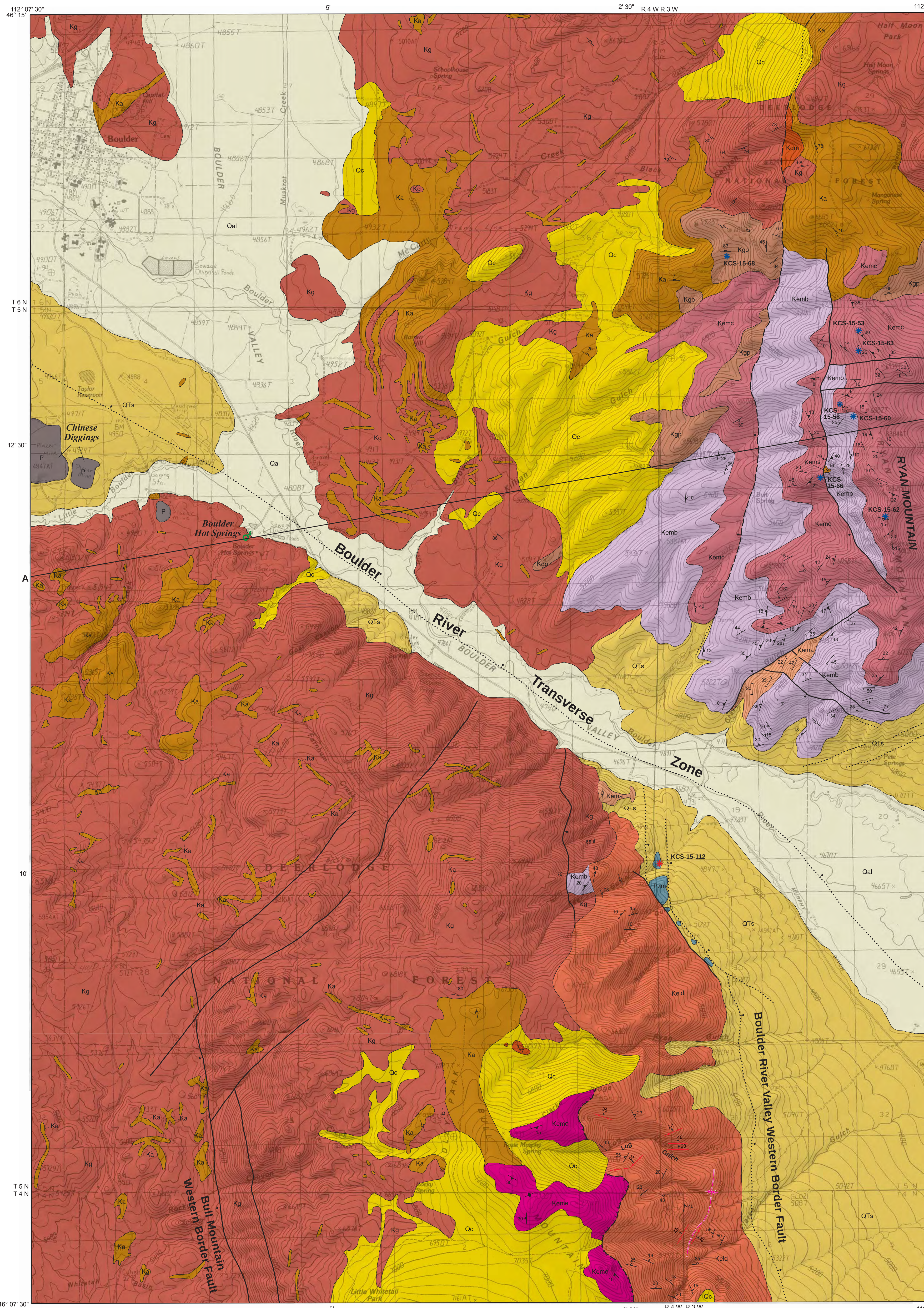
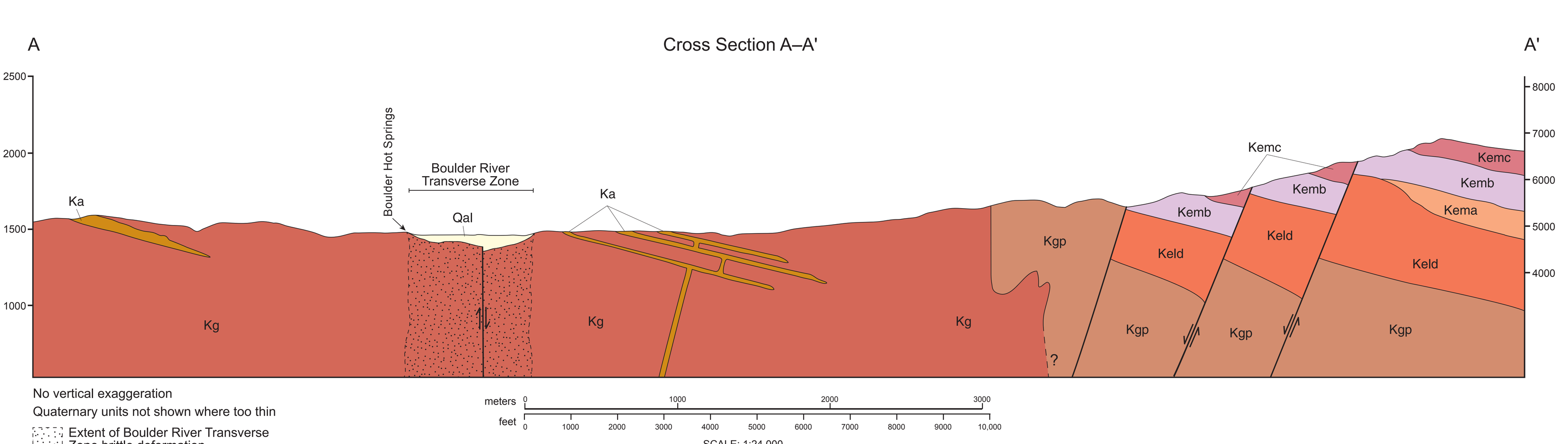


Base map produced by the United States Geological Survey
Boulder East 1:24,000-scale topographic map
Control by: USGS, NOS/NOAA and USFS
Compiled from aerial photographs taken 1980
Field checked: 1981. Map edited: 1985
Projection: Lambert Conformal Conic
Grid: 1000-meter Universal Transverse Mercator Zone 12
UTM grid declination: 0°46' West
1988 Magnetic North Declination: 16° 30' East
Vertical Datum: National Geodetic Vertical Datum of 1929
Horizontal Datum: 1927 North American Datum

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

Maps may be obtained from:
Publications Office
Montana Bureau of Mines and Geology
1300 West Park Street
Butte, Montana 59701-8997
Phone: (406) 496-4174 Fax: (406) 496-4451
http://www.mbmg.mtech.edu

Cross Section A–A'

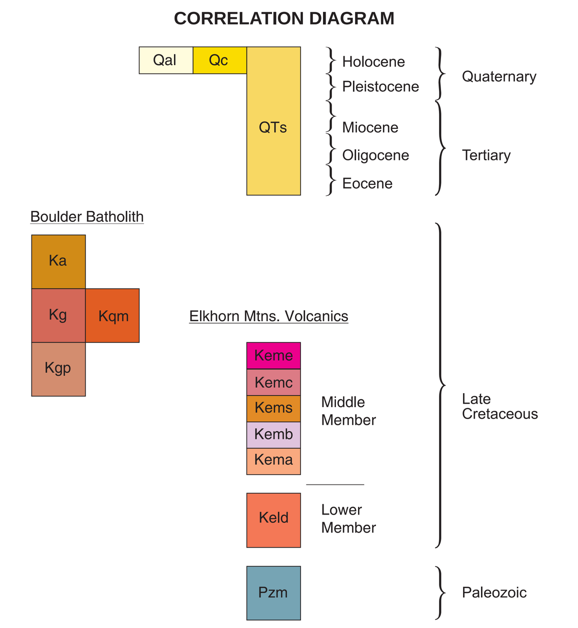


No vertical exaggeration
Quaternary units not shown where too thin
Extent of Boulder River Transverse Zone brittle deformation
SCALE 1:24,000

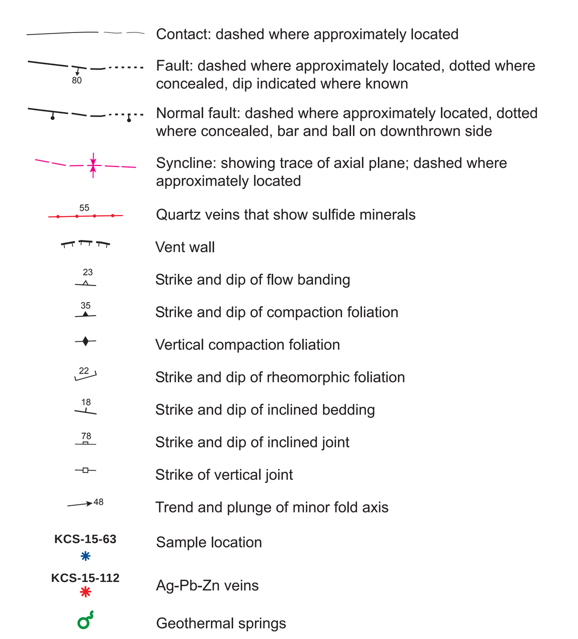
Research supported by the U.S. Geological Survey, National Cooperative Geologic Mapping Program, under USGS award number G15AC00219. The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.

GIS production: Yiwen Li and Paul Thale, MBMG. Map layout: Susan Smith, MBMG. Editing: Susan Barth, MBMG.

CORRELATION DIAGRAM



MAP SYMBOLS



INTRODUCTION

The Boulder East 7.5' quadrangle is located 28 mi (45 km) northeast of Butte in southwestern Montana (fig. 1). Interstate 15 and the town of Boulder (pop. 1,200) lie in the northwestern corner of the quadrangle. The stark topographic contrast between the Boulder River Valley (elev. 4,700 ft) and the high peaks of Bull Mountain (elev. 7,330 ft) and Ryan Mountain (elev. 6,940 ft) is the main physiographic feature of the landscape (fig. 2).

PREVIOUS MAPPING

Weeks (1974) produced a 1:48,000-scale geologic map of the quadrangle and Prostka (1966) named and described Elkhorn Mountains Volcanics (EMV) ignimbrites (A, B, and C) in the Dry Mountain 7.5' quadrangle (fig. 1). These reports were used to compile the distribution of aplite in the Boulder Batholith, and for EMV stratigraphic nomenclature.

GEOLOGIC SUMMARY

A remnant of the Mesozoic Cordilleran volcanic arc is preserved in the Boulder East 7.5' quadrangle. The contact between plutonic (Boulder Batholith) and volcanic (Elkhorn Mountains Volcanics) arc rocks is continuous for ~100 km on the east side of the batholith (fig. 1), and is well exposed in the quadrangle. The arc rocks (Rutland and others, 1989) formed concurrently during Late Cretaceous fold-thrust belt shortening (Lageson and others, 2001), and together represent an exceptionally well-preserved and voluminous record of continental magmatism.

The Elkhorn Mountains Volcanics (EMV) are 700 m thick in the Ratio Mountain 7.5' quadrangle (Olson and others, 2016), where they consist of three large-volume ignimbrite sheets capped by two thin pyroclastic units. The ignimbrites are traceable into the Boulder East 7.5' and adjacent quadrangles (fig. 1), and conservative estimates of individual eruption volumes for ignimbrites A, B, and C are on the order of 200–300 km^3.

STRUCTURE AND SEISMICITY

The quadrangle is in the Late Cretaceous Fold-Thrust belt of western Montana (fig. 1), yet Miocene-Recent Basin and Range block faults and high-angle transverse fault zones (Reynolds, 1979) control regional physiography (fig. 2). Left-lateral transpression along the Lewis and Clark Zone (fig. 1) cut the Fold-Thrust belt during the Laramide orogeny (Sears and others, 2010). The Lewis and Clark Zone has acted as a right-lateral transtensional zone at least since the onset of Miocene Basin and Range extension (Reynolds, 1979; Sears and Hendrix, 2004).

The quadrangle lies within the Intermountain Seismic Belt, a broad zone of Quaternary faulting and seismicity in western Montana (fig. 1) (Stickney and others, 2000). Quaternary faults include the north-striking Boulder River Valley western border fault and the Bull Mountain western border fault (fig. 2) (Stickney and others, 2000). Both Quaternary fault blocks lose topographic relief along their strike to the north and disappear into the Boulder River Valley (fig. 2). The river valley is superimposed on a high-angle transverse fault zone, named here the Boulder River Transverse Zone (BRTZ), that separates domains of Basin and Range block faults (e.g., Faulds and Varga, 1998).

Several small magnitude (0.5–3.5) earthquakes have occurred at depths of 0.6–17.8 km (0.4–11.1 mi) in the Boulder region since 1982 (M. Stickney, written comm, 2016) (fig. 2). Fault plane solutions or focal mechanisms are determined from P-wave first motions recorded by a regional seismograph network and are used to infer the type of faulting and the maximum (P-axis) and minimum (T-axis) compressive stress orientations. T-axes and P-axes data from earthquakes in the Boulder region are consistent with northeast–southwest-directed extension (figs. 2, 3). The BRTZ (fig. 2), like northwest-striking faults of the Lewis and Clark Zone (fig. 1), is favorably oriented to accommodate extensional and perhaps right-lateral slip under northeast–southwest-directed extensional stress. The BRTZ is roughly 750 m wide (see cross section).

GEOTHERMAL AND MINERAL RESOURCES

The Boulder Hot Springs occur at the northwest end of the Boulder River transverse zone. Surface-water temperature at the hot springs ranges from 54 to 74°C and water chemistry suggests that it originates from a 140°C subsurface reservoir (Metesh, 2000). These observations imply slow and deep (4.7 km) water circulation, assuming a regional geothermal gradient of 30°C/km (Sonderegger, 1984). The Boulder Hot Springs are actively depositing metallic minerals. Veinlet filling near the hot springs contains Au (0.05 oz/ton) and Ag (0.4 oz/ton), and hydrothermally altered granite is stained with Cu (Weed, 1900).

Polymetallic veins occur in an aligned series of marble knobs (Pzm) located in the southeastern corner of the quadrangle along the north extension of the Boulder River western border fault. The veins contain galena, sphalerite, and pyrite. Spot analyses (n=5) by handheld XRF (Niton XL3 Analyzer) of metallic vein material (sample: KCS-15-112, see map) detected ~2–5 wt. percent Pb and Zn, and a trace of Ag and Au.

Small sulfide-bearing quartz veins cut dacite flow domes (Keld) in Log Gulch, located in the southeastern corner of the map. Rust-colored ridgelines are visible in aerial imagery and may be an indication of concentrated base metals, particularly on the north side of Log Gulch. These veins sometimes occur with small dikes, and exhibit spheroidal weathering texture similar to the 78.57 ± 0.17 Ma ($^{40}Ar/^{39}Ar$ on hornblende) mafic rocks in the Wilson Park 7.5' quadrangle (Scarberry, 2015; 2016).

DESCRIPTION OF MAP UNITS

Anthropogenic units

P **Placer gravels (Holocene)—**Alluvial deposits historically worked for gold. Sapphire is known to occur in gravels at the Chinese Diggings (Berg, 2015).

Sediments

Qal **Alluvium (Holocene)**—Well-sorted gravel, sand, silt, and clay concentrated along the modern floodplain and tributaries to the Boulder River. Thickness variable.

Qc **Colluvium (Holocene)**—Broad areas of debris found on hillsides and upland basins or parks. Consists of a mantle of stony soils and unconsolidated deposits of boulder debris resulting from slope wash, mud flows, creep, and related mass-wasting processes (Weeks, 1974). May include cliff debris and alluvial fan deposits. Thickness undetermined.

QTs **Sediment (Holocene–Eocene?)**—May include cliff debris and alluvial fan material. The ages of the Boulder River Valley basin-fill are unknown. The valley sediments formed in response to Miocene–Holocene block faulting and uplift of Bull Mountain along the active Bull Mountain western border fault and the Boulder River Valley western border fault (Stickney and others, 2000). Recent faulting produced an apron of talus and broad alluvial fan deposits that effectively masks older sediments. The Boulder River Valley is the northern extent of the Jefferson Basin, which regionally contains extensive Miocene through Eocene sediments of the Sixmile Creek and Renova Formations, respectively (Kuenzi and Fields, 1971; Vuke and others, 2004). Well logs in the Boulder River Valley northwest of the Boulder River Transverse Zone (BRTZ) suggest that the valley-fill is less than 55 m thick. South of the BRTZ valley-fill thickens to 100–120 m.

Igneous rocks

Boulder Batholith (Late Cretaceous)

Ka **Aplite (Late stage)**—Light tan sheet-like outcrops that appear layered in places, but lack volcanic or sedimentary structures. The rock is typically fine-grained with a sugary and equigranular texture, although moderately coarse varieties occur. Minerals include minor biotite and/or muscovite, and near-equal amounts of quartz and feldspar. Includes small masses of pegmatitic rocks that contain radiating tourmaline crystals, potassium feldspar, and plagioclase. Aplite on the west side of the Boulder Batholith, north of Butte, is 74.8 ± 0.6 Ma (LA-ICPMS, U-Pb on zircon) (Boise State University, written comm, 2016).

Kg **Butte Granite (main stage)**—Massive jointed granite of the principal pluton, by volume, of the Boulder Batholith. Coarse, medium, and fine varieties occur and contain normal-zoned plagioclase (45–50 percent), orthoclase (20–30 percent), and quartz (5–10 percent) (Berg and Hargrave, 2004). Hornblende and biotite generally make up 15–20 percent of the rock and occur at a 1:1–1:2 ratio. Accessory minerals include sphene, apatite, magnetite, and rare zircon (Weeks, 1974). The Butte Granite has an age of 76.28 ± 0.12 Ma (TIMS U-Pb on zircon) (Martin and Dilles, 2000).

Kqm **Quartz monzonite (main stage)**—Massive dark gray and blue crystalline monzonite contains phenocrysts of 4-mm-long plagioclase, potassium feldspar, quartz, biotite, and hornblende. Alteration minerals include epidote and chlorite. Felsic, equigranular granitic rocks near the contact with underlying Butte Granite (Kg) (Becraft and others, 1963) represent either the chilled margin of the Boulder Batholith, or recrystallized EMV.

Kgp **Quartz granodiorite porphyry**—Blocky and jointed brown rocks that contain conspicuous 2–4 mm, rounded quartz "eyes," potassium feldspar, and biotite. Groundmass is anhedral quartz, potassium feldspar, and micropegmatitic intergrowths of potassium feldspar and quartz, and in part orthoclase. Weeks (1974) assigned the unit to the late stage of Boulder Batholith formation. A new U-Pb age of 80.2 ± 0.8 Ma (fig. 4) indicates that the unit pre-dates main stage Butte Granite (Kg) in the Boulder East 7.5' quadrangle.

Elkhorn Mountains Volcanics (Late Cretaceous)

Middle Member of the Elkhorn Mountains Volcanics

The Elkhorn Mountains Volcanics in the quadrangle belong to the middle member of the formation as defined by Klepper and others (1957).

Keme **Ignimbrite E—**Dark blue to gray and green flow-banded andesite to dacite ignimbrite. Contains approximately 30 percent crystals of plagioclase, clinopyroxene, hornblende, biotite, and Fe-Ti oxide minerals. Lapilli tuff and breccia occur in the unit. Subvertical fiammé and compaction foliations indicate proximity to a vent. The unit is about 50 m thick and correlates with the lower ignimbrite of unit e in the Ratio Mountain 7.5′ quadrangle (units Kemel and Kemelv of Olson and others, 2016). A $^{40}Ar/^{39}Ar$ age of 83.7 ± 0.3 Ma was obtained from the upper ignimbrite of unit e in the Ratio Mountain 7.5' quadrangle (Olson and others, 2016).

Kemc **Ignimbrite C**—Pink, purple, and orange ridge-forming outcrops of light color and low phenocryst content distinguish this rhyolite (fig. 6) unit from older ignimbrites. Phenocrysts include plagioclase (10 percent) and 1 to 2-mm-long biotite (1–3 percent). Small lithic clasts make up 1–3 percent of the rock. Elongate and flattened (5–10:1 length:width) fiammé, 1–10 cm in length, are prevalent at the base. Rectangular blocks 0.5 m long of aphanitic rhyolitic rock and porphyritic clasts of underlying Kemb, occur as rip-ups near the base. The middle is moderately rheomorphic and transitions upward into conspicuous vitroclastic texture. The uppermost part is densely welded and contains abundant 1 to 25-cm-long flattened pumice. Ignimbrite C is ~180 m thick in the Boulder East 7.5' quadrangle. The unit is regionally extensive and more than 50 m thick in the Dry Mountain 7.5' quadrangle (Prostka, 1966); it is 100 m thick in the Ratio Mountain 7.5' quadrangle (see fig. 1) (Olson and others, 2016).

Kems **Volcanogenic sediments**—Conglomerate, pebbly sandstone, and sandstone observed at one location, on the west side of Ryan Mountain. The unit contains andesite and dacite polylithic clasts in volcanic sandstone matrix. The base consists of 10 to15-cm-long subrounded to rounded clasts that transition upward to alternating, laminar beds of sandstone (10 cm) and pebbly sandstone (20 cm). The composite thickness of the deposit is 10–15 m. The presence of volcanogenic sediments between ignimbrites C (Kemc) and B (Kemb) indicates an erosional unconformity between the ignimbrites.

Kemb **Ignimbrite B**—Gray to purple and brown cliff-forming outcrops of crystal-rich, rhyolite (fig. 6) ignimbrite. Phenocrysts include 10–20 percent plagioclase; 3–10 percent, 2 to 5-mm-long biotite; and 1–2 percent hornblende. Lithic fragments constitute <1–10 percent, which locally contains 10–20 percent small (< 1 cm long) fiammé. The basal 5–10 m varies from poorly to densely welded. Poorly welded sections form unstable outcrops with embedded, angular tuff blocks. A thin local basal vitrophyre is characteristic of densely welded outcrops. Upwards the tuff is rheomorphic and exhibits 50:1 stretched, planar pumice. Rheomorphic texture (fig. 5A) decreases upwards and in the top part vitroclastic texture and elongate and flattened (5–10:1) pumice become prominent. The ignimbrite is 180–200 m thick in the Boulder East 7.5' quadrangle. The ignimbrite is regionally extensive, and 60 m thick in the Dry Mountain 7.5' quadrangle (Prostka, 1966) and 180–200 m thick in the Ratio Mountain 7.5' quadrangle (fig. 1) (Olson and others, 2016). The unit is 81.3 ± 0.8 Ma (SHRIMP-RG U-Pb on zircon) in the Ratio Mountain 7.5' quadrangle (Olson and others, 2016).

Kema **Ignimbrite A**—Gray, pink to orange, and white rhyolite ignimbrite with phenocrysts of 5–10 percent plagioclase (oligoclase), 1–3 percent altered biotite, and sparse magnetite. Lithic-poor with 10–15 percent pumice that is difficult to recognize in densely welded sections. The lower 20 m exhibits eutaxitic texture and pumice flattened parallel to the flow base. Upward the unit is highly rheomorphic with pumice stretched greater than 100:1. Folds several meters across occur alongside centimeter-scale folds and indicate rheomorphism as it moved across pre-existing topography during cooling. The upper half of the unit is strongly welded and rheomorphic. The unit is regionally extensive, 185 m thick in the Dry Mountain 7.5' quadrangle (Prostka, 1966), and 160 m thick in the Ratio Mountain 7.5' quadrangle (fig. 1) (Olson and others, 2016). The ignimbrite is 50–70 m thick in the Boulder East 7.5' quadrangle and the base is not exposed. The unit is 84.9 ± 2.6 Ma (LA-ICPMS U-Pb on zircon) in the Ratio Mountain 7.5' quadrangle (Olson and others, 2016).

Lower Member of the Elkhorn Mountains Volcanics

Keld Dacite porphyry lava domes and flows (Cretaceous)—Purple, green, and gray outcrops that are predominantly structureless and locally banded or brecciated (Prostka, 1966). The rocks appear bleached and flooded with silica where near Butte Granite (Kg). Phenocrysts include plagioclase, augite, hornblende, and minor biotite and magnetite. Some outcrops exhibit shallow and steeply dipping gray, purple, and black flow-bands, 1–25 cm thick, that illustrate ramp structures. Contains andesite enclaves (fig. 5B) locally. The unit correlates with dacite lava domes and flows (unit Keld) in the Ratio Mountain 7.5′ quadrangle that is approximately 85 Ma (Olson and others, 2016). The dacite sequence is over 600 m thick in the Boulder East 7.5' quadrangle.

Metasedimentary rocks

Pzm **Metamorphosed carbonate (Paleozoic?)**—Crudely bedded section of white, gray, pale blue, and orange metamorphosed sedimentary rocks. Outcrops are aligned, knobby, and restricted to the northern end of the Boulder River western border fault. Limestone occurs locally. Crystalline dolomitic marble is cut by a network of fine-grained silica stringers and limonite (Weeks, 1974). Several prospect pits and at least one well-worked adit occur in the unit. Vein material from mine dumps (sample KCS-15-112; see map for location) contains galena, sphalerite, and pyrite. The proximity to the batholith, and style of mineralization (Pb–Zn–Ag), suggest that metamorphism and mineralization occurred during emplacement of the Butte Granite (Kg). The protolith is likely the lower 30 m of the Amsden Formation and the uppermost 45–90 m of the Mission Canyon Formation (Weeks, 1974). The total exposed thickness is 75–120 m.

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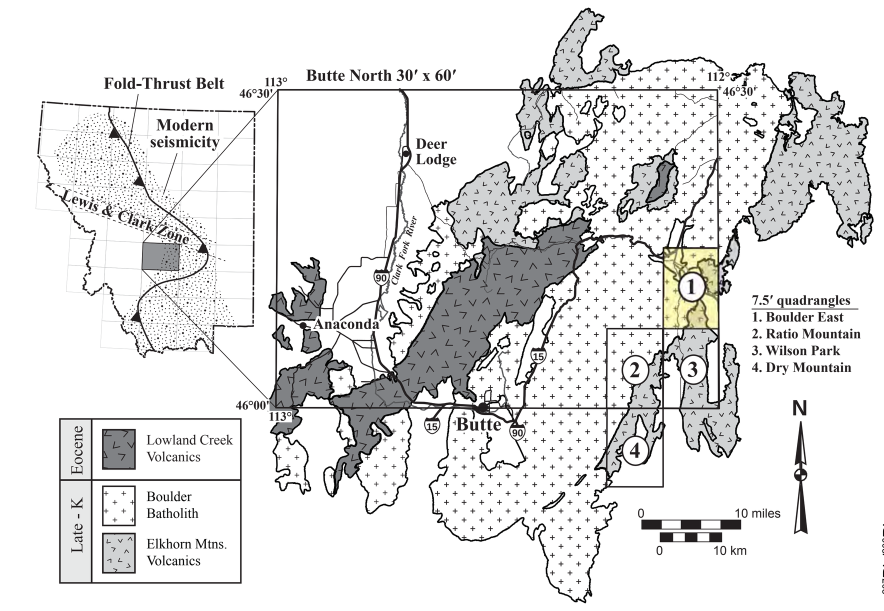


Figure 1. Igneous geology of the Butte North 30' x 60' quadrangle in southwestern Montana (after Vuke and others, 2007) and location of the Boulder East 7.5' (highlighted) and nearby quadrangles.

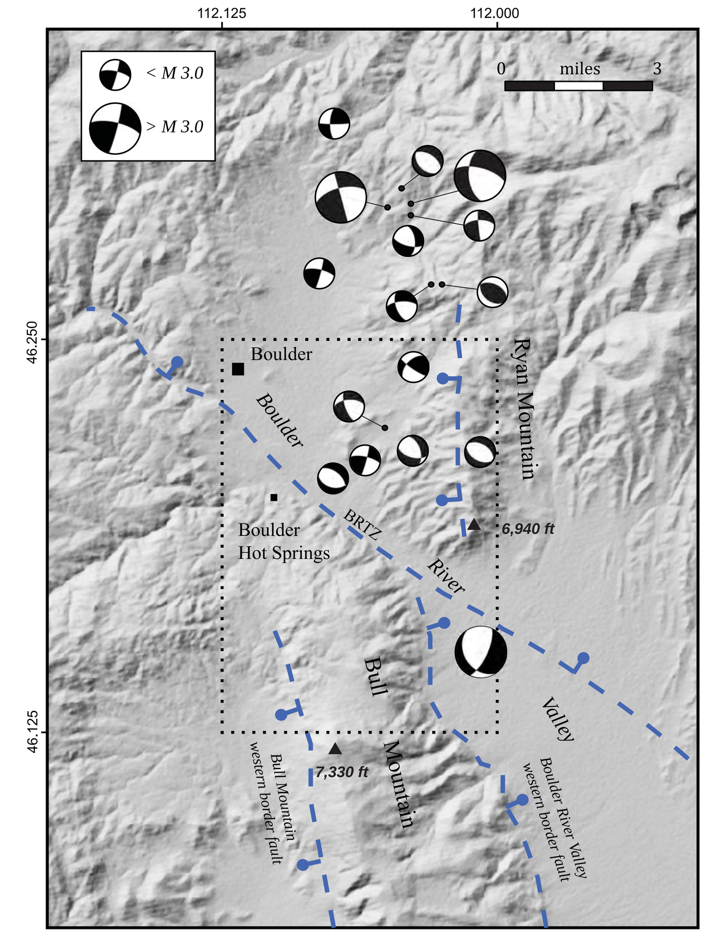


Figure 2. Physiography, structure, and seismicity of the Boulder River Valley. Dashed line marks the Boulder East quadrangle boundary. Beach-ball symbols are focal mechanisms created from earthquake data recorded since 1982 (M. Stickney, written comm, 2016). Note that normal, reverse, strike-slip, and oblique slip faulting are recorded by the focal mechanisms. Bars and balls are on the down-dropped sides of normal faults. Arrows show interrelated relative motion along the Boulder River Transverse Zone (BRTZ).

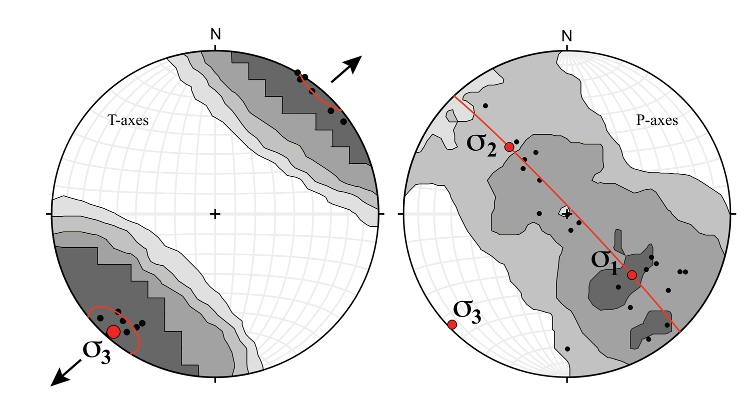
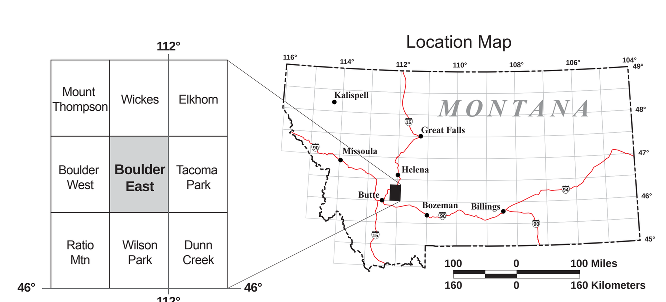


Figure 3. Lower hemisphere equal area stereonet projections show contoured T-axes and P-axes data derived from earthquake focal mechanisms near Boulder (fig. 2). The red small circle (left diagram) shows the conical best fit to the T-axes (red circle). The red line (right diagram) shows the cylindrical best fit to the P-axes. Red dots show orientations of the maximum (σ_1), intermediate (σ_2), and minimum (σ_3) compressive stress axes. The trend and plunge of σ_3 (T-axes) is similar on both diagrams, with orientations of 221°, 6° (left diagram) and 226°, 3° (right diagram). Diagrams created using the stereonet program (Allmendinger and others, 2012; Cardozo and Allmendinger, 2013).

Location Map



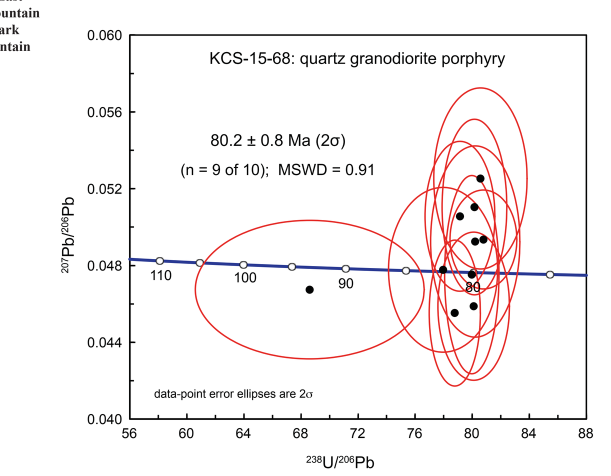


Figure 4. SHRIMP-RG (Sensitive High Resolution Ion Microprobe Reverse Geometry) U-Pb zircon age data (Olson and Dilles, unpublished data) for quartz granodiorite porphyry located in the northeast map corner (sample KCS-15-68; see map for location). Reported error on the age is 2σ (95% confidence), based on the standard error of the mean age. The blue line represents the age concordia curve. Note that one of ten grains analyzed is discordant, and was likely inherited from older rocks.

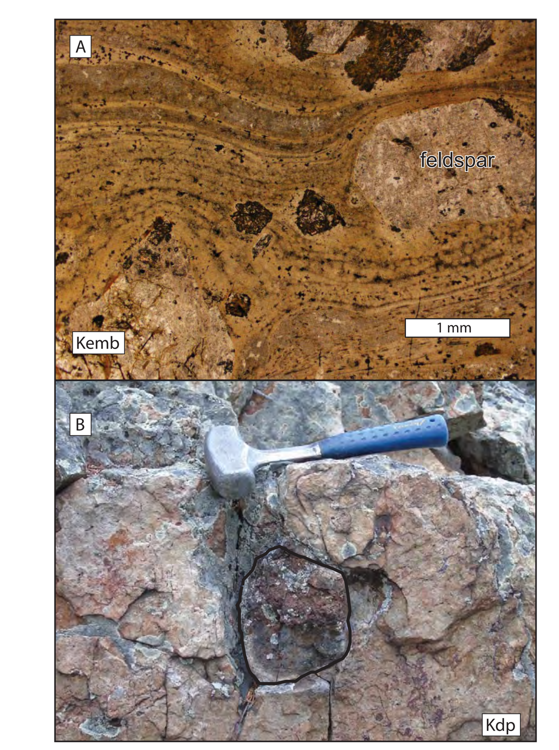


Figure 5. (A) Photomicrograph (plane-polarized light) shows flow-banded texture in ignimbrite B (Kemb). Image obtained from sample KCS-15-63 located in the northeastern map corner (see map for precise location). (B) Subrounded andesite rip-up inclusion entrained in bleached dacite porphyry lavas (Kdp).

Table 1. Whole-rock major oxide and trace element geochemical data.

Sample ID	KCS-15-63	KCS-15-66	KCS-15-62	KCS-15-60	KCS-15-53	KCS-15-58
map unit	Kemc	Kemc	Kemc	Kemb	Kemc	Kemc
XRF (wt. %)						
SiO_2	70.54	73.16	72.19	71.15	71.62	71.98
TiO_2	0.47	0.39	0.45	0.44	0.43	0.37
Al_2O_3	15.72	14.42	14.66	15.27	15.10	15.52
$*FeO_T$	1.89	1.72	2.32	2.02	1.77	1.48
MnO	0.07	0.04	0.04	0.09	0.07	0.05
MgO	0.42	0.22	0.39	0.32	0.38	0.27
CaO	1.56	1.50	1.59	1.66	1.51	1.25
Na_2O	4.11	3.13	3.74	3.89	3.86	4.09
K_2O	5.11	5.34	4.53	5.08	5.19	4.92
P_2O_5	0.09	0.07	0.09	0.08	0.07	0.07
LOI	0.64	1.03	0.77	0.82	0.39	1.00
a.t.	98.47	98.21	98.59	98.46	98.68	98.27
Trace elements (ppm) (XRF)						
Ni	3	4	1	3	3	2
Cr	3	1	2	2	1	2
Sc	8	6	7	7	7	5
V	19	18	22	20	17	18
Ba	1537	1468	1453	1487	1601	1360
Rb	124	142	125	132	136	126
Sr	417	363	382	403	372	303
Zr	275	254	261	275	287	253
Y	31	29	29	31	31	27
Nb	14	14	14	15	16	14
Ga	15	14	15	16	16	13
Cu	3	7	1	2	1	5
Zn	55	59	41	58	49	113
Pb	25	31	15	21	22	31
La	45	43	46	48	49	49
Ce	90	79	83	91	92	83
Th	13	13	13	14	14	13
Nd	39	31	36	37	36	34
U	3	3	4	2	3	2

Major oxides normalized to 100% anhydrous. *All Fe expressed as Fe^{2+}.
Samples analyzed by the Peter Hooper GeoAnalytical Laboratory at Washington State University.

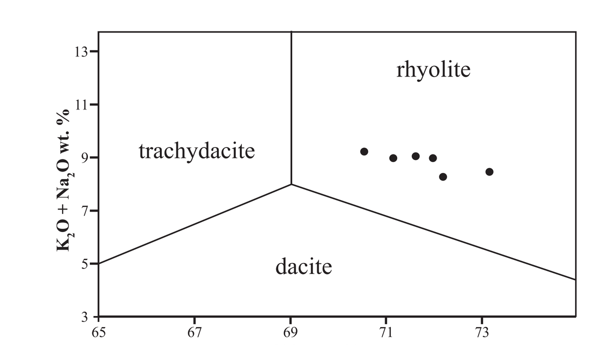


Figure 6. Composition of EMV ignimbrites (Kemb and Kemc). Chemical classification after Le Bas and others (1986).

MBMG Geologic Map 68

Geologic Map of the Boulder East 7.5' Quadrangle, Southwest Montana

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