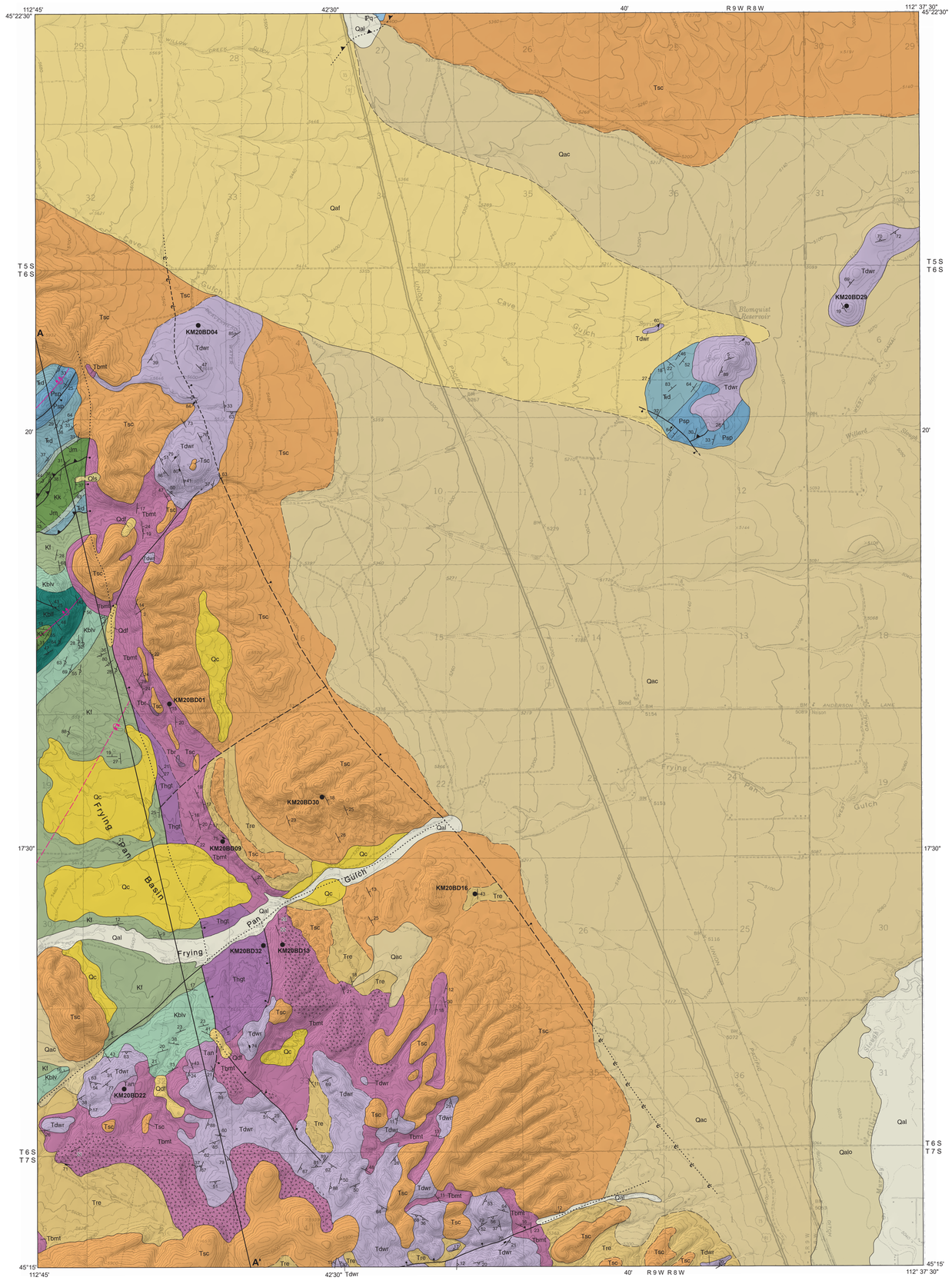
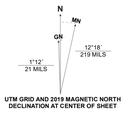


Bond 1:24,000-scale quadrangle map
Base map produced by the United States Geological Survey
Topography compiled 1960. Planimetry derived from imagery taken 1995 and other sources. Public Land Survey System and survey control current as of 1999.
Projection: Universal Transverse Mercator
Grid:1000-meter Universal Transverse Mercator Zone 12
Vertical Datum: National Geodetic Vertical Datum of 1929
Horizontal Datum: 1927 North American Datum

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

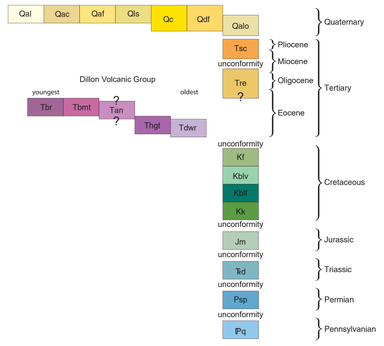


SCALE 1:24,000

CONTOUR INTERVAL 40 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

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

CORRELATION DIAGRAM



MAP SYMBOLS

- Contact: dashed where approximately located
- Fault: dashed where approximately located; dotted where concealed
- Normal fault: dashed where approximately located; dotted where concealed, bar and ball on downthrown side; question mark where identity or existence questionable
- Reverse or thrust fault: dashed where approximately located; dotted where concealed, teeth on upthrown block
- Overturned anticline
- Overturned syncline: dashed where approximately located
- Inclined bedding—Showing strike and dip
- Overturned bedding—Showing strike and dip
- Inclined igneous foliation—Showing strike and dip
- Vertical igneous foliation—Showing strike
- Small, minor inclined joint—Showing strike and dip
- Welded tuff outcrops
- KM20BD04 Sample point location

INTRODUCTION

The Montana Bureau of Mines and Geology (MBMG), in conjunction with the STATEMAP advisory committee, selected the Bond 7.5′ quadrangle in southwest Montana for detailed mapping as part of the MBMG's ongoing effort to complete the Dillon 30° x 60° (1:100,000-scale) geologic map. The quadrangle is located in the upper Beaverhead Valley, which is bordered by the Ruby Range to the east and the Blacktail and Pioneer Mountains to the south and west, respectively (fig. 1). Interstate 15 and the Union Pacific Railroad transect the quadrangle.

PREVIOUS MAPPING AND METHODS

The Bond 7.5′ quadrangle is included in the regional scale (1:250,000) geologic map of the Dillon 1° x 2° quadrangle (Ruppel and others, 1993). Larger-scale maps by Matthews (1989, scale 1:24,000) and Myers (1952, scale 1:31,680) cover parts of the west half of the quadrangle. New mapping for this project was completed during 2020, using a USGS topographic base map, 2009 orthoimagery from the National Agricultural Imagery Program (NAIP), and a handheld Trimble Juno GPS for collecting point data.

Rock samples collected for geochemistry and U-Pb geochronology were processed at the MBMG mineral separation laboratory. A ~100–200 g split of the crushed material was prepared for bulk-rock geochemical analysis and subsequently analyzed by X-ray fluorescence (XRF) and inductively coupled plasma mass spectrometry (ICP-MS) at the Peter Hooper GeoAnalytical Lab, Washington State University. Zircon was isolated from selected samples by standard density and magnetic separation techniques. Zircon separates were analyzed by Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) by Jesse Mosolf, MBMG, at the University of California, Santa Barbara.

GEOLOGIC SUMMARY

The Bond quadrangle is underlain by extensive Tertiary and Quaternary valley-fill deposits, Tertiary volcanic rock, and Paleozoic and Mesozoic sedimentary rock. The quadrangle lies along the eastern margin of the fold-thrust belt and is within the Beaverhead Graben, one of several intermontane structural basins formed during the onset of Basin and Range-style extension in southwestern Montana (Pardee, 1950; Ruppel, 1982; Sears and Fritz, 1998; Sears and others, 2009).

The oldest rocks are folded and faulted Pennsylvanian through Cretaceous carbonate and clastic units that are well exposed in northeast–trending folds along the western edge of the map and as isolated outcrops further to the north and east. The older bedrock is unconformably overlain by Tertiary lava flows and tuffs (fig. 2) of the Eocene Dillon Volcanic Group, the generally fine-grained, ash-rich sedimentary deposits of the Renova Formation, and mostly coarse-grained gravel deposits of the Sixmile Creek Formation. Radiometric age dates indicate the rhyolites and associated tuff and ash beds were emplaced around ~48–46 Ma (table 2) and are part of the informal "lower Dillon volcanics" (Fritz and others, 2007). The volcanic rocks are overlain by and intercalated with the early Eocene to early Miocene Renova Formation, a volcanic and volcaniclastic sequence deposited as fluvial, lacustrine, floodplain, and locally derived debris flow deposits (Kuenzi and Fields, 1971; Fritz and others, 2007; Schwartz and Schwartz, 2013). Cobble and boulder gravels of the Middle Miocene to Pliocene Sixmile Creek Formation unconformably overlie the Renova Formation. The Sixmile Creek is interpreted as fluvial and debris flow deposits that accumulated in the Beaverhead Graben (Fritz and Sears, 1993; Fritz and others, 2007).

The youngest deposits in the quadrangle are Quaternary alluvium and colluvium. The large alluvial fan in the northwest corner of the map is associated with the Cave Gulch and Birch Creek drainages and may include glacial outwash. Younger alluvial deposits are located along modern drainages. Widespread colluvium mantles the gentle slopes in the western part of the map.

STRUCTURE

The oldest structures in the Bond quadrangle are northeast-trending, upright and overturned-to-the-southeast folds and associated thrust faults. The thrust faults dip to the northwest and place rocks as old as Early Triassic over Late Cretaceous strata. These structures formed during Late Cretaceous contractional deformation and are characteristic of the leading edge of the Cordilleran thrust belt in southwest Montana (Ruppel and Lopez, 1984). The youngest structures are steep, generally northwest- and northeast-trending extensional faults that offset the older structures. The extensional faults cut both Eocene volcanic rock and Miocene Sixmile Creek Formation and formed during Cenozoic extension in southwestern Montana (Sears and Fritz, 1998; Sears and others, 2009).

Quaternary faults have not been recognized in the Argenta quadrangle (Stickney, 2007), but the epicenter of the 2005 Mw 5.6 Dillon earthquake was located approximately 1 km (0.6 mi) east of the northeast corner of the quadrangle (fig. 1). The main shock occured at a depth of ~10 km (~6.3 mi) on an apparent north- to northwest-trending, east-dipping blind normal fault based on the main shock fault plane solution (Stickney, 2009). The northwest-trending normal fault mapped to the west of Interstate 15 may represent the trace of that fault as suggested by the presence of tufa beds (fig. 3) near the fault (NE corner of section 27, T. 6 S., R. 9 W.) and a shear zone in Tertiary gravels just east of Overnight Reservoir (NW corner of section 8, T. 6 S., R. 9 W.).

DESCRIPTION OF MAP UNITS

Qal **Alluvium (Holocene)**—Unconsolidated gravel, sand, silt, and clay deposited primarily by the Beaverhead River. Clasts generally subrounded to well rounded and consist predominantly of quartzite. Thickness as much as 10 m (33 ft).

Qac **Alluvium and colluvium (Holocene and Pleistocene?)**—Unconsolidated sand, silt, and clay, and subordinate gravel, deposited on gentle slopes by fluvial and gravity processes. Variable thickness, generally less than 10 m (33 ft).

Qaf **Alluvial-fan deposit (Holocene and Pleistocene)**—Unconsolidated, poorly sorted, cobbles, gravel, sand, and silt forming fan-shaped deposit. Estimated thickness about 20 m (65 ft).

Qls **Landslide deposit (Holocene and Pleistocene)**—Mass-wasting deposit that consists of unsorted mixture of clay- to boulder-size sediment. Characterized by hummocky topography at the toe and a subdued landslide scarp. Thickness less than 10 m (33 ft).

Qc **Colluvium (Holocene and Pleistocene)**—Unconsolidated, locally derived slope deposits that contain rounded to angular, poorly size-sorted clasts, primarily with clasts that are pebble size and larger. Thickness generally less than 10 m (33 ft).

Qdf **Debris-flow deposit (Holocene and Pleistocene)**—Angular, subangular, and subrounded clasts of chaotic and unstratified boulders and cobbles and subordinate finer sediment. Some fine sediment was probably removed by erosion, leaving coarser clasts as lag deposits. Estimated thickness about 15 m (50 ft).

Qalo **Alluvium, older (Holocene and Pleistocene)**—Unconsolidated, stratified to unstratified gravel, sand, silt, and clay deposited by the Beaverhead River prior to deposition of Qal. Adjacent to but at elevations higher than Qal. Estimated thickness 0–30 m (0–100 ft).

Tsc **Sixmile Creek Formation (Pliocene and Miocene)**—Pale orange to brown, unconsolidated to consolidated, tuffaceous to quartz-rich silt, sand, gravel, and conglomerate. Conglomerates are the predominant lithology and cap low ridges in the western part of the map. They are poorly sorted, with locally derived sub-angular to rounded pebbles, cobbles, and boulders in a coarse, sandy matrix. Clasts are predominantly quartzite but locally include abundant volcanic clasts, limestone, and granitic cobbles. In the southwest corner of the map, large boulders of quartzite and granite [up to 3 m (10 ft) in diameter] characterize the deposits. The finer-grained intervals are very thin- to medium-bedded, massive to cross-stratified, silt, sand, and gravel with lenses and beds of conglomerate, along with intervals of gray volcanic ash and very pale orange to tan, massive tuffs. In places, the finer-grained intervals contain burrows, nodules, bone fragments, and caliche-cemented intervals with abundant rhizoliths that are interpreted as paleosols. The finer-grained intervals are best exposed north of Frying Pan Gulch (sections 34 and 35, T. 7 S., R. 8 W.) and are correlated with the Anderson Ranch member of the Sixmile Creek Formation (Fritz and Sears, 1993) based on a new U-Pb maximum depositional age of 15.5 ± 0.1 Ma (table 2, sample KM20BD30). Thickness variable but estimated to be as much as 305 m (1,000 ft) thick.

Tre **Renova Formation (Tertiary: Miocene and Eocene)**—Very pale orange, grayish orange, white, and pale yellowish brown tuffaceous mudstone, organic-rich siltstone, tuff, and fine to coarse-grained sandstone. Sandstone intervals are poorly sorted, often micaceous, with angular to subrounded granules, pebbles, and cobbles. Cobble size clasts are predominantly quartzite, limestone, and volcanic rock. Locally contains petrified wood, paper shales, and clay-rich intervals that weather to a "popcorn" texture. In section 27, T. 6 S., R. 9 W., thin tufa intervals (fig. 3) may be related to nearby faulting. An ash sample from the exposure with the tufa beds yielded a U-Pb zircon age of 31.8 ± 0.2 Ma (table 2, sample KM20BD16). Estimated thickness around 790 m (2,600 ft) thick but up to 900 m (3,000 ft) regionally as reported by Hanna and others (1993).

Tbr **Volcanic breccia (Tertiary: Eocene)**—Grayish, poorly sorted, matrix-supported breccia with predominantly angular reddish rhyolite and welded rhyolite tuff clasts, subordinate angular basalt clasts, and rounded quartzite and granite cobbles. Clasts up to 0.5 m (1.5 ft). Intercalated with rhyolite tuff (map unit Trt). Matthews (1989) interpreted the breccias as channelized, debris flow deposits with a maximum horizontal extent of approximately 100 m (333 ft) and a maximum thickness of 14 m (46 ft).

Tbmt **Burns Mountain Tuff (Tertiary: Eocene)**—Massive, white to light gray weathering tuff and welded tuff. Tuff/ash flow intervals contain smoky quartz and biotite (<1 percent) phenocrysts. Small fragments (~5 mm) of pumice, volcanic rock, fine-grained sedimentary rock, and silicified wood are common. Intervals of ash with planar, low-angle cross bedding suggest local fluvial reworking. Welded tuff is white, moderate orange pink, and pale purple with anhedral smoky quartz, plagioclase, biotite, and hornblende. Well exposed south of Frying Pan Gulch where it overlies unwelded tuffs. Base not exposed but at least 60 m (200 ft) thick. Three samples yielded U-Pb zircon ages spanning 46.3 ± 0.2 to 46.9 ± 0.2 Ma (table 2, samples KM20BD01, KM20BD09, and KM20BD13).

Tan **Andesite flows (Tertiary: Eocene)**—Dark brown to black andesite flows (58.2 wt. percent SiO_2, table 1) with an aphanitic groundmass and <2–3 percent phenocrysts of olivine, pyroxene, rare plagioclase, and quartz. Forms isolated, knobby outcrops that weather pale reddish brown to black and often have a vesicular texture.

Thgt **Hennebury Gulch Tuff (Tertiary: Eocene)**—White to light brown, poorly exposed lithic-vitric tuff. Composed of crude bedforms that are ~1–2 m thick and massive. Contains broken phenocrysts (up to ~30 percent) of quartz, feldspar, biotite, and occasional amphibole in a vitric groundmass composed of cuspate glass shards that are mostly fresh but are devitrified locally. Tuff intervals commonly include small fragments (~5 mm) of pumice, accidental volcanic clasts (up to ~1 m), and petrified wood. Thin intervals of planar, low-angle cross-bedded tuffaceous sand occur locally. This unit yielded a U-Pb zircon age of 48.6 ± 0.2 Ma (table 2, sample KM20BD32). As thick as 150 m (500 ft).

Tdwr **Dillon West Rhyolite (Tertiary: Eocene)**—Moderate to dark reddish brown, pale red to grayish red, and light gray to grayish blue weathering, aphanitic rhyolite (70.3 to 70.4 wt. percent SiO_2, table 1) with sparse (<5 percent) phenocrysts of biotite, hornblende, feldspar, and quartz. Individual flows can be vuggy, massive, or exhibit conspicuous flow foliation. Discontinuous intervals of vitrophere and autobreccia occur locally. Two samples yielded U-Pb zircon ages spanning 50.4 ± 0.7 Ma to 48.4 ± 0.9 Ma (table 2, samples KM20BD04 and KM20BD29).

Kf **Frontier Formation (Late Cretaceous)**—Dominantly gray, brown, brownish gray, and greenish gray siltstone and mudstone, and subordinate medium- to coarse-grained, and locally very coarse-grained sandstone, conglomerate, limestone, and minor porcellanite. The beds of mudstone, siltstone, limestone, and sandstone form fining-upward depositional cycles tens of meters thick. Sandstone and conglomerate are rich in quartz and chert. Conglomerate clasts are rounded pebbles and cobbles of chert and quartz, but locally contain limestone and mudstone cobbles. Volcaniclastic sandstone and bentonitic mudstone occur in the upper part. Lower 100–200 m (330–660 ft) is distinctive brown to brownish gray siltstone and mudstone. Top not exposed but thickness about 900 m (3,000 ft) north of the quadrangle (Tysdal and others, 1994; Dyman and Nichols, 1988).

Kblv **Blackleaf Formation, Vaughn Member (Early to Late Cretaceous)**— Olive green, yellowish green, bright green, and gray green, hard, dense, and calcareous siltstone and porcellanitic (silicified) mudstone. Subordinate gray, greenish gray and olive gray, fine- to medium-grained, and locally coarse-grained lithic sandstone, with common volcaniclastic debris, and matrix-supported conglomerate and conglomeratic sandstone with clasts mostly of chert and quartzite. An association of distinctive lithologies is present in the uppermost part, which consists of maroon mudstone and siltstone, gray freshwater limestone, or locally very calcareous mudstone and siltstone, dark gray shale, and bright green porcellanite. Upper contact is mapped at top of a porcellanite bed, interbedded with micritic limestone, that directly overlies the highest maroon mudstone (after Tysdal and others, 1994; Dyman and Tysdal, 1998). A porcellanite bed approximately 25 m (80 ft) below the top of the Vaughn in the Frying Pan Basin yielded a U-Pb age of 94.8 ± 0.5 Ma (Zartman and others, 1995). Top not exposed but at least 360 m (1,180 ft) thick in the quadrangle.

Kblf **Blackleaf Formation, Flood Member (Early Cretaceous)**—Upper part: pale brown to brownish gray, fine- to medium-grained and locally coarse-grained to conglomeratic, quartz- and chert-rich lithic sandstone, and conglomerate. Trough crossbedding common in sandstone. Middle part: dominantly gray mudstone, shale, and minor interbeds of siltstone and quartz-rich sandstone. Lower part: medium gray and locally green and red calcareous siltstone and mudstone, gray shale, and gray, calcareous, fine- to medium-grained sandstone that is rich in quartz and chert grains (Tysdal and others, 1994; Dyman and Nichols, 1988). Thickness 230 m (750 ft).

Kk **Kootenai Formation (Early Cretaceous)**—Mapped as one unit, but consists of four distinct members described below (after Myers, 1952). Combined thickness of all members is about 245 m (800 ft).
Gastropod limestone member: Light gray, thick-bedded, gastropod coquina or gastropod-rich limestone that may also contain charophytes and ostrocodes. Forms conspicuous ridges.
Upper clastic member: Variegated shale and mudstone, dominated by red, orange, and purple, and subordinate light and medium gray colors, interbedded with minor reddish quartz- and chert-rich lithic sandstone. Poorly exposed, recessive unit.
Middle limestone member: Pale yellowish gray to pale brown, dense limestone and shaly limestone with interbedded shale.
Lower clastic member: Upper part recessive, mostly reddish and greenish mudstone; lower part is ridge-forming, coarse- to medium-grained, cross-bedded to massive, brown to yellowish gray chert-rich lithic sandstone with local lenses of chert-rich conglomerate and limestone pebble conglomerate; interbedded with reddish and greenish mudstone.

Jm **Morrison Formation (Jurassic)**—Green, red, and gray variegated mudstone, shale, and siltstone with thin, interbedded yellowish brown to grayish orange, very fine-grained sandstone and siltstone and thin, gray limestone beds. Poorly exposed recessive interval. Thickness about 45–55 m (150–175 ft).

Ꞧd **Dinwoody Formation (Lower Triassic)**—Interbedded shale, limestone, and calcareous sandstone characterized by distinctive pale to light grayish brown weathered surfaces and the presence of phosphatic pelecypod *lingula*. Upper part has massive calcareous, rippled sandstone beds as much as 1 m (3 ft) thick with shaley interbeds. Massive, gray, pinkish gray weathering limestone as much as 1 m (3 ft) thick is major component in upper part. Lower part is predominantly olive drab, chippy-weathering, hard fissile shale with interbedded dark brown weathering, silty limestone beds 10 cm (4 in.) or thinner. Thickness about 245 m (800 ft).

Psp **Shedhorn and Phosphoria Formations, undivided (Permian)**—Shedhorn Formation: grayish brown, fine-grained, thin- to thick-bedded quartz sandstone, and cherty sandstone with chert and quartz cement. Vertical and horizontal burrows are relatively common. Phosphoria Formation: dark gray to black, carbonaceous and phosphatic mudstone with scarce phosphate beds, grayish and gray brown cherty quartz sandstone, cherty or sandy dolomite, fine-grained dolomitic sandstone, and yellowish tan sandy siltstone with subordinate beds of vitreous quartz sandstone. Thickness approximately 89 m (300 ft).

Ꝑq **Quadrant Formation (Pennsylvanian)**—Light gray to light yellowish brown, fine-grained, vitreous quartz sandstone. Poorly exposed and mapped on the basis of float along the north boundary of the map. Thickness approximately 245 m (800 ft) based on mapping in north-adjacent Glen 7.5′ quadrangle (Yakovlev, 2019).

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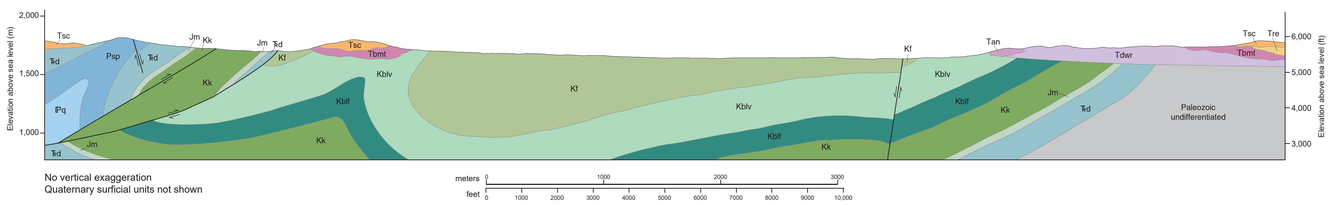
Cross Section A–A′



No vertical exaggeration
Quaternary surficial units not shown

meters 0 1000 2000 3000
feet 0 1000 2000 3000 4000 5000 6000 7000 8000 9000 10,000
SCALE: 1:24,000

Location Map

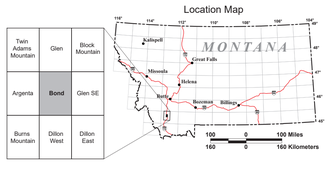


TABLE 1. Whole-rock chemistry

Sample ID	KM20BD04	KM20BD22	KM20BD29
Map unit	Tdwr	Tan	Tdwr
Latitude (°N)	45.3438	45.2677	45.3456
Longitude (°W)	-112.7278	-112.7387	-112.6363
Major elements (wt %)			
SiO_2	70.42	58.16	70.28
TiO_2	0.32	1.30	0.33
Al_2O_3	14.55	15.76	14.97
FeO*	1.97	5.82	2.11
MnO	0.01	0.09	0.05
MgO	0.23	4.20	0.40
CaO	1.42	5.95	1.87
Na_2O	3.94	3.49	4.05
K_2O	4.18	2.62	4.20
P_2O_5	0.32	0.35	0.10
Sum	97.37	97.74	98.36
LOI	2.06	1.85	1.22
Trace elements (ppm)			
Ni+	7.7	65.1	8.0
Cr+	14.9	153.4	14.0
V+	26.3	116.5	26.3
Ga+	20.7	20.1	20.2
Cu+	6.0	23.9	8.1
Zn+	51.2	103.5	43.3
La	57.6	62.2	61.7
Ce	81.9	111.4	99.1
Pr	8.6	12.6	9.8
Nd	26.9	45.6	31.1
Sm	3.5	7.7	4.3
Eu	0.9	2.0	0.9
Gd	2.0	5.9	2.7
Tb	0.3	0.8	0.4
Dy	1.3	4.1	1.9
Ho	0.2	0.8	0.3
Er	0.6	1.9	0.9
Tm	0.1	0.3	0.1
Yb	0.5	1.7	0.8
Lu	0.1	0.3	0.1
Ba	1754.9	1747.2	1848.9
Th	25.7	12.9	22.1
Nb	15.5	23.0	12.8
Y	5.8	21.4	10.1
Hf	5.8	7.3	5.5
Ta	1.0	1.2	0.8
U	2.1	2.1	2.7
Pb	28.4	12.0	32.6
Rb	135.1	69.4	123.8
Cs	1.4	0.9	1.2
Sr	339.5	615.4	353.4
Sc	2.8	14.2	2.9
Zr	224.9	302.3	210.2

Note: All major elements and trace elements denoted by + were analyzed by XRF, all other trace elements were measured by ICP-MS. FeO* indicates all Fe expressed as Fe^{2+}.
LOI is loss on ignition.
All samples were prepared and analyzed by X-ray fluorescence (XRF) and inductively coupled plasma mass spectrometry (ICP-MS) at the Washington State University GeoAnalytical Lab. Datum used for sample coordinates is World Geodetic Survey 1984 (WGS84).

Table 2. U-Pb zircon geochronology.

Sample	Lithology	Unit	Latitude (°N)	Longitude (°W)	# of spot analyses	Age (Ma)	2σ	MSWD
KM20BD01	Rhyolite tuff	Tbmt	45.3061	-112.7321	39	46.3	0.2	1.2
KM20BD04	Rhyolite	Tdwr	45.3438	-112.7278	38	50.4	0.7	0.3
KM20BD09	Rhyolite tuff	Tbmt	45.2924	-112.7247	39	46.9	0.2	0.8
KM20BD13	Welded tuff	Tbmt	45.2820	-112.7163	40	46.6	0.2	0.6
KM20BD16	Ash	Tre	45.2870	-112.6891	30	31.8	0.2	1.0
KM20BD29	Rhyolite	Tdwr	45.3456	-112.6363	33	48.4	0.9	2.7
KM20BD30*	Sediment	Tsc	45.2967	-112.7106	198	15.5	0.1	0.8
KM20BD32	Rhyolite tuff	Thgt	45.2820	-112.7189	40	48.6	0.2	1.2

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

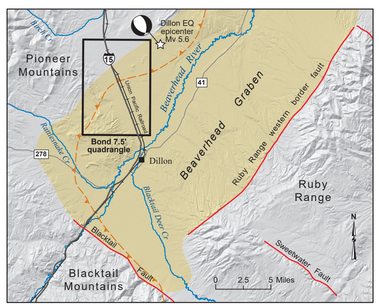


Figure 1. Location map of the Bond area. Tectonic features shown are the Beaverhead Graben (yellow shaded area), the leading edge of the fold-thrust belt (orange line with triangles), and identified Quaternary faults (red lines). Quaternary faults from the U.S. Geological Survey and MBMG fault and fold database (accessed 5/17/2021).

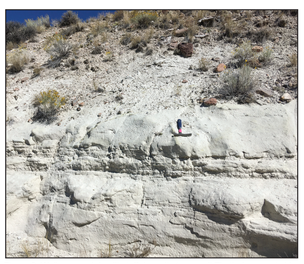


Figure 2. Well-exposed rhyolite tuff deposits (map unit Thgt) along east side of Frying Pan Basin. Hammer near center of photo for scale.

Figure 3. Photo of tufa beds within the Renova Formation that may be related to fluid flow associated with nearby faults. Photo looking NE near mouth of Frying Pan Gulch (sec. 27, T. 6 S., R. 9 W.).

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Montana Bureau of Mines and Geology

Geologic Map 90

Geologic Map of the Bond 7.5′ Quadrangle, Beaverhead County, Montana

Catherine McDonald

2022

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