of plagioclase, orthoclase, biotite, hornblende, and occasional quartz. Porphyries contain plagioclase phenocrysts up to one centimeter; pink orthoclase crystals up to 2–3 cm; and interstitial biotite, augite, and quartz crystals in an aphanitic groundmass. Occur as dikes, sills, and large stocks. The contact with country rock is typically irregular with wide contact areoles of hornfels and associated mineralization. Mapped as the Silver Bell Stock east of Lincoln by Whipple and others (1987) with reported K-Ar ages of 52.0 Ma (Schmidt and others, 1994) and 48.5 Ma (Parker, 1995). Two samples of the Silver Bell Stock yielded U-Pb zircon ages of 47.9 ± 0.2 Ma and 48.0 ± 0.2 Ma.

Ttdad Trachydacite dike (Tertiary: Eocene)—Porphyritic trachydacite dike, 2–3 m (7–10 ft) wide, that cross-cuts the Gravely Mountain Syncline near the southwest part of the Avon Valley. Contains phenocrysts of plagioclase, hornblende, and rare quartz in an aphanitic groundmass. The dike yielded a U-Pb zircon age of 51.5 ± 0.3 Ma, and therefore is the oldest Tertiary volcanic unit identified in the map area.

Tgrr Granite and rhyolite (Tertiary?)—Pale pinkish to gray granite and rhyolite. Rhyolite has aphanitic groundmass with phenocrysts of quartz, feldspar, and rare biotite. Occurs as small plugs in the northeast part of the quadrangle (secs. 10 and 14, T. 13 N., R. 6 W.) with surface exposures less than 1 km2. The largest plug occurs as weathered, fine-grained granitic boulders. After Bregman (2017).

TKgb Gabbro (Tertiary or Late Cretaceous)—Dark gray to greenish black, medium- to coarse-grained gabbro composed primarily of pyroxene, plagioclase, and sparse quartz, biotite, hornblende, and magnetite. Includes rocks with a diabasic texture.

Kbd Basalt and diorite, sills and dikes (Late Cretaceous)—Pyroxene–biotite basalt and diorite sills and dikes. Euhedral pyroxene crystals common. Intruded into the upper Carter Creek Formation and older Cretaceous units in the Garrison area (Kunz, 2003). A sill located just west of the Elliston quadrangle yielded a $^{40}Ar/^{39}Ar$ date of 75.9 ± 1.2 Ma (Sears and others, 1998).

Krdp Rhyodacite porphyry (Late Cretaceous)—Greenish gray rhyodacite porphyry. Aphanitic groundmass with 1–3 cm phenocrysts of white oligoclase and 1 mm phenocrysts of black hornblende. Forms sills, dikes, and small intrusive bodies in northeast corner of the quadrangle. After Bregman (2017).

Kla Latite (Late Cretaceous)—Gray to dark gray, brown-weathered, porphyritic latite sill. Groundmass is aphanitic with phenocrysts of plagioclase up to 2 mm long and biotite and augite up to 1 mm long. Many plagioclase phenocrysts are altered to clay. Forms a resistant sill as much as 305 m (1,000 ft) thick in northeast corner of the quadrangle, close to map boundary. After Bregman (1981).

Kdip Diorite porphyry (Late Cretaceous)—Small stocks, dikes, and sills of diorite with andesine and less conspicuous hornblende and biotite phenocrysts in a microcrystalline groundmass (Knopf, 1963). Exposed in southeast corner of map, around the Scratchgravel Hills Stock and northern part of Boulder Batholith. A small diorite plug exposed on the north side of Sevenmile Creek in sec. 36, T. 11 N., R. 5 W. exhibits rhythmic layering in which hornblende layers up to 5 mm thick alternate with plagioclase-rich layers of similar thickness (Berg and Lonn, 2011).

Kgdp Granodiorite porphyry (Late Cretaceous)—Light gray, coarse-grained granodiorite porphyry with uniformly distributed potassium feldspar megacrysts up to 3 cm long. Major constituents include plagioclase, potassium feldspar, quartz, biotite, hornblende; minor magnetite, titanite, apatite, and zircon. After Smedes and others (1988).

Kmp Monzonite porphyry (Late Cretaceous)—Gray to purple-gray monzonite porphyry. Phenocrysts are white plagioclase up to 3 mm long, biotite, and hornblende. Groundmass consists of plagioclase, potassium feldspar, hornblende, and biotite (Bregman, 1981). Intrudes the Mesoproterozoic Spokane Formation north of the Scratchgravel Hills (fig. 2) in east-central part of quadrangle. Also forms sill and dikes in Spokane Formation in northeast corner of quadrangle.

Kqm Quartz monzonite (Late Cretaceous)—Medium-grained, granular, equigranular, and porphyritic biotite–hornblende quartz monzonite, quartz monzodiorite, and granodiorite. Consists of plagioclase, potassium feldspar, quartz, hornblende, and biotite. Forms the Blackfoot City and Scratchgravel Hills stocks and smaller related intrusives. After Schmidt and others (1994).

Kqmp Quartz monzonite porphyry (Late Cretaceous)—Quartz monzonite porphyry with light pinkish gray groundmass of sanidine, quartz, oligoclase, and minor ferromagnesian minerals. Phenocrysts of salmon-colored orthoclase are typically 1–5 mm long. Forms sills and dikes intruded into Mesoproterozoic Belt rocks in northeast corner of the quadrangle. After Bregman (2017).

Kmgf Felsic monzogranite (Late Cretaceous)—Pinkish and yellowish gray, medium-grained monzogranite with orthoclase, microcline, and subordinate calcium feldspar. Contains common biotite books and flakes, interstitial quartz crystals, nodules of tourmaline, and fracture-filling tourmaline. Mapped as a biotite granite in the east adjacent Canyon Ferry Dam 30′ x 60′ quadrangle (Reynolds and Brandt, 2005). Intrudes the Butte Granite (map unit Kg) and Unionville granodiorite (Kgd) in southeast corner of map.

Kg Butte Granite (Late Cretaceous)—Light gray, medium gray, and light pinkish gray, fine- to coarse-grained, equigranular and locally porphyritic granitic rock. Intruded by aplite and pegmatite dikes and locally contains abundant xenoliths of diorite and other crystalline rock. Forms the Butte Pluton of the Boulder Batholith (Knopf, 1963; Smedes, 1988). Zircons from the Butte Pluton yielded U-Pb age dates ranging from 76.5 to 74.5 Ma (Lund and others, 2002; du Bray and others, 2012).

Klmo Leucomonzonite (Late Cretaceous)—Light gray, medium-grained, equigranular quartz monzonite west of the Cherry Creek Fault in southeast part of map. Composed of plagioclase, potassium feldspar, quartz, hornblende, and biotite. Originally mapped as the Priest Pass leucomonzonite by Knopf (1963).

Kgd Granodiorite (Late Cretaceous)—Light to dark gray, fine- to coarse-grained, equigranular to weakly porphyritic granodiorite to porphyritic monzogranite. Mafic minerals, primarily hornblende and biotite, comprise about 15–20 percent of the rock. Occurs as stocks, sills, and dikes, and in the southeast corner of map, it forms the Unionville Pluton of the Boulder Batholith (Knopf, 1963). Samples from the Unionville Pluton and the Marysville Stock yielded U-Pb zircon ages of 78.2 ± 0.5 Ma and 78.8 ± 1.6 Ma, respectively (Lund and others, 2002).

Kgb Gabbro (Late Cretaceous)—Dark gray to greenish black, equigranular to porphyritic medium- to coarse-grained gabbro and quartz gabbro. In the Washington Creek drainage, northeast of the Avon Valley, unit is a quartz gabbro composed primarily of pyroxene and plagioclase with minor biotite and magnetite. Pyroxene occurs as prismatic crystals up to 4 mm long.

Kemm Elkhorn Mountains Volcanics, middle member (Late Cretaceous)—Light gray, gray, and greenish gray basaltic andesitic dacite, welded rhyolite ignimbrite, rhyolite tuff, and laterally discontinuous breccia (Schmidt and others, 1994; Scarberry and others, 2019). The ignimbrites are characterized by flattened and stretched pumice fragments and, in places, are crystal rich with plagioclase laths up to 7 mm long and common euhedral biotite. Near McDonald Pass, the ignimbrites contain abundant pyroclasts, with banded pumice up to 20 cm (8 in). Thickness about 550 m (1,800 ft).

Keml Elkhorn Mountains Volcanics, lower member (Late Cretaceous)—Dark gray, brownish gray weathering, basaltic and andesitic lava flows and autobreccia; dark brown, green, and white to medium gray dacite and dacite porphyry lavas and dome complexes, vitrophyre, and intercalated volcanogenic sediments. Amygdaloidal layers, vesicles, and breccia along flow margins are distinguishing features of the basaltic to andesitic lavas (Schmidt and others, 1994; Derkey and others, 2004; Scarberry and others, 2018). Thickness about 450 m (1,475 ft).

Kgs Golden Spike Formation (Late Cretaceous)—Alternating sequences of volcaniclastic sandstone and diamictite; non-volcaniclastic pebble conglomerate, siltstone, and mudstone; and intercalated aphanitic andesitic lava flows (Gwinn, 1961; Gwinn and Mutch, 1965). The Golden Spike Formation and Elkhorn Mountains Volcanics intertongue east of Garrison (Gwinn, 1961). Thickness ranges from 1,220 to 1,830 m (4,000–6,000 ft).

Ktmv Two Medicine Formation, volcanic facies (Late Cretaceous)—Alternating clastic volcanic rocks and volcanic flows and tuffs. Green, grayish green, gray, dark greenish gray, dark brown, grayish purple, brownish gray, and maroon clastic volcanic conglomerate, sandstone, siltstone, and mudstone; locally crossbedded and in some places with rounded pebbles of andesite, latite, and welded rhyolitic tuff. Green, grayish green, tan, red, and grayish red, rubbly pumiceous tuff and red, purple, and brown, densely welded rhyolitic and dacitic tuff. Brownish gray and reddish purple trachyte flows. Gray and grayish purple, massive and porphyritic, latite flows at base. Thickness approximately 1,356 m (4,450 ft). After Bregman (1981) and Schmidt (1972).

Ktms Two Medicine Formation, sedimentary facies (Late Cretaceous)—Lower part is green, gray, and brown, fine- to medium-grained calcareous, thin- to medium-bedded sandstone, siltstone, and mudstone; minor thin beds of brown to black carbonaceous shale and lignite near the base. Thickness about 76 m (250 ft). After Bregman (1981) and Schmidt (1972).

PALEOZOIC AND MESOZOIC SEDIMENTARY ROCKS

Kvi Virgelle Formation (Late Cretaceous)—Light gray and light greenish gray, fine- to medium-grained, massive sandstone. Some beds are locally iron-impregnated and crossbedded. Titaniferous magnetite sandstone beds up to 6 m (20 ft) thick at the top of the formation commonly form a prominent rimrock. Fossils include rare pelecypods. Thickness about 40 m (130 ft).

Ktc Telegraph Creek Formation (Late Cretaceous)—Interbedded gray and greenish gray, tan weathering, fine- to very fine-grained, thinly bedded, calcareous sandstone and light to dark gray mudstone. Transitional unit between the underlying Marias River Formation shale and overlying sandstone of the Virgelle Formation. Thickness about 100 m (330 ft).

Kmr Marias River Formation (Late Cretaceous)—Interbedded siltstone, clay-rich siltstone, and bentonite in upper part (Kevin Member); interbedded dark gray siltstone and silty mudstone and ledge-forming, medium gray and medium olive gray sandstone in middle part (Ferdig Member); dark gray, olive gray, and dark brownish gray, calcareous and noncalcareous mudstone and dark gray, fine-grained sandstone in lower part (Floweree and Cone Members). Estimated thickness 180 m (590 ft).

Kcc Carter Creek Formation (Late Cretaceous)— Tan to gray, and gray-green quartzose sandstone, siltstone, shale, and siliceous mudstone. Basal sandstones are thin-bedded to massive with shaly partings, abundant oyster shells, and some chert and volcanic pebbles. Interbedded siliceous mudstone beds are common in upper 460 m (1,500 ft) of the formation. Thickness 610–762 m (2,000–2,500 ft). After Gwinn (1960).

Kmk Marias River Formation, Kevin Member (Late Cretaceous)—Dark gray to black fissile shale and minor thin beds of olive gray siltstone and yellowish orange bentonite. Light gray ovoid limestone concretions, up to 0.5 m (1.5 ft) across, and pelecypods and ammonites are locally abundant. Thickness about 90 m (300 ft).

Kclk Colorado Group and Kootenai Formation, undivided (Cretaceous)—Contact metamorphosed rocks of the Colorado Group (Cody through Thermopolis Formations) and Kootenai Formation adjacent to intrusive rocks in the southeast corner of the quadrangle. The unmetamorphosed Colorado Group and Kootenai Formation are predominantly mudstone, shale, sandstone, some conglomerate, and limestone.

Kj Jens Formation (Late Cretaceous)—Upper part is dominantly medium gray to tan shale with subordinate thin calcareous sandstone; middle part is variegated tan, gray, reddish, purplish, and greenish volcanic-rich, siliceous sandstone, siltstone, and silty mudstone; lower part is dark gray to olive, fissile shale and siltstone, with minor sandstone and limestone. Beds are typically bioturbated but the formation is generally not fossiliferous. Thickness as much as 460 m (1,510 ft). After Gwinn (1960).

Kc Coberly Formation (Late Cretaceous)— Dominantly tan, calcareous sandstone with subordinate variegated green-brown mudstone and siltstone; locally shaly lignite, gray to black fossiliferous limestone, and sandy coquina. Sandstone has abundant chert and quartz grains giving it a “salt and pepper” appearance. The sandstones in the Coberly differ markedly from sandstones in the Blackleaf and Jens Formations in that they contain much less volcanic detritus and are always calcareous. Limestone beds are dark gray-brown with abundant large gastropods, pelecypods, and oyster coquinas. Thickness as much as 198 m (650 ft). After Gwinn (1960).

Kblv Blackleaf Formation, Vaughn Member (Late and Early Cretaceous)—Gray-green, gray, and dark gray volcanic mudstone, siltstone, chert, and lithic-rich (salt and pepper) sandstone with several interbeds of pebble conglomerate and volcanic tuff. Chert-pebble conglomerate beds are common at base; upper part is multicolored siltstone and mudstone. Abundant light gray, white, and tan porcellanite and siliceous siltstone beds form distinct horizons. Originally mapped as the Dunkleberg Formation by Gwinn (1960). Revised to Vaughn Formation by Tysdal and others (1989). Thickness approximately 460–520 m (1,510–1,706 ft).

Kblt Blackleaf Formation, Taft Hill Member (Early Cretaceous)—Tan to light gray, calcareous sandstone interbedded with gray to green siltstone and mudstone. Lower 90 m (300 ft) is crossbedded sandstone. Lenticular volcaniclastic beds are prevalent in the upper ~60 m (195 ft). Thickness about 275–305 m (900–1,000 ft).

Kblf Blackleaf Formation, Flood Member (Early Cretaceous)—The upper 150 m (492 ft) consists of dark gray to black, non-calcareous fissile shale with minor thin interbeds of carbonaceous siltstone and fine-grained, calcareous, ripple-bedded sandstone. The lower 80 m (262 ft) is tan, gray, and yellow-brown, often iron-oxide-stained, sandy limestone, siltstone, fine-grained sandstone, and resistant quartzite. Total thickness of the Flood Member is about 230 m (754 ft).

KJkme Kootenai and Morrison Formations, and Ellis Group, undivided (Early Cretaceous, and Late to Middle Jurassic)—Metamorphosed sedimentary rocks considered to be Jurassic and Cretaceous based on comparison with unmetamorphosed sedimentary rocks of this age to the east (Knopf, 1963). Mostly light olive gray to light gray, medium-grained, feldspathic quartzite with prominent biotite porphyroblasts (?) and hornfels. Exposed in southeast part of the map where it is in contact with Elkhorn Mountains Volcanics and Cretaceous intrusions. After Berg (2009).

Kk Kootenai Formation (Early Cretaceous)— Predominantly variegated mudstone, siltstone, limestone, and "salt and pepper" sandstone, with an overall red-maroon weathering characteristic. The base of the Kootenai Formation is typically marked by lenticular beds of red-brown to gray, pebble to cobble conglomerate, or a silica-cemented vitreous sandstone. The top of the formation is distinguished by dark brown to dark gray, coarsely crystalline limestone composed almost entirely of gastropod shells. Thickness about 330 m (1,085 ft).

Jme Morrison Formation and Ellis Group, undivided (Late to Middle Jurassic)—Undivided unit exposed in southern part of map.

Morrison Formation (Late Jurassic)—Poorly exposed olive green, gray to grayish green mudstone, shale, siltstone, and minor sandstone. Siltstone near the base of the formation is calcareous and flaggy bedded. Dense, "salt and pepper" sandstone and minor concretionary limestone occur in the upper part of the formation. Thickness about 47–67 m (154–220 ft).

Ellis Group (Late to Middle Jurassic)—Swift Formation: Upper part is brown to yellowish brown, often calcareous and glauconitic, "salt and pepper" sandstone with interbedded siltstone and micaceous shale. Basal sandstone contains lenses of black chert-pebble conglomerate. Minor fossils include oyster, belemnite, and wood fragments. Thickness about 37–75 m (115–246 ft). Rierdon Formation: Dark brownish gray to dark gray calcareous shale, ripple marks common on bedding planes. Base marked by brown, oolitic or sandy limestone. Thickness approximately 18–23 m (59–75 ft). Sawtooth Formation: Lower part is dark gray to black, fossiliferous, calcareous buff-weathering siltstone; middle part is very calcareous dark gray shale or argillaceous limestone that weathers creamy white; upper part is interbedded calcareous shale, siltstone, and limestone. Approximate thickness 75 m (246 ft).

PℙPpq Phosphoria and Quadrant Formations, undivided (Permian and Pennsylvanian)—Undivided unit exposed in south-central and western part of map.

Pp Phosphoria Formation (Permian)— Bluish gray and brown weathering sandstone, shale, bedded chert, and oolitic phosphatic rock. Basal part locally is a chert breccia and siltstone. Thickness about 80 m (260 ft).

ℙq Quadrant Formation (Pennsylvanian)— White to tan, poorly bedded to massive, fine- to medium-grained vitreous quartzite. Thin interbeds of light gray and tan siltstone, sandstone, and dolomite occur in lower part. Weathers to a greenish gray or rusty brown surface with black spots of lichen. Forms resistant ridges. Up to 60 m (200 ft) thick.

PℙMps Phosphoria and Quadrant Formations, and Snowcrest Range Group, undivided (Permian, Pennsylvanian, and Mississippian)—Undivided unit exposed in the Garrison Mountain Anticline in southwest part of the map.

ℙMsr Snowcrest Range Group (Pennsylvanian and Mississippian)—Red, purple, gray, and tan shale and siltstone with interbedded red, yellow, and gray limestone and dolomite in thrust sheets in the south-central part of the map. About 40 m (130 ft) thick. After Schmidt and others (1994).

ℙMa **Amsden Formation (Pennsylvanian and Mississippian)**—Reddish brown, fine-grained sandstone, calcareous siltstone, shale, and limestone. A thin interval of pebble conglomerate marks the top of the formation. Thickness about 90 m (295 ft).

Mm Madison Group (Mississippian)—Upper part: gray, massive biosparite, biomicrite, and micrite that correlates with the Mission Canyon Limestone. Lower part: thin-bedded gray limestone that contains scattered dark gray, black, and brown chert nodules and lenses that correlates with the Lodgepole Limestone. Thickness 450 m (1,460 ft). After Schmidt and others (1994).

MDtm Three Forks, Jefferson, and Maywood Formations, undivided (Early Mississippian to Late Devonian)—Undivided unit exposed in the Garrison Mountain Anticline in southwest part of the map.

MDt Three Forks Formation (Early Mississippian and Late Devonian)—Gray, greenish gray, yellowish gray, and brownish gray shale, siltstone, argillaceous limestone, and minor sandstone. Thickness about 80 m (260 ft).

Dj Jefferson Formation (Late Devonian)—Gray to black, thick-bedded, coarsely crystalline, fetid dolomite with thin interbeds of light gray limestone. Contains lenses of brachiopod fragments and thin beds of stromatoporoid algae. Thickness 230 m (750 ft).

Djm Jefferson and Maywood Formations, undivided (Late Devonian)—Undivided unit that occurs as isolated exposures within the Garnet Range Volcanic Field in the western part of the map.

DЄmr Maywood and Red Lion Formations, undivided (Late Devonian and Late Cambrian)—Undivided unit exposed in southwest part of map.

Maywood Formation (Late Devonian)—Red, gray, and grayish green shale, siltstone, limestone and dolomite. Thickness approximately 10 m (30 ft). After Schmidt and others (1994).

Єrpi Red Lion and Pilgrim Formations, undivided (Late Cambrian)—Undivided unit that occurs as isolated exposures within the Garnet Range Volcanic Field in the western part of the map.

Єrl Red Lion Formation (Late Cambrian)—Medium to light gray, thin-bedded limestone beds separated by unevenly bedded, internally laminated siliceous and argillaceous orange- and red-weathering dolomite beds. Base of unit is interbedded grayish red, grayish green, and gray shale, siltstone, limestone, and dolomite. Exposed in west-central and southeast part of map. Thickness about 100 m (325 ft). After Schmidt and others (1994).

Єpi Pilgrim Formation (Late Cambrian)—Light gray, massive to thinly laminated, finely crystalline and microcrystalline dolomite. Thickness about 185 m (600 ft). After Schmidt and others (1994).

Єpm Park and Meagher Formations, undivided (Late Cambrian)—Undivided unit that occurs as isolated exposures within the Garnet Range Volcanic Field in the western part of the map.

Єp Park Formation (Late Cambrian)—Grayish green, fissile, waxy shale and interbedded siltstone and gray limestone. Very poorly exposed. Thickness approximately 80 m (260 ft). After Schmidt and others (1994).

Єm Meagher Formation (Late Cambrian)—Gray, thin- to thick-bedded micrite and biomicrite containing distinctive thin interbeds of uneven and discontinuous, gold- and orange-weathering, siliceous and argillaceous dolomite. Thickness 180 m (590 ft). After Schmidt and others (1994).

Єwf Wolsey and Flathead Formations, undivided (Early to Late Cambrian)—Undivided unit that occurs as isolated exposures within the Garnet Range Volcanic Field in the western part of the map.

Єw Wolsey Formation (Late to Early Cambrian)—Greenish gray, micaceous shale and glauconitic siltstone interbedded with thin beds of gray limestone near the top and with glauconitic quartzite near the base. Poorly exposed, recessive unit found in southeast part of map. Thickness 90–120 m (295–390 ft). After Schmidt and others (1994).

Ꞓf **Flathead Formation (Late Cambrian)**—Gray, tan, and grayish purple, thin- to thick-bedded, fine- to medium-grained, crossbedded quartz arenite. Locally is coarse-grained with rare conglomerate lenses that contain quartz pebbles as large as 1 cm in diameter. Thin interbeds and partings on bedding planes of greenish gray, micaceous shale common in places. Exposed in southeast part of map. Thickness 0–30 m (0–100 ft). After Schmidt and others (1994).

NEOPROTEROZOIC INTRUSIVE ROCKS

Zdi **Diorite (Neoproterozoic)**—Dark gray to greenish black, medium-grained equigranular diorite composed of andesine–labradorite, augite, biotite, magnetite, and sparse apatite and quartz. Weathers a characteristic rusty brown. Forms sills associated with thick zones of hornfels in the Spokane and Empire Formations. A sill from the Lewis and Clark Range north of the Elliston quadrangle yielded a K-Ar age of 750 ± 25 Ma (Mudge and others, 1968). Several sills and dikes in the east-adjacent Canyon Ferry Dam 30′ x 60′ quadrangle have reported K-Ar ages of 826 ± 41 Ma, 741.3 ± 32.2 Ma, and 744 ± 37 Ma (Reynolds and Brandt, 2005). Thickness as much as 460 m (1,500 ft) but typically 60–150 m (195–500 ft) thick (Whipple and others, 1987).

Zgb **Gabbro (Neoproterozoic)**—Porphyritic and non-porphyritic mafic dikes and sills, typically with diabasic texture. Variable composition, but gabbro and gabbronorite are most prevalent; diorite is rare. Occurs as sills and irregular bodies around the Scratchgravel Hills Stock west of the Helena Valley. After Schmidt and others (1994).

MESOPROTEROZOIC BELT SUPERGROUP

Ya **Metaandesite and metadiorite sills and dikes (Mesoproterozoic)**—Dark, blackish green to greenish gray, metamorphosed andesite and diorite, commonly porphyritic. Forms sills and dikes less than 3 m thick within the Piegan Group in northwest part of map. Age probably Mesoproterozoic. After Whipple and others (1987).

Ym **McNamara Formation (Mesoproterozoic)**—Couplets and microcouplets of variegated red and green fine-grained quartzite, siltite, and waxy argillite containing diagnostic red or green chert beds and chert rip-up clasts. Mudcracks and mud rip-up clasts common. Top part is light gray, thick-bedded, fine- to medium-grained, crossbedded quartzite containing abundant red argillite rip-up clasts, uncommon red chert rip-up clasts, and abundant thin, red, mudcracked argillite interbeds. Thickness about 670 m (2,200 ft).

Ybo **Bonner Formation (Mesoproterozoic)**—Pink to red, medium- to coarse-grained, poorly sorted, very feldspathic quartzite. Abundant trough and planar crossbeds are typically 0.5–1.0 m thick. Thicker beds are often separated by thin (0.1–1.0 cm), red to maroon argillite beds. Contains abundant well-rounded, coarse quartz grains and sparse subangular granules, pebbles, and small cobbles. Thickness about 550 m (1,800 ft).

Yms3 **Mount Shields Formation, member 3 (Mesoproterozoic)**—Grayish red to blackish red, fine-grained quartzite to argillite couples and couplets with abundant desiccation cracks, mud chips, and diagnostic, well-formed, cubic salt casts. Includes green interbeds and some red microlaminae. Thickness about 365 m (1,200 ft).

Yms2 **Mount Shields Formation, member 2 (Mesoproterozoic)**—Pink to red, poorly sorted, medium- to coarse-grained, feldspathic quartzite that is commonly planar and trough crossbedded. Contains sparse subangular granules. Lower part is thinner bedded, consisting of couples of white to pink, medium-grained quartzite and thin red argillite that contain abundant red mud chips at the bases of the quartzite beds. The lower part of the unit was included in the top part of member 1 of Schmidt and others (1994). Two slabbed and stained samples from the Ophir Creek 7.5′ quadrangle east of the Avon Valley contained 65–75 percent quartz, 5–15 percent potassium feldspar, and 20 percent plagioclase. Thickness about 790 m (2,600 ft) but thins to 180 m (580 ft) in area of Cherry Creek Fault west of Helena (Berg and Lonn, 2011).

Yss Shepard and Snowslip Formations, undivided (Mesoproterozoic)—Undivided unit exposed in southeast part of map.

Ysh Shepard Formation (Mesoproterozoic)—Dolomitic and non-dolomitic, dark green siltite and light green argillite in microlaminae and couplets of non-dolomitic red quartzite to argillite. Poorly exposed, but weathers into thin plates that when dolomitic have a characteristic orange brown rind. Ripple marks and load casts are common, mudcracks are rare. The upper half of the formation contains intervals of pink to gray, fine-grained feldspathic quartzite that were probably included in Mount Shields member 1 by Schmidt and others (1994). In the Elliston quadrangle map, the upper contact is placed at the top of a 50-m-thick (160 ft) interval of distinctive rose-colored dolomitic siltite–argillite couplets as was done in areas to the west (Lonn and others, 2010). The lower contact is placed at the bottom of the lowest dolomite-bearing beds, although in areas to the west the Snowslip Formation also contains dolomite-bearing intervals (Lonn and others, 2010). A stromatolite bed is often found near the base. Thickness about 550–610 m (1,800–2,000 ft) but thins to 250 m (800 ft) in area near Cherry Creek Fault west of Helena (Berg and Lonn, 2011).

Ysn Snowslip Formation (Mesoproterozoic)—Interbedded intervals of quartzite to red argillite couplets, and dark green siltite to light green argillite couplets and microlaminae. Desiccation cracks and mud rip-up clasts are common throughout. Argillite beds often contain irregular "bumps" that are thought to be ill-defined salt casts. Contains beds and lenses of distinctive white, coarse-grained, well-sorted, feldspar-poor quartzite with some well-rounded, frosted quartz grains. Lower 50 m (160 ft) dominated by microlaminated green dolomitic siltite and argillite. Upper 50–75 m (160–245 ft) is red, flat-laminated medium-grained quartzite in beds 0.5–1.0 m (1.5–3 ft) thick. Thickness approximately 1,430 m (4,700 ft).

Ypn Piegan Group, Helena and Wallace Formations, undivided (Mesoproterozoic)—Gray to dark gray dolomitic limestone, limestone, calcareous siltite, dark gray argillite, and minor fine-grained quartzite; weathers yellowish orange to gray. The upper 300 m (1,000 ft) consists of cycles of dark gray limestone interbedded with dark gray calcareous argillite. Typically forms platy talus slopes and may correlate with the Wallace Formation (Winston and Sears, 2013). Below this interval, the Helena Formation is characterized by cycles consisting of a basal clastic zone of tan to gray siltite and fine-grained quartzite, overlain by tan dolomite, and capped by dark gray argillaceous limestone (Schmidt and others, 1994). Outcrops typically characterized by planar and wavy lamination, molar-tooth structure, syneresis (shrinkage) cracks, oolites, recessive weathering calcitic pods, asymmetrical ripple marks, scour-and-fill, and fluid-escape structures. These units are commonly metamorphosed to calc-silicate and hornfels near intrusion contacts. Gradational contact with underlying Empire Formation is placed at first interval where siliciclastic and calcitic beds with sharp scoured bases are overlain by intraclasts of molar-tooth fragments. Mafic (metaandesite and metadiorite) sills and dikes within the Piegan Group in the northwest corner of the map are probably Mesoproterozoic age (Whipple, 1987). Estimated thickness of combined Helena and Wallace Formations about 1,525 m (5,000 ft), about the same as that reported by Eby (1977) at Red Mountain, 11 km (7 mi) northeast of the quadrangle.

Yhe Helena and Empire Formations, undivided (Mesoproterozoic)—Exposed on west side of Scratchgravel Hills Stock in southwest corner of the map.

Ye Empire Formation (Mesoproterozoic)—Grayish green, medium green, and light green argillite and siltite, thinly bedded, often lenticular with microlaminae and mud cracks; also some calcareous and dolomitic beds with rare stromatolites. Gradational contact with underlying Spokane Formation is placed at first thick (>1 m) interval of green argillite. Thickness about 610 m (2,000 ft).

Ys Spokane Formation (Mesoproterozoic)—Grayish red, red, dark greenish, and purplish red argillite and siltite with even microlaminae and couplets and common mudcracks and mud rip-up clasts; some uncracked, lenticular, and undulating couplets and beds of flat-laminated couples. Thickness about 1,830 m (6,000 ft).

Yg Greyson Formation (Mesoproterozoic)—Dark greenish gray, interbedded and thinly laminated siltite and argillite with a few beds of lenticular feldspathic quartzite and dolomitic siltite; dolomitic siltite beds contain sparse algal laminations. Weathers into thin slabs with well-developed, closely spaced joints. Contact with overlying Spokane Formation is gradational and is placed at the first appearance of shallow water sedimentary structures including ripple marks, rip-up clasts, and polygonal mudcracks diagnostic of the Spokane Formation. Thickness about 1,675 m (5,500 ft).

REFERENCES CITED

Adam, Z.R., Skidmore, M.L., and Mogk, D.W., 2016, Paleoenvironmental implications of an expanded microfossil assemblage from the Chamberlain Formation, Belt Supergroup, Montana, in MacLean, J.S., and Sears, J.W., eds, Belt Basin: Window to Mesoproterozoic Earth: Geological Society of America Special Paper 522, p. 101–119.

Balgord, E.A., Mahoney, J.B., Potter, J.J., Pignotta, G.S., Wittkop, C., King, N.E., Ihinger, P.D., Hardel, B.G., and Kadulski, B., 2010, Geologic map of the Esmeralda Hill 7.5′ quadrangle, Lewis and Clark County and Powell County, Montana: Montana Bureau of Mines and Geology EDMAP 8, 1 sheet, scale 1:24,000.

Berg, R.B., 2009, Geologic map of the Black Mountain 7.5′ quadrangle, southwestern Montana: Montana Bureau of Mines and Geology Open-File Report 587, scale 1:24,000.

Berg, R.B., and Lonn, J.D., 2011, Geologic map of the Austin 7.5′ quadrangle, central Montana: Montana Bureau of Mines and Geology Open-File Report 603, 10 p., 1 sheet, scale 1:24,000.

Bierwagen, E.E. 1964, Geology of the Black Mountain area, Lewis and Clark and Powell Counties, Montana: Princeton, N.J., Princeton University, Ph.D. dissertation, 166 p., 3 plates, scale 1:31,250.

Bregman, M.L., 1981, Structural geology of the Sheep Creek and Rattlesnake Mountain quadrangles, Lewis and Clark County, Montana: Montana Bureau of Mines and Geology Geologic Map 26, scale 1:24,000.

Bregman, M.L., 2015, Geologic map of the Mitchell Mountain 7.5′ quadrangle, west-central Montana: Montana Bureau of Mines and Geology Open-File Report 663, scale 1:24,000.

Bregman, M.L., 2017, Geologic map of the Wilborn 7.5′ quadrangle, west-central Montana: Montana Bureau of Mines and Geology Open-File Report 691, scale 1:24,000.

Brooks, J.A., and Sears, J.W., 2009, Geologic map of the Bailey Mountain and Griffin Creek 7.5′ quadrangles, Montana: Montana Bureau of Mines and Geology EDMAP 1, 2 sheets, scale 1:24,000.

Burtis, E.W., Sears, J.W., and Chamberlain, K.R., 2007, Age and petrology of Neoproterozoic intrusions in the northern Rocky Mountains, U.S.A., correlation with the Gunbarrel magmatic event, in Link, P.K., and Lewis, R.S., eds., Proterozoic geology of western North America and Siberia: Society for Sedimentary Geology Special Publication 86, p. 175–191.

Callmeyer, T.J., 1984, The structural, volcanic, and hydrothermal geology of the Warm Springs Creek area, eastern Garnet Range, Powell County, Montana: Bozeman, Montana State University, M.S. thesis, 79 p., 2 sheets, scale 1:41,700.

Cas, R., and Wright, J.V., 1987, Volcanic successions—Modern and ancient: A geological approach to processes, products, and successions: London, Allen and Unwine, 529 p.

Derkey, R.E., Watson, S.M., Bartholomew, M.J., Stickney, M.C., and Downey, P.J., 2004, Geologic map of the Deer Lodge 15′ quadrangle, southwestern Montana: Montana Bureau of Mines and Geology Open-File Report 271, scale 1:48,000.

du Bray, E.A., Aleinikoff, J.N., and Lund, K., 2012, Synthesis of petrographic, geochemical, and isotopic data for the Boulder Batholith, southwest Montana: U.S. Geological Survey Professional Paper 1793, 39 p.

Eby, D.E., 1977, Sedimentation and early diagenesis within eastern portions of the 'Middle Belt carbonate interval' (Helena Formation), Belt Supergroup (Precambrian-Y), western Montana: Stony Brook, State University of New York, Ph.D. dissertation, 702 p.

Evans, K.V., Aleinifoff, J.N., Obradovich, J.D., and Fanning, C.M., 2000, SHRIMP U-Pb geochronology of volcanic rocks, Belt Supergroup, western Montana: Evidence for rapid deposition of sedimentary strata: Canadian Journal of Earth Sciences, v. 37, p. 1289–1300.

Fisher, R.V., and Schmincke, H.U., 1984, Pyroclastic rocks: Berlin, Springer-Verlag, 472 p.

Foster, D.A., Doughty, P.T., Kalakay, T.J., Fanning, C.M., Coyner, S., Grice, W.C., and Vogl, J., 2007, Kinematics and timing of exhumation of metamorphic core complexes along the Lewis and Clark fault zone, northern Rocky Mountains, USA, in Till, A.B., Roeske, S.M., Sample, J.C., and Foster, D.A., eds., Exhumation associated with continental strike–slip fault systems: Geological Society of America Special Paper 434, p. 207–232.

Foster, D.A., Grice, W.C., and Kalakay, T.J., 2010, Extension of the Anaconda metamorphic core complex: 40Ar/39Ar thermochronology and implications for Eocene tectonics of the northern Rocky Mountains and the Boulder Batholith: Lithosphere, v. 2, no. 4, p. 232–246.

French, A.B., 1979, Younger over older thrust faulting in the eastern Garnet Range, west-central Montana: Tucson, University of Arizona, M.S. thesis, 15 p., scale 1:62,500.

Gwinn, V.E., 1960, Cretaceous and Tertiary stratigraphy and structural geology of the Drummond area, western Montana: Princeton, N.J., Princeton University, Ph.D. dissertation, 153 p.

Gwinn, V.E., 1961, Geology of the Drummond area, central-western Montana: Montana Bureau of Mines and Geology Geologic Map GM 4, 1 sheet, scale 1:62,500.

Gwinn, V.E., and Mutch, T.A., 1965, Intertongued Upper Cretaceous volcanic and nonvolcanic rocks, central-western Montana: Geological Society of America Bulletin, v. 76, p. 1125–1144.

Hargrave, P.A., Bregman, M.L., and Lonn. J.D., 2011, Geologic map of the Silver City 7.5′ quadrangle, west-central Montana: Montana Bureau of Mines and Geology Open-File Report 602, 6 p., 1 sheet, scale 1:24,000.

Harlan, S.S., Heaman, L., LeCheminant, A.N., and Premo, W.R., 2003, Gunbarrel mafic magmatic event: A key 780 Ma time marker for Rodinia plate reconstructions: Geology, v. 31, p. 1053–1056.

Harrison, J.E., 1972, Precambrian Belt Basin of the northwestern United States, its geometry, sedimentation, and copper occurrences: Geological Society of America Bulletin, v. 83, p. 1215–1240.

Ihinger, P., Mahoney, J.B., Johnson, B.R., Kohel, C., Guy, A.K., Kinbrough, D.L., and Friedman, R.M., 2011, Late Cretaceous magmatism in southwest Montana: the Boulder Batholith and Elkhorn Mountains Volcanics, Geological Society of America, Abstracts with Programs, v. 43, no. 5, p. 647.

Knopf, A., 1963, Geology of the northern part of the Boulder Bathylith and adjacent area, Montana: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-381, scale 1:48,000.

Konizeski, R.L., 1961, Paleoecology of an early Oligocene biota from Douglass Creek basin, Montana: Geological Society of America Bulletin, v. 72, p. 1633–1642.

Konizeski, R.L., 1965, Tertiary deposits in basins marginal to the Flint Creek Range: Billings Geological Society Sixteenth Annual Field Conference Guidebook, p. 10–18.

Konizeski, R.L., and Donohoe, J.C., 1958, Faunal and stratigraphic relationships of the Cabbage Patch beds, Granite County, Montana: Society of Vertebrate Paleontology Guidebook, Eighth Annual Field Conference, p. 45–49.

Krause, H.H., 1964, Geology of the Saddle Mountain-Carten Creek area, Powell County, Montana: Lawrence, University of Kansas, M.S. thesis, 57 p., 2 sheets, scale 1:24,000.

Kunz, R.C., 2003, The alkalic intrusion of Garrison Montana: A possible extension of the Central Montana Alkalic Province: Missoula, University of Montana, M.S. thesis, 175 p.

Lane, E.W., 1947, Report of the subcommittee on sediment terminology: Transactions of the American Geophysical Union, v. 28, no. 6, p. 936–938.

Le Bas, M.J., LeMaitre, R.W., Streckeisen, A., and Zanettin, B., 1986, A chemical classification of volcanic rocks based on the total alkali silica diagram: Journal of Petrology, v. 27, p. 745–750.

Le Bas, M.J., and Streckeisen, A.L., 1991, The IUGS systematics of igneous rocks: Journal of the Geological Society of London, v. 148, p. 825–833.

Lewis, R.S., 1998, Geologic map of the Butte 1º x 2º quadrangle: Montana Bureau of Mines and Geology Open-File Report 363, 16 p., scale 1:250,000.

Lipman, P.W., 1984, The roots of ash flow calderas in western North America: Windows into the tops of granitic batholiths: Journal of Geophysical Research, v. 89, no. B10, p. 8801–8841.

Loen, J.S., 1986, Origin of gold placers in the Pioneer District, Powell County, Montana: Fort Collins, Colorado State University, M.S. thesis, 164 p.

Loen, J.S., 1990, Lode and placer gold deposits in the Ophir District, Powell, and Lewis and Clark Counties, Montana: Fort Collins, Colorado State University, Ph.D. dissertation, 268 p.

Lonn, J.D., 2015, Geologic field guide to the Cherry Creek Fault, a possible Proterozoic fault near Helena, Montana: Northwest Geology, v. 44, p. 189–194.

Lonn, J.D., and Vuke, S.M., 2015, Geologic map of the Ophir Creek 7.5′ quadrangle, Lewis and Clark, and Powell Counties, Montana: Montana Bureau of Mines and Geology Open-File Report 666, 1 sheet, scale 1:24,000.

Lonn, J.D., McDonald, C., Sears, J.W., and Smith, L.N., 2010, Geologic map of the Missoula East 30′ x 60′ quadrangle, western Montana: Montana Bureau of Mines and Geology Open-File Report 593, 2 sheets, scale 1:100,000.

Lund, K., Aleinikoff, J.N., Kunk, M.J., Unruh, D.M., Zeihen, G.D., Hodges, W.C., du Bray, E.A., and O'Neill, M.J., 2002, SHRIMP U-Pb and 40Ar/39Ar age constraints for relating plutonism and mineralization in the Boulder Batholith region, Montana: Economic Geology, v. 97, p. 241–267.

McCune, J.G., and Hendrix, M.S., 2009, Geologic map of the Helmville basin, west-central Montana: Montana Bureau of Mines and Geology Open-File Report 574, 10 p., 2 sheets, scale 1:24,000.

McDonald, Catherine, 2017, Geologic map of the Moose Creek 7.5′ quadrangle, Lewis and Clark, and Powell Counties, Montana: Montana Bureau of Mines and Geology Open-File Report 686, scale 1:24,000.

McDonald, C., and Lonn, J.D., 2015, Geologic map of the Nevada Mountain and Granite Butte 7.5′ quadrangles, west-central Montana: Montana Bureau of Mines and Geology Open-File Report 665, 1 sheet, scale 1:24,000.

McDonald, C., and Mosolf, J.G., 2016, Geologic map of the Nevada Lake 7.5′ quadrangle, Lewis and Clark, and Powell Counties, Montana: Montana Bureau of Mines and Geology Open-File Report 673, scale 1:24,000.

McDonald, C., Mosolf, J.G., and Vuke, S.M, 2016, Geologic map of the Finn 7.5′ quadrangle, Lewis and Clark, and Powell Counties, Montana: Montana Bureau of Mines and Geology Open-File Report 672, scale 1:24,000.

McDonald, C., and Vuke, S.M., 2017, Geologic map of the Helmville 7.5′ quadrangle, Powell County, Montana: Montana Bureau of Mines and Geology Open-File Report 687, scale 1:24,000.

Melson, W.G., 1964, Geology of the Lincoln area, Montana and contact metamorphism of the impure carbonate rocks: Princeton, N.J., Princeton University, Ph.D. dissertation, 153 p., 4 plates, scale 1:31,680.

Mosolf, J.G., 2016, Geologic map of the Windy Rock 7.5′ quadrangle, Powell County, Montana: Montana Bureau of Mines and Geology Open-File Report 675, scale 1:24,000.

Mosolf, J.G., and Vuke, S.M., 2017, Geologic map of the Gravely Mountain 7.5′ quadrangle, Powell County, Montana: Montana Bureau of Mines and Geology Open-File Report 693, scale 1:24,000.

Mudge, M.R., 1970, Origin of the Disturbed belt in northwestern Montana: Geological Society of American Bulletin, v. 81, p. 377–392.

Mudge, M.R., and Earhart, R.L., 1983, Bedrock geologic map of part of the northern Disturbed Belt, Lewis and Clark, Teton, Pondera, Glacier, Flathead, Cascade, and Powell Counties, Montana: U.S. Geological Survey Miscellaneous Investigations Map I-1375, 2 sheets, scale 1:250,000.

Mudge, M.R., Earhart, R.L., Whipple, J.W., and Harrison, J.E., 1982, Geologic and structure map of the Choteau 1° x 2° quadrangle, western Montana:

U.S. Geological Survey Miscellaneous Investigations Map I-1300, 2 sheets, scale 1:250,000.

Mudge, M.R., Erickson, R.L., and Kleinkopf, M.D., 1968, Reconnaissance geology, geophysics, and geochemistry of the southern part of the Lewis and Clark Range, Montana: U.S. Geological Survey Professional Paper 1252-E, 35 p.

Mutch, T.A., 1961, Geologic map of the northeast flank of the Flint Creek Range, western Montana: Montana Bureau of Mines and Geology Geologic Map 5, 1 sheet, scale 1:63,360.

O'Brien, M.W., 2000, Stratigraphic analysis of the Albian through Campanian Colorado Group within the Garrison Depression, west-central Montana: Missoula, University of Montana, M.S. thesis, 122 p.

Olson, N.H., Sepp, M.D., Mankins, N.E., Blessing, J.M., Dilles, J. H., and Scarberry, K.C., 2017, Geologic map of the Mount Thompson 7.5' quadrangle, southwest Montana: Montana Bureau of Mines and Geology EDMAP 11, 13 p., 1 sheet, scale 1:24,000.

Parker, D.B., 1995, The geology, petrology, and volcanic history of the Crater Mountain Volcanic Complex, Lewis and Clark County, Montana: Missoula, University of Montana, M.S. thesis, 240 p., 1 sheet, scale 1:24,000.

Peccerillo, A., and Taylor, S.R., 1976, Geochemistry of Eocene calc-alkaline volcanic rocks from the Kastamonu area, northern Turkey: Contributions to Mineralogy and Petrology, v. 58, issue 1, p. 63–81.

Peterson, M.P., 1985, The geology of the southwest quarter of the Avon 15-minute quadrangle, Powell County, Montana: Butte, Montana College of Mineral Science and Technology, M.S. thesis, 78 p., 1 sheet, scale 1:62,500.

Rasmussen, D.L., 1977, Geology and mammalian paleontology of the Oligocene-Miocene Cabbage Patch Formation, central-western Montana: Lawrence, University of Kansas, Ph.D. dissertation, 794 p.

Rasmussen, D.L., 1989, Depositional environments, paleoecology, and biostratigraphy of Arikareean Bozeman Group strata west of the Continental Divide in Montana, in French, D.E., and Grabb, R.F., eds., Geological Resources of Montana, v. 1: Montana Geological Society, Montana Centennial Edition, 1989 Field Conference, Guidebook, p. 205–215.

Reynolds, M.W., 1979, Character and extent of basin-range faulting, western Montana and east-central Idaho, in Newman, G.W., and Goode, H.D., eds., Basin and Range Symposium: Rocky Mountain Association of Geologists, p. 185–193.

Reynolds, M.W., 2000, Generalized bedrock geologic map of the Helena area, west-central Montana, in Thamke, J.N., Hydrology of the Helena area bedrock, west-central Montana, 1993–1998, with a section on geologic setting and a generalized bedrock geologic map: U.S. Geological Survey Water Resources Investigations Report 00-4212, 119 p.

Reynolds, M.W., and Brandt, T.R., 2005, Geologic map of the Canyon Ferry Dam 30′ x 60′ quadrangle, west-central Montana: U.S. Geological Survey Scientific Investigations Map 2860, 32 p., 3 plates, scale 1:100,000.

Roll, T.E., Neeley, M.P., Speakman, R.J., and Glascock, M.D., 2005, Characterization of Montana cherts by LA-ICP-MS, in Speakman, R.J. and Neff, H., eds., Laser Ablation-ICP-MS in Archaeological Research, p. 69–74.

Ross, C.P., 1963, The Belt Series in Montana, U.S. Geological Survey Professional Paper 349,119 p.

Ruppel, E.T., 1963, Geology of the Basin quadrangle, Jefferson, Lewis and Clark, and Powell Counties, Montana: U.S. Geological Survey Bulletin 1151, 121 p.

Scarberry, K.C., Coppage, E.L., and English, A.R., 2019a, Field guide to the geology and metallic mineral deposits along the western contact between the Boulder Batholith and the lower and middle members of the Elkhorn Mountains Volcanic Field: Northwest Geology, v. 48, p. 61–70.

Scarberry, K.C., Gammons, C.H., and Kallio, I.M., 2019b, Field guide to the geology and metallic mineral deposits along the eastern contact between the Boulder Batholith, the Elkhorn Mountains Volcanic Field, and Cretaceous-Paleozoic sedimentary rocks: Northwest Geology, v. 48, p. 97–107.

Scarberry, K.C., Elliott, C.G., and Yakovlev, P.V., 2019c, Geology of the Butte North 30' x 60' quadrangle, southwest Montana: Montana Bureau of Mines and Geology Open-File Report 715, 30 p., 1 sheet, scale 1:100,000.

Scarberry, K.C., and Yakovlev, P.V., 2019, An overview of Mesozoic magmatism, in Montana Mining and Mineral Symposium, Butte, Montana, 2018, Proceedings: Montana Bureau of Mines and Geology Special Publication 120, p. 57–61.

Scarberry, K.C., Coppage, E.L., and English, A.R., 2018, Geologic map of the Bison Mountain 7.5′ quadrangle, Powell and Jefferson Counties, Montana: Montana Bureau of Mines and Geology Geologic Map 71, 10 p., 1 sheet, scale 1:24,000.

Schmidt, R.G., 1972, Geologic map of the Wolf Creek quadrangle, Lewis and Clark County, Montana: U.S. Geological Survey Geologic Quadrangle Map GQ-974, scale 1:24,000.

Schmidt, R.G., Loen, J.S., Wallace, C.A., and Mehnert, H.H., 1994, Geology of the Elliston region, Powell, and Lewis and Clark Counties, Montana: U.S. Geological Survey Bulletin 2045, 25 p., scale 1:48,000.

Sears, J.W., and Hendrix, M., 2004, Lewis and Clark Line and the rotational origin of the Alberta and Helena Salients, North American Cordillera, in Sussman, A.J., and Weil, A.B., eds., Orogenic curvature: Integrating paleomagnetic and structural analyses: Geological Society of America Special Paper 383, p. 173–186.

Sears, J.W., Hendrix, M., Webb, B., and Archibald, D., 1998, Constraints on deformation of the northern Rocky Mountain fold-thrust belt in Montana from 40Ar/39Ar geochronology of andesite sills: American Association of Petroleum Geologists Annual Convention, Salt Lake City, Utah, Abstract 587.

Sears, J.W., Webb, B., and Taylor, M., 2000, Bedrock geology of Garrison and Luke Mountain 7.5′ quadrangle: Montana Bureau of Mines and Geology Open-File Report 403, 17 p., 3 sheets, scale 1:24,000.

Smedes, H.W., 1966, Geology and igneous petrology of the northern Elkhorn Mountains, Jefferson and Broadwater Counties, Montana: U.S. Geological Survey Professional Paper 510, 116 p.

Smedes, H.W., Klepper, M.R., and Tilling, R.I., 1973, The Boulder Batholith, Montana: A summary in Miller, R.N., ed., Guidebook for the Butte field meeting of Society of Economic Geologists: Littleton, CO, Society of Economic Geologists, E1–3.

Smedes, H.W., Klepper, M.R., and Tilling, R.I., 1988, Preliminary map of plutonic units of the Boulder Batholith, southwestern Montana: U.S. Geological Survey Open-File Report 88-283; Montana Bureau of Mines and Geology Open-File Report 201, 1 sheet, scale 1:200,000.

Stickney, M., 2015, Seismicity within and adjacent to the eastern Lewis and Clark Line, west-central Montana: Northwest Geology, v. 44, p. 19–36.

Stickney, M.C., and Vuke, S.M., 2017, Geologic map of the Helena Valley, west-central Montana: Montana Bureau of Mines and Geology Open-File Report 689, scale 1:50,000.

Stout, Koehler, 1949, Geology and mines of the Ogden Mountain mining district, Powell County, Montana: Butte, Montana School of Mines, M.S. thesis, 56 p.

Trombetta, M.J., 1987, Evolution of the Eocene Avon Volcanic Complex, Powell County, Montana: Bozeman, Montana State University, M.S. thesis, 112 p., 2 sheets, scale 1:24,000.

Trombetta, M.J., and Berg, R.B., 2012, Geologic map of the Avon 7.5′ quadrangle, Powell County, Montana: Montana Bureau of Mines and Geology Geologic Map 63, scale 1:24,000.

Tysdal, R.G., Dyman, T.S., and Nichols, D.J., 1989, Lower Cretaceous bentonitic strata in southwestern Montana assigned to Vaughn Member of Mowry Shale (East) and of Blackleaf Formation (West): Mountain Geologist, v. 26, no. 2, p. 53–61.

Walker, T.F., 1967, The geology of the Elliston area, western Montana: Grand Forks, University of North Dakota, M.S. thesis, 136 p.

Wallace, C.A., Lidke, D.J., and Schmidt, R.G., 1990, Faults of the Lewis and Clark Line and fragmentation of the Late Cretaceous foreland basin in west-central Montana: Geological Society of America Bulletin, v. 102, p. 1021–1037.

Wallace, C.A., Schmidt, R.G., Lidke, D.J., Waters, M.R., Elliott, J.E., French, A.B., Whipple, J.W., Zarske, S.E., Blaskoski, M.J., Heise, B.A., Yeoman, R.A., O'Neill, J.M., Lopez, D.A., Robinson, G.D., and Klepper, M.R., 1987, Preliminary geologic map of the Butte 1º x 2º quadrangle, western Montana: U.S. Geological Survey Open-File Report OF-86-292, scale 1:250,000.

Whipple, J.W., Mudge, M.R., and Earhart, R.L., 1987, Geologic map of the Roger's Pass area, Lewis and Clark County, Montana: U.S. Geological Survey Miscellaneous Investigations Series Map I-1642, scale 1:48,000.

Winston, D., 2013, Analysis of sheetflood fluvial systems in the Middle Proterozoic Belt Supergroup, northern Idaho and northwestern Montana: Northwest Geology, v. 42, p. 71–74.

Winston, D., 1986a, Sedimentology of the Ravalli Group, middle Belt carbonate, and Missoula Group, Middle Proterozoic Belt Supergroup, Montana, Idaho, and Washington, in Roberts, S.M., ed., Belt Supergroup: A guide to Proterozoic rocks of western Montana and adjacent areas: Montana Bureau of Mines and Geology Special Publication 94, p. 85–124.

Winston, D., 1986b, Sedimentation and tectonics of the Middle Proterozoic Belt Basin, and their influence on Phanerozoic compression and extension in western Montana and northern Idaho, in Peterson, J.A., ed., Paleotectonics and sedimentation in the Rocky Mountain region, United States: American Association of Petroleum Geologists Memoir 41, p. 87–118.

Winston, D., and Link, P.K., 1993, Middle Proterozoic rocks of Montana, Idaho, and eastern Washington: Belt Supergroup, in Reed, J.C., Bickford, M.E., Houston, R.S., Link, P.K., and Ranking, D., eds., The Geology of North America: Precambrian, Conterminous U.S.: Boulder, Colorado, Geological Society of America, The Geology of North America, The Decade of North American Geology, v. C-2, p. 487–517.

Winston, D., and Sears, J.W., 2013, Stratigraphy of the Proterozoic Belt Supergroup and structure of the Belt Basin: Glacier National Park and Blackfoot River Canyon, Montana: Northwest Geology, v. 42, p. 237–256.

Witkind, I.J., and Weber, W.M., 1982, Reconnaissance geologic map of the Big Fork-Avon environmental study area, Flathead Lake, Lewis and Clark, Missoula, and Powell Counties, Montana: U.S. Geological Survey Miscellaneous Investigations Series Map I-1380, scale 1:125,000.

Wittkop, C., 2009, Glacial sediments of the Little Blackfoot River Valley, Montana: revisiting the Pleistocene Boulder Mountains ice cap: Geological Society of America Rocky Mountain Section, Abstracts with Programs, v. 41, no. 6, p. 13.

APPENDIX A

Bulk-rock geochemistry (XRF and ICP-MS) data and methods

Major and Trace Element (XRF and ICP-MS) Data

Data tables are available for free download from this publication's page on our website (mbmg.mtech.edu)

Major and Trace Element (XRF and ICP-MS) Methods

Rock samples were crushed at the MBMG mineral separation laboratory and a split of 100–200 g from each sample was sent to the Peter Hooper GeoAnalytical Lab at Washington State University for major and trace chemical analysis. The samples were powdered and fused into glass beads following standard grinding, heating, and polishing techniques. Major elements were measured by X-ray fluorescence (XRF) analysis of the polished glass beads using established instrumentation protocols (e.g., Johnson and others, 1999). The glass beads were then reground for trace element analysis by inductively coupled plasma mass spectrometry (ICP-MS) following standard laboratory procedures (e.g., Doherty, 1989). Whole-rock chemical data acquired by this study are provided in the tables available online.

Notes about the data:

* Composition is Total Alkali Silicia (TAS) classification after LeBas and others (1986).

* FeO is all Fe expressed as Fe^{2+}. LOI is loss on ignition.

* Location datum used for sample coordinates is World Geodetic Survey 1984 (WGS84).

* Sample ES-86 was collected approximately 1,000 m north of the Elliston 30’ x 60’ quadrangle boundary, within the Crater Mountain Volcanic Field. It is included with the geochemistry data in appendix A but is not shown on the geologic map.

References

Doherty, W., 1989, An internal standardization procedure for the determination of yttrium and the rare earth elements in geological materials by inductively coupled plasma-mass spectrometry: Spectrochimica Acta, v. 44B, p. 263–280.

Johnson, D.M., Hooper, P.R., and Conrey, R.M., 1999, XRF analysis of rocks and minerals for major and trace elements on a single low dilution li-tetraborate fused bead: Advances in x-ray analysis, v. 41, p. 843–867.

Le Bas, M.J., LeMaitre, R.W., Streckeisen, A., and Zanettin, B., 1986, A chemical classification of volcanic rocks based on the total alkali silica diagram: Journal of Petrology, v. 27, p. 745–750.

APPENDIX B

U-Pb geochronology data and methods

U-Pb Geochronology Data

Data tables are available for free download from this publication's page on our website (mbmg.mtech.edu)

U-Pb Geochronology Methods

Zircon was separated from 1–2 kg of sample using standard density and magnetic separation techniques at the MBMG mineral separation laboratory. Approximately 100–200 representative zircon grains were hand selected per sample and set in a 2.5-cm epoxy grain mount. Zircon crystal structure was assessed by scanning electron microscopy cathodoluminescence and then subsequently analyzed by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) at the University of California, Santa Barbara. Approximately 40 zircon grains were analyzed per sample. All LA-ICP-MS data are provided in the data tables. "Best age" is the ^{207}Pb corrected $^{206}Pb/^{238}U$ age for spot analyses younger than 1,400 Ma, and the $^{207}Pb/^{206}Pb$ age for samples older than 1,400 Ma. "Rho" is the correlation error associated with the measured $^{206}Pb/^{238}U$ and $^{207}Pb/^{206}Pb$ ratios, respectively. The weighted mean of select $^{206}Pb/^{238}U$ ages for igneous samples are reported in table 1.