Preliminary Geologic Map of the Bowen Mountain Quadrangle, Grand and Jackson Counties, Colorado

By James C. Cole, William A. Braddock, and Theodore R. Brandt

View northward over Miocene boulder-gravel deposit toward Blue Ridge and Cascade Mountain
(photo by J. Cole, 2007)

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Contents

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Abstract

The map shows the geology of an alpine region in the southern Never Summer Mountains, including parts of the Never Summer Wilderness Area, the Bowen Gulch Protection Area, and the Arapaho National Forest. The area includes Proterozoic crystalline rocks in fault contact with folded and overturned Paleozoic and Mesozoic sedimentary rocks and Upper Cretaceous(?) and Paleocene Middle Park Formation. The folding and faulting appears to reflect a singular contractional deformation (post-Middle Park, so probably younger than early Eocene) that produced en echelon structural uplift of the Proterozoic basement of the Front Range. The geologic map indicates there is no through-going "Never Summer thrust" fault in this area. The middle Tertiary structural complex was intruded in late Oligocene time by basalt, quartz latite, and rhyolite porphyry plugs that also produced minor volcanic deposits; these igneous rocks are collectively referred to informally as the Braddock Peak intrusive-volcanic complex whose type area is located in the Mount Richthofen quadrangle immediately north (Cole and others, 2008; Cole and Braddock, 2009). Miocene and upper Oligocene boulder gravel deposits are preserved along high-altitude ridges that probably represent former gravel channels that developed during uplift and erosion in middle Tertiary time.

Geologic Mapping

The geology was mapped primarily by W.A. Braddock (deceased, 2003) during the summers of 1985–1990. The eastern two-thirds of the quadrangle was compiled and published with the geologic map of Rocky Mountain National Park (Braddock and Cole, 1990). Cole conducted additional field work, chiefly in the western part of the quadrangle, in 2006–2008, revised some of the previous mapping, and wrote the report and supporting materials. Brandt developed all of the digital database materials for the publication.

The Mount Richthofen quadrangle to the north was mapped in detail by O'Neill (1981), and the Trail Mountain quadrangle to the south was mapped by Izett (1974). Reconnaissance mapping of the Rand 15-minute quadrangle to the west was completed by Kinney (1970). All of the Bowen Mountain quadrangle geology was compiled with the geologic map of the Estes Park 30' x 60' quadrangle (Cole and Braddock, 2009). Metzger (1974) completed a detailed map of the Oligocene breccia-pipe in the Illinois

River headwaters west of Bowen Mountain and most of his mapping is incorporated in this report.

Stratigraphic Notes

The Middle Park Formation consists largely of sandstone and conglomerate deposited in response to mountain uplift in Late Cretaceous–early Tertiary time (the Laramide orogeny; Tweto, 1957, 1975). The most thorough description of the unit is presented by Izett (1968) for the area of the Hot Sulphur Springs quadrangle, immediately southwest of the Bowen Mountain quadrangle. In broad terms, the basal Middle Park is marked in this area by mafic volcaniclastic conglomerate and sandstone of the Windy Gap Volcanic Member. The Windy Gap is overlain by volcaniclastic sandstone and conglomerate that grades upward into increasingly arkosic sedimentary rocks. This sequence of compositions reflects erosion of a mafic volcanic center (location unknown) followed by erosion of Proterozoic basement rocks from the rising mountain blocks (Tweto, 1957; Izett, 1968). A similar lithic sequence is recorded in the Middle Park Formation in the Bowen Mountain quadrangle although the volcanic and arkosic subunits were not well characterized by Braddock and transitions between them were not studied in detail by Cole.

The Middle Park Formation appears to pass laterally northward into similar strata named Coalmont Formation in the North Park Basin (Hail, 1968; Izett, 1968; Tweto, 1975). The arbitrary line of distinction between the two formations has traditionally been the Continental Divide across the Rabbit Ears Range, and it traverses the northwestern corner of the Bowen Mountain quadrangle between Willow Creek and the Illinois River. For simplicity, all of these strata are referred to in this report as Middle Park Formation.

The Middle Park Formation lies disconformably on the sandy, middle unit of the Pierre Shale throughout much of this area. This relation implies that the upper several thousand feet of the Pierre Shale was eroded (without much tilting) prior to deposition of the lowermost Middle Park Formation.

Age of the lower part of the Middle Park Formation is not well known. Izett (1968) inferred it to be Late Cretaceous on the basis of one collection of fossil leaves from sandstone overlying the Windy Gap Volcanic Member east of Hot Sulphur Springs. In addition, a single pollen sample "about 100 ft above the Windy Gap Member … contains pollen and spores that … indicate a Late Cretaceous age" (Izett, 1968, p. 25–26, quoting R.H. Tschudy); the possibility of reworked pollen was not addressed.

Several attempts to obtain a radiometric age on volcanic flows from the Windy Gap Volcanic Member have not been successful due to alteration and due to the low-potassium content of the andesitic and basaltic rocks. One clast of hornblende-bearing andesite in the conglomerate at Windy Gap yielded a credible argon-plateau age of 65.2 $\pm$ 0.3 Ma (G.L. Farmer, written commun., 2009). This result indicates the Windy Gap Volcanic Member is younger than about 65 Ma, and thus Paleocene, in this locality.

Until more definitive evidence is produced, the Windy Gap Volcanic Member is listed in this report as Upper Cretaceous(?).

The top of the Middle Park Formation is eroded in this area. Izett (1968, p. 25–26) summarized the paleobotanical data for the Middle Park Formation that are chiefly Paleocene. At the end of that discussion, he stated "beds included in the Coalmont Formation that may be partly equivalent to beds in the upper part of the Middle Park

Formation contain pollen and spore assemblages that indicate an Eocene age (Hail and Leopold, 1960), perhaps early Eocene. The possibility exists that the upper part of the Middle Park Formation may also be of Eocene age, but no samples have yet yielded Eocene pollen and spores." Hail (1968, p. 46–49) summarized abundant pollen data for the Coalmont Formation (exposed in the North Park area northwest of Bowen Mountain) that indicate the lower part is Paleocene but the middle and upper parts are Paleocene–Eocene and Eocene, respectively. Distinction of the Middle Park and Coalmont Formations is not clear along the Rabbit Ears Range divide, and it largely appears that they are continuous and coeval (see also Tweto, 1957, 1975).

Structure

The major structural elements in the Bowen Mountain quadrangle are a series of sub-parallel folds and high-angle reverse faults that locally place Proterozoic basement rocks westward above the Upper Cretaceous Pierre Shale. These faults and folds are displayed in the Cretaceous and younger rocks in the Willow Creek drainage west of the Cascade Mountain–Blue Ridge divide. The easternmost fault that marks the structural contact between Proterozoic crystalline rocks and the Pierre Shale has been referred to as the "Stillwater overthrust" (Tweto, 1957) or, more commonly, the "Never Summer thrust" (O'Neill, 1981; Cole and Braddock, 2009). The position of the fault is well documented by the distribution of scattered outcrops of upper- and lower-plate rocks. The fault appears to dip 15°–30° eastward (based on local three-point topographic relations whose accuracies cannot be independently assessed) but is more likely 50°–65° eastward (based on the dip of overturned beds in the footwall block and on regional-scale topographic relations). This fault continues northward into the Mount Richthofen quadrangle where it dips 40°–60° eastward (O'Neill, 1981), but it cannot be traced south of the Porphyry Peaks area beyond the Bowen Mountain quadrangle, because it is intruded by Oligocene stocks and plugs.

The dip of this "Never Summer thrust" could also be inferred from the geology of the Neogene intrusive tuff-breccia pipe in the upper Illinois River drainage (Metzger, 1974), but the geologic relations are not definitive. Metzger (1974) inferred that the pipe intruded only Proterozoic rocks (only upper-plate rocks) because he reported no breccia clasts of Phanerozoic rock; his cross-section shows the "Never Summer thrust" steepening downward in a position completely west of the intrusive center of the pipe. Braddock (in Braddock and Cole, 1990) reported that the tuff-breccia contained some clasts of probable Mesozoic sedimentary formations, suggesting that the fault has a gentler eastward dip and that the underlying footwall sedimentary units were penetrated by the breccia pipe. These observations were not confirmed by Cole and so the geometry of the fault remains undetermined.

A north-trending hangingwall anticline and reverse fault are inferred from the geologic relations between Lost Lake and the Pony Park area southward. The amount of throw on the fault appears to vary considerably over its length. North of Lost Lake, the hangingwall and footwall are both composed of Upper Cretaceous Pierre Shale. At the southern boundary of the Bowen Mountain quadrangle, the hangingwall carries Jurassic Morrison Formation over the Pierre. In the Trail Mountain quadrangle to the south of Pony Park (Izett, 1974), this fault places Triassic Chugwater Formation against the lower Pierre Shale, but farther southward the displacement declines over a mile strike-length to

the juxtaposition of Cretaceous Benton Group against Pierre. Thus, this fault-fold pair is a relatively minor structure within the Never Summer fault zone.

The Middle Park Formation displays additional north-trending folds along the western margin of the Bowen Mountain quadrangle that are broadly conformable with the folds and faults described above. From the Windy Gap Volcanic Member westward, these comprise a broad syncline and a sharp-crested, asymmetric, west-vergent anticline. The form of the anticline suggests it reflects a steep, east-dipping reverse fault at depth. A similar, sharp, west-vergent anticline was mapped in the Middle Park Formation to the west (Kinney, 1970) along La Fevre Ridge .

These north-trending folds and faults appear to be genetically related because they are geometrically similar, affect the same parts of the Middle Park Formation, and form an en echelon set of faults and folds in a belt of deformation along the western margin of the Bowen Mountain quadrangle. Taken together, they suggest that the feature known as the "Never Summer thrust" is not a major crust-penetrating fault but rather a southward-diminishing, high-angle reverse fault whose deformation is transferred to similar structures progressively westward in the quadrangle. On the basis of all local evidence, the Never Summer structure is most accurately designated as a reverse fault, not a thrust, because it is not laterally persistent; it (and parallel faults) probably steepens with depth, and there is no firm evidence of a major structural overhang of younger rocks.

Folding and faulting probably occurred following deposition of the Middle Park Formation and laterally equivalent beds in the Coalmont Formation to the north. Local, minor unconformities were described in parts of the Coalmont Formation by Hail (1968), but the strata above and below these minor angular discordances are similar fluvial sandstones and siltstones. No unconformities were described in the upper parts of the Middle Park Formation (Izett, 1968). With specific regard to the area near the Bowen Mountain quadrangle, Tweto (1975, p. 18) stated, "In the North Park-Middle Park basin, orogenic sediments of latest Cretaceous(?) to Eocene age lie with marked unconformity on older rocks …" Regarding the time of deformation, he stated (p. 33), "In North Park, where the Coalmont Formation is involved in the mountain-front folds and faults, deformation must have been younger than early Eocene."

Oil Exploration

Three wildcat oil-exploration wells were drilled in the Bowen Mountain quadrangle between 1961 and 1981; one well was deepened in 1985. All are located near the Stillwater Pass road (Forest Road FR 123) along Willow Creek and appear to have been sited to explore the carbonaceous marine Cretaceous rocks that are folded and overturned in the footwall of the Never Summer reverse fault. No production was reported and all three wells are classified as "dry holes."

Well name (year completed)

Well identification number (API = American Petroleum Institute system)
Public Land Survey System location by quarter-quarter-quarter section, Township, and Range; UTM Zone 13 coordinates (NAD 83)
Elevation of K.B. = Kelly bushing on the drilling platform
Depths to tops of formation boundaries
T.D. = total depth to bottom of well

All data reported to the Colorado Oil and Gas Commission.

Brooks EB Jr #1 (1973; deepened 1985)

API 05049 06005
NE. SE. sec. 13, T4N., R77W.; 418575 E., 4462400 N.
K.B. elev 9,675 ft
Top Pierre (eroded) .....Ground surface
Top Niobrara .....2,259 ft
Top Dakota.....3,722 ft
T.D. .....4,380 ft (prior T.D. 2,505 ft)

Sunray DX #1-D (1961)

API 05049 05021
SE. NE. NE. sec.14, T4N., R77W.; 416860 E., 4462970 N.
K.B. elev. 9,350 ft
Top Coalmont/Middle Park (eroded).....Ground surface
Top volcanic (Windy Gap Member?) .....3,600 ft
Top Niobrara .....5,942 ft
Top Dakota .....6,923 ft
Top Morrison .....7,324 ft
Fault zone.....7,506–7,592 ft
Niobrara beneath fault
T.D .....7,882 ft

Voyager Fed-Gilsonite #1 (1981)

API 05049 06026
SW. SE. SE. sec. 10, T4N., R77W.; 415145 E., 4463325 N.
K.B. elev. 9,532 ft
Top Middle Park/Coalmont (eroded).....Ground surface
Top Niobrara (eroded) .....880 ft
Top Dakota.....1,606 ft
Top Morrison .....1,799 ft
Top Proterozoic basement.....2,178 ft
T.D. .....6,161 ft

These data seem somewhat contradictory. For example, the Voyager Fed-Gilsonite #1 well penetrates a very thin section of Middle Park/Coalmont and then enters the Niobrara. The “missing” Pierre Shale might indicate the Middle Park/Coalmont here was deposited on a pre-existing structural high, but no nearby evidence has been mapped. The data for the Sunray DX #1-D well is consistent penetrating an overturned syncline, but Pierre Shale should have been noted beneath the “volcanic” unit. The 1985 log for the deepened rooks EB Jr #1 well indicates the Niobrara and Dakota (identified by M. Dechesne, written comm., 2011) are much higher than previously indicated, consistent with a stacked thrust beneath the Never Summer fault.

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DESCRIPTION OF MAP UNITS

[Color terms are descriptive of fresh rock/sediment material]

ALLUVIAL UNITS

Qva **Mountain valley alluvium (Holocene and upper Pleistocene)**—Gravel, sand, and silt along courses of major and intermittent streams in bedrock-cut valleys, in alluvial fans along montane valley margins, and in outwash deposits downstream from terminal moraines of Pinedale and Bull Lake age. Unit underlies narrow, high-altitude valleys. Thickness variable, generally less than 20 ft

Qgy **Stream-terrace gravel deposit (Holocene and upper Pleistocene)**—Gravel, sand, and silt deposit preserved beneath low terrace (about 20–40 ft above modern drainage) along Willow Creek at western quadrangle boundary. Deposit probably reflects redeposition of till (glacial outwash) during deglaciation of the drainage basin. Deposit appears to be about 20 ft thick

GLACIAL UNITS

Qr **Rock glacier deposit (Holocene and upper Pleistocene)**—Lobate mass of rock rubble, silty sand, and ice that is veneered by angular blocks and boulders in alpine cirques and valleys above 10,000-ft elevation. Surface typically marked by conspicuous arcuate ridges and a steep lobate front (Gable and Madole, 1976). Thickness variable

Qo **Organic-rich sediment (Holocene and upper Pleistocene)**—Bog and marsh deposits in formerly glaciated terrain, locally overlain by glacial-outwash sediments. Bog deposits also form near the basal contact of Neogene gravel deposits (Ng), for example east of Blue Ridge, probably due to groundwater discharge from the gravels. Thickness indeterminate, but probably less than 20 ft

Qtp **Till of Pinedale age (upper Pleistocene)**—Subangular to subrounded boulders, cobbles, and pebbles in a silty sand matrix. Prominent, sharp-crested moraines are numerous, most clasts are slightly weathered, and soils are thin. Unit contains small bodies of Holocene till in cirque basins. Some areas mapped as till in the southwest corner of the quadrangle may include slightly transported cobbly material that was weathered from the underlying gravels and sandstones of the Middle Park Formation. Pinedale glaciation occurred between about 30 ka and 12 ka in this region (Madole and others, 1998). Thickness variable, but probably several tens of feet in most areas and thickest beneath moraine ridges, based on more detailed work in adjacent areas (Madole and others, 1998)

Qtb **Till of Bull Lake age (upper and middle Pleistocene)**—Subangular to subrounded boulders, cobbles, and pebbles in a silty-sand matrix. Morainal form subdued, clasts variably weathered, and soils well developed. Bull Lake glaciation occurred between about 300 ka and 120 ka in this region (Madole and others, 1998). Thickness indeterminate, but probably less than a few tens of feet in most areas

MASS-MOVEMENT UNITS

Qc **Colluvium (Holocene and upper Pleistocene)**—Deposits of rock debris ranging in size from silt to boulders, formed by a variety of mass-wasting processes. Unit chiefly mapped on nonglaciated, moderate slopes west of the trace of the Never Summer reverse fault, in local colluvial aprons surrounding Oligocene intrusive plugs, and in extensive areas near and above timberline where freeze-thaw action has aided mass wasting and downslope movement. Thickness variable

Qta **Talus deposits (Holocene and upper Pleistocene)**—Angular blocks of rock on steep slopes below cliffs. Unit is chiefly shown in alpine and subalpine areas in the northern part of the quadrangle at the bases of steep slopes that expose Proterozoic gneiss. Thickness variable

Qls **Landslide deposits (Holocene and upper Pleistocene)**—Includes slumps, earth flows, and minor debris flows. Landslides common in glacial deposits north of Bowen Gulch and on the southeast flank of Gravel Mountain. Prominent landslide on northwest slope of Porphyry Peaks involves hydrothermally altered Oligocene intrusive rocks that probably overlie Pierre Shale at shallow depth; jumbled blocks and irregular landform suggests late Pleistocene or younger age. Most landslide masses are shallow and less than 30 ft thick; the large slide northwest of Porphyry Peaks appears to be more than 100 ft thick, based on topographic relations

Qdf **Debris-flow deposit (Holocene)**—Prominent and distinctive deposit of coarse angular blocks of Oligocene quartz latite of Apiatan Mountain (Ꝑqla) that underlies a sparsely forested, arcuate, elongate mass on the northwest slope of Porphyry Peaks. This debris-flow deposit lies on top of an older, complex landslide jumble of similar materials that probably rests on Pierre Shale at shallow depth. Debris-flow deposit contains many clasts larger than 5 ft and preserves sharp lateral levees adjacent to the flow centerline. Several small topographic depressions within the debris flow enclose shallow, ephemeral lakes. Thickness indeterminate, but probably less than 50 ft

EOLIAN DEPOSIT

Qlo **Loess (Holocene and upper Pleistocene)**—Pale-brown sandy to clayey silt deposited by wind. Unit is limited to a singular deposit east of Gravel Mountain where prevailing westerly winds appear to have transported silt and sand from the disaggregated Middle Park Formation to the lee slope of a nearby 11,240+ ft peak. Thickness variable but appears to be less than 20 ft

POST-LARAMIDE SEDIMENTARY ROCKS

NPEg **Fluvial gravel (Miocene and upper Oligocene)**—Unsorted, unstratified deposits of boulders (as large as 10-ft diameter), cobbles, and pebbles in a dominantly coarse sandy matrix with some silt. High-level fluvial-gravel deposits at Gravel Mountain, Blue Ridge, and flanking Apiatan Mountain probably mark paleocanyons of the early Colorado River drainage. Most

clasts are Silver Plume-type granite, pegmatite, and fine-grained, biotite-rich, equigranular granite, minor biotite gneiss, and rare quartz sandstone (well-sorted, well-rounded, frosted quartz grains cemented by silica; resembles Dakota Sandstone). Volcanic rocks of the late Oligocene Braddock Peak complex (source in northern Never Summer Mountains; Cole and others, 2008; Cole and Braddock, 2009) were not found at Blue Ridge, but "porphyritic andesite pebbles of Laramide age" were noted in the adjoining Hot Sulphur Springs quadrangle by Izett (1968). These gravel deposits may locally be as old as late Oligocene because some clasts closely resemble the quartz latite of Apiatan Mountain (PEqla) that is about 28 Ma. Madole (1982) concluded these kinds of deposits might be formed in ancient valley systems that were subsequently disrupted by younger Neogene uplift of the Front Range. Thickness unknown, but appears to locally exceed 200 ft

NPEt **Troublesome Formation (lower Miocene and upper Oligocene)**—Pale brown and grayish brown, tuffaceous mudstone and sandstone, volcanic ash beds, and granule conglomerate; locally interbedded with basalt and trachyandesite (unit PEba). Unit is sparsely preserved along the eastern margin of the quadrangle; base is a significant unconformity with as much as 650 ft of local relief on older rocks (Braddock and Cole, 1990; Cole and Braddock, 2009). Lower part of Troublesome Formation is locally interlayered with Oligocene basalt (26.4 $\pm$ 0.9 Ma) and latite breccia (28.4 $\pm$ 2.3 Ma) in the Granby Basin to the south (Izett, 1974). Thickness variable due to pre- and post-Troublesome erosion, but locally exceeds 2,500 ft in the Granby Basin (Izett, 1974); only a few tens of feet of Troublesome remain in the Bowen Mountain area

POST-LARAMIDE INTRUSIVE ROCKS

NPEi **Intrusive rocks, undivided (Miocene(?) to Oligocene)**—Dikes, sills, and small plugs; typically very fine grained, porphyritic, and altered; compositions range from basalt and andesite to rhyolite. Intrusions are chiefly located in Never Summer Mountains and westward in Illinois River drainage (Metzger, 1974; O'Neill, 1981)

PErp **Rhyolite porphyry (late Oligocene)**—Variegated pale-pink, cream, or light-reddish-brown, flow-banded, porphyritic rock containing 20–40 percent phenocrysts of quartz, sanidine, oligoclase, biotite, and brown hornblende in an aphanitic matrix; forms small plugs. Intrusive body south of Porphyry Peaks was dated at 25.6 $\pm$ 2.0 Ma and 26.2 $\pm$ 2.3 Ma (zircon fission-track; ages corrected in 1979 for revised decay constants) by Naeser and others (1973)

PEIx **Intrusive tuff-breccia (late Oligocene)**—Yellowish-gray to grayish-yellow-green, poorly sorted, weakly bedded tuff-breccia consisting of fragments of cognate volcanic rock (lapilli- and ash-sized vesicular clasts of the erupted magma), comminuted Proterozoic rocks, and Oligocene igneous rocks (andesite porphyry and quartz latite). Forms a singular pipe-like body northwest of Bowen Mountain that covers an area about 6,000 ft by 4,000

ft (Metzger, 1974) within Proterozoic rocks; planar fabric (pyroclastic layering) defined by clast sorting dips moderately inward. Tuff-breccia is intruded by quartz latite and latite porphyry (Metzger, 1974), presumably of late Oligocene age. Metzger (1974) reported no Phanerozoic sedimentary clasts in the tuff-breccia, but Braddock (*in* Braddock and Cole, 1990) described "sparse siltstone and sandstone of possible Mesozoic age" within the pipe deposits.

Ꝑbi **Intrusive basalt (late Oligocene)**—Dark gray to black, dense rock intruded into Pierre Shale in a single body located about 1.4 mi east of Gravel Mountain. Age is inferred from correlation to similar mafic igneous rocks in adjoining areas (Izett, 1974; Cole and Braddock, 2009)

Ꝑqla **Quartz latite of Apiatan Mountain (late Oligocene)**—Gray to brownish-gray porphyry containing about 25–40 percent phenocrysts of pale-yellow oligoclase-andesine (as long as 3 cm), glassy twinned sanidine, minor hexagonal biotite, and minor clinopyroxene in a microcrystalline groundmass rich in potassium feldspar; intruded at 28.4 ± 2.3 Ma (zircon fission-track; Marvin and others, 1974; Izett, 1974; corrected in 1979 for revised decay constants)

POST-LARAMIDE VOLCANIC ROCKS

Ꝑv **Volcanic rocks, undivided (upper Oligocene)**—A singular, small deposit of felsic volcanic ash and breccia is located in the south side of the topographic saddle between the Porphyry Peaks; thickness less than 40 ft

Ꝑba **Basalt and trachyandesite (upper Oligocene)**—Dark-gray and dark greenish-gray, very fine grained rock that weathers to grayish brown or grayish purple. Locally contains 10–15 percent small phenocrysts of pyroxene and altered olivine(?); vesicles locally filled with fibrous zeolite minerals. Unit only observed near intrusive quartz latite (Ꝑqla) and rhyolite porphyry bodies (Ꝑrp) in the southwestern part of the quadrangle. Interlayered with the Troublesome Formation (NꝐt) in the adjoining Trail Mountain quadrangle (Izett, 1974); erupted at 26.7 ± 0.9 Ma (whole-rock K-Ar; Izett, 1974; Marvin and others, 1974; corrected in 1979 for revised decay constants)

LARAMIDE SEDIMENTARY AND VOLCANIC ROCKS

Middle Park Formation (Paleocene and Upper Cretaceous?)—Thick fluvial and alluvial deposits transported into the broad, synclinal Middle Park–North Park structural basin during late Laramide uplift of the adjacent Front Range and Vasquez Mountains Proterozoic basement blocks. Only partially preserved in this area, but thickness exceeds 7,000 ft in region west of this quadrangle in Middle Park Basin (Izett, 1968). The volcanic and arkosic units were mapped in adjacent areas to the west by Kinney (1970).

Ꝑma **Arkosic unit** (Paleocene)—Interbedded light- to medium-brown and gray, arkosic sandstone and siltstone, and lenses of pebble to boulder conglomerate characterized by clasts of Proterozoic Silver Plume-type

granite, pegmatite, felsic gneiss, biotite gneiss, and rare hornblende gneiss, in addition to mafic-to-intermediate volcanic porphyries. Contact with underlying volcanic unit is gradational, and felsic, Proterozoic clasts increase in abundance upward. Thickness incomplete due to erosion but exceeds 2,000 ft on east slope of Gravel Mountain

PEmv **Volcanic unit (Paleocene)**—Interbedded medium-brown, greenish-gray, and gray sandstone, siltstone, and pebble-cobble conglomerate marked by conspicuous clasts of brown, purple, and greenish-gray, mafic volcanic porphyry; locally contains some felsic Proterozoic clasts. Generally overlies the Windy Gap Volcanic Member; thickness approximately 1,500 ft on east slope of Gravel Mountain

Kmw **Windy Gap Volcanic Member (Upper Cretaceous?)**—Brown or greenish-brown, gray, or purple, massive volcanic conglomerate and discontinuous volcanic sandstone; interbedded with rare, probable flows of trachyte porphyry or basalt. Thickness about 200 ft along western quadrangle boundary

PRE-LARAMIDE SEDIMENTARY ROCKS

Pierre Shale (Upper Cretaceous)—Thick, dark-gray to black, marine shale; unit poorly exposed in the quadrangle in the footwall of the Never Summer reverse fault. Sandy beds in the middle of the Pierre are inferred to correlate with sandstone members (for example, the Hygiene, Richard, Larimer, or Rocky Ridge Sandstone Members) recognized in the region (Izett, 1968, 1974; Scott and Cobban, 1986); total thickness is as great as 6,200 ft in Denver Basin (Higley and Cox, 2005)

Kpu **Upper shale unit**—Primarily dark-gray to black silty shale above the Middle sandy unit; erosionally truncated northward by the Windy Gap Volcanic Member of the Middle Park Formation. Thickness unknown

Kps **Middle sandy unit**—Light-brown, fine- to medium-grained marine sandstone beds and interlayered black shale; thickness estimated to be about 300–500 ft

Kpl **Lower shale unit**—Primarily dark-gray to black silty shale beneath the Middle sandy unit; thickness indeterminate due to folding and poor exposure

Kn **Niobrara Formation (Upper Cretaceous)**—Light-gray-weathering, platy, calcareous shale; weathers buff near top; thin, light-gray biomicrite beds near middle; thin, light-gray micritic limestone at base. Thickness indeterminate due to folding and poor exposure

Kd **Dakota Sandstone (Lower Cretaceous)**—Light-gray, fine-grained sandstone and interbedded shale in upper part, and chert-pebble conglomerate and sandstone in lower part; total thickness about 175–230 ft in nearby areas (Izett, 1986), but no complete sections exposed here

Jm **Morrison Formation (Upper Jurassic)**—Green, red, yellow, and white blocky-weathering claystone, siltstone, and gray micrite, and gray, fine- to

medium-grained sandstone. Singular occurrence is located along the southern quadrangle boundary just west of Apiatan Mountain; thickness indeterminate due to poor exposure

ŦPc **Chugwater Formation and older units (Lower Triassic and Upper Permian)**—Reddish-brown to orange-red shale, siltstone, and fine-grained sandstone; laminated to thin bedded; poorly exposed. Locally contains light-gray to white finely laminated limestone (possible Forelle Limestone Member of Late Permian age) and underlying red shale (possible Satanka Shale). Occurrence is limited to two small localities immediately underneath the Never Summer reverse fault. Thickness indeterminate due to poor exposure and structural disruption

MESOPROTEROZOIC INTRUSIVE ROCKS

YgLP **Granite of Longs Peak batholith**—Light- to medium-gray, grayish-orange, orange-pink, or red-purple monzogranite to syenogranite that contains characteristic tabular microcline phenocrysts. Biotite is the principal dark mineral (5–12 percent), locally accompanied by magmatic sillimanite and (or) garnet plus minor accessory minerals. Equigranular matrix is locally fine, medium or coarse grained and weakly foliated by aligned biotite grains. Granite intruded the Longs Peak–St. Vrain batholith as a viscous magma that extensively deformed metamorphic wall-rocks (Cole, 1977; Braddock and Cole, 1979, 1990). Intruded at 1,420 ± 25 Ma (Rb-Sr isochron; Silver Plume Granite of Peterman and others, 1968). Secondary muscovite (non-oriented, porphyroblastic) is locally present and formed by subsolidus hydration of sillimanite + potassium feldspar or breakdown of primary biotite to muscovite + magnetite

MESOPROTEROZOIC AND (OR) PALEOPROTEROZOIC INTRUSIVE ROCKS

YXp **Pegmatite**—White, medium-grained to very coarse grained pegmatite with accessory biotite, muscovite, garnet, and (or) tourmaline. Most pegmatites probably intruded along with granite of Longs Peak batholith (YgLP) but some are folded with enclosing metamorphic rocks and may be related to older intrusive events; reliable field criteria for distinguishing pegmatite ages have not been established

PALEOPROTEROZOIC METAMORPHIC ROCKS

Biotite-bearing schist and gneiss unit (Xbq) is metasedimentary rock; hornblende gneiss units (Xh) and granitic-gneiss units (Xf, Xfb) were probably volcanic rocks prior to metamorphism (Cole and Braddock, 2009). Protolith of biotite granofels (Xfb) is uncertain. The age of metamorphism is 1,713 ± 30 Ma (Rb-Sr isochron; Peterman and others, 1968) and 1,715–1,690 Ma (U-Pb zircon; Premo and others, 2007), similar to the emplacement age for widespread intermediate-composition, calc-alkaline igneous rocks of the Routt Plutonic Suite (Premo and Fanning, 2000). The primary age of interbedded volcanic rocks ranges between about 1,790 Ma and 1,760 Ma (U-Pb zircon; Premo and others, 2007), consistent with model Sm-Nd ages of about 1,800 Ma for formation of earliest continental crust in northern Colorado (DePaolo, 1981)

Xbq **Quartzofeldspathic biotite schist and gneiss**—Conspicuously banded rock marked by alternating layers of contrasting composition that probably reflect original sedimentary layering, as well as effects of metamorphic segregation and partial melting. Dark-gray to black, medium- to coarse-grained layers (uncommon) are rich in biotite, sillimanite, and magnetite, and locally contain high-grade cordierite and (or) garnet (Gable and Sims, 1969; Cole, 1977, 2004b). Irregular quartzofeldspathic layers, bordered by selvages rich in biotite, sillimanite, and oxide minerals, formed in place during partial melting at peak of metamorphism (Cole and Braddock, 2009)

Xfb **Biotite granofels**—Light- to medium-gray, fine- to medium-grained, granoblastic to weakly foliated rock, commonly contains garnet and sillimanite; locally interlayered with minor quartzofeldspathic biotite gneiss and schist (Xb) and amphibolite (Xh). Unit only occurs in northern part of this quadrangle and adjoining parts of the southern Never Summer Mountains (O'Neill, 1981)

Xh **Hornblende gneiss and amphibolite**—Dark-gray, greenish-gray, fine- to medium-grained, weakly to strongly layered hornblende-plagioclase gneiss and hornblende-biotite schist, locally interlayered with massive amphibolite. Contains thin layers and pods of white to light-green calc-silicate gneiss

Xf **Granitic gneiss**—Light- to medium-gray, fine- to coarse-grained, moderately to strongly foliated rock composed primarily of quartz, oligoclase, and biotite. Microcline is generally present but amount varies from sparse to abundant; hornblende, garnet, and rare sillimanite locally present. Rocks have been described as gneissic granite, gneissic quartz monzonite, or gneissic granodiorite in adjoining areas, depending on mineralogy or bulk chemistry