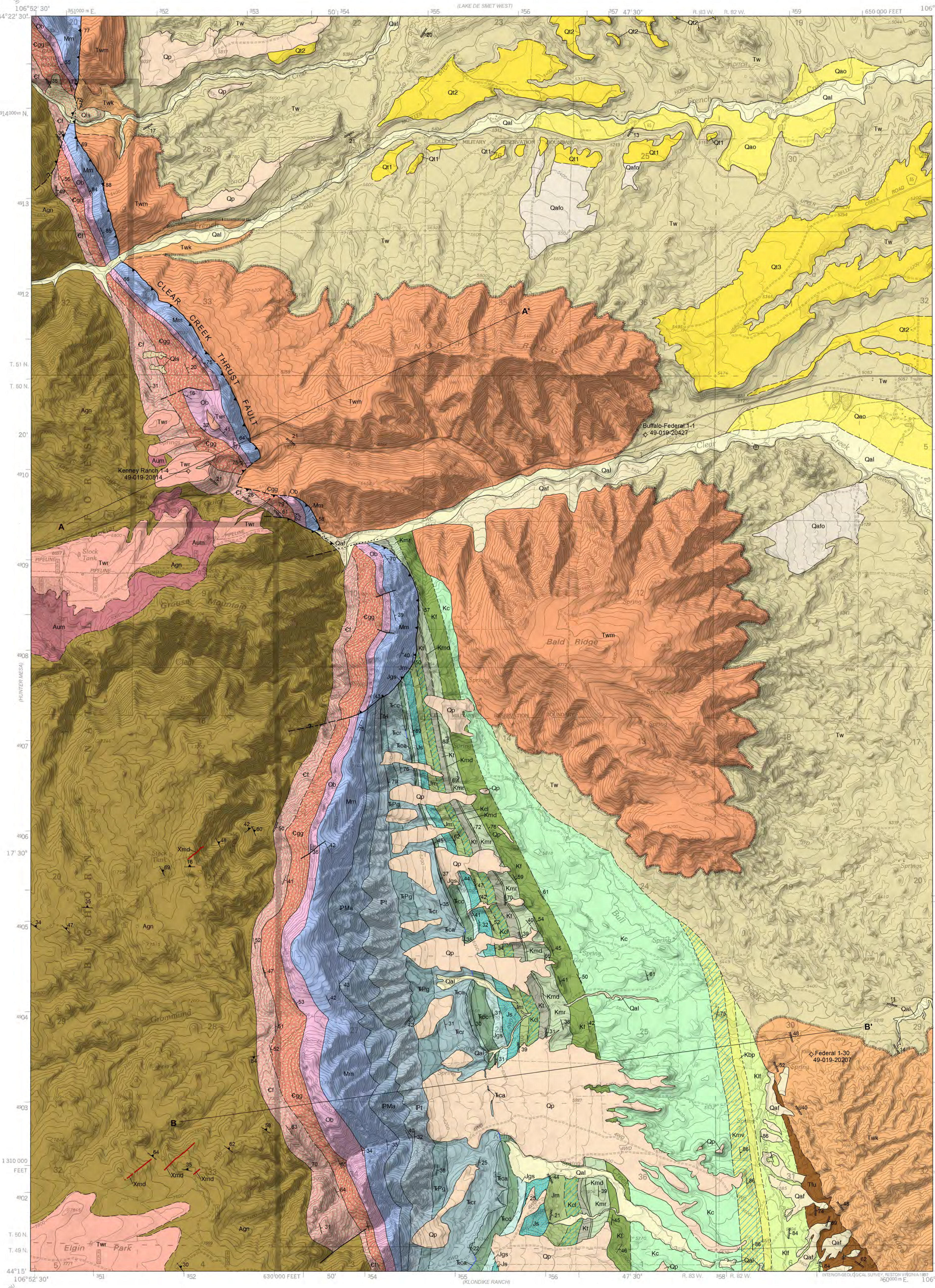
WYOMING STATE GEOLOGICAL SURVEY
Thomas A. Drean, Director and State Geologist
Laramie, Wyoming

Geology - Interpreting the past - Providing for the future

OPEN FILE REPORT 14-3
North Ridge 1:24,000-scale
Bedrock Geologic Map



Base map from U.S. Geological Survey 1:24,000-scale topographic map of the North Ridge, Wyoming Quadrangle, 1993

Base hillshade derived from USDA/NRCS–National Cartography & Geospatial Center 10-meter Digital Elevation Model (DEM), 2000; azimuth 315º, sun angle 45º, vertical exaggeration 1.2

Projection: Universal Transverse Mercator (UTM), zone 13
North American Datum of 1927 (NAD 27)
1,000-meter grid ticks: UTM, zone 13
10,000-foot grid ticks: Wyoming State Plane Coordinate System, east central zone

Wyoming State Geological Survey
P.O. Box 1347 - Laramie, WY 82073-1347
Phone: 307-766-2286 - Fax: 307-766-2605
Email: wsgs.sales@wyo.gov

UTM GRID AND 2014 MAGNETIC NORTH DECLINATION AT CENTER OF SHEET

MN, GN, 1°16', 9°54'

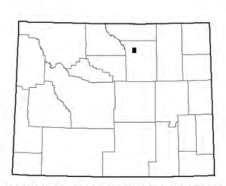
SCALE 1:24,000

1 0.5 0 1 Mile

1,000 0 1,000 2,000 3,000 4,000 5,000 6,000 7,000 Feet

1 0.5 0 1 Kilometer

CONTOUR INTERVAL 40 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929



WYOMING QUADRANGLE LOCATION

Digital cartography by Ranie M. Lynds and Rachel N. Toner

Map edited by Suzanne C. Luhr

Prepared in cooperation with and research supported by the U.S. Geological Survey, National Cooperative Geologic Mapping Program, under USGS award number G13AC000243. 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.

PRELIMINARY GEOLOGIC MAP OF THE NORTH RIDGE QUADRANGLE, JOHNSON COUNTY, WYOMING

by

Ranie M. Lynds, Erin A. Campbell-Stone, and Rachel N. Toner

2014

CORRELATION OF MAP UNITS

- Qal, Qls, Qaf, Qt1, Qt2, Qt3, Qao, Qafo, Qp — Holocene, Pleistocene, Pliocene — QUATERNARY
- Unconformity
- Twr — Oligocene — TERTIARY
- Unconformity
- Twm, Twk, Tw — Eocene
- Tfu — Paleocene — CENOZOIC
- Unconformity
- Klf, Kbp, Kmv, Kc, Kf — Upper Cretaceous
- Kmr, Kmd, Kt, Kcl — Lower Cretaceous — CRETACEOUS
- Unconformity
- Jm — Upper Jurassic
- Js — Middle Jurassic — JURASSIC
- Unconformity
- Jgs — MESOZOIC
- Unconformity
- T̄cc, T̄ca, T̄cr — Upper Triassic, Lower Triassic — TRIASSIC
- T̄Pg — Permian — PERMIAN
- Unconformity
- P̄t, P̄Ma — Pennsylvanian — PENNSYLVANIAN
- Unconformity
- Mm — Upper Mississippian, Lower Mississippian — MISSISSIPPIAN — PALEOZOIC
- Unconformity
- Ob — Upper and Middle Ordovician — ORDOVICIAN
- Unconformity
- €gg, €f — Upper Cambrian, Middle Cambrian — CAMBRIAN
- Unconformity
- Xmd — Paleoproterozoic — PROTEROZOIC
- Aum — Neoarchean
- Agn — Mesoarchean — ARCHEAN — PRECAMBRIAN

MAP SYMBOLS

Definitions
Certain—Location known <25 m
Approximate—Estimated location 25–100 m
Inferred—Estimated location >100 m

Formation contact—Continuous where certain; long dash where approximate; short dash where inferred

Gradational formation contact

Fault—Continuous where certain; long dash where approximate; short dash where inferred; dotted where concealed; queried where identity or existence uncertain; sawteeth on upper plate of thrust fault

Dike—Continuous where certain; long dash where approximate

Line of cross section

Horizontal bedding

Strike and dip of inclined bedding

Strike of vertical bedding

Strike and dip of overturned bedding

Strike and dip of inclined bedding in crossbedded rocks

Strike and dip of foliation

Federal 1-30 49-019-20207 **Dry hole**—Showing well name and API number

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EXPLANATION

DESCRIPTION OF MAP UNITS

Cenozoic

Qal **Alluvium (Holocene)**—Unconsolidated to poorly consolidated clay, silt, sand, gravel, cobbles, and boulders, mainly along river courses and in floodplains. Alluvial material derived from all local geologic units. Thickness approximately 0–8 m (0–25 ft)

Qls **Landslide Debris (Holocene)**—Blocks and slumps of locally derived bedrock. Occurs as flows and hummocky topography when derived from the Cambrian Gros Ventre and Gallatin formations. Thickness less than 37 m (120 ft)

Qaf **Alluvial Fan Deposits (Holocene and Pleistocene[?])**—Unconsolidated subangular to subrounded cobble and boulder gravels in a coarse sandy matrix of sedimentary, igneous, and metamorphic rocks, generally derived from the Kingsbury and Moncrief Members of the Wasatch Formation on the flanks of Kingsbury, Bald, and North Ridges; coalesce with landslides along the south bank of Clear Creek. Thickness approximately 0–15 m (0–50 ft)

Terrace Deposits (Holocene and Pleistocene[?])—Unconsolidated to locally cemented silt, sand, gravel, cobbles, and boulders of sedimentary, igneous, and metamorphic rocks, located along rivers and streams. Terrace designations modified from Mapel (1959). Thickness generally less than 3 m (10 ft)

Qt1 3–30 m (10–100 ft) above present river level

Qt2 30–67 m (100–220 ft) above present river level

Qt3 67–107 m (220–350 ft) above present river level

Qao **Older Alluvium (Holocene and Pleistocene[?])**—Unconsolidated to poorly consolidated clay, silt, sand, gravel, cobbles, and boulders, mainly in older stranded floodplains. Alluvial material derived from all local geologic units. Thickness approximately 0–8 m (0–25 ft)

Qafo **Older Alluvial Fan Deposits (Holocene and Pleistocene[?])**—Unconsolidated subangular to subrounded cobble and boulder gravels in a coarse sandy matrix of igneous, metamorphic, and sedimentary rocks, generally derived from the Moncrief Member of the Wasatch Formation on the flanks of Bald and North Ridges. Thickness approximately 0–15 m (0–50 ft)

Qp **Pediment Deposits (Holocene, Pleistocene, and Pliocene[?])**—Smooth surfaces that gently dip to the east less than five degrees and steepen to the west near the Pennsylvanian Tensleep Sandstone; comprised of sedimentary, igneous, and metamorphic cobbles and boulders in an unconsolidated coarse sand matrix; majority of the clasts are limestones and dolostone. Local thickness less than 3 m (10 ft)

Twr **White River Formation (Oligocene)**—Poorly exposed flat-topped ridges and treeless grassy areas at elevations ranging from 2,036 m (6,680 ft) near Mosier Gulch to 2,391 m (7,845 ft) in Elgin Park. Conglomerate of flat-lying cobbles and boulders of moderately to well-rounded and poorly sorted Precambrian igneous and metamorphic rocks, interbedded with meter-thick claystone and poorly sorted medium- to coarse-grained, tabular, clayey sandstone. Basal contact is sharp and unconformable, although pinching out locally. Local thickness 30–75 m (100–245 ft)

Tw **Wasatch Formation (Eocene and Paleocene[?])**—Medium- to coarse-grained sublitharenite sandstone; light gray with orange staining; 20–80 cm (7.9–31.5 in) high dune- and bar-scale cross-stratification is common. Interbedded conglomerate with clasts of metamorphic, igneous, and sedimentary rocks are subangular to subrounded, moderately sorted, and as large as 6 cm (2.4 in) in diameter; mud ripups are common. Bedding on the scale of millimeters to centimeters is defined by a change in grain size and orange staining parallel to bedding. Sharp basal contact is an angular unconformity with many of the underlying Mesozoic formations. Thickness 152 m (500 ft) in the Crazy Woman Creek area (Hose, 1955) and more than 305 m (1,000 ft) thick in the Buffalo-Lake DeSmet area (Mapel, 1959)

Twm **Moncrief Member**—Resistant but poorly exposed, gently dipping, cobble and boulder clast-supported conglomerate of North Ridge and Bald Ridge. Clasts up to 2 m (6.6 ft) in diameter are subrounded to rounded Precambrian igneous and metamorphic rocks in a poorly sorted, subangular, medium- to coarse-grained sandstone matrix. Conspicuous absence of Mesozoic and Paleozoic sedimentary clasts and shallower dips distinguishes the Moncrief from Kingsbury member. Sharp unconformable contact with all formations except the main body of the Wasatch Formation where it is gradational. Local thickness approximately 400 m (1,312 ft)

Twk **Kingsbury Member**—Interbedded conglomerate, sandstone, siltstone, and claystone of Kingsbury Ridge and the low proximal valleys of Johnson and French Creeks. Tan, brown, reddish-brown, and dark-gray sandstone in beds a few centimeters to 1 m (3.3 ft) thick, some beds are carbonaceous. Channelized conglomerate lenses contain centimeter to meter-scale clasts of subrounded to rounded sandstone, limestone, and more rare Precambrian rocks; imbrication is common. Boulders up to 2 m (6.6 ft) are present. Sharp unconformable contact with all formations except the main body of the Wasatch Formation where it is gradational. Local thickness at Kingsbury Ridge approximately 213 m (700 ft)

Tfu **Fort Union Formation (Paleocene)**—Poorly exposed sparse outcrops on the west side of Kingsbury Ridge include thinly bedded, medium-grained, moderately rounded and sorted, friable calcareous sandstone. Sandstone commonly ferruginous with yellow and purple alteration; weathers brown but is light gray when fresh. Coal and carbonaceous shale are common in nearby outcrops but were not observed within the map area. Only the basal Fort Union is exposed on the quadrangle; basal contact is sharp and unconformable. Local thickness approximately 518 m (1,700 ft) (Mapel, 1959); regional thickness 1,204 m (3,950 ft) (Hose, 1955)

Mesozoic

Klf **Lance Formation and Fox Hills Sandstone, undivided (Upper Cretaceous)**—Lance Formation is a poorly exposed coarsening-upward sequence of light-gray to yellow, fine- to medium-grained, lenticular sandstone interbedded with thin dark carbonaceous shales and coals. Fox Hills Formation is a coarsening-upward, light- to yellowish-gray or greenish-brown non-calcareous sandstone interfingered with dark sandy shales and siltstones (modified from Ver Ploeg and Boyd, 2002); not exposed in outcrop. Basal contact is gradational and conformable. Thickness 541–545 m (1,723–1,727 ft) from geophysical logs

Kbp **Bearpaw Shale (Upper Cretaceous)**—Medium to dark greenish-gray marine shale interbedded with thin lenses of light-gray, very fine to fine-grained sandstones, coals, and bentonite. Marine fossils such as bivalves and ammonites are common (Dunlap, 1958). Conformable basal contact. Not exposed in the map area. Thickness approximately 91–105 m (300–344 ft) from geophysical logs

Kmv **Mesaverde Formation (Upper Cretaceous)**—Series of alternating sandstones and shales intercalated with thin coal and bentonite layers. Shales are dark greenish-gray, commonly carbonaceous and bentonitic; sandstones include the light brownish-gray, very fine to medium-grained, carbonaceous Teapot Sandstone Member and the orange-brown, well-sorted and rounded, fine-grained Parkman Sandstone Member that crops out as thin, sub-vertical, and heavily fractured fins. Basal contact is conformable but not exposed. Thickness 168–175 m (550–575 ft) from geophysical logs

Kc **Cody Shale, Niobrara Formation, and Carlile Shale, undivided (Upper Cretaceous)**—Poorly exposed, dark bluish-gray calcareous and fossiliferous marine shale interbedded with light- to medium-gray fine-grained sandstones and siltstones and abundant bentonite beds. Isolated sub-vertical sandstone outcrops are tentatively correlated to the fine-grained glauconitic and bioturbated Sussex Sandstone Member and coarsening-upward bioturbated and lenticular silty Shannon Sandstone Member. The Niobrara Formation and Carlile Shale are visible on geophysical logs but not exposed and not mapped individually. Conformable basal contact. Thicknesses 884–914 m (2,900–3,000 ft) from geophysical logs; 1,082 m (3,550 ft) south of the map area (Mapel, 1959)

Kf **Frontier Formation (Upper Cretaceous)**—Interbedded succession of poorly exposed sandstone, siltstone, and shale. Shales are dark to medium gray, fissile, silty claystones that break into beds a few millimeters thick; sandstones are a few millimeters to several centimeters thick, very fine to fine-grained, subrounded to subangular, and well-sorted litharenites that weather orange. Bentonite interbeds are common. Upper contact is mapped locally at a black chert-pebble conglomerate; basal contact is sharp and conformable. Thicknesses approximately 198 m (650 ft) from geophysical logs; 146–158 m (480–517 ft) (Hose, 1955; Mapel, 1959)

Kmr **Mowry Shale (Upper Cretaceous)**—Organic-rich, dark brownish-gray to black siliceous shale with interbedded siltstones, sandy shales, and sandstones that weather to a platy silvery-gray. Grayish-green bentonite layers are regionally continuous. Fish scales are abundant. The Clay Spur Bentonite Bed marks the uppermost bed; basal contact is sharp but conformable. Local thickness approximately 122 m (400 ft); 152–161 m (500–527 ft) (Hose, 1955; Mapel, 1959)

Kmd **Muddy Sandstone (Lower Cretaceous)**—Fine- to medium-grained, light-gray to white, friable quartzite sandstone with centimeter-scale cross-stratification; highly altered to orange-brown and lichen-covered near the southern map border. Crops out intermittently with variable thickness due to valley-filling depositional environment. Sharp basal contact. Local thickness 0–16 m (0–52 ft)

Kt **Thermopolis Shale (Lower Cretaceous)**—Non-resistant dark-gray marine shale that is poorly exposed and often only seen as dark-gray soil. Lower half is interbedded black shales and light-gray to brown siltstone; upper half is soft, black fissile shale. Basal contact is gradational and conformable, marked by a resistant brown siltstone layer with dahllite concretions. Thickness 46–61 m (150–200 ft) from geophysical logs; 38–50 m (125–165 ft) (Hose, 1955; Mapel, 1959)

Kcl **Cloverly Formation (Lower Cretaceous)**—Fine-grained, tan to white, cross-bedded quartz arenite sandstone and rare chert pebble conglomerate at base, overlain by interbedded purple and black claystones and thin, light brown siltstone and fine-grained sandstone lenses with dahllite concretions, locally termed the "rusty beds"; capped by a persistent ledge of brown calcareous siltstone (Mapel, 1959). Poorly exposed in map area. Basal contact is sharp and unconformable. Thickness 41 m (135 ft) from geophysical logs; 48 m (156 ft) (Hose, 1955; Mapel, 1959)

Jm **Morrison Formation (Upper Jurassic)**—Non-resistant series of variegated siltstones and claystone with rare thin sandstone interbeds; often forms grassy slopes. Colors include light purple, light pink, gray, and white. Sandstones are lenticular, friable to concretionary, fine-grained, light-gray to medium-brown siltstones with ripple cross-laminae and 0.5 m (1.6 ft) dune-scale cross-stratification. Sharp unconformable basal contact is marked by concretionary brown sandstone. Thickness 50 m (165 ft) from geophysical logs; 39 m (127 ft) (Mapel, 1959); 56 m (185 ft) (Hose, 1955)

Js **Sundance Formation (Upper and Middle Jurassic)**—Poorly exposed throughout the map area, generally forms grassy slopes with no outcrop. Interbedded gray limestone, grayish-green shale and sandy shale, and light-gray and white sandstone. Base is greenish-gray flaggy and limey sandstone 5–10 cm (2–4 in) thick. Upper contact marked by tan, very fine to fine-grained, moderately well-rounded, well-sorted quartzarenite with cross-stratification and some frosted quartz grains in a calcareous cement. Belemnites and *Gryphaea* common. Basal contact is sharp and conformable. Thickness 61 m (200 ft) from geophysical logs; 87 m (285 ft) (Hose, 1955; Mapel, 1959)

Jgs **Gypsum Spring Formation (Middle Jurassic)**—Lower part consists of dark-red claystone and shale with rare gypsum (Mapel, 1959) overlain by interbedded gray to greenish-gray siltstone, light-gray limestone, and rusty-red siltstone. Forms grassy slopes with poor exposure and bright red-orange soil. Unconformable basal contact is sharp when exposed but is often covered. Local thickness 49–50 m (160–165 ft)

Chugwater Formation (Upper and Lower Triassic)

T̄cc **Crow Mountain Member**—Light-pink to salmon-red, very fine to medium-grained, well-sorted, subrounded, clean quartzarenite sandstone with tabular and trough cross-stratification. Rare grains of coarse frosted quartz. Weathers to bulbous orange-salmon-colored semi-friable bluffs; often poorly exposed and forms grassy slopes of reddish soil. Basal contact sharp. Local thickness 15–26 m (50–85 ft)

T̄ca **Alcova Member**—Resistant ridge of pale-pink to purple-gray micritic limestone in beds 3–8 cm (1.2–3.1 in) thick. Upper beds contain wavy lamina. Basal contact sharp. Mapped as marker bed when not exposed as a dip slope. Local thickness 4–5 m (13–16 ft)

T̄cr **Red Peak Member**—Reddish-orange and reddish-brown, poorly sorted, cross-stratified and rippled sandstone and siltstone. Poorly exposed, forms grassy valleys with sparse vegetation. Basal contact is conformable with the Goose Egg Formation and distinct when exposed. Thickness 232 m (760 ft) from geophysical logs; 221 m (726 ft) (Mapel, 1959); 213 m (700 ft) (Hose, 1955)

Mesozoic and Paleozoic

T̄Pg **Goose Egg Formation (Lower Triassic and Permian)**—Interbedded red shale, red siltstone, gypsum, and light-gray limestone. Lower portion is primarily siltstone and shale; upper portion is gypsiferous, poorly exposed and may be identified through red and reddish-brown soil and tree-covered slopes. Upper contact of brecciated limestone may form hills and may crop out as boulders. Basal contact is sharp and unconformable. Thickness 49–64 m (160–210 ft) from geophysical logs; 55 m (180 ft) (Mapel, 1959); 76 m (250 ft) (Hose, 1955)

Paleozoic

P̄t **Tensleep Sandstone (Upper and Middle Pennsylvanian)**—Light-tan to light-gray, fine- to medium-grained, well-rounded, well-sorted quartzarenite sandstone with frosted grains and eolian cross-stratification up to several meters in height. Interbedded with blue-gray limestone and dolostone near base in beds less than 1 m (3.3 ft) thick. Forms prominent ridges and is frequently a steep range-bounding dip slope. Basal contact is unconformable and sharp. Thickness 84–107 m (275–350 ft) (Hose, 1955; Mapel, 1959)

P̄Ma **Amsden Formation and Darwin Sandstone (Middle and Lower Pennsylvanian and Upper Mississippian)**—Heterogeneous interbedded red and purple-brown sandstone and gray dolomite in lower part; upper part is gray and yellowish-tan dolomite in layers 0.2–2 m (0.5–6.6 ft). Commonly forms slopes covered with pine trees; when exposed it forms low outcrops of sandstone and limestone. Mississippian Darwin Sandstone locally exposed at base. Basal contact is sharp and unconformable. Local thickness 76 m (250 ft)

Mm **Madison Limestone (Upper and Lower Mississippian)**—Resistant, ridge-forming tan to gray limestone, dolomitic limestone, and dolostone that weathers to yellowish-tan or bluish-gray with dark-gray stain. Thin to massive bedding; contains orange-brown chert nodules or chert horizons. Basal layers are sandy limestone with rare cross-stratification 10–20 cm (3.9–7.9 in) high; upper surface locally karsted and filled with Darwin Sandstone. Basal contact is sharp and unconformable. Thickness 168–204 m (550–670 ft) (Hose, 1955; Mapel, 1959)

Ob **Bighorn Dolomite (Upper and Middle Ordovician)**—Predominantly tan to light-gray, massively bedded, cliff-forming dolostone that weathers to pitted, fretted, yellowish-tan with gray staining. Locally contains white, gray, and brown chert nodules. Basal unit is 20 m (65 ft) of light-gray, fine-grained, well-sorted quartzarenite beneath 0.6–0.9 m (2–3 ft) of yellowish calcareous sandstone, possibly Harding Sandstone equivalent. Dolostone forms conspicuous cliffs and fins. Basal contact is sharp and unconformable. Thickness 108–120 m (355–395 ft) (Hose, 1955; Mapel, 1959)

€gg **Gallatin and Gros Ventre Formations, undivided (Upper and Middle Cambrian)**—Gallatin Formation is grayish-red thinly bedded limestone, interbedded with green and red shale, minor layers of flat-pebble limestone conglomerate; weathers red and can form short cliffs beneath the Bighorn Dolomite. Gradational contact with underlying Gros Ventre Formation which is comprised of greenish-gray, glauconitic siltstone interbedded at centimeter scale with brown and gray sandstone and siltstone, grayish-green limestones, and flat-pebble limestone conglomerate; limestone layers up to 0.3 m (1 ft) thick; sandstone beds up to 0.5 m (1.6 ft) thick. Forms grassy slopes with poor exposure, small to large landslides common. Basal contact is sharp but conformable. Thickness 168–197 m (550–645 ft) (Hose, 1955; Mapel, 1959)

€f **Flathead Sandstone (Middle Cambrian)**—Tan to yellowish-gray, medium- to coarse-grained cross-stratified quartzarenite to sublitharenite; weathers to orange, red, or brown; bedding at scale of 0.5–1 m (1.6–3.3 ft). Forms rounded ridges covered with grass or pine trees and crops out along hillsides or small ridges. Basal conglomerate of subrounded chert pebbles sits unconformably on Archean basement. Thickness 79–105 m (260–344 ft) (Hose, 1955; Mapel, 1959)

Proterozoic

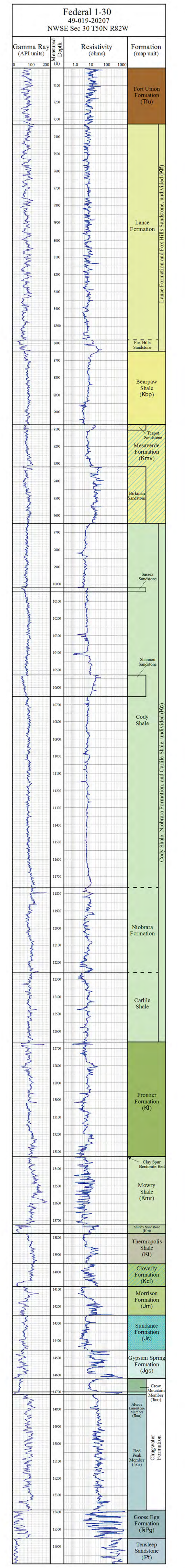
Xmd **Mafic dikes (Paleoproterozoic[?])**—Dark-gray to black, fine- to medium-grained diabase dikes form low ridges; weather brownish-gray with red staining and gray lichen. Euhedral to subhedral and rare porphyritic plagioclase, subhedral pyroxene that weathers to reddish-brown pits, and minor stubby subhedral black hornblende crystals. Dikes trend generally N40°–45°E and are 1–3 m (3–10 ft) wide. Dikes in the central Bighorn Mountains with this trend were emplaced into the Archean granitic gneiss at 2,155 ± 2 Ma (Kilian and others, in press)

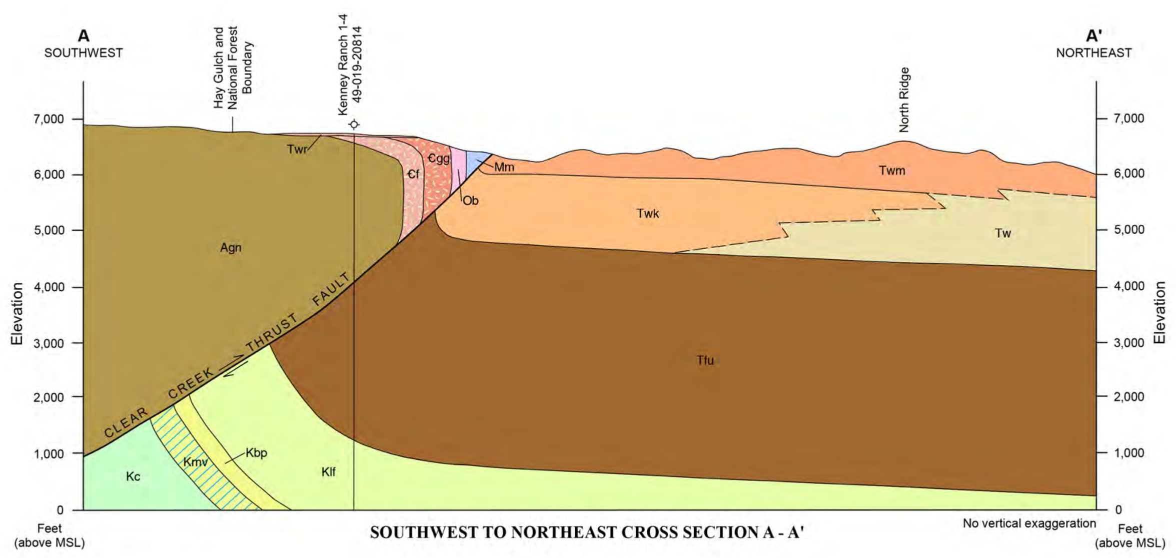
Archean

Aum **Trailside ultramafic complex (Neoarchean)**—Black to dark greenish-gray pyroxenite grading to norite toward the south-southwest. Forms low outcrops and grassy hills; outcrops weather to rusty brown. Pyroxenite can be foliated and is comprised of coarse-grained anhedral to subhedral orthopyroxene, clinopyroxene, and olivine, with minor magnetite, plagioclase, serpentine, and biotite. Norite is black, weathering to dark brown, medium-grained to pegmatitic, shows plagioclase-defined banding, and contains accessory hornblende, biotite, magnetite, ilmenite, pyrite, quartz, alkali feldspar, apatite, and chlorite. Description modified from Luth (1960). Norite was dated using U-Pb thermal ionization mass spectrometry at 2,683.6 ± 0.9 Ma in this study; samples were collected just west of the map area

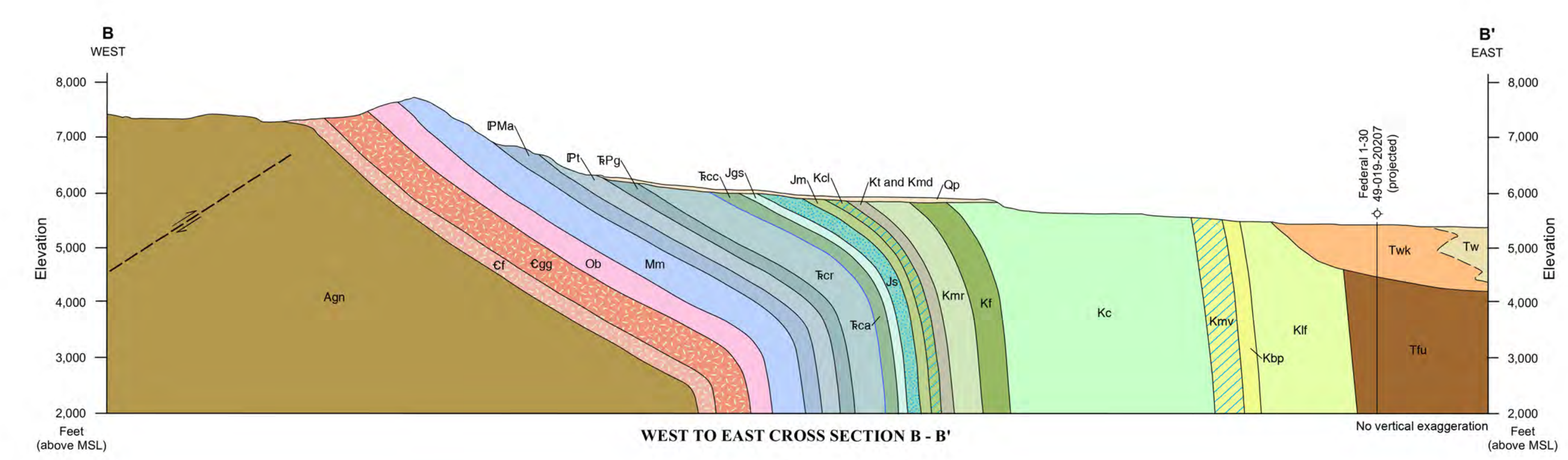
Agn **Granitic gneiss (Mesoarchean)**—Coarse- to medium-grained gray biotite-rich tonalitic gneiss dominates the southwest portion of the map area; hosts minor microcline, Fe-Ti oxides, titanite, zircon, allanite, epidote, and chlorite. Feldspar augen and more hornblende-rich varieties occur locally. Foliation ranges from poorly developed to clearly visible and is defined by compositional banding and deformed or aligned minerals. Weathers yellow, pink, or tan. Unit also includes amphibolites, quartzites, schists, and diorites (Frost and others, 2006), although only medium- to coarse-grained hornblende-rich diorite was observed within the map area. Thin pegmatite and aplite dikes locally cut the gneiss. Geochronology by Frost and Fanning (2006) indicate the tonalitic gneiss was emplaced at 2.89 Ga and the deformation event that created the foliation occurred between 2.89 Ga and 2.86 Ga

GEOPHYSICAL LOG





SOUTHWEST TO NORTHEAST CROSS SECTION A - A'



WEST TO EAST CROSS SECTION B - B'

WYOMING STATE GEOLOGICAL SURVEY
P.O. BOX 1347, LARAMIE, WY 82073
307-766-2286 • 307-766-2605 (fax)
wsgs.info@wyo.gov • www.wsgs.uwyo.edu
Director & State Geologist
Thomas A. Drean

Preliminary Geologic Map
of the
North Ridge Quadrangle
Johnson County, Wyoming

by

Ranie M. Lynds, Erin A. Campbell-Stone, and
Rachel N. Toner

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This report is preliminary and has not been reviewed for conformity with Wyoming State Geological Survey editorial standards or with the North American Stratigraphic Code.

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INTRODUCTION

The North Ridge quadrangle is located in north central Wyoming, on the western margin of the Powder River Basin and east flank of the Bighorn Mountains. Previous work in the area identified the Clear Creek Thrust Fault; this study identified an additional splay of the fault south of Highway 16. This study also provided more detailed mapping at a larger scale. Bedding and foliation orientations were documented across the map area, and faults were precisely located. Locations of the gradational contact between the Wasatch, Kingsbury and Moncrief units were more closely located where exposed. Mapping was completed in cooperation with the U.S. Geological Survey 2014 STATEMAP grant award G13AC00243.

Original mapping of the North Ridge quadrangle was undertaken for the 1:48,000 scale regional map by Mapel (1959). Following maps include a structural study and map by Hoppin (1961), a 1:50,000 map by Kanizay and others (1976), and the 1:100,000 Buffalo 30'x60' quadrangles by Heinrichs and others (1990) and by Ver Ploeg and Boyd (2002).

We wish to acknowledge and thank the landowners and caretakers for access to their private lands. This project would not have been possible without their generosity.

LOCATION

The North Ridge 1:24,000 quadrangle is located in northwestern Johnson County, Wyoming, in Townships 49, 50, and 51 north, and Ranges 82 and 83 west. The quadrangle is accessible via U.S. Highway 16, or the Cloud Peak Skyway, approximately 4.5 km (2.8 mi) to 15 km (9.3 mi) west of downtown Buffalo. Access to the quadrangle is also possible from the north via Upper French Creek Road and from the southeast via Klondike Road. Much of the area covered by the North Ridge 1:24,000 quadrangle is on private land and permission from the land owner must be obtained before entering private lands. Public access within the map includes the Bighorn National Forest along the western portion of the quadrangle and City of Buffalo property along Clear Creek.

GEOLOGIC SETTING

Exposures in the North Ridge 1:24,000 quadrangle record the formation and deformation of Archean gneiss, deposition of Paleozoic and Mesozoic units, the formation of the Laramide Bighorn uplift, and Tertiary sedimentation, exhumation and geomorphologic evolution. Archean gneiss was emplaced at ~2.89 Ga, and the foliation formed between 2.89 Ga and 2.86 Ga (Frost and Fanning, 2006). The gneiss is cut by the Trailside ultramafic complex dated at 2,683.7 ± 0.9 Ma (see Appendix) and by Paleoproterozoic mafic dikes (Kilian and others, in press). The overlying Paleozoic, Mesozoic, and Paleocene sections from the Cambrian Flathead sandstone through the Fort Union Formation were tilted and folded during the Laramide orogeny that uplifted the Archean basement during the Late Cretaceous to Eocene. The evolution of the uplift is recorded in the Eocene Wasatch Formation, and Kingsbury and Moncrief Members of the Wasatch Formation, which contain clasts reflecting unroofing of the basement rocks. The Oligocene White River Formation is a remnant of the fill that was deposited in the Powder River Basin and buried much of the Bighorn Mountains. The geomorphology created during exhumation is recorded by Quaternary pediments and terraces. Landslides, alluvium, and colluvium are the most recent deposits.

STRUCTURE

The dominant structure within the North Ridge 1:24,000 quadrangle is the Clear Creek Thrust Fault, which is exposed in the northern half of the map area. This Laramide thrust places Archean and Paleozoic hanging wall rocks over Tertiary syntectonic deposits (see cross section A-A' on map). The thrust system that uplifted basement rocks during the late Cretaceous to Paleogene consists of splays of thrust and reverse faults that are interpreted to be intermittently exposed at the surface, but may also exist as blind thrusts, and includes the Buffalo Deep Fault that has been imaged seismically in the Powder River Basin, east of the Bighorn Mountains (Robbins and Grow, 1992). In the southern portion of the map, the thrust fault system does not break the surface, but may consist of a single or multiple blind splay (see cross section B-B' on map). The thrust faults tilt overlying sedimentary units into orientations ranging from gently dipping to vertical or slightly overturned due to the proximity of the faults and amount of offset (Figure 1). Small tear faults are also present, marked by changes in dip or offset contacts. These smaller features are probably related to accommodation of movement on the larger thrust splays.

Figure 1. Dip change along range front looking south.

RADIOMETRIC DATING

Two samples were analyzed for radiometric ages from norite within the Trailside ultramafic complex. The analyses revealed a magmatic age of 2,683.7 ± 0.9 Ma for samples NR-13-6 and NR-13-7, which places them as younger than the 2.89 Ga gneiss (Frost and Fanning, 2006). Techniques and results are described in the Appendix. Both samples were collected just west of the map boundary.

DESCRIPTION OF MAP UNITS

Cenozoic Deposits and Sedimentary Rocks

Quaternary

Alluvium (Qa)

Alluvium in the map area consists of unconsolidated to poorly consolidated clay, silt, sand, gravel, and cobbles, mainly along river courses and in floodplains. The alluvial material is derived from all local geologic units. Alluvium generally ranges from 0 to 8 m (25 ft) in thickness.

Landslide Debris (Qls)

Landslide debris contains blocks and slumps of locally-derived bedrock. Landslides commonly form from steep slopes of the Gros Ventre and Gallatin Formations forming flow features and hummocky topography. Landslide debris is less than 37 m (120 ft) in thickness.

Alluvial Fan Deposits (Qaf)

Alluvial fan deposits are generally derived from the Kingsbury and Moncrief Members of the Wasatch Formation on the flanks of Kingsbury, Bald, and North Ridges, and they coalesce with landslides along the south bank of Clear Creek. They consist of unconsolidated subangular to subrounded cobble and boulder gravels in a coarse sandy matrix of sedimentary, igneous, and metamorphic rocks. Alluvial fan deposits range in thickness from approximately 0 to 15 m (50 ft).

Terrace Deposits (Qt1, Qt2, Qt3)

Terrace deposits are located on planar erosional surfaces along rivers and streams, reflecting terrace levels formed during erosion. The highest terrace levels are defined as ranging from 67 to 107 m (220 to 350 ft) above present river level; these are the oldest terraces, labeled as Qt3. Terraces at lower elevations are defined as Qt2, which range from 30 to 67 m (100 to 220 ft) above present river level, and as Qt1, which range from 3 to 30 m (10 to 100 ft) above present river level. These terrace designations are modified from Mapel (1959). Terrace deposits consist of unconsolidated to locally cemented silt, sand, gravel, cobbles, and boulders of sedimentary, igneous, and metamorphic rocks (Figure 2), with thicknesses generally less than 3 m (10 ft).

Figure 2. Terrace deposit.

Older Alluvium (Qao)

Older alluvial deposits are mainly found in higher stranded floodplains. They consist of unconsolidated to poorly consolidated clay, silt, sand, gravel, cobbles, and boulders derived from all local geologic units. The thickness is approximately 0 to 8 m (25 ft).

Older Alluvial Fan Deposits (Qafo)

Older alluvial fan deposits are those cut and overlain by terrace deposits and older alluvium. They consist of unconsolidated subangular to subrounded cobble and boulder gravels in a coarse sandy matrix of igneous, metamorphic, and sedimentary rocks. These deposits are found on the flanks of Bald Ridge and North Ridge, and the thickness is approximately 0 to 15 m (50 ft).

Pediment Deposits (Qp)

Pediment deposits are smooth surfaces that gently dip to the east less than five degrees and steepen to the west near the Pennsylvanian Tensleep Sandstone (Figure 3). These pediments are comprised of sedimentary, igneous, and metamorphic cobbles and boulders in an unconsolidated coarse sand matrix. The majority of the clasts are resistant limestones and dolostones. Local thickness is less than 3 m (10 ft).

Figure 3. Pediment surfaces gently dipping to the east.

Paleogene

White River Formation, Oligocene (Twr)

The White River Formation forms flat-topped ridges and treeless grassy areas on the western border of the map area, at elevations ranging from 2,036 m (6,680 ft) near Mosier Gulch to 2,391 m (7,845 ft) in Elgin Park. Outcrops are generally poorly-exposed flat-lying cobbles and boulders of rounded Precambrian igneous and metamorphic rocks.

The best exposures of the White River Formation are west of the map area along U.S. Highway 16 (Figure 4). At this road cut, boulders are moderately well rounded and up to 2 m (6.6 ft) in diameter. The clasts are poorly sorted, but the majority are 10 to 70 cm (4 to 28 in) in diameter and comprised entirely of white, gray, and black Precambrian rock. The cobbles and boulders are concentrated in discontinuous layers and can be either matrix- or clast-supported. The clast-rich layers are interbedded with meter-thick claystone and poorly sorted, medium- to coarse-grained, subangular clayey sandstone.

The lower contact is sharp when the White River Formation overlies the Paleozoic formations, but can be difficult to determine when it rests on the Archean gneiss. For consistency, the contact between the White River Formation and the Archean gneiss was placed at the slope break underlying the White River Formation. Thickness ranges from 30 to 75 m (98 to 245 ft).

Figure 4. Panorama of White River Formation along road cut west of the map on U.S. Highway 16.

*Wasatch Formation, Eocene (*Tw, Twm, Twk*)*

The Eocene Wasatch Formation is comprised of the main body of the Wasatch Formation, as well as the proximal alluvial fan facies of the Kingsbury and Moncrief Members.

*Main Body of the Wasatch Formation (*Tw*)*: The main body of the Wasatch Formation is a medium- to coarse-grained sandstone deposited from rivers draining the Bighorns to the west. The sandstone is light gray with orange staining, and exhibits 20 to 80 cm (8 to 31 in) high dune- and bar-scale crossbeds (Figure 5). The sandstone is generally a coarse-grained sublitharenite, with subangular to subrounded and moderately sorted clasts as large as 2 cm (0.8 in) in diameter. Mud ripups up to 4 cm (1.6 in) long are common. At some locations the sandstone is interbedded with conglomerate with subrounded metamorphic, igneous, and sedimentary clasts up to 6 cm (2.4 in) in diameter. Bedding on the scale of millimeters to centimeters is defined by a change in grain size and orange staining parallel to bedding.

Figure 5. Wasatch Formation exposed along Clear Creek.

The main body of the Wasatch Formation is the non-conglomeratic basinward facies of the Kingsbury and Moncrief conglomerates, and has a sharp unconformable contact that cuts down section west of Bald Ridge and North Ridge. The Wasatch is very poorly exposed on the gentle hills in the eastern portion of the map area, where small outcrops can be found along road cuts or underlying Quaternary terrace deposits. The best exposure of the Wasatch Formation is in the cliffs on the south side of Clear Creek, on the northeast flank of Bald Ridge. The Wasatch Formation is primarily exposed east of the map area where it infills much of the Powder River Basin, containing thick coal beds from Buffalo to Gillette. The distinctive burned coal beds (clinker) east of Buffalo are Wasatch Formation coals. The

Wasatch Formation is described as 152 m (500 ft) thick in the Crazy Woman Creek area (Hose, 1955) and more than 305 m (1,000 ft) thick in the Buffalo-Lake DeSmet area (Mapel, 1959). The upper contact of the Wasatch is gradational and interbedded with the Kingsbury and Moncrief Conglomerates.

*Moncrief Conglomerate Member (*Twk*)*: The Moncrief Conglomerate forms the resistant North Ridge and Bald Ridge that straddle Clear Creek and Highway 16. The Moncrief is poorly exposed and covered with vegetation on the slopes of these ridges, but forms a resistant flat-lying conglomerate capping both ridges.

Figure 6. Moncrief Member of the Wasatch Formation in the footwall of the Clear Creek Thrust Fault along U.S. Highway 16.

The Moncrief is well exposed along Highway 16 as part of the footwall of the Clear Creek thrust system (Figure 6). At this location, the Moncrief Conglomerate is a clast-supported generally brown conglomerate with grey, white, and dark clasts up to 2 m (6.6 ft) in diameter (Figure 7). Sixty to 75 percent of the clasts are rounded to subrounded, weathered Precambrian igneous and metamorphic rocks. The matrix is similar to that of the main body of the Wasatch Formation but contains more dark lithic fragments, giving the member its overall brown appearance. The matrix is angular to subangular, poorly sorted, ranges in grain size from medium to coarse, and is generally a sublitharenite with approximately 20 percent lithic fragments. The most notable difference between the Moncrief and Kingsbury conglomerates is that the Kingsbury contains clasts of primarily Mesozoic and Paleozoic sedimentary rocks while the Moncrief Member clasts are mostly igneous and metamorphic.

Figure 7. Typical Moncrief conglomerate outcrop with weathered Precambrian boulders.

The Moncrief Member unconformably overlies the Kingsbury Member, although this contact is not well exposed. On the west side of Bald Ridge, the Moncrief overlies the Cody Shale (although the contact is covered) suggesting more than 244 m (800 ft) of original depositional relief. The Moncrief also grades laterally into the main body of the Wasatch Formation. Along the east flank of Bald Ridge and the east and north flanks of North Ridge, the Moncrief-Wasatch contact was mapped near the base of the treed Moncrief slope, near the break in slope from steeper Moncrief to the underlying, less steep main body of the Wasatch, which approximately corresponds to the main mass of conglomerate and is consistent with mapping by Sharp (1948) and Mapel (1959). The Moncrief Member of the Wasatch Formation is mapped as approximately 400 m (1,312 ft) thick.

*Kingsbury Conglomerate Member (*Twk*)*: The Kingsbury Member of the Wasatch Formation consists of interbedded conglomerate, sandstone, siltstone, and claystone. The sandstone and siltstone are tan, brown, reddish-brown, and dark gray in beds a few centimeters to 1 m (3.3 ft) thick; some beds are carbonaceous. Conglomeratic lenses cut into these finer-grained layers and are filled with millimeter- to centimeter-sized clasts of subrounded to rounded sandstone, limestone, and more rare metamorphic rocks. The channel-cuts are up to 2 m (6.6 ft) thick, filled with clasts that commonly show imbrication near the base. Yellow to orange-brown nodules a few centimeters in diameter are haloed by yellow stains; they are present, but rare, in intermittent layers and comprise less than 5 percent of the layer. Other layers of siltstone exhibit maroon staining. The bedding is on the scale of 5 to 10 cm (2.0 to 3.9 in).

Figure 8. Kingsbury Ridge, comprised of the Kingsbury Member of the Wasatch Formation.

The best exposures of the Kingsbury Member are in the southeastern corner of the map along Kingsbury Ridge. Conglomerate lenses several meters thick form resistant tree and bush-covered ridges that generally parallel strike; sandstones and siltstones form slopes that are generally devoid of bushes and are less resistant (Figure 8). Clasts are in the gravel to cobble range, and can be up to 10 cm (3.9 in) in diameter. Clasts are primarily subrounded with moderate sphericity.

The Kingsbury Member has been interpreted as a synorogenic alluvial fan deposit showing progressive unroofing of the Bighorn Mountains (Mapel, 1959; Hoy and Ridgway, 1997). Clasts change from mostly Paleozoic limestones and sandstones near the base, to Precambrian igneous and metamorphic rocks near the top, with rare recycled Kingsbury Member clasts at the top of Kingsbury Ridge (Hoy and Ridgway, 1997). The Kingsbury Member dips 40 to 50 degrees to the east, and has a sharp erosive and unconformable basal contact that progressively overlies the Fort Union Formation, Lance Formation, Bearpaw Shale, and Mesaverde Formation on the west to northwest side of Kingsbury Ridge. Along Johnson Creek, the Kingsbury Member is overturned in the footwall of the Clear Creek Thrust Fault (Figure 9). The Kingsbury Member grades laterally into the main body of the Wasatch Formation to the east. In most places, neither the upper nor lower contacts are well exposed, and are mapped based on dip, slope break, and bush-forming conglomeratic ridges. As mapped, the Kingsbury Member is approximately 213 m (700 ft) thick.

Figure 9. Overturned Kingsbury Member in the footwall to the Clear Creek Thrust Fault along Johnson Creek.

*Fort Union Formation, Paleocene (*Tfu*)*

The Paleocene Fort Union Formation is very poorly exposed within the map area. Sparse outcrops can be found in drainages on the west side of Kingsbury Ridge (Figure 10). Outcrops consist of 1 to 3 cm (0.4 to 1.2 in) thick beds of medium-grained, moderately round and sorted sandstone Sandstones crop out as brown lenses, but fresh surfaces are light gray. Ferruginous and friable calcareous sandstone with yellow and purple alteration is common. Hose (1955) describes the lower 152 m (500 ft) of the Fort Union as ferruginous sandstone ledges interbedded with siltstone and shale, overlain by 579 m (1,900 ft) of less resistant siltstone and shale, with fewer ferruginous sandstone ledges. A few miles southeast of the map area the Fort Union is 1,204 m (3,950 ft) thick (Hose, 1955), but only the basal 518 m (1,700 ft) of Fort Union Formation is exposed on the North Ridge quadrangle; the upper Fort Union is buried under Kingsbury Ridge. Although described elsewhere, no Fort Union coals are exposed on the North Ridge quadrangle.

Figure 10. Fort Union Formation outcrops on west side of Kingsbury Ridge.

The lower contact with the underlying Lance Formation is the Cretaceous-Tertiary (Paleogene) boundary, which is marked by a thin clay layer elsewhere in the Powder River Basin (Connor, 1992). However, the Lance-Fort Union contact is not exposed in the map area, and is placed below the first ferruginous sandstone.

Mesozoic Sedimentary Rocks

Cretaceous

*Lance Formation and Fox Hills Sandstone, undivided (*Klf*)*

The Upper Cretaceous Lance Formation is a coarsening-upward, light-gray to yellow, fine- to medium-grained fluvial sandstone interbedded with thin, dark carbonaceous shales and coals. Outcrop exposures are poor, with the exception of a channelized lens of sandstone exposed west of Kingsbury Ridge and east of Klondike Road, near the southern border of the map. This several-meter-thick, friable outcrop is a dune-scale, cross-bedded, calcareous, fine-grained sandstone that grades upward into ripples in the upper 1.5 m (5 ft). The sandstone contains as much as 15 percent lithic fragments, but is otherwise composed of quartz grains. The Lance Formation is approximately 518 m (1700 ft) thick on the west side of Kingsbury Ridge, where it is exposed as sub-vertical beds of poorly exposed non-resistant sandstone (Figure 11). The Lance Formation is equivalent to the Hell Creek Formation in Montana.

Figure 11. Sub-vertical thin sandstone beds of the Lance Formation exposed along Klondike Road.

The base of the Lance Formation intertongues with and conformably overlies the Fox Hills Sandstone, which is not exposed on the North Ridge quadrangle, but is penetrated by all three wells on the quadrangle (see map for well locations) and is distinguishable on a clean gamma ray geophysical log by a few thin beds of high gamma signature, and generally high resistivity. The Fox Hills Sandstone grades conformably from the underlying Bearpaw Shale through a succession of marginal marine sandstones, siltstones, and shales. The Fox Hills Sandstone itself is a massive, coarsening-upward, light- to yellowish-gray or greenish-brown non-calcareous sandstone interfingered with dark sandy shales and siltstones (Ver Ploeg and Boyd, 2002). The Fox Hills Sandstone varies from 23 to 27 m (76 to 90 ft) thick, as interpreted from geophysical logs, and both the Lance Formation and Fox Hills Sandstone have a combined thickness of 541 to 545 m (1,723 to 1,727 ft).

*Bearpaw Shale (*Kb*)*

The Upper Cretaceous Bearpaw Shale represents the last deepwater shale deposited by the Cretaceous Interior Seaway. Within the North Ridge quadrangle, the unit is referred to as the Bearpaw Shale, but toward the south end of the western Powder River Basin it is referred to as the Lewis Shale, which is the common name elsewhere in Wyoming.

The Bearpaw Shale is not exposed in outcrop on the North Ridge quadrangle, but is visible on geophysical logs and was mapped based on log thickness. The Bearpaw is a non-resistant shale on the west side of Kingsbury Ridge, where it is covered by vegetation. Hose (1955) describes the Bearpaw

Shale in the Crazy Woman Creek area as "dark-greenish-gray shale with light-gray siltstone laminae." Both the upper and lower contacts are conformable and gradational. Geophysical logs show the Bearpaw Shale to be approximately 91 to 105 m (300 to 344 ft) thick.

*Mesaverde Formation (*Kmv*)*

The Upper Cretaceous Mesaverde Formation consists of the Parkman Sandstone at the base, overlain by an unnamed shale, and capped by the Teapot Sandstone. Only the Parkman Sandstone Member crops out on the North Ridge quadrangle, but the unnamed shale and Teapot Sandstone are visible on geophysical logs. The Mesaverde Formation is approximately 168 to 175 m (550 to 575 ft) thick.

The Parkman Sandstone crops out as a light orange-brown ridge 0 to 15 m (49 ft) thick, with 20-cm to 1-m thick (8 in to 3 ft) siltstone interbeds and sandstone layers 2 to 3 m (7 to 10 ft) thick. The sandstone is tan and weathers to yellow-tan, and is plane-bedded with low-relief truncation surfaces, as well as crossbeds up to 1 m (3 ft) thick. This sublitharenite is fine-grained, well sorted and rounded, and exhibits brown iron concretions a few centimeters to a few meters in diameter, mantled with an orange stain. Outcrops are exposed as sharp sub-vertical fins with significant fractures (Figure 12). The upper and lower contacts of the Parkman Sandstone are not exposed, but are conformable with the Cody Shale and the overlying unnamed shale member of the Mesaverde. The Parkman Sandstone Member is equivalent to the Judith River Formation of Montana. Thickness is approximately 100 m (328 ft).

Figure 12. Typical vertical fin of Parkman Sandstone Member of the Mesaverde Formation.

*Cody Shale, Niobrara Formation, and Carlile Shale, undivided (*Kc*)*

The Upper Cretaceous Cody Shale is rarely exposed on the North Ridge quadrangle and generally forms grass-covered slopes and valleys (Figure 13). In the map area, the Niobrara Formation and Carlile Shale are not exposed in outcrop, and are grouped with the Cody Shale for mapping purposes. However, geophysical well logs in the map area make it possible to differentiate members within the Cody Shale, including the Sussex Sandstone and Shannon Sandstone Members, as well as the Niobrara Formation and the Carlile Shale. The full, undivided succession is 884 to 915 m (2,900 to 3,000 ft) thick determined from well logs, and has a conformable upper contact with the Parkman Sandstone at the base of the Mesaverde Formation and a conformable basal contact with the underlying Frontier Formation.

The Cody Shale is dark bluish-gray calcareous marine shale interbedded with light- to medium-gray fine-grained sandstones and siltstones and abundant gray and brownish-gray bentonite beds. The only sandstone exposure observed within the map area was a resistant outcrop with concretions up to

2 m (6.6 ft) in diameter and orange spar calcite veins. This may correlate to the Sussex or Shannon Sandstone Members, although field identification of these sandstones is tenuous at best. Geophysical logs show the Sussex Sandstone Member as approximately 8 m (25 ft) thick, and the Shannon Sandstone Member as 37 m (120 ft) thick.

Figure 13. Typical grass-covered slopes of the Cody Shale, Niobrara Formation, and Carlile Shale.

The Niobrara Formation is identifiable on well logs as 186 to 197 m (610 to 645 ft) thick. South of the map area near Elgin Creek, it is 300 m (985 ft) (Mapel, 1959) and consists primarily of dark-gray shale with minor interbeds of bentonite, and becomes increasingly calcareous toward the top of the member (Mapel, 1959).

The Carlile Shale Member is 102 to 122 m (335 to 400 ft) thick based on geophysical well logs, and 48 m (156 ft) thick near Elgin Creek (Mapel, 1959). Mapel (1959) describes the Carlile Shale as consisting of a lower unit of interbedded dark-grey shale and light-gray fine-grained sandstone, a middle unit of dark-gray siltstone with ironstone concretions, and an upper unit of dark-gray shale with fossiliferous dark-gray limestone concretions up to 30 cm (1 ft) in diameter.

Frontier Formation (Kf)

The Upper Cretaceous Frontier Formation contains interbedded thin sandstones, shales, and bentonitic horizons (Figure 14). Shales are generally dark to medium gray, non-calcareous, silty and fissile claystones that break into beds a few millimeters thick. The shales extend for 10 to 20 m (33 to 66 ft). Thin sandstones are generally millimeters to a few centimeters in thickness, very fine to fine-grained, subrounded to subangular and well-sorted litharenites to sublitharenites. The sandstones generally weather orange. Bentonite, interbedded throughout the formation, is observable as medium- to light-gray popcorn-weathering slopes commonly several meters thick. Seven meters below the top of the formation is a poorly-sorted, coarse-grained 1-m (3-ft) thick dark gray limestone topped by a 15-cm (6-in) thick coquina with shell fragments as large as 5 cm (2 in). These layers form a low, resistant ridge that weathers orange-brown.

Figure 14. Small fold observed at Frontier-Mowry contact.

The basal contact of the Frontier is the Clay Spur Bentonite Bed, which was not observed in outcrop in the map area, but is visible on geophysical logs. On the map, the basal contact is placed above the last observable Mowry Shale outcrop and before the first thin sandstone of the Frontier Formation, on a non-resistant grass-covered slope with an accuracy of 10 to 15 m (33 to 49 ft). The upper contact with the overlying Cody Shale is generally covered, but is observed south of the map area as a black chert pebble conglomerate (Hose, 1955). In places, well-rounded black chert pebbles up to 2 cm (0.8 in) in diameter can be found densely distributed on the soil; the contact was placed at this dense accumulation wherever possible. Although Mapel (1959) mapped the Frontier Formation as 152 m (500 ft) thick south of the map area near Dry Muddy Creek, geophysical logs and current mapping show the Frontier Formation to be approximately 198 m (650 ft) thick at this location.

*Mowry Shale (*Kmr*)*

The Upper Cretaceous Mowry Shale is a siliceous siltstone and, in places, claystone, that forms low-lying light-gray hills. The basal Mowry Shale is a poorly-exposed dark gray, thinly-bedded, and fissile siltstone and claystone. Fish scales are common. The upper more siliceous Mowry crops out as light gray hills with minimal vegetation (Figure 15). The upper beds are silvery-gray, millimeter to centimeter in scale, and fish scales are also common. The underlying contact with the Muddy Sandstone is abrupt but conformable. The overlying contact with the Frontier Formation is at the Clay Spur Bentonite, the uppermost bed of the Mowry Shale, and is usually a covered interval. The Mowry Shale is 122 m (400 ft) thick in the map area.

Figure 15. Typical silicious Mowry Shale outcrop showing continuous thin bedding.

*Muddy Sandstone (*Kmd*)*

The Lower Cretaceous Muddy Sandstone, equivalent to the Newcastle Sandstone in the eastern Powder River Basin, abruptly overlies the Thermopolis Shale as a 0 to 16-m (52 ft) thick sandstone. Thickness is variable due to the valley-filling depositional environment of the Muddy Sandstone. Trees commonly define the outcrop in an otherwise treeless, grassy landscape. Outcrops are generally a fine- to medium-grained, light-gray to white, friable quartzite sandstone with centimeter-scale cross beds (Figure 16). Some highly altered outcrops near the southern map border are orange-brown and covered in orange lichen. The upper contact is abrupt but conformable with the overlying

Figure 16. Muddy Sandstone.

Mowry Shale, while the basal contact is abrupt but uncomformable with the underlying Thermopolis Shale.

*Thermopolis Shale (*Kt*)*

Equivalent to the Skull Creek Shale in eastern Wyoming, the Lower Cretaceous Thermopolis Shale is a non-resistant dark gray marine shale. The upper half of the formation is soft, black, flaky shale, while the lower Thermopolis Shale contains interbedded black shales and light-gray to brown siltstones (Mapel, 1959) and can be difficult to discern from the underlying conformable Cloverly Sandstone. The lower contact is marked by a resistant brown siltstone with dahllite concretions (Mapel, 1959). The Thermopolis Shale is very poorly exposed in the map area and is only discernible at a few localities where the soil is very dark gray. The thickness ranges from 46 to 61 m (150 to 200 ft) on geophysical logs, and is described as 38 to 50 m (125 to 165 ft) thick by Hose (1955) and Mapel (1959).

*Cloverly Formation (*Kcl*)*

The base of the Lower Cretaceous Cloverly Formation is a 5- to 14-m (15- to 45-ft) thick, fine-grained unaltered white quartz arenite sandstone that weathers yellowish tan. The sandstone is 98 percent rounded to subrounded, fine, frosted quartz grains, and two percent fine, subrounded black lithics. Other than this basal sandstone, the shale beds of the Cloverly Formation do not crop out but form gentle grass-covered slopes. The contact with the overlying Thermopolis Shale is gradational and not exposed. Previous investigations place the upper contact at a resistant siltstone ledge below which are brown siltstone beds (often termed the "rusty beds" or "Dakota silt") with dahllite concretions (Hose, 1955; Mapel, 1956; Fox, 1993). The basal contact is sharp and unconformable. Due to lack of exposure in this area, the Cloverly-Thermopolis contact was mapped using the 41-m (135-ft) thicknesses observed from geophysical logs. North of Muddy Creek, Mapel (1959) measured the Cloverly at 48 m (156 ft).

Jurassic

*Morrison Formation (*Jm*)*

The Upper Jurassic Morrison Formation is a non-resistant series of siltstones and claystones with rare thin sandstone interbeds. In the vicinity of Kelly Creek near the southern border of the map, the Morrison claystones display typical Morrison variegated coloring of light-purple to light-pink, gray, and white. Sandstone outcrops are uncommon, but when found can be friable to concretionary, fine-grained, light-gray to medium-brown sublitharenite, with cross-stratification on the order of 0.5 m (1.5 ft) (Figure 17). Sandstones are presumably channelized, and are laterally

Figure 17. Tabular cross-stratified sandstone within variegated siltstones and claystones in the Morrison Formation. Sandstone approximately 1.5 m (5 ft) thick.

discontinuous on the scale of several hundred meters. According to the caretaker of the private land on which all of the Morrison outcrops occur, many of these sandstone outcrops have been excavated for dinosaur fossils. These excavations help mark the boundaries of the Morrison Formation.

A distinct, resistant, 1- to 3-m (3- to 10-ft) thick, concretionary, ripple- and dune-scale cross-stratified, calcareous brown sandstone marks the sharp, unconformable lower contact with the Sundance Formation, and can be traced for 2.4 km (1.5 mi) on the southwest side of Bald Ridge. The abrupt upper contact is ubiquitously covered and was mapped using the geophysical log thickness of 50 m (165 ft). Regional thicknesses have been recorded up to 56 m (185 ft) (Hose, 1955).

*Sundance Formation (*Js*)*

The Upper and Middle Jurassic Sundance Formation is poorly exposed throughout the map area and commonly forms grass-covered slopes with no outcrop, with some greenish-gray shales present near the base. Belemnites and *Gryphaea*, common throughout the Sundance Formation elsewhere in Wyoming, were rarely observed in the map area but have been noted in nearby exposures (Hose, 1955; Mapel, 1959).

The abrupt basal contact was mapped at greenish-gray flaggy limey sandstone that is 5 to 10 cm (2 to 4 in) thick, above which lies brown soil and no outcrops. The upper contact with the overlying Morrison Formation is sharp and was placed at a 1- to 3-m (3- to 10-ft) thick, dune-scale cross-stratified and rippled calcareous and concretionary brown sandstone. This upper sandstone is tan and weathers to gray. It is a very fine to fine-grained, moderately well rounded, well-sorted, quartzarenite with some frosted quartz grains in a calcareous cement. The Sundance Formation is approximately 61 m (200 ft) thick based on well logs, and has a regional thickness of 87 m (285 ft) (Hose, 1955; Mapel 1959).

*Gypsum Spring Formation (*Jgs*)*

The lower 20 meters (66 ft) of the Middle Jurassic Gypsum Spring Formation consists of dark-red claystone and shale with occasional discontinuous beds of gypsum (Mapel, 1955). It forms grassy slopes with unremarkable ridges of thin limestone (5 to 10 cm, 2 to 4 in, thick), and orange to rusty-orange soil with mineral-licks used by local wildlife (Figure 18).

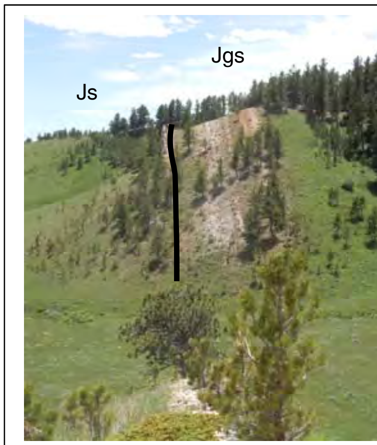

Figure 18. Contact between the Gypsum Spring Formation (right) and the Sundance Formation (last resistant outcrop on the left).

The upper 30 meters (98 ft) contains interbedded layers of gray to greenish-gray siltstone, light-gray limestone, and rusty-red siltstone. The white to tan siltstone layers are 5 to 8 cm (2 to 3 in) thick and comprise 30 percent of the outcrop. The gray limestone layers are less than 0.5 m (1.6 ft) thick, and display thin (millimeter scale) bedding of argillaceous shale. The gray limestone layers are thin and platy, with micrite and crystalline limestone comprising up to 20 percent of the outcrop. Poorly exposed, 5- to 8-m (16- to-25 ft) thick, rusty-red siltstones with rare 2- to 4-cm (1- to 2-in) thick chert interbeds comprise 50 percent of the outcrop.

The upper contact of the Gypsum Springs Formation is marked by 5- to 10-cm (2- to 4-in) thick greenish-gray, flaggy limestone. The Gypsum Springs Formation unconformably overlies the Crow Mountain Member of the Chugwater Formation, and the contact is distinct when exposed southwest of Bald Ridge and difficult to determine when covered near the southern border of the map. The Gypsum Springs Formation is 49 to 50 m (160 to 165 ft) thick based on well log thickness, and has been measured regionally at 44 to 56 m (145 to 185 ft) in the Buffalo-Lake De Smet region (Mapel, 1959), and 37 m (120 ft) at Elgin Creek (Hose, 1955).

Triassic

Chugwater Formation (TRcr, TRca, TRcc)

The Triassic Chugwater Formation is comprised of three members; the upper Crow Mountain, middle Alcova Limestone, and basal Red Peak Member, for a total thickness of approximately 232 m (760 ft). The upper Popo Agie member, present in central Wyoming, is not exposed or present(?) in this map area.

Crow Mountain Member (TRcc): The Crow Mountain Member is light pink to salmon red when fresh and weathers to bulbous orange-salmon-colored semi-friable bluffs (Figure 19). This quartzarenite is a very fine to fine-grained, well-sorted, subrounded clean sandstone. Although the Crow Mountain Member is often poorly exposed and forms grassy slopes of reddish soil, rare outcrops contain cross-stratified sandstone in beds up to 0.5 m (1.6 ft) thick. The Crow Mountain Member is 15 to 26 m (50 to 85 ft) thick. The basal contact is sharp, and the upper contact is unconformable.

Figure 19. Salmon-orange outcrops of the Crow Mountain Member.

Alcova Limestone Member (TRca): The Alcova Limestone is an obvious ridge of pale pinkish-gray, or purplish-gray micritic limestone, 4 to 5 m (13 to 15 ft) thick (Figure 20). Limestone is in beds 3 to 8 cm (1 to 3 in) thick, containing rare stylolites. The lower and upper 5 to 10 cm (2 to 4 in) contains wavy lamina characteristic of the Alcova Limestone throughout Wyoming. The basal contact is sharp and unconformable, and the upper contact is sharp.

Figure 20. Alcova Limestone Member of the Chugwater Formation.

Red Peak Member (Ꞧcr): The 206-m (675-ft) thick Red Peak Member is exposed only below the resistant ledge of the Alcova Limestone Member as a reddish-orange and reddish-brown, poorly sorted, ripple- and dune-scale cross-stratified sandstone and siltstone (Figure 21). The lower portion is poorly exposed and forms valleys. Trees and bushes are sparser than on the Goose Egg Formation or Alcova Limestone Member. The lower contact with the Goose Egg Formation is conformable and distinct when exposed, however, the contact is rarely observed in outcrop and is mapped at the slope break from the more resistant Goose Egg to less resistant Red Peak. A 1.5-m (5-ft) thick brecciated limestone may be exposed at the basal contact, and appears to be causing the change in slope between formations. The upper contact with the Alcova Limestone is sharp. Regionally the unit thins from 221 m (726 ft) south of the map area to 146 m (480 ft) near Sheridan, Wyoming (Hose, 1955; Mapel, 1959). The basal contact is sharp and conformable.

Figure 21. Alcova Limestone capping the Red Peak Member.

Mesozoic and Paleozoic Sedimentary Rocks

Triassic and Permian

Goose Egg Formation (ꞦPg)

The Lower Triassic and Permian Goose Egg Formation is poorly exposed within the map area and is mappable as non-resistant red and reddish-brown soils and slopes. Trees commonly grow on these slopes, further hindering the exposures, but thick-bedded white gypsum is exposed in places (Figure 22). The Goose Egg Formation is the lateral gypsiferous equivalent to the Phosphoria Formation. The base of the Goose Egg lies in sharp unconformable contact with the underlying Tensleep Sandstone. The basal contact was mapped above the last resistant Tensleep Sandstone outcrop where the soil changes from gray (Tensleep) to reddish-brown (Goose Egg). The top of the Goose Egg has a 1.5-m (5-ft) thick brecciated limestone as described by Mapel (1959) and Hose (1955). The upper contact was mapped at this limestone when it was visible holding up small hills or in meter-scale float. The upper contact is conformable with the overlying Chugwater Formation. The Goose Egg Formation is 49 to 64 m (160 to 210 ft) thick in the map area, and 76 m (250 ft) thick to the south in the Crazy Woman Creek Area (Hose, 1955).

Figure 22. Gypsum in the Goose Egg Formation.

Paleozoic Sedimentary Rocks

Pennsylvanian

*Tensleep Sandstone (*IPt*)*

The Middle and Upper Pennsylvanian Tensleep Sandstone crops out along the eastern flank of the Bighorn Mountains as range-bounding ridges along the southern half of the map (Figure 23). It forms fins and hogbacks of weathered yellow, tan, and buff-colored sandstone that is light tan to light gray on fresh surfaces. The formation is predominantly very fine to medium-grained quartzarenite sandstone with clean, moderately well-rounded, well-sorted, and commonly frosted quartz grains. Tabular and trough cross-stratification up to several meters in height are prevalent. The cement is generally silicious, but can be locally carbonate. In places, the Tensleep Sandstone weathers to round sandstone nodules 1 cm (0.4 in) in diameter that are more resistant than the surrounding sandstone, and the unit occasionally exhibits nodules or stringers of gray chert. The Tensleep Sandstone is interbedded with blue-gray limestone layers that form less resistant, covered slopes. The upper contact with the Goose Egg is unconformable and sharp, and is mapped above the last prominent sandstone layer and at the change in soil color from gray (Tensleep) to reddish-brown (Goose Egg). The basal contact with the Amsden Formation is sharp and marked by a change from resistant sandstone to the slope-forming dolomites, sandstone and siltstone of the Amsden Formation. The Tensleep Sandstone was measured at 85 m (280 ft) thick at Sayles Creek, north of the map area (Mapel, 1959) and at 108 m (355 ft) thick in the Crazy Woman Creek area, south of the map area (Hose, 1955).

Figure 23. Tensleep Sandstone forms prominent white ridge at the base of the treed slope.

Pennsylvanian and Mississippian

*Amsden Formation (*PMa*)*

The Middle and Lower Pennsylvanian and Upper Mississippian Amsden Formation is a slope forming unit, mostly covered with pine trees and small vegetation (Figure 24). The top of the unit consists of 1 m (3 ft) of platy, purplish-brown, very fine grained, rounded, well-sorted quartzarenite, interbedded with shale on a scale of 1 to 2 m (3 to 7 ft). The upper 15 m (49 ft) alternates between small ledges of gray-green limestone and dolomite with wavy bedding, interbedded with layers of purple and red dolomite, and covered slopes of shale. Most of the formation is not exposed, but in the lower half of the unit, within a section of slope-forming siltstone, there are 2 m (7 ft) of light tan, cross-stratified, sandy limestone, that weathers grayish tan. At the base of the Amsden Formation is a fine-grained, red quartzarenite with rounded to subrounded, well-sorted grains and red hematite cement. The beds are 3 to 20 cm (1 to 8 inches) thick and interbedded with slope forming siltstone and 0.5 m (20 inch) thick gray limestone. The upper contact with the Tensleep Sandstone is mapped at the lowest resistant sandstone (Tensleep), above the slope-forming dolomites, sandstone and siltstone of the Amsden Formation. The basal contact is marked by a sharp change from slopes covered with red soil to resistant carbonates of the Madison Limestone. The Amsden Formation is 76 m (250 ft) thick (Hose, 1955; and Mapel, 1959).

Figure 24. Typical poorly exposed red sandstone of the Amsden Formation.

Mississippian

*Madison Limestone (*Mm*)*

The Upper and Lower Mississippian Madison Limestone is a resistant unit that forms the highest ridges along the eastern range front (Figure 25). The lowest layers of the Madison Limestone form the crest, and the middle and upper parts of the unit form steep dip slopes. It consists of tan to gray limestone, dolomitic limestone, and dolostone that weather to yellowish-tan or bluish-gray with dark-gray stain. The bedding is thin to massive, and the unit contains rare orange-brown chert nodules and chert horizons. Near the base it hosts sandy, yellow limestone beds that weather to yellowish-gray, with cross-stratification 10 to 30 cm (4 to 12 in) high.

Figure 25. Sub-vertical resistant Madison Limestone.

The upper surface is locally karsted and filled with Darwin Sandstone (Ver Ploeg and Boyd, 2002), and the upper contact is sharp and unconformable. The basal contact is sharp and unconformable, and cuts out the Bighorn Dolomite to the south (Hose, 1955). The Madison Limestone is 168 to 204 m (550 to 679 ft) thick (Hose, 1955; Mapel, 1959).

Ordovician

*Bighorn Dolomite (*Ob*)*

The Bighorn Dolomite forms large west-facing cliffs (Figure 26) and pointed fins of tan to light gray dolostone. The main, middle body of the unit is massively bedded on a scale up to 3 m (10 ft) and weathers to a distinctive yellowish-tan with dark-gray staining, and a mottled, pocked, and fretted surface. The Bighorn Dolomite locally contains rounded or irregular, gray, white and brown chert nodules that comprise less than 5 percent of the outcrop. The lower 20 m (65 ft) of the unit is non-resistant, friable, light-gray to red, fine-grained quartzarenite with well-rounded, well-sorted grains, topped by a 1 m (3 ft) yellowish-gray calcareous sandstone (Mapel, 1959). This may be the Harding Sandstone equivalent (Love and others, 1993). The upper 30 meters (100 ft) is more thinly bedded, locally brecciated, and is often eroded, forming a slope covered by pine trees and talus of Madison Limestone.

The Bighorn Dolomite is truncated by the overlying Madison Limestone, and decreases in thickness to the south from 120 m (395 ft) in the Buffalo-Lake De Smet region (Mapel, 1959), to 46 m (150 ft) near the southern end of the Bighorn Mountains (Hose, 1955). Within the map area, the Bighorn Dolomite is between 108 and 120 m (355 and 395 ft) thick (Hose, 1955; Mapel, 1959). The basal contact is sharp and unconformable.

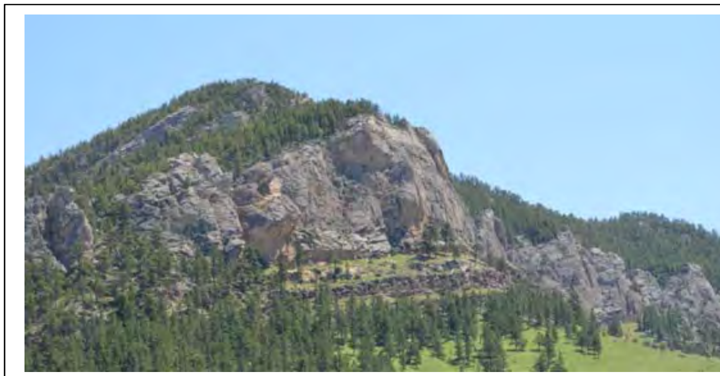

Figure 26. Bighorn Dolomite forms the massive cliffs, overlain by the Madison Limestone and underlain by the less resistant Gallatin and Gros Ventre Formations.

Cambrian

Gallatin and Gros Ventre Formations, undivided (Ꞓgg)

The Upper and Middle Cambrian Gallatin and Gros Ventre Formations form grassy slopes with poor exposure beneath bold cliffs of the Bighorn Dolomite. They are best exposed along U.S. Highway 16 (Figure 27). Small to large landslides are common within these formations.

The Gallatin Formation consists of grayish-red, thinly bedded limestone interbedded with green and red shale. It contains distinctive layers of greenish-gray flat-pebble limestone conglomerate. The Gallatin is often exposed just beneath the Bighorn Dolomite as 18 to 27 m (60 to 90 ft) cliffs of slabby, thinly bedded, light-gray and grayish-red limestone interbedded with pink, red, and green shale and shaly limestone. Near the upper contact is a 1- to 3-m (3- to 10-ft) thick, very fine grained, white sublitharenite with calcite cement. The lower contact of the Gallatin is gradational with the less resistant Gros Ventre Formation.

Figure 27. Gallatin and Gros Ventre Formations exposed along U.S. Highway 16.

The Gros Ventre Formation consists of greenish-gray glauconitic sandstone interbedded at the centimeter scale with brown and gray sandstone and siltstone beds up to 0.5 m (1.6 ft) thick, grayish-green limestones up to 0.3 m (1 ft) thick, and grayish-green, flat-pebble limestone conglomerate (Figure 28). Shale in the middle of the unit exhibits ripple marks and worm burrows. Toward the base of this unit is a 37- to 46-m (120- to 150-ft) thick medium-grained glauconitic, brownish-green to light-tan sandstone with rounded to subangular grains (Hose, 1955). This unit is poorly or rarely exposed, and forms gentle slopes.

Figure 28. Flat-pebble conglomerate typical of both the Gallatin and Gros Ventre Formations.

Although rarely exposed, the basal contact is sharp but conformable. It can be identified by a change in slope from the gentle Gros Ventre to the steeper Flathead, or can be located at the low point of a saddle or valley. The total thickness of the Gros Ventre and Gallatin Formations ranges from 168 to 197 m (550 to 645 ft) (Hose, 1955; Mapel, 1959).

Flathead Sandstone (€f)

The Middle Cambrian Flathead Sandstone is a tan to yellowish-gray, medium- to coarse-grained quartzarenite to sublitharenite. It weathers to orange, red, or brown and is commonly covered with lichen (Figure 29). It forms rounded ridges covered with grass or pine trees, and crops out along hillsides or small ridges. Grains are subrounded to rounded, equant, and well sorted. The Flathead Sandstone displays bedding up to 1 m (3 ft) thick and low-angle tabular cross-stratification at a scale of 0.5 m (1.6 ft).

The upper contact is sharp but conformable, and is commonly covered by grass or small landslide deposits of the overlying Gallatin and Gros Ventre Formations. Where covered, the contact can be inferred at a steepening in slope; the Gros Ventre forms gentle slopes, while the Flathead forms steeper cliffs. In places the contact between the Gros Ventre and Flathead lies in a saddle or streambed, with the Gros Ventre forming a gentle slope on one side of the valley and the Flathead a steeper slope on the other side.

Figure 29. Flathead Sandstone with low-angle tabular cross-stratification.

The contact between the Flathead and the Archean Gneiss is a nonconformity marked by a 0.6 to 1.5 m (2 to 5 ft) basal conglomerate of subrounded chert pebbles less than 3 cm (1.2 in) in diameter. The thickness of the Flathead Sandstone ranges from 79 to 105 m (260 to 344 ft) (Hose, 1955; Mapel, 1959).

Paleoproterozoic

Mafic dikes (Xmd)

Figure 30. Diabase dike.

Diabase dikes generally form rounded resistant ridges, and may have grassy cover within the forested area of the granite gneiss (Figure 30). The dikes are 1 to 3 m (3 to 10 ft) wide, fine- to medium-grained, dark gray to black diabase that weathers brownish-gray with red staining and gray lichen. The dikes are comprised of euhedral tabs to needles of plagioclase up to 3 mm (0.1 in) long, subhedral pyroxene 1 to 2 mm (0.04 to 0.08 in) long that weathers to reddish-brown pits, and stubby black subhedral hornblende crystals 1 to 2 mm (0.04 to 0.08 in) long. The mafic dikes in the map area generally strike N40°–45°E. Kilian and others (in press) indicate that dikes in the central Bighorn Mountains with this trend were emplaced into the Archean granitic gneiss at ~2,155± 2 Ma.

Archean

*Trailside ultramafic complex (*Aum*)*

The Neoarchean Trailside ultramafic complex is located along and to the south of U.S. Highway 16. This black to dark-greenish-gray ultramafic body (Figure 31) intrudes the Archean gneiss, and was named the Trailside complex by Luth (1960). It is primarily pyroxenite throughout its northern and eastern extent and grades to norite in the south-southwest. The pyroxenite forms low outcrops and hills that are often covered with grass. Fresh outcrops are black and weather to rusty brown. The pyroxenite is composed of anhedral black orthopyroxene 1 to 3 cm (0.4 to 1 in) in length, subhedral black clinopyroxene 0.5 to 1 cm (0.2 to 0.4 in) long, subhedral green olivine 1 to 2 mm (<0.1 in), with minor magnetite, plagioclase, serpentine, and biotite. Luth (1960) suggests that the pyroxenite varied from bronzite to the north to websterite in the south. Foliation is intermittent within the pyroxenites, and is defined by aligned minerals.

In the southern part of the intrusion, black, medium-grained to pegmatitic, friable norite weathers easily to a dark brown color, making fresh outcrops rare. Petrographic analyses by Luth (1960) indicated a composition for the norite of 45 to 60 percent plagioclase, 15 to 22 percent orthopyroxene, 5 to 16 percent clinopyroxene, and accessory hornblende, biotite, magnetite, ilmenite, pyrite, quartz, alkali feldspar, apatite, and chlorite. Compositional banding is present within the norite, consisting of millimeter- to centimeter-wide plagioclase zones that cross cut each other.

Figure 31. Trailside ultramafic complex dated at 2,683 ± 0.9 Ma.

U-Pb thermal ionization mass spectrometry (TIMS) of 8 single zircon grains from samples NR-13-6 and NR-13-7 within the norite resulted in a date of 2,683.6 ± 0.9Ma (95 percent confidence, MSWD 0.99) (see Appendix). The samples were collected from the norite in the southwest region of the intrusion, just west of the map area.

Granitic Gneiss (Agn)

Figure 32. Tonalitic gneiss.

The Mesoarchean granitic gneiss dominates the southwest portion of the map area, as coarse- to medium-grained, gray, biotite-rich tonalitic gneiss (Figure 32). It weathers to yellow, pink, or tan subrounded boulders, and is commonly covered with gray lichen. Minerals include subhedral to anhedral plagioclase up to 1 cm (0.4 in), anhedral clear quartz up to 0.5 cm (0.2 in) that frequently exhibits red, pink, or yellow staining, and biotite in clots and bands. It also contains minor microcline, Fe-Ti oxides, titanite, zircon, allanite, epidote, chlorite, and localized hornblende. At some outcrops the gneiss contains plagioclase augen; this rock is medium- to fine-grained, gray to tan, weathering gray with lichen, with biotite less than 1 mm (0.04 in) in diameter evenly distributed rather than forming clots, and with subrounded plagioclase augen 0.5 to 3 cm (0.2 to 1 in) showing no sense of shear. The gneiss commonly displays subparallel compositional banding, which defines a foliation that ranges from poorly developed to clearly visible (Figure 33).

Figure 33. Compositional banding in gneiss.

Throughout the central gneiss terrain of the Bighorn Mountains, amphibolites, quartzites, schists, and diorites are found within the gneiss (Frost and others, 2006), although only medium- to coarse-grained hornblende-rich diorite was observed within the map area with foliation defined by bands of undeformed subhedral plagioclase. Thin, undeformed pegmatite and aplite dikes locally cut the gneissic foliation. Geochronology by Frost and Fanning (2006) indicate that the tonalitic gneiss was emplaced at ~2.89 Ga and that the deformational event that created the foliation occurred between 2.89 Ga and 2.86 Ga.

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APPENDIX

The data presented below were used to calculate the radiometric age of 2,683.7 ± 0.9 Ma for samples NR-13-6 and NR-13-7 from the Trailside ultramafic complex. Data and description are by Dr. Kevin Chamberlain, Research Professor, University of Wyoming.

Zircon grains were separated from two samples collected from the norite unit of the complex (NR-13-6, N44.316425, W106.876426; and NR-13-7, N44.316543, W106.876925). The samples were collected from the southwest end of the intrusion, which lies just west of the map area. These locations were chosen because they offered the best composition and texture, and the freshest samples. Each sample contained massive zones and more felsic veins and pegmatites. These zones were crushed and dated separately to test whether the veins and pegmatites were significantly younger. All four samples yielded zircons with similar and distinctive morphologies, namely elongate, striated forms that are typical of magmatic zircons from mafic magmas (Figure 34). The U-Pb data from these zircons were also indistinguishable and are averaged for the final dates.

Selected zircons were annealed at 850 °C for 50 hours, then dissolved in two steps in a chemical abrasion, thermal ionization mass spectrometric U-Pb dating method (CA-TIMS) modified from Mattinson (2005). The first dissolution step was in hydrofluoric acid (HF) and nitric acid (HNO_3) at 180 °C for 12 hours. This removed the most metamict zircon domains in the annealed crystals. Individual grains were then spiked with a mixed ^{205}Pb-^{233}U-^{235}U tracer (ET535), completely dissolved in HF and HNO_3 at 240 °C for 30 hours, and then converted to chlorides. The dissolutions were loaded onto rhenium filaments with phosphoric acid and silica gel without any further chemical processing. Pb and UO2 isotopic compositions were determined in single Daly-photomultiplier mode on a Micromass Sector 54 mass spectrometer. Data were reduced and ages calculated using PbMacDat and ISOPLOT/EX after Ludwig (1988, 1991).

Eight single grain analyses produced concordant data that overlap within error (Figure 35, Table 1). Weighted mean $^{207}Pb/^{206}Pb$ date is 2,683.7 ± 0.9 Ma (95 percent confidence, MSWD 0.99; Figure 36) and is interpreted as the best estimate of the magmatic age of the pyroxenite. The Concordia Age (Ludwig, 1998) from these data, which includes uncertainties in the two U decay constants, is 2,685.5 ± 4.5 Ma (95 percent confidence, MSWD 0.28; Figure 37).

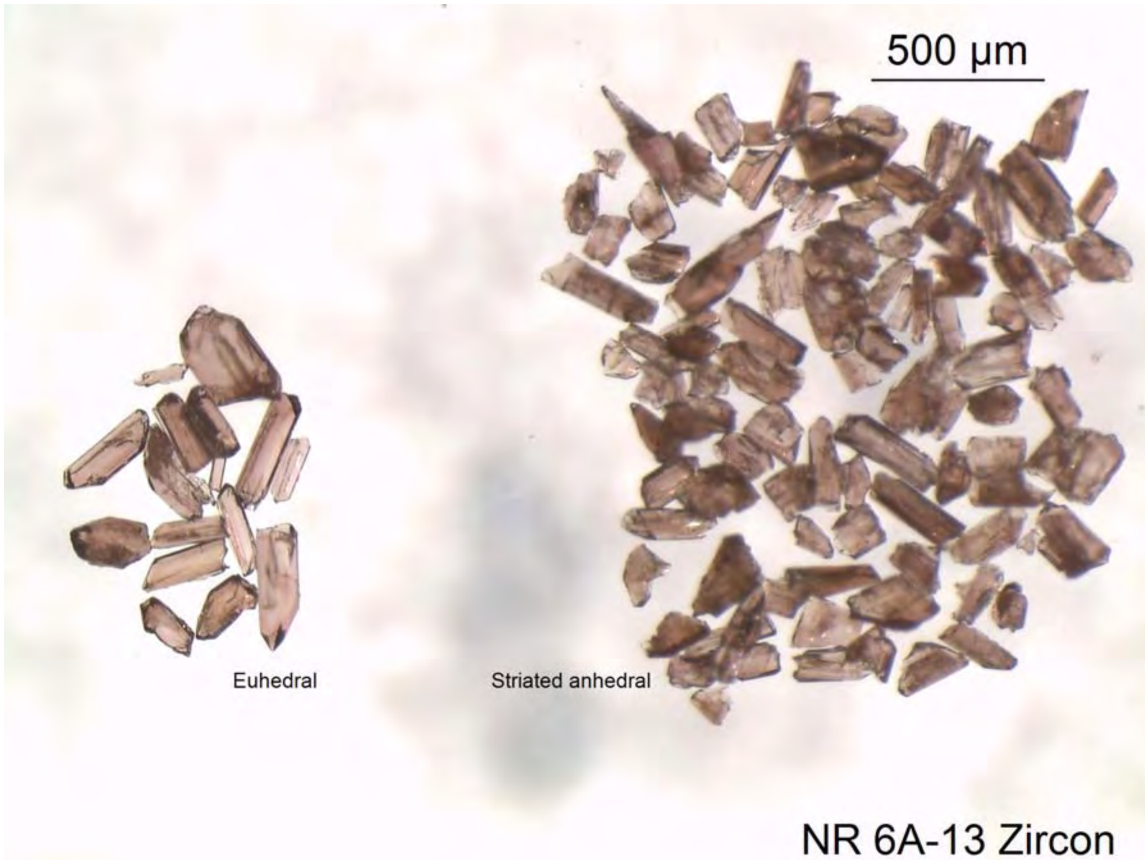

Figure 34. Representative zircons separated from massive portion of norite sample NR-13-6. Similar morphologies were separated from the felsic veins in NR-13-6, and both massive and pegmatitic portions of NR-13-7. These elongate, striated, anhedral to euhedral morphologies are characteristic of magmatic zircons in mafic melts.

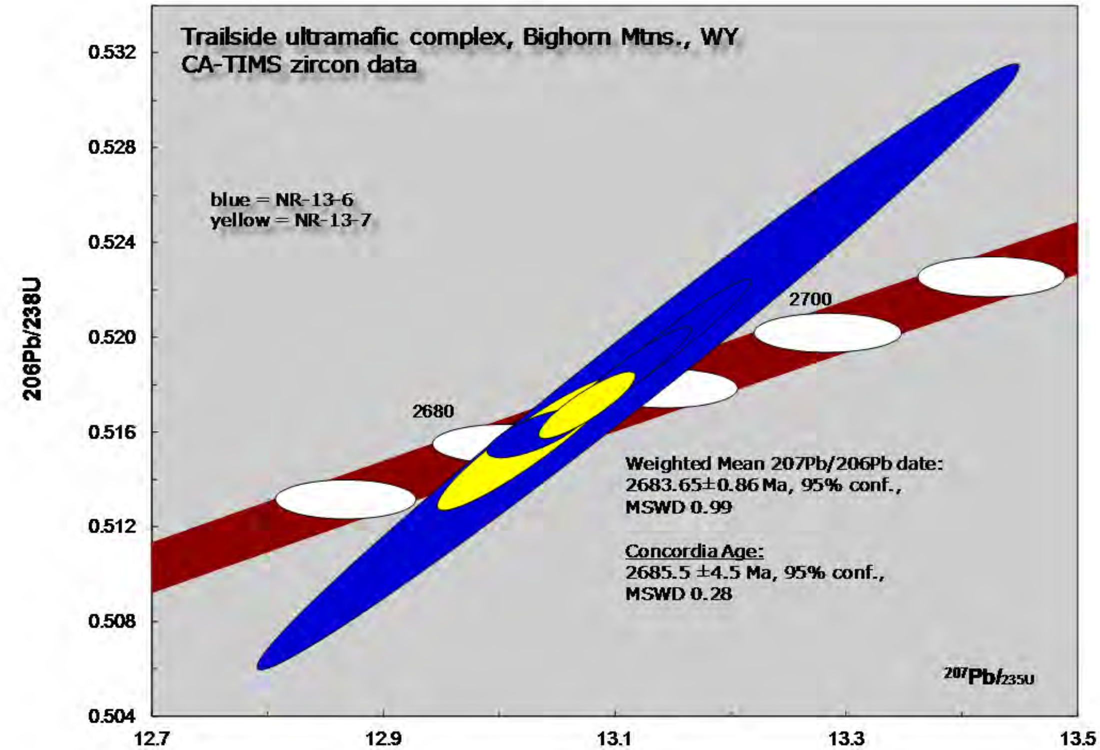

Figure 35. U-Pb zircon data from single grain CA-TIMS analyses from NR-13-6 (blue ellipses) and NR-13-7 (yellow ellipses). Decay constant errors are included to display Concordia as a swath. Weighted mean $^{207}Pb/^{206}Pb$ date is interpreted as the best estimate of the crystallization age.

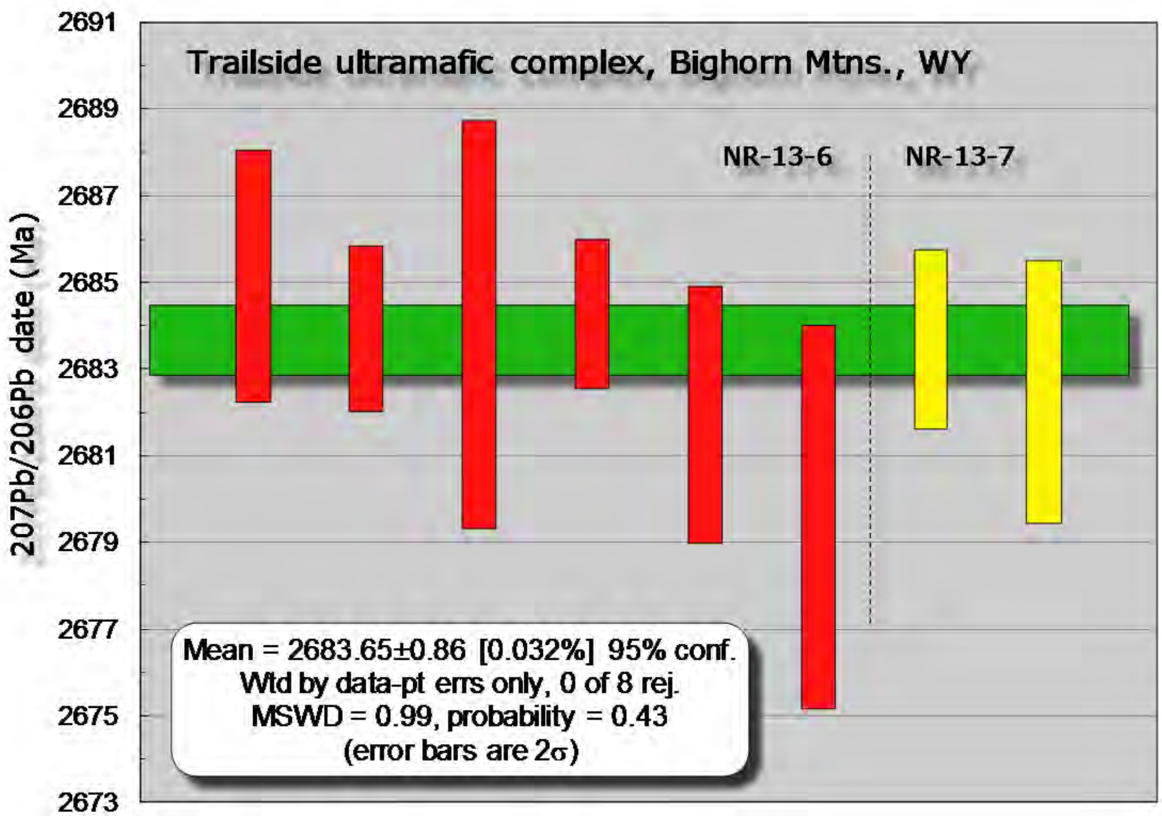

Figure 36. Weighted mean plot of $^{207}Pb/^{206}Pb$ data from single zircon analyses from Trailside ultramafic complex. Samples NR-13-6 (red bars) and NR-13-7 (yellow bars) both came from the same unit at different locations in the same outcrop, so the data are averaged for the final date.

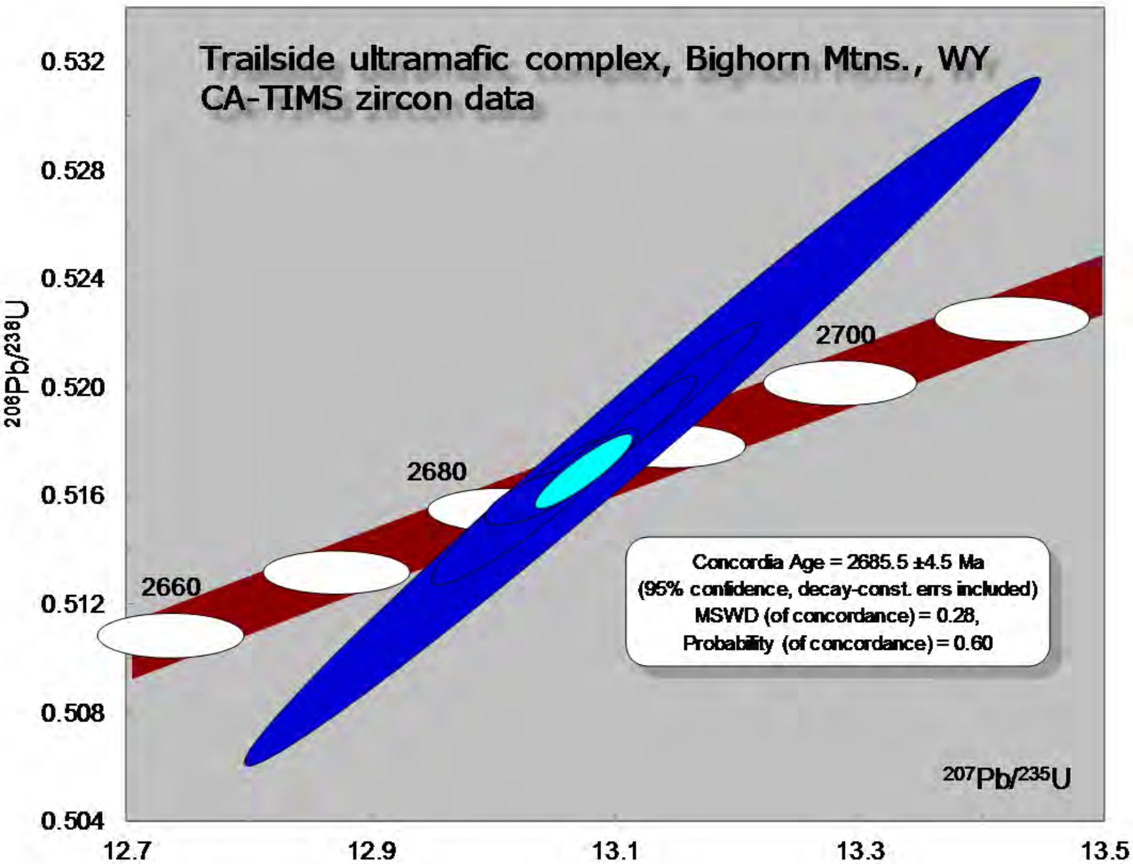

Figure 37. Concordia Age calculation after Ludwig (1998), which includes decay constant uncertainties.

Table 1. U-Pb CATIMS zircon data for the Trailside ultramafic complex.

							Corrected atomic ratios													
	Weight	U		sample Pb	TcPb	Pb*/	^{206}Pb/	^{206}Pb/		^{206}Pb/^{238}U		^{207}Pb/^{235}U		^{207}Pb/^{206}Pb	206/238	207/235	207/206			%
Sample	(µg)	(ppm)	(ppm)	(pg)	(pg)	Pbc	^{204}Pb	^{208}Pb	(rad.)	%err	(rad.)	%err	(rad.)	%err	Age (Ma)	Age (Ma)	Age (Ma)	err	Rho	disc.
NR-13-6 norite (44.3164248695304, -106.876425729267)										*crystallization age = 2683.7±0.9 Ma 95% conf. (MSWD=0.99) weighted mean 207Pb/206Pb date*										
6B-sB	11.1	93	68	759	2.4	311	14194	2.29	0.5227	(0.90)	13.2282	(0.92)	0.1835	(0.18)	2710.6	2696.1	2685.2	±2.9	0.98	-1.16
6B-sF	13.6	84	62	840	1.5	544	24584	2.20	0.5197	(0.43)	13.1460	(0.44)	0.1834	(0.10)	2698.0	2690.2	2684.3	±1.7	0.97	-0.62
6B-sG	1.7	86	61	102	3.0	34	1630	2.62	0.5187	(2.02)	13.1194	(2.04)	0.1834	(0.28)	2693.9	2688.3	2684.1	±4.7	0.99	-0.45
6A-sC	13.5	76	52	706	1.8	391	18739	2.78	0.5185	(0.31)	13.1121	(0.33)	0.1834	(0.11)	2692.8	2687.8	2684.0	±1.9	0.94	-0.40
6A-sH	1.4	77	55	77	1.6	47	2195	2.48	0.5159	(0.16)	13.0317	(0.26)	0.1832	(0.18)	2681.9	2681.9	2682.0	±3.0	0.73	0.00
6B-sI	1.6	55	37	61	2.3	26	1279	2.75	0.5151	(0.18)	12.9909	(0.36)	0.1829	(0.27)	2678.2	2679.0	2679.6	±4.4	0.71	0.07
NR-13-7 norite (44.3165426382111, -106.876925100882)																				
peg sC	2.5	137	90	228	2.2	102	5126	3.42	0.5171	(0.22)	13.0754	(0.26)	0.1834	(0.13)	2686.9	2685.1	2683.7	±2.1	0.87	-0.15
mass sD	3.8	108	68	259	5.7	45	2359	4.15	0.5155	(0.44)	13.0243	(0.49)	0.1832	(0.18)	2680.0	2681.4	2682.5	±3.0	0.93	0.11

Notes: sample: 6B = felsic vein portion of 6; 6A = massive portion of 6; peg = pegmatitic portion of 7; mass = massive portion of 7; s_=single grain

Weight: represents estimated weight after first step of CATIMS dissolution. U and Pb concentrations are based on this weight and may be over-estimations depending on how much material was dissolved and leached in the first step. Picograms (pg) sample and initial Pb from the second dissolution step are measured directly.

sample Pb: sample Pb (radiogenic + initial) corrected for laboratory blank

TcPb: total common Pb. All is assigned to laboratory blank.

Pb*/Pbc: radiogenic Pb to total common Pb (blank + initial)

Corrected atomic ratios: ^{206}Pb/^{204}Pb corrected for mass discrimination and tracer, all others corrected for blank, mass discrimination, and tracer, values in parentheses are 2 sigma errors in percent.

Rho: ^{206}Pb/^{238}U vs ^{207}Pb/^{235}U error correlation coefficient

% disc.: percent discordant

Zircon dissolution and chemistry were adapted from methods developed by Krogh (1973), Parrish and others (1987), and Mattinson (2005). All zircons were chemically abraded (CATIMS). Final dissolutions were spiked with a mixed ^{205}Pb/^{233}U/^{235}U tracer (ET535). Pb and U samples were loaded onto single rhenium filaments with silica gel. Isotopic compositions were measured in single Daly mode Micromass Sector 54 mass spectrometer at the University of Wyoming. Mass discrimination of 0.212 ± 0.10 and 0.247±0.10 %/amu for Pb were determined by replicate analyses of NIST SRM 981, dependent on silica gel batch. U fractionation was determined internally during each run. Procedural blanks averaged 2 pg Pb during the course of the study. Isotopic composition of the Pb blank was measured as 18.851±1.2, 15.665±0.75, and 38.188±1.2 for 206/204, 207/204 and 208/204, respectively. U blanks were consistently less than 0.1 pg. Concordia coordinates, intercepts, and uncertainties were calculated using MacPBDAT and ISOPLOT programs (based on Ludwig 1988, 1991); initial Pb isotopic compositions were estimated by Stacey and Kramers (1975) model. The decay constants used by MacPBDAT are those recommended by the I.U.G.S. Subcommission on Geochronology (Steiger and Jäger, 1977): 0.155125 x 10^{-9}/yr for ^{238}U, 0.98485 x 10^{-9}/yr for ^{235}U and present-day ^{238}U/^{235}U = 137.88.