GEOLOGIC MAP OF THE STILLWATER COMPLEX WITHIN THE BEARTOOTH MOUNTAINS FRONT LARAMIDE TRIANGLE ZONE SOUTH-CENTRAL MONTANA

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PURPOSE

The purpose of the geologic map is to:

(1) publically present on a topographic base the Johns-Manville stratigraphic nomenclature (Todd and others, 1982) for the entire Stillwater mafic to ultramafic layered igneous intrusive;

(2) present results and structural interpretations from detailed (1:12,000 and 1:6,000) outcrop mapping by the author (2005 to 2012) along the Stillwater Complex portion of the Beartooth Mountains front that stresses the importance of triangle-zone features (Jones, 1996) (forethrusts, backthrusts, lateral ramps) in a Laramide, basement-involved terrain (Sterne, 2006); and

(3) extend these triangle-zone interpretations along the front and outside of areas mapped by the author to provide just one possible structural interpretation, stressing the importance of Laramide thrusting and ramping, of rock-unit map patterns presented previously by a number of geologists in both the crystalline rocks and sedimentary strata.

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DESCRIPTION OF MAP UNITS

CENOZOIC DEPOSITS

Qal **Alluvium (Holocene)**—Gravel, sand, silt, and clay in channels of modern rivers and streams. Clasts generally subrounded to well rounded, resistant rocks. Thickness is generally less than 10 m (33 ft).

Qc **Colluvium (Holocene and Pleistocene?)**—Unconsolidated, locally derived slope deposit that contains angular, poorly size-sorted clasts, generally with clasts that are pebble size and larger. Thickness is generally less than 10 m (33 ft).

Qta **Talus deposit (Holocene and Pleistocene)**—Unconsolidated, very locally derived apron-like deposits with angular clasts on and below relatively steep slopes. Includes some rock-slide deposits. Thickness is variable, generally less than 10 m (33 ft).

Qls **Landslide deposit (Holocene and Pleistocene)**—Mass-wasting deposit that consists of stable to unstable, unsorted mixtures of clay- to boulder-size sediment. Includes rotated or slumped blocks of bedrock and surficial sediment, earthflow deposits, and mudflow deposits. Color and lithology reflect that of parent rocks and transported surficial materials. Thickness is variable, probably less than 30 m (100 ft).

Qg **Glacial deposits, undivided (Holocene and Pleistocene)**—Unsorted and unstratified deposits of locally derived silt, sand, pebbles, cobbles, and boulders of Pleistocene glacial moraines and other associated glacial and glaciofluvial deposits. May also include Holocene glacial deposits, rock glacier deposits, and subordinate alluvium, colluvium, talus, landslide deposits, and boulder fields.

MESOZOIC AND PALEOZOIC ROCKS—

Unit descriptions modified from Berg and others (1999), Berg and others (2000), Lopez (2000), and Lopez (2001) for the geologic maps of the Gardiner, Livingston, Big Timber, and Red Lodge 30′ x 60′ quadrangles, respectively; and Vhay (1934), Vail (1955), Garbarini (1957), and Richards (1957).

Kdi **Diorite and diorite porphyry (Upper Cretaceous)—**Dark gray to medium gray, fine-grained diorite and diorite porphyry, phenocrysts of plagioclase, hornblende, pyroxene, and locally biotite. Unit occurs as stocks north of the Beartooth Mountains front. It also occurs as small plugs, dikes, and sills of diorite, diorite porphyry, and andesite porphyry. Some of the sills intrude Stillwater Complex layers. Xenoliths of Stillwater Complex rocks occur in the Lodgepole, Enos Mountain, and Susie Peak stocks (Brozdowski, 1983, 1985) and in the Iron Mountain (Sliderock Mountain) stock (Lopez, 2000). Radiometric age is 75-78 Ma for Iron Mountain and Lodgepole stocks based on $^{40}Ar/^{39}Ar$ data (du Bray and Harlan, 1998).

Klsr **Sliderock Mountain formation of Livingston Group (Upper Cretaceous)—**Unit includes all volcanic rocks erupted from the Sliderock Mountain stratovolcano (du Bray and others, 1994). Mostly andesite breccia (lahars), gray, pale purple gray, pale greenish gray. Andesite in clasts is porphyritic with phenocrysts of chalky plagioclase, hornblende, and

pyroxene; matrix is similar but lighter in color and slightly finer grained. Very resistant, forming cliffs and very rugged topography near the vent zone in Sliderock Mountain area. In distal areas,such as near the town of Fishtail, unit contains interbeds of andesitic conglomerate and coarse-grained sandstone, and the clasts are less angular. Locally the unit contains minor flows of porphyritic andesite and basaltic andesite, with phenocrysts of plagioclase, hornblende and pyroxene. Thickness is at least 300 m (1,000 ft) (du Bray and others, 1994).

Kjre **Judith River through Eagle Formations, undivided (Upper Cretaceous)**

Kjr **Judith River Formation (Upper Cretaceous)—**Interbedded brownish gray sandy shale and light brown to pale yellowish brown, argillaceous, very fine- to fine-grained lenticular sandstone in beds as much as 3 m (10 ft) thick. A basal, massive cliff-forming sandstone is commonly referred to as the Parkman Sandstone and resembles sandstone in the Eagle Sandstone. Sandstones are friable to moderately well indurated, crossbedded, burrowed to bioturbated, and support growths of pine trees. Greenish gray and pale maroon gray mudstone, poor quality coal, and easily eroded sandstone occur near the top of the formation. Thickness is 215-305 m (700-1,000 ft).

Kcl **Claggett Shale (Upper Cretaceous)—**Brownish gray, fissile shale with minor interbeds of light brownish gray, very argillaceous sandstone. Light brownish gray to light brown, calcareous concretions common; commonly fossiliferous. The upper contact is gradational, conformable, and is placed at the change to ledge-forming sandstone of Judith River Formation. Thickness is 30-90 m (100-300 ft), decreasing westward.

Ke **Eagle Sandstone (Upper Cretaceous**)—Light brownish gray to pale orange, very fine to fine-grained, crossbedded sandstone; burrowed to bioturbated in part. Locally contains calcareous, light brown sandstone concretions as much as 5 m (15 ft) in diameter. Usually two or more sandstone intervals with interbedded shale. Contains at least one coal bed north of Nye. Thickness is about 45 m (150 ft).

Ktcn **Telegraph Creek and Niobrara Formations, undivided (Upper Cretaceous**)

Ktco **Telegraph Creek and Cody Formations, undivided (Upper Cretaceous)**

Ktc **Telegraph Creek Formation (Upper Cretaceous**)—Shale and sandy shale, brownish gray to medium dark gray with thin, interbedded sandstone. Dusky red concretions common near base. Sandstone beds thicker and more abundant upward, grading into Eagle Sandstone. Maximum thickness is about 45-76 m (150-250 ft).

Kn **Niobrara Formation (Upper Cretaceous**)—Shale, olive gray and dark brownish gray, fissile, that contains abundant thin bentonite beds. Upper half calcareous, containing a few very thin bentonite beds, and near top contains thin beds of very calcareous laminated sandstone, siltstone, and sandy limestone. Concretions medium light gray to pale yellowish brown and from 5 cm (2 in) to less than 0.5 m (1-2 ft) in diameter are commonly present. *Inoceramus* prisms common. Upper contact placed at change from

calcareous shale to non-calcareous shale of Telegraph Creek. Zone of dusky red concretions in the Telegraph Creek just above the contact also helps establish its position. Estimated thickness is about 400 m (1,300 ft).

Kco **Cody Shale (Upper Cretaceous)**—Gray shale and mudstone interbedded with grayish green and olive gray sandstone and siltstone and minor brown-weathering nodular limestone and yellowish gray bentonite. Entire formation is locally fossiliferous and contains fish scales, starfish, ammonites and other mollusks. Thickness is about 370-400 m (1,200-1,300 ft).

Knbf **Niobrara through Belle Fourche Formations, undivided (Upper Cretaceous)**

Kf **Frontier Formation (Upper Cretaceous)—**Light brownish gray, fine-grained, thick-bedded to massive, "salt and pepper" sandstone. Contains three sandstone intervals interbedded with dark gray, fissile shale. The Frontier Formation is missing in the eastern part of the map area. Thickness is up to 190 m (630 ft).

Kmfr **Mowry through Fall River Formations, undivided (Upper Cretaceous)**

Km **Mowry Shale (Upper Cretaceous)—**Interbedded, siliceous, very fine to fine-grained sandstone, siltstone, and shale. Contains several prominent bentonite beds. Sandstones and siltstones mostly light gray to medium gray, with a silvery sheen. Fish scales on bedding planes of sandstones and siltstones are characteristic. Thickness is about 90 m (300 ft).

Ktf **Thermopolis and Fall River Formations, undivided (Upper Cretaceous)—**

Thermopolis Shale: Predominantly dark gray, fissile shale containing several beds of bentonite. Hematitic concretionary zone near base.

Fall River Sandstone: Brownish gray, thin-bedded, argillaceous, fine-grained, quartz sandstone. Generally poorly exposed in map area; mostly covered by glacial deposits.

Thickness of both formations combined is about 200-305 m (650-1,000 ft).

Kk **Kootenai Formation (Lower Cretaceous)—**Mostly reddish brown, olive gray, and dusky purple mudstone with interbedded, lenticular, fine- to coarse-grained sandstone. Locally thick, lenticular, fine-grained fluvial sandstone at top. At the base is the distinctive Pryor Conglomerate Member, a brown chert-pebble conglomerate and pebbly coarse-grained sandstone 6-18 m (20-60 ft) thick that is an excellent mapping marker unit. Thickness is about 90-150 m (300-500 ft).

Jme **Morrison Formation and Ellis Group, undivided (Upper and Middle Jurassic)**

Jm **Morrison Formation (Upper Jurassic)**—Variegated, mainly greenish gray and pale reddish brown mudstone. Very fine to fine-grained, quartzose, calcareous, crossbedded, tan sandstones is commonly present at about mid-section, 1.5-3 m (5-10 ft) thick, but locally can be as much as 9 m (30 ft) thick. Fossil dinosaur remains locally present. Thickness is about 60-120 m (200-400 ft).

Je **Ellis Group (Upper and Middle Jurassic)—**Includes the Swift, Rierdon, and Piper Formations.

Jsw **Swift Formation (Upper and Middle Jurassic)—**Interbedded medium gray shale, limestone, and calcareous sandstone; fossiliferous. Brownish gray, fossiliferous, very sandy limestone occurs at the top of the formation, and commonly has brownish gray coquina at the top. The Swift Formation is a reliable marker mapping unit that forms mini-palisades where bedding is vertical. Thickness is 30 m (100 ft).

Jrp **Rierdon and Piper Formations, undivided (Middle Jurassic)**

Jr **Rierdon Formation (Middle Jurassic)**—Mostly pale greenish gray, very fossiliferous shale with minor, interbedded, brownish gray limestone. Typically poorly exposed, forming smooth slopes littered with fossils, including oysters (*Gryphaea and Ostrea),* belemnites (*Pachyteuthis),* and crinoid fragments (*Pentacrinus).* Thickness is 30 to 50 m (90-160 ft).

Jp **Piper Formation (Middle and Upper Jurassic)**—Interbedded medium gray, and pale reddish gray, thin-bedded limestone and medium gray shale. Includes thin, interbedded gypsum. Forms ledge below smooth slopes of the Rierdon Formation. Outcrops of Rierdon and Piper Formations are rare, and the contact between these units is dashed and placed using average total formational thickness between the Swift and Chugwater Formation marker units. Thickness is 70-105 m (240-350 ft).

Trc **Chugwater Formation (Lower Triassic)**—Interbedded, bright reddish brown, fine-grained sandstone, siltstone, and mudstone. In spite of not forming many outcrops, the Chugwater is a reliable marker mapping unit because of its bright red color in soils. Maximum thickness is about 75 m (250 ft), thinning westward and pinching out in the Picket Pin Mountain and Enos Mountain 7.5' quadrangles. Stillwater Mining Company drill hole #36172, collared near the inactive Benbow chrome mill site, intersected 76 m true thickness (249 feet) of Chugwater.

PPpq **Phosphoria and Quadrant Formations, undivided (Permian and Pennsylvanian)**

PPMpa **Phosphoria, Quadrant, and Amsden Formations, undivided (Permian, Pennsylvanian, and Mississippian)**

Phosphoria Formation (Permian)—Poorly exposed yellowish gray shale, light gray limestone, sandstone, and quartzite, commonly grayish pink, cherty; thickness is 0-25 m (0-85 ft). Stillwater Mining Company drill hole #36172, collared near the inactive Benbow chrome mill site, intersected 17 m true thickness (56 feet) of Phosphoria.

IPq **Quadrant Formation (Pennsylvanian)**—Quartzite, white, buff, light yellowish, to reddish gray, well-sorted, fine-grained sandstone, locally crossbedded. Thickness is 30 m (100 ft).

IPt **Tensleep Sandstone (Pennsylvanian)**—Light brown to very pale orange sandstone, fine-grained, well sorted, well rounded, crossbedded. Locally contains thin limestone beds, locally cherty near the top, and locally silicified to form quartzite. Thickness is about 45-75 m (150-250 ft). Stillwater Mining Company drill hole #36172, collared near the inactive Benbow chrome mill site, intersected 30 m true thickness (100 feet) of Tensleep.

IPMa **Amsden Formation (Pennsylvanian and Mississippian)**—Interbedded dolomite and siltstone in upper part; yellowish tan dolomite and red and green shale in lower part; mostly concealed. Unconformably overlies karst surface developed on limestone of the Madison Group. Thickness is about 25-60 m (80-200 ft). Stillwater Mining Company drill hole #36172, collared near the inactive Benbow chrome mill site, intersected 59 m true thickness (193 feet) of Amsden.

Mm **Madison Group, undivided (Mississippian)**—Limestone and dolomitic limestone, light gray to light brownish gray. Madison Group is a prominent marker mapping horizon. Thick-bedded to massive in the upper part, the upper Mission Canyon Limestone forms prominent palisades along the mountain front. The lower Lodgepole Limestone, is thin- to thick-bedded and also contains thin, interbedded gray shale. Fossils are present throughout the group. Chert beds are most prominent in the lower part of the Lodgepole Limestone, where the rock may be a dolostone locally. A 1 m-thick (3 ft) black shale occurs at the base of the Lodgepole Limestone in the access tunnels to East Boulder palladium/platinum mine and locally on surface. This black shale is either the Little Chief Mountain Member of the Lodgepole or the upper shale unit of the Bakken Shale. Stillwater Mining Company drill hole #36172, collared near the inactive Benbow chrome mill site, intersected 4 m true thickness (14 feet) of Bakken Shale (upper shale, sandstone, lower shale) at the base of the Madison Group. Thickness of the Madison Group is about 260-305 m (860-1,100 ft). Stillwater Mining Company drill hole #36172, intersected 280 m true thickness (915 feet true) of Madison Group, about 180 m (595 feet) of Mission Canyon Limestone, and 100 m (319 feet) of Lodgepole Limestone.

MDtj **Three Forks and Jefferson Formations, undivided (Mississippian and Late Devonian)**

MDt **Three Forks Formation (Mississippian and Late Devonian)**—Yellowish-weathering, light gray, pyritiferous, argillaceous dolomite that is very poorly exposed. Thickness is 12-38 m (40-125 ft). Stillwater Mining Company drill hole #36172, collared near the inactive Benbow chrome mill site, intersected 38 m true thickness (126 feet) of Three Forks. Stillwater Mining Company drill hole #98-0001, drilled at East Boulder mine as a geotechnical hole for Tunnel #1, intersected 35 m (115 feet true thickness) of Three Forks.

Dj **Jefferson Limestone (Late Devonian)**—Dominantly limestone, some dolostone, light brownish gray, poorly exposed; typically occurs as float. Much of the Jefferson Limestone exhibits a strong petroleum smell on freshly broken surfaces. Thickness is 75-120 m (240-390 ft). Stillwater Mining Company drill hole #36172, collared near the inactive Benbow chrome mill site, intersected 100 m true thickness (324 feet) of Jefferson. Stillwater Mining Company drill hole #98-0001, drilled at East Boulder mine as a geotechnical hole for Tunnel #1, intersected 75 m true thickness (252 feet) of Jefferson.

Ob **Bighorn Dolomite (Middle Ordovician)**—The upper unit, the Leigh Member, is a distinctively chalky white, fine-grained, thin-bedded dolomite, about 20 m (65 ft) thick. The lower unit is a coarse-grained, poorly bedded, massive dolomite that forms palisades

and exhibits a distinctive pitted weathered surface. Both units are reliable marker mapping horizons. Total formation thickness is 60 m (200 ft). Stillwater Mining Company drill hole #36172, collared near the inactive Benbow chrome mill site, intersected 70 m true thickness (222 feet) of Bighorn, including 11 m (36 feet) of Leigh. Stillwater Mining Company drill hole #98-0001, drilled at East Boulder mine as a geotechnical hole for Tunnel # 1, intersected 70 m true thickness (232 feet) of Bighorn, including 17 m (48 feet) of Leigh.

Cs **Sedimentary rock, undivided (Upper and Middle Cambrian)—**Includes Snowy Range, Pilgrim, Park, Meagher, Wolsey, and Flathead Formations.

Csr **Snowy Range Formation (Upper Cambrian)—**Green shale and gray limestone that is dominantly a flat-pebble conglomerate; bed of columnar fractured limestone locally present in lower part of Snowy Range Formation; mostly concealed. Formation is subdivided into 3 members that were readily mapped in the access tunnels at East Boulder mine and in drill hole #98-0001. From top to bottom these are: 1) Grove Creek Member – light-gray limestone-pebble conglomerate with distinctively round pebbles. Thickness is 12 m (40 feet); 2) Sage-Pebble Conglomerate – interbedded, gray limestone-pebble conglomerate (flat pebbles) and greenish-gray shale. Thickness is 45 m (140 feet); 3) Dry Creek Shale – green to maroon shale. Thickness is 15 m (50 feet). Total thickness of Snowy Range Formation is 70 to 90 m (230 to 300 feet). Stillwater Mining Company drill hole #36172, collared near the inactive Benbow chrome mill site, intersected 70 m true thickness (238 feet) of Snowy Range, including 11 m (37 feet) of Grove Creek; 48 m (159 feet) of Sage Pebble; and 13 m (42 feet) of Dry Creek. Stillwater Mining Company drill hole #98-0001, drilled at East Boulder mine as a geotechnical hole for Tunnel #1, intersected 70 m true thickness (230 feet) of Snowy Range, including 12 m (40 feet) of Grove Creek; 43 m (140 feet) of Sage Pebble; and 15 m (50 feet) of Dry Creek.

Cpi **Pilgrim Limestone (Upper Cambrian)**—Massive, cliff-forming oölitic, mottled, magnesian and dolomitic limestone with edgewise intraformational limestone-pebble conglomerate, interbedded shale and siltstone, and glauconitic limestone. Thickness is about 40 m (140 feet). Stillwater Mining Company drill hole #36172, collared near the inactive Benbow chrome mill site, intersected 35 m true thickness (119 feet) of Pilgrim. Stillwater Mining Company drill hole #98-0001, drilled at East Boulder mine as a geotechnical hole for Tunnel #1, intersected 45 m true thickness (152 feet) of Pilgrim.

Cpw **Park, Meagher, and Wolsey Formations, undivided (Upper and Middle Cambrian)**

Cpf **Park, Meagher, Wolsey, and Flathead Formations, undivided (Upper and Middle Cambrian)**

Cp **Park Shale (Upper Cambrian)**—Multicolored shale with thin beds of argillaceous limestone, siltstone, and sandstone; mostly concealed. Thickness 45–115 m (150–380 feet). Stillwater Mining Company drill hole #36172, collared near the inactive Benbow chrome mill site, intersected 35 m true thickness (254 feet) of Park.

Cmw **Meagher and Wolsey Formations, undivided (Middle Cambrian)**

Cmf **Meagher, Wolsey, and Flathead Formations, undivided (Middle Cambrian)**

Cm **Meagher Limestone (Middle Cambrian)**—Thin-bedded, silty, medium gray limestone and yellowish gray dolomite; locally oölitic. Thickness 20 m (65 feet). Stillwater Mining Company drill hole #36172, collared near the inactive Benbow chrome mill site, intersected 40 m (140 feet true thickness) of Meagher.

Cwf **Wolsey and Flathead Formations, undivided (Middle Cambrian)**

Cw **Wolsey Shale (Middle Cambrian)**—Greenish gray, micaceous, calcareous shale, mudstone, and siltstone with thin beds of limestone; mostly concealed. Thickness 30 m (100 feet). Stillwater Mining Company drill hole #36172, collared near the inactive Benbow chrome mill site, intersected 40 m (130 feet true thickness) of Wolsey.

Cf **Flathead Quartzite (Middle Cambrian)**—Gray to red quartzose sandstone and quartzite; locally conglomeratic in lower part. Thickness 0-23 m (0-75 feet).

STILLWATER LAYERED COMPLEX—The Stillwater Complex, a layered ultramafic to mafic suite of intrusive rocks, can be subdivided into three main Series, from top to bottom: 1) Banded (Layered) Series, 2) Ultramafic Series, and 3) Basal Series (Todd and others, 1982). Each Series is associated with a dominant metal zone or zones: 1) Banded – Palladium and Platinum (J-M Reef, Picket Pin zone); 2) Ultramafic – Chrome (13 horizons); and 3) Basal – Nickel and Copper deposits. The subdivision of the Complex presented below is based on the Johns-Manville model of Todd and others (1982).

Rock names are based on modal proportions of cumulate minerals.

Anorthosite – >95% plagioclase feldspar
Norite – plagioclase feldspar and orthopyroxene
Gabbbro – plagioclase feldspar and clinopyroxene
Gabbronorite – plagioclase feldspar, clinopyroxene, and orthopyroxene
Troctolite – plagioclase feldspar and olivine
Bronzitite – Orthopyroxene
Harzburgite – Orthopyroxene and olivine;
Dunite – Olivine.

Banded (Layered) Series

Aaz7 **Anorthosite Zone 7 (Archean)**—Strictly anorthosite; observed in the subsurface only in the access tunnels for the East Boulder mine (Sam Corson, 1999, written communication). Thickness of Aaz7 is > 75 m (240 feet).

Apgz6 **Pigeonite Gabbro Zone 6 (Archean)**—Topmost zone of the Stillwater Complex on surface. Gabbro dominant with cumulus pigeonite (McCallum and others, 1980; Todd and others, 1982). Modal composition: 59% plagioclase feldspar (bytownite to labradorite, An_{75} to An_{62}), 21% clinopyroxene (augite), 7% orthopyroxene (bronzite to hypersthene, En_{75} to

En_{67}), 14% pigeonite (McCallum and others, 1980; Radeke, 1982). Thickness is about 585 m (1,920 feet) in the East Boulder mine access tunnels #1 and 2.

Agz6 **Gabbro Zone 6 (Archean)**—Strictly gabbronorite, thickness is about 375 m (1,225 feet). Thickness in the East Boulder mine access tunnels is 340 m (1,120 feet) .

Atgz5 **Troctolite-Gabbro Zone 5 (Archean)—**Troctolite at base, gabbronorite at top; the basal troctolite is a distinctive, reliable stratigraphic and structural mapping marker horizon (Segerstrom and Carlson, 1982). Thickness is about 115 m (385 feet). Thickness is about 120 m (400 feet) in the East Boulder mine access Tunnel #1.

Aaz5 **Anorthosite Zone 5 (Archean)**—Strictly anorthosite; host to the Picket-Pin platinum-palladium mineralized zone near the top of unit. The Picket Pin sulfide zone can be traced for about 22 km (14 miles). Rock is 100% plagioclase feldspar (bytownite, An_{73-79}) (McCallum, 1996, p. 462) based on modal % of cumulus minerals. Thickness varies from 200 m (650 feet) to 600 m (1,970 feet) (McCallum, 1996). Thickness is about 350 m (1,140 feet) in the East Boulder mine access Tunnel #1.

Atgz4 **Troctolite-Gabbro Zone 4 (Archean)**—Succession of three olivine-bearing gabbros separated by anorthosite layers with gabbronorite at the top of unit. Locally unit has rare layers of the distinctive “4-phase cumulate”, a rock with cumulus plagioclase feldspar, orthopyroxene, clinopyroxene, and olivine (McCallum, 1996, p. 463). Thickness is about 200 m (660 feet) (Todd and others, 1982). Thickness is about 110 m (360 feet) in the East Boulder mine access Tunnel #1.

Aatz4 **Anorthosite-Troctolite Zone 4 (Archean)**—Anorthosite at base (about 75 m (250 feet) thick), leucotroctolite to troctolite at top. Thickness is about 225 m (740 feet) (Todd and others, 1982). Thickness is about 200 m (670 feet) in the East Boulder mine access Tunnel #1.

Atgz3 **Troctolite-Gabbro Zone 3 (Archean)**—Laminated olivine gabbronorite in the upper 115 m (385 feet) of this zone; olivine gabbro in the middle part; leucotroctolite dominant at base. The upper olivine gabbronorite is a unique and reliable stratigraphic and structural marker unit referred to as the “4-phase cumulate” (cumulus plagioclase feldspar, orthopyroxene, clinopyroxene, and olivine in one rock unit). This is the only occurrence in the Stillwater Complex stratigraphic column where these 4 cumulate minerals are observed together in a mappable unit. Thickness of Atgz3 is about 400 m (1,300 feet) (Todd and others, 1982). Thickness is about 365 m (1,200 feet) in the East Boulder mine access Tunnel #1.

Aaz3 **Anorthosite Zone 3 (Archean)**—Strictly anorthosite, 100% plagioclase feldspar (average composition bytownite, An_{77} (McCallum, 1996, p. 462) based on modal % of cumulus minerals. Thickness is about 320 m (1,050 feet) (Todd and others, 1982). Thickness is about 300 m (1,000 feet) in the East Boulder mine access Tunnel #1.

Ataz2 **Troctolite-Anorthosite Zone 2 (Archean)**—A thin zone, average thickness is 50 m (160 feet) (Todd and others, 1982). Not everywhere observed. Thickness of Ataz2 is about 35 m (110 feet) in the East Boulder mine access tunnel #1.

Agz2 **Gabbro Zone 2 (Archean)**—The thickest zone in the Banded Series. Dominantly a laminated gabbronorite (modal composition: 59% plagioclase feldspar, 21% augite, 20% orthopyroxene (McCallum and others, 1980). It is host to a number of anorthosite subzones, some of which are distinctive, reliable mapping horizons. The 2400 plagioclase cumulate (pC) is 8 to 15 m (25 to 50 feet) thick. "2400" is based on this anorthosite's location 2,400 feet (730 m) above the Aubz/Anz1 contact, considered to be the "zero" mark point in Stillwater Complex stratigraphy. The 2400 plagioclase cumulate is located about 15 m (50 feet) above the base of Gabbro Zone 2 (Agz2) and can be traced on surface for 30 km (19 miles). A distinctive zone of "inch-scale" layering near the top of Gabbro Zone 2 can be traced on surface for about 16 km (10 miles) (Segerstrom and Carlson, 1982). Thickness of Agz2 is about 760 m (2,500 feet), thinning to about 300 m (1,000 feet) at the west end of the Complex. Thickness is about 580 m (1,900 feet) in the East Boulder mine access Tunnel #1. Radiometric age is 2707 Ma based on U-Pb data from zircon-baddeleyite from the 2400 pC (Premo and others, 1990).

Aa_3sz **Anorthosite 3 Subzone of Gabbro Zone 2 (Archean)**—The thickest of the mappable subzones within Gabbro Zone 2, this subzone, dominated by anorthosite, and containing interlayered troctolite, leucotroctolite, norite and gabbro, is located in the middle of Agz2 and can be mapped on surface for about 37 km (23 miles). Johns-Manville geologists referred to this mappable unit as the mid-Gabbro Zone 2 layered sequence. Thickness is about 30 m (100 feet) in the East Boulder mine access Tunnel #1.

Anz2 **Norite Zone 2 (Archean)**—Dominantly norite and leuconorite, the basal contact of this unit with underlying Ataz1 is marked by an up to 2 m (6 feet) zone of inch-scale layering. Thickness of Anz2 is about 235 m (765 feet) (Todd and others, 1982). Thickness is about 200 m (650 feet) in the East Boulder mine access Tunnel #1.

Ataz1 **Troctolite-Anorthosite Zone 1 (Archean)**—Zone hosts the J-M Reef palladium-platinum deposit. The J-M Reef can be traced on surface for about 45 km (28 miles). Johns-Manville geologists further subdivided Ataz1 into 4 subzones: at the base, 1) Gabbro Subzone – interlayered gabbronorite, norite, anorthosite, and troctolite, about 60 m (200 feet) thick; 2) Anorthosite 1 Subzone (host to the J-M Reef) – dominantly anorthosite, troctolite, and leucotroctolite, about 35 m (115 feet) thick; 3) Norite Subzone – often referred to as the ragged-textured norite, about 10 m (33 feet) thick; and 4) Anorthosite 2 Subzone – dominantly anorthosite and leuconorite, about 15 m (50 feet) thick. Total thickness of Ataz1 typically is about 100 to 120 m (350 to 400 feet) (Todd and others, 1982; LeRoy, 1985). Thickness is about 145 m (475 feet) in the East Boulder mine access Tunnel #1. Radiometric age is 2701 Ma to 2704 Ma based on U-Pb data from zircon-baddeleyite (Premo and others, 1990).

Agz1 **Gabbro Zone 1 (Archean)**—Gabbronorite dominant. Modal composition: 58% plagioclase feldspar (bytownite An_{78-83}), 24% orthopyroxene (bronzite En_{75-83}), 18% clinopyroxene

(augite) (McCallum and others, 1980; McCallum, 1996). Thickness of Agz1 is typically about 125 m (415 feet) but pinches out at two locations (Todd and others, 1982) Thickness is about 55 m (185 feet) in the East Boulder mine access Tunnel #1.

Anz1 **Norite Zone 1 (Archean)**—Norite and leuconorite. A mappable anorthosite marker layer, the All-American Anorthosite, is 3 m (10 feet) thick (Todd and others, 1982, p. 1462) and occurs in the middle of Anz1. Thickness is about 265 m (865 feet) (Todd and others, 1982).

Ultramafic Series

Aubz **Upper Bronzitite Zone (Archean)—**A thick zone of bronzitite (En_{85}) (McCallum, 1996), the thickness of Aubz is about 600 m (2,000 feet) on average, but thins to 335 m (1,100 feet) at the west end of the Complex east of the main Boulder River. The maximum thickness is 1,065 m (3,500 feet) (Page and Nockleberg, 1974). The contact between Aubz (top of the Ultramafic Series) and Anz1 (base of the Banded Series), a readily recognizable marker, is considered a zero point for measuring to other marker horizons (for example, the 2400 plagioclase cumulate of Agz2).

Apz **Peridotite Zone (Archean)—**Interlayered dunite, harzburgite, and bronzitite; host to 13 chromite horizons (designated A through K plus G′ and H′), two of which have been historically mined. One of the mined zones, G, has a surface trace of 29 km (18 miles). Representative average cumulus modal compositions (Cooper, 1997) are: 1) Dunite – 97% olivine, 3% chromite; 2) Harzburgite – 26 to 73% olivine, 25 to 73% orthopyroxene; 1 to 2% chromite; 3) Orthopyroxenite – 98% bronzite, 1% olivine, 1% chromite. Representative mineral compositions at Chrome Mountain are: olivine – $Fo_{80\text{-}84}$, chrysolite; orthopyroxene – $En_{83\text{-}85}$, bronzite (McCallum, 1996). Average thickness of Apz is 915 to 1,065 m (3,000 to 3,500 feet), thinning to 400 m (1,300 feet) east of the main Boulder River.

Basal Series

Abbz **Basal Bronzitite Cumulate Zone (Archean)**—This unit is the lowermost cumulate layer in the Stillwater Complex. Thickness ranges from 30 to 200 m (100 to 700 feet) (Page and Nockleberg, 1974), averaging around 120 m (400 feet).

Asd **Sill-dike member** (Zientek, 1983) **(Archean)—**Discontinuous sills and dikes of diabase, mafic norite, gabbronorite and massive sulfides that intruded metasedimentary rocks at the base of the Stillwater Complex. The sill-dike member and closely adjacent hornfels host the nickel-copper deposits. Thickness of this member is 0 to 120 m (0 to 400 feet). Radiometric age is 2703 to 2713 Ma based on U-Pb data from zircon-baddeleyite, Pb-Pb internal isochron, and Sm-Nd internal isochron (Premo and others, 1990).

BEARTOOTH FRONT METAMORPHIC AND IGNEOUS ROCKS—Unit descriptions are from Butler (1966), Page and others (1973a, 1973b), Page and Nockleberg (1974), Reid and others (1975), McCallum and others (1980), Segerstrom and Carlson (1982), Todd and others (1982),

Zientek (1983), Mogk and others (1988), McCallum (1996), and Cooper (1997). In some instances they are modified.

p€m **Mafic intrusive rock (Proterozoic and Archean)**—Dominantly narrow, straight-walled dikes, commonly diabase, that cut Archean metamorphic and igneous rocks. Four age groups, based on K-Ar and Rb-Sr determinations, have been reported for mafic dikes in the Beartooth Mountains: (1) 2800 to 2500 Ma, with diverse sets of strikes and dips; (2) 2100 to 2000 Ma, generally oriented north-south; (3) 1300 Ma, typically with strikes of around 120/300 degrees; and (4) 740 Ma, consistently with strikes of 105/285 degrees (Mueller and Wooden, 1988, p. 138-139).

p€my **Mylonite (Proterozoic or Archean)**—Fine-grained, laminated, and schistose, metamorphosed to the lower greenschist facies. Not radiometrically dated and may be Proterozoic in age based on comparison with similar rocks in the western Beartooths (Erslev, 1992) that are the northern extension of the Madison mylonite zone (Erslev and Sutter, 1990).

p€fcg **Falls Creek Gneiss (Proterozoic and/or Archean)** (Reid and others, 1975)—Gray to pink, sheet-form unit, generally strongly foliated. The gray layers are trondhjemitic (tonalitic) and the pink layers are granodioritic. Metamorphosed to lower amphibolites facies. Reid and others (1975) reported a Proterozoic age of 2200 Ma (K-Ar biotite date).

Aqmf **Biotite quartz monzonite, fine grained (Archean)**—Grain size < 1 mm. Modal composition: 29-34% quartz, 30-40% alkali feldspar, 22-35% plagioclase feldspar (An_{5-32}), 7-10% biotite (Page and Nockleberg, 1974).

Aqmm **Biotite quartz monzonite, medium-grained (Archean)**—Grain size 1-5 mm; modal composition: quartz - 27-32% , alkali feldspar - 28-33%, plagioclase feldspar (An_{17-25}) - 24-38%, biotite - 4-11% (Page and Nockleberg,1974).

Aqmc **Biotite quartz monzonite, coarse-grained (Archean)**—Grain size > 5 mm. Modal composition: 27-31% quartz, 22-29% alkali feldspar, 34-39% plagioclase feldspar (An_{25-30}), 3-7% biotite (Page and Nockleberg, 1974). Radiometric age is 2700 Ma based on U-Pb data from zircons (Nunes and Tilton, 1971; Page and others,1988, p. 126).

Agnm **Quarzofeldspathic gneiss (Archean)**—Fine-grained, mylonitic.

Ah **Contact metamorphic rock (Archean)—**Metamorphosed by the intrusion of the Stillwater Complex at about 2705 Ma (Premo and others, 1990); pyroxene hornfels close to the Complex (orthopyroxene isograd within 0.3 to 1.6 km (0.2 to 1 mile) of the southern boundary of the Complex), amphibole hornfels farther away (cummingtonite + cordierite isograd 1.2 to 3.4 km (0.7 to 2 miles) south of the Complex) (Labotka and Kath, 2001). Protoliths for these hornfels have been dated at about 3140 Ma based on U-Pb zircon data (Nunes and Tilton, 1971).

Amca **Mount Cowen Gneiss (Archean)** (Reid and others, 1975; Mogk and others, 1988)—Coarse-grained, gray, granodioritic, augen (mostly alkali feldspar) gneiss. Near its contact with the Davis Creek Schist (see below), the gneiss is an ultramylonite (Reid and others, 1975) based on grain-size reduction and marked laminated texture. The Mount Cowen Gneiss has a Rb-Sr whole-rock age of about 2737 Ma and is considered by Mogk and others (1988) to be the westernmost extent of the Late Archean metamorphic and igneous rocks characteristic of the eastern and central Beartooth Mountains.

Aggn **Granitic gneiss (Archean)** (Butler, 1966; Page and others, 1973a, b)—Alternating layers of felsic and mafic rocks; medium- to coarse-grained, feldspar porphyroblasts common. Locally grades into a plagioclase gneiss (tonalite) containing less than 5% alkali feldspar. Modal composition of the gneiss: quartz – 24-48%, alkali feldspar – 8-34%, plagioclase feldspar – 27-54%, biotite – 1-15% (Page and Nockleberg, 1974). Metamorphosed to amphibolites facies. Unit also contains large volumes of igneous rocks that belong to the distinctively Archean TTG (trondhjemite, tonalite, granodiorite) suite (Mueller and others, 1985). Radiometric ages on the tonalities range from 2900 to 2800 Ma (U-Pb zircon) (Mueller and others, 2008). A biotite quartz monzonitic gneiss at Hawley Mountain is dated at about 2750 Ma (Lafrenz and others, 1986), and a pink granite at Hawley Mountain yields a **Proterozoic** age, 2090 Ma (whole rock Rb-Sr isochron) (Lafrenz and others, 1986).

Apgn **Plagioclase gneiss (Archean)** (Page and Nockleberg, 1974)—Tonalitic gneiss similar to Aggn but contains less than 5% alkali feldspar. This unit also contains large volumes of igneous rocks that belong to the TTG (trondhjemite, tonalite, granodiorite) suite (Mueller and others, 1985). Radiometric ages on the tonalites range from 2900 to 2800 Ma (U-Pb zircon) (Mueller and others, 2008).

Adcs **Davis Creek Schist (Archean)** (Reid and others, 1975)—Fine- to medium-grained, brown-weathering mica schist with scattered plagioclase porphyroblasts. Subordinate layers of quartzite, amphibolite, and rarely marble occur locally. Metamorphosed to greenschist facies (Mogk and others, 1988).

Apag **Paragneiss (Archean)** (Mogk and others, 1988)—Dominant lithologies are quartzofeldspathic gneisses, psammitic schists, amphibolites, and banded iron formation. These rocks were included in Mount Delano Gneiss of Reid and others (1975). Metamorphosed to upper-amphibolite facies.

Abs **Biotite schist (Archean)** (Page and others, 1973 a,b; Butler, 1966)—Well-developed foliation. Modal composition: biotite – 25-48%, quartz – 20-50%, plagioclase feldspar – 0-10%, staurolite – 0-10%, garnet – 1-5%, cordierite – trace. Metamorphosed to upper-amphibolite facies.

Abg **Biotite quartzofeldspathic gneiss (Archean)** (Page and others, 1973a).

Aif **Banded (layered) iron formation (Archean)—**Interlayered rocks rich in magnetite, quartz, orthopyroxene, and fayalite (Page and Nockleberg, 1974). Usually associated with

adjacent layers of a distinctive blue metaquarzite. The iron formation was the exploration target for U.S. Steel Corporation in the 1950's but no mining has been undertaken on these deposits (Page and others, 1985).

Aagn **Amphibolite gneiss (Archean)** (Page and others,1973 a, b; Butler, 1966)—Well-developed layering and foliation. Modal composition: hornblende – 19-70%, plagioclase feldspar – 10-40%; biotite – 4-18%; quartz, garnet, and staurolite – 9-30%. Metamorphosed to upper-amphibolite facies.

Adg **Mount Delano Gneiss (Archean)** (Reid and others, 1975)—Typically a medium to coarse-grained, gray, tonalitic gneiss with abundant amphibolite layers and inclusions. Layers of schist occur locally. The gneiss is composed of plagioclase feldspar, quartz, and biotite and is devoid of alkali feldspar. Mogk and others (1988) stressed the mylonitic character of parts (Mogk's Trondhjemitic Gneiss-Amphibolite Complex) of the Mount Delano Gneiss just to the south of this map and reported a modal composition for their trondhjemitic gneiss of: plagioclase feldspar (sodic oligoclase) – 45-50%, quartz – 40-45%, biotite - <10%. Just to the south of this map, zircons from what Reid and others (1975) called Mount Delano Gneiss have yielded a U-Pb age of 3500 Ma, establishing the trondhjemitic mylonite as the oldest rock yet documented in the Wyoming Archean province (Mueller and others, 1996).

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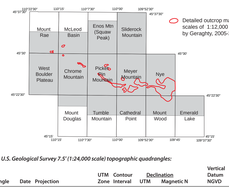


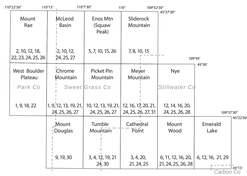
Bases from U.S. Geological Survey 7.5' (1:24,000 scale) topographic quadrangles:

7.5' Quadrangle	Date	Projection	UTM Zone	Contour Interval	Declination UTM	Declination Magnetic N	Vertical Datum NGVD	Horizontal Datum NAD
Mount Rae	1981*	Polyconic	12	20	0°29' E	16° 16'E	1929	1927
McLeod Basin	1981*	Polyconic	12	20	0°33' E	16° 16'E	1929	1927
Squaw Peak**	1951	Polyconic	12	40	0°46' E	15° 18'E	1929	1927
Sliderock Mtn	1985*	Polyconic	12	40	0°46' E	15° 13.7'E	1929	1927
W Boulder Plateau	1987	Lambert Conformal Conic	12	40	0°29' E	15° 5'E	1929	1927
Chrome Mtn	1987	Lambert Conformal Conic	12	40	0°33' E	15° 5'E	1929	1927
Picket Pin Mtn	1986	Lambert Conformal Conic	12	40	0°40' E	15° 5'E	1929	1927
Meyer Mtn	1986	Lambert Conformal Conic	12	40	0°45' E	15° 5'E	1929	1927
Nye	1986	Lambert Conformal Conic	12	40	0°51' E	15° 5'E	1929	1927
Mount Douglas	1987	Lambert Conformal Conic	12	40	0°33' E	15° 5'E	1929	1927
Tumble Mtn	1986	Lambert Conformal Conic	12	40	0°40' E	15° 5'E	1929	1927
Cathedral Point	1986	Lambert Conformal Conic	12	40	0°45' E	15° 5'E	1929	1927
Mount Wood	1986	Lambert Conformal Conic	12	40	0°51' E	15° 5'E	1929	1927
Emerald Lake	1985*	Polyconic	12	40	0°56' E	15° 5'E	1929	1927

*Maps from 1950's, Photorevised in 1980's
Maps from 1986-87 are provisional maps.

** In 2004 Squaw Peak was renamed Morning Star Peak. USGS published a new map of the area named Enos Mountain in 2000. We used the Squaw Peak version because that is what we had available as a digital file.

Previous Geologic Mapping and Index of 7.5' quadrangles



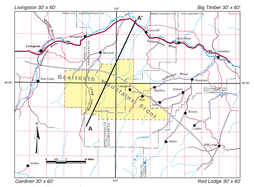
Numbers in the quadrangles above correspond to the numbers below.

1. Berg and others (1999)
2. Berg and others (2000)
3. Butler (1962)
4. Butler (1966)
5. Brostkowski (1983)
6. Cooper (1985)
7. du Bray and others (1994)
8. du Bray and Harlan (1998)
9. Elliott and others (1983)
10. Garbarini (1957)
11. Jackson and others (1955)
12. Jones and others (1960)
13. Laboska and Kath (2001)
14. Langston (1985)
15. Lopez (2000)
16. Lopez (2001)
17. Mann and others (1985)
18. Mogk and others (1988)
19. Page and others (1973a)
20. Page and others (1973b)
21. Page and Nokleberg (1974)
22. Reid and others (1975)
23. Richards (1957)
24. Segerstrom and Carlson (1982)
25. Todd and others (1982)
26. Todd and others (unpublished geologic maps) with permission*
27. Vail (1955)
28. Vhay (1934)
29. Washburn (1985)
30. Wilson (1936)
31. Zientek (1983)

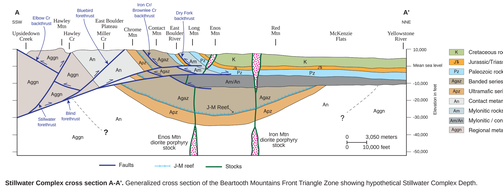
* Appreciation is expressed to Stillwater Mining Company for permission to incorporate selected unpublished company data into this map.

Map symbols

- Contact: dashed where approximately located; dotted where concealed
- Fault: unknown sense of movement; dashed where approximately located; dotted where concealed; includes some lateral ramps
- Normal fault: dashed where approximately located; dotted where concealed; bar and ball on downthrown side
- Strike-slip fault: here concealed; Arrows along fault trace indicate relative strike-slip displacement; includes some lateral ramps
- Reverse or thrust fault: teeth on upthrown block; dashed where approximately located; dotted where concealed
- Syncline: dashed where approximately located; dotted where concealed
- Anticline: dashed where approximately located; dotted where concealed
- Overturned anticline: showing trace of axial plane and bedding dip direction; dashed where approximately located, dotted where concealed
- Overturned syncline: showing trace of axial plane and bedding dip direction; dashed where approximately located, dotted where concealed
- Outer boundary of the Stillwater Complex
- Strike and dip of inclined beds
- Strike and dip of overturned beds
- Vertical beds
- Strike and dip of inclined layering of Stillwater Complex
- Strike and dip of overturned layering of Stillwater Complex
- Vertical layering of Stillwater Complex
- Strike and dip of foliation or compositional layering
- Vertical foliation or compositional layering
- 2400 marker anorthosite in Agp2 (about 2400 feet above the Arz1/Aubz contact)
- Dikes, mostly diorite
- G chromite horizon in Apz
- Mafic dikes, many are diabase, and sills in Archean gneisses
- Granitic dikes and sills in Archean gneisses

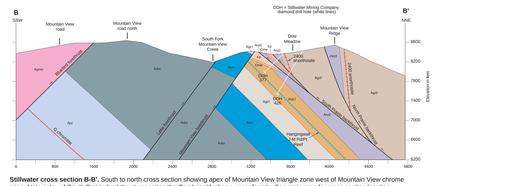


Location of cross section A–A'

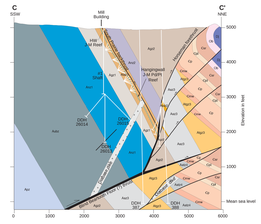


Stillwater Complex cross section A-A'. Generalized cross section of the Beartooth Mountains Front Triangle Zone showing hypothetical Stillwater Complex Depth.

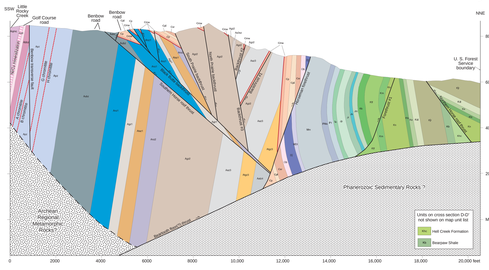
- K — Cretaceous rocks
- Js — Jurassic/Triassic rocks
- Pz — Paleozoic rocks
- Aprc — Banded series - Stillwater Complex
- Agp — Ultramafic series - Stillwater Complex
- An — Contact metamorphic rocks
- Arc — Mylonitic rocks
- Arc/An — Mylonitic / contact metamorphic rocks
- Agpr — Regional metamorphic rocks



Stillwater cross section B-B'. South to north cross section showing apex of Mountain View triangle zone west of Mountain View chrome mine. Note splay of South Prairie backthrust repeating the Cambrian/Archean unconformity. See main map for cross section location.



Stillwater cross section C-C'. South to north cross section showing subsurface location of blind Beartooth floor (?) thrust known only from deep drilling. See main map for cross section line C-C'. DDH = Stillwater Mining Company diamond drill hole. Unlabeled drill hole fans, shown in white, are definition drill fans at Stillwater mine.



Stillwater Complex cross section D-D'. South to north cross section showing backthrust-dominated terrain of eastern Benbow part of Stillwater Complex. The Cambrian/Archean unconformity (red line) is repeated 8 times by backthrusting. Note splays of Black Butte regional-scale backthrust; minor structures mimicking the major structures. Inferred roof thrusts bound the northern and southern compartments or horses that are marked by dramatic and sharp dip changes. Cross section line shown on main map.

Map Units

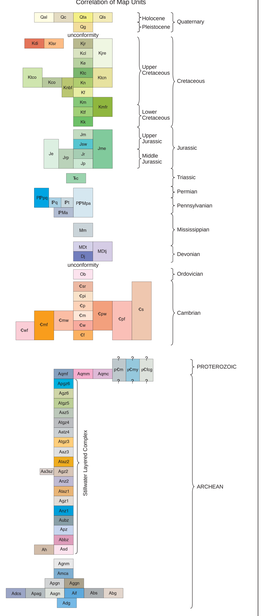
- Qal — Alluvium
- Qc — Colluvium
- Qls — Talus deposit
- Qls — Landslide deposit
- Qg — Glacial deposit
- Kdi — Diorite (dated at 75 Ma, see text)
- Klsr — Sliderock Mtn. member of Livingston Group
- Kjrs — Judith River through Eagle Formations, undivided
- Kjr — Judith River Formation
- Kcl — Claggett Shale
- Ke — Eagle Sandstone
- Kbm — Telegraph Creek and Niobrara Formations, undivided
- Kbm — Telegraph Creek Formation and Cody Shale, undivided
- Kfa — Telegraph Creek Formation
- Kn — Niobrara Formation
- Kcc — Cody Shale
- Kmbf — Niobrara through Bell Fourche Formations, undivided
- Kf — Frontier Formation
- Kmbf — Mowry through Fall River Formations, undivided
- Kbc — Mowry Shale
- Kfd — Thermopolis and Fall River Formations, undivided
- Kk — Kootenai Formation
- Jsw — Morrison Formation and Ellis Group, undivided
- Jm — Morrison Formation
- Je — Ellis Group, undivided
- Jsw — Swift Formation
- Jrp — Rierdon and Piper Formations, undivided
- Jr — Rierdon Formation
- Jp — Piper Formation
- Tkc — Chugwater Formation
- PPhs — Phosphoria and Quadrant Formations, undivided
- PPhsq — Phosphoria through Amsden Formations, undivided
- Pq — Quadrant Formation
- Pt — Tensleep Sandstone
- PMa — Amsden Formation
- Mm — Madison Group, undivided
- MDq — Three Forks and Jefferson Formations, undivided
- MDt — Three Forks Formation
- Dj — Jefferson Limestone
- Ob — Bighorn Dolomite
- Cs — Sedimentary rock, undivided
- Csr — Snowy Range Formation
- Cpa — Pilgrim Limestone
- Cpw — Park through Wolsey Formations, undivided
- Cpf — Park through Flathead Formations, undivided
- Cp — Park Shale
- Cmw — Meagher and Wolsey Formations
- Cmf — Meagher through Flathead Formations, undivided
- Cm — Meagher Limestone
- Cwf — Wolsey and Flathead Formations
- Cw — Wolsey Shale
- Cf — Flathead Quartzite

STILLWATER LAYERED COMPLEX (ARCHEAN)

- Agpmh — Pigeonite Gabbro Zone 6
- Agpb — Gabbro Zone 6
- Agp5 — Troctolite Gabbro Zone 5
- Aan5 — Anorthosite Zone 5
- Agp4 — Troctolite Gabbro Zone 4
- Aan4 — Anorthosite Troctolite Zone 4
- Agp3 — Troctolite Gabbro Zone 3
- Aan3 — Anorthosite Zone 3
- Aroz — Ronan Peridotite Zone 2
- Aanz — Anorthosite Zone 2
- Arz — Peridotite Zone
- Abbz — Basal Bronzitite Cumulate Zone
- Aad — Sill-Dike Member (dated at 2703–2713 Ma, see text)
- Arz1 — Norite Zone 1
- Aanz — Upper Bronzitite Zone
- Arz — Peridotite Zone
- Abbz — Basal Bronzitite Cumulate Zone
- Aad — Sill-Dike Member (dated at 2703–2713 Ma, see text)

BEARTOOTH FRONT PROTEROZOIC AND ARCHEAN ROCKS

- pCm — Mafic intrusive rock, many are diabase dikes
- pCmy — Mylonite
- pCbg — Falls Creek Gneiss, granodiorite to trondhjemitic
- Agpf — Quartz monzonite, fine-grained
- Agpmm — Quartz monzonite, medium-grained
- Agpc — Quartz monzonite, coarse-grained (dated at 2700 Ma, see text)
- Agym — Mylonitic gneiss
- Ai — Hornfels, contact metamorphosed by Stillwater Complex at 2705 Ma (protolithis dated at 3140 Ma, see text)
- Amgg — Migmatitic gneiss, monzonitic to granodioritic (dated at 2737 Ma, see text)
- Agp — Quartzofeldspathic gneiss with associated TTG igneous rocks (dated at 2800 to 2920 Ma, see text)
- Agpz — Tonalitic gneiss with associated TTG igneous rocks (dated at 2800 to 2900 Ma, see text)
- Adcs — Davis Creek Schist
- Apag — Paragneiss Unit
- Abs — Biotite schist
- Abg — Biotite quartzofeldspathic gneiss
- Af — Iron formation with associated blue metaquartzite
- Aagn — Amphibolite gneiss
- Adg — Mount Delano Gneiss, trondhjemitic with amphibolite (similar rocks to south dated at 3500 Ma, see text)



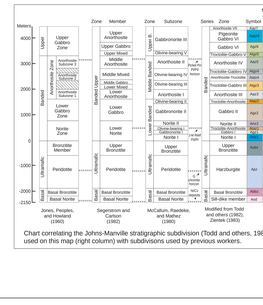
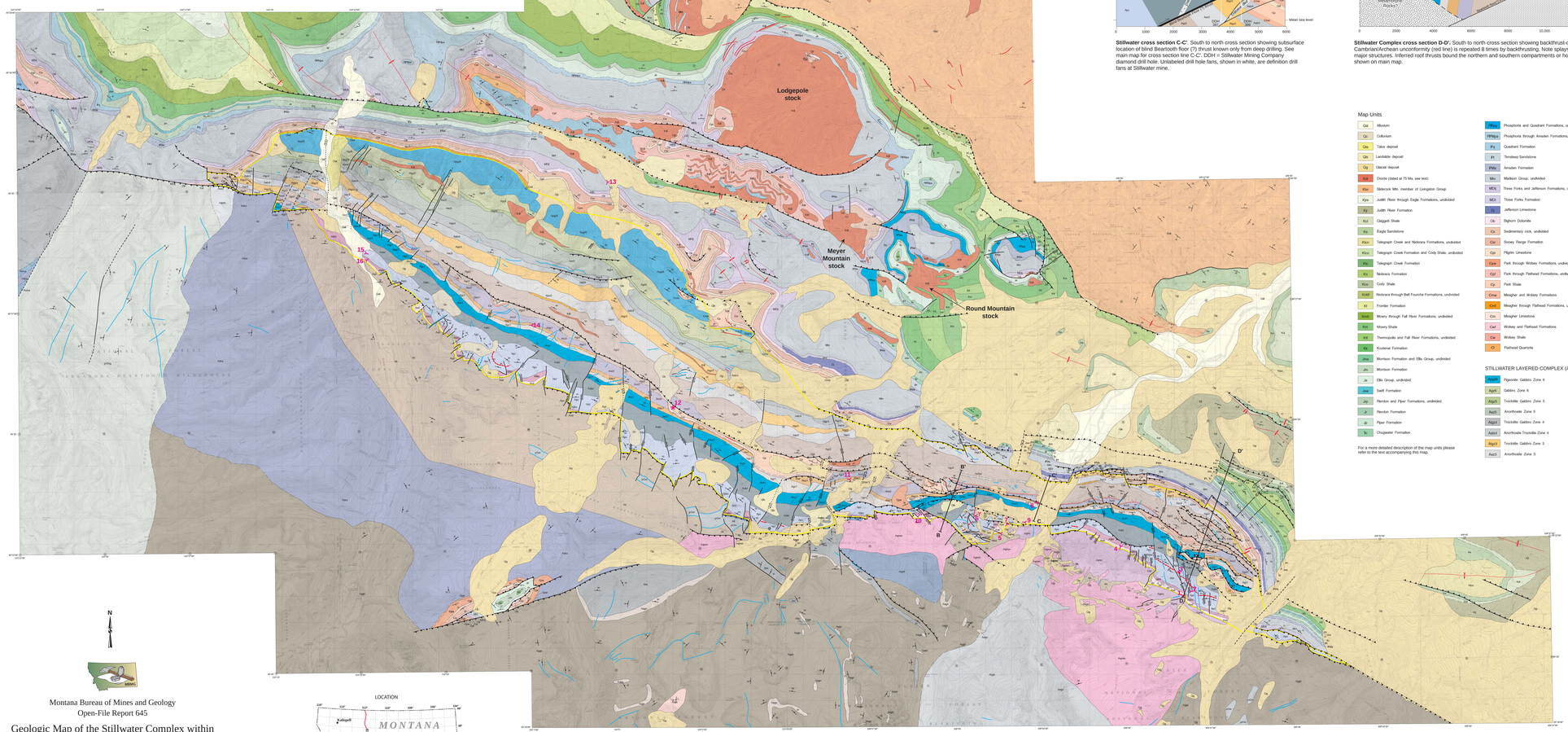


Chart correlating the Johns-Manville stratigraphic subdivision (Todd and others, 1982) used on this map (right column) with subdivisions used by previous workers.



KILOMETERS 1 0 1 2 3 4 5
MILES 0 1 2 3 4

SCALE 1:48 000
CONTOUR INTERVAL 20 METERS

1 Stillwater Complex Mines and Adits with metals produced

1. Blue Jay #1 adit — Nickel and copper
2. East Benbow mine — Chrome
3. West Benbow mine — Chrome
4. Nye basin adit — Nickel and copper
5. Verdigris Creek adits — Nickel and copper
6. Mouat-Sampson mine — Chrome
7. Mouat mine — Nickel and copper
8. Stillwater mine — Palladium and platinum
9. Monte Alto tunnel — Chrome
10. Initial Creek deposit — Nickel and copper
11. West Fork adit — Palladium and platinum
12. Brass Monkey exploration camp – Johns-Manville — Chrome
13. East Boulder mine — Palladium and platinum
14. Frog Pond adit — Palladium and platinum
15. Gish mine — Chrome
16. Main Boulder River adit — Nickel and copper

Research supported by the U.S. Geological Survey, National Cooperative Geologic Mapping Program, under USGS award number G10AC00365. 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: Ken Sandau and Paul Thale, MBMG. Map layout: Susan Smith, MBMG.

Montana Bureau of Mines and Geology
Open-File Report 645

Geologic Map of the Stillwater Complex within the Beartooth Mountains Front Laramide Triangle Zone, South-Central Montana

Compiled and selectively mapped by
Ennis Geraghty

2013

Maps may be obtained from
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