COLORADO SCIENTIFIC SOCIETY
Fall Field Trip 2008

"The Search for Braddock's Caldera"

11,960+ summit above Lake Agnes proposed as Braddock Peak

September 6-7, 2008

Leaders:

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OVERVIEW

This field trip will focus primarily on the post-Laramide history of the northern Front Range involving the Late Oligocene magmatic activity in the Never Summer Mountains (about 30 to 27 Ma), coeval and younger faulting, and the evolution of drainage systems since then. We will also examine late Laramide (middle Eocene?) thrust faulting just west of Cameron Pass and complications arising from younger high-angle faults and possible wrench faults.

Most of the geology of this area was mapped by Prof. Bill Braddock (University of Colorado, Boulder) and graduate students under his direction in the 1970's and 1980's. Prior work by Gorton (1953) and other CU students in the Cameron Pass - Never Summer Mountains area (Ward, 1957; Corbett, 1964) established many of the major elements of the stratigraphy and structure, and detailed studies related to mineral resources were conducted farther south by Chevillon (1973) and Metzger (1974). O'Neill (1981) incorporated much of this prior work in the geologic map of the Mount Richthofen quadrangle and part of the Fall River quadrangle, and more recent work by Braddock to the north was compiled in the geologic map of Rocky Mountain National Park (Braddock and Cole, 1990). The regional geology has recently been compiled and updated somewhat for the Estes Park 100K quadrangle (Cole and Braddock, in press) and the Fort Collins 100K quadrangle (Workman and others, in prep.), and Kellogg and others (2008) completed the geologic map of the Clark Peak quadrangle just north of the Never Summer Mountains.

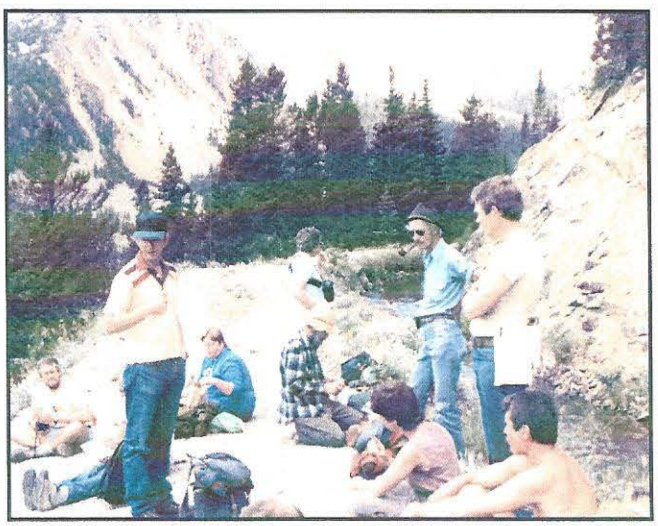

Fig. 1 – Bill Braddock (with signature pipe and hat) leading field trip in the 1970's along the Grand Ditch

Following Bill's untimely passing in 2003, former students initiated the process with the US Board of Geographic Names to officially designate an alpine mountain peak in his name. "Braddock Peak", when it is granted status, is here in the Never Summer Mountains where he spent many years mapping and guiding student work. It rises to 11,960+ ft on the west side of Lake Agnes (Stop 9, Day 2) and consists of Pierre Shale baked by the intrusion of the Mt Richthofen stock.

Fig. 2 – Google Earth view to the northwest showing location of "Braddock Peak" (11,960+ ft) proposed to the US Board of Geographic Names; Lake Agnes in right foreground

Official designation is anticipated before the end of 2008, just in time to be included on the new geologic map of the Estes Park 30′ x 60′ quadrangle that is currently in press (Cole and Braddock, 2008/9).

That map and report introduce the term "**Braddock Peak complex**" for the varied late Oligocene intrusive and volcanic rocks that are preserved in the Never Summer Mountains and adjoining areas of the Front Range and southern Medicine Bow Mountains

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TRAVEL: The trip begins at the junction of Highway 287 and the Red Feather Lakes road (County Road CR 74E), about 20 miles northwest of Fort Collins, at the Livermore general store.

STOP 1 - Livermore general store

Here's an opportunity to stretch, get a fresh cup of coffee, and visit the restroom.

We are headed westward into the "home office" of the volcanic and intrusive rocks of the late Oligocene Braddock Peak complex. We will not only examine the various igneous rocks generated at that time, but will also see evidence for significant uplift and erosion in this part of the northern Front Range. All of this igneous and structural activity was accompanied by major erosion, drainage development, and sedimentation. From the outside-in, then, we will first look at the fluvial sediments that were eroded from the general mountain uplift and from the volcanic edifice of the Braddock Peak complex.

TRAVEL: From Livermore general store, drive west on CR 74E toward Red Feather Lakes along the south side of the Livermore "embayment", a Laramide structural low that contains flat-lying Pennsylvanian-Permian strata flanked by steep reverse faults and elevated Proterozoic basement.

Cross canyon of North Fork Cache la Poudre River at old Livermore townsite. About 6 miles west of Livermore general store, note grassy slopes and flat-topped mesas to the north that are underlain by coarse fluvial gravel deposits of the mid-Tertiary Cache la Poudre River. Ledgy red beds in lower slopes are Pennsylvanian-Permian Fountain Formation.

Road curves south and climbs through exposures of the coarse boulder gravel deposits. Most clasts are subrounded Proterozoic Silver Plume-type granite and pegmatite, typically 5 to 10 in, as large as 3 ft.

At top of climb, rock quarry on south side of road

About 1.5 mi farther west, TURN LEFT at stone gateway entrance to Glacier Ridge development; pass convenience store and small lake on good dirt road. Continue about 2 miles south and west on main access road (Eiger Road to Many Thunders Mountain Drive)

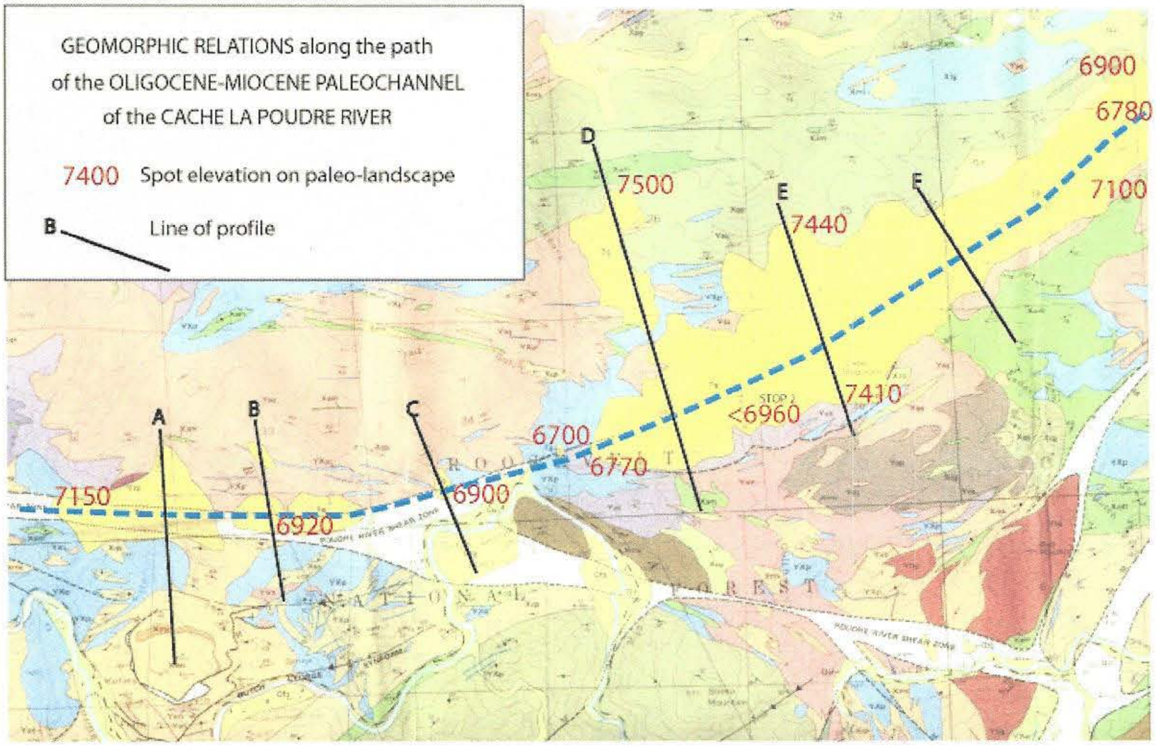
TURN LEFT on Meadow Mountain Drive and circle east and south around summit of Green Mountain to Milner Mountain Way

STOP 2 - Mid-Tertiary high-level gravels: The coarse bouldery gravel deposits are fairly well exposed along the roadcuts here for a considerable distance to the east. Roadside exposure here shows rare detail of some interbedded coarse arkosic sand in a channel trending eastward. Cobbles and boulders are subangular to subrounded, poorly sorted, and locally show hints of imbrication toward the east. Most are Proterozoic granite and pegmatite, but

20% to 30% here are granite gneiss, biotite schist/gneiss, and rarer amphibole gneiss (fig 3). A very small percentage of clasts consist of yellowish-gray or greenish-gray altered porphyritic volcanic rock with altered feldspar phenocrysts.

Fig. 3 – Roadcut photograph (J. Cole) of coarse fluvial gravel deposit at Green Mountain that was deposited by the late Oligocene-Miocene Cache la Poudre River

View to the west shows distribution of similar gravel deposits in the paleocanyon of the mid-Tertiary Cache la Poudre River (grass-covered slopes). These gravels are present at modern altitudes at least 700 ft lower than the summit of Green Mountain. Map relations (fig. 4; Big Narrows quadrangle; Abbott, 1976) indicate the bottom of these gravels declines smoothly toward the east, with only minor inferred faulting. By inference, this paleocanyon was at least 700 ft deep in mid-Tertiary time. The paleocanyon in this area appears to have a fairly straight course that suggests it might have formed on a moderately tilted surface as it cut deeply into the Proterozoic basement rocks. The gradient on the bottom of the paleochannel (about 125 ft/mile; fig. 5) is similar to the gradient on the modern Cache la Poudre River.



Geology from Big Narrows quadrangle (Abbott, 1976)

Fig. 4 – Stop 2, Gravel deposits of the late Oligocene-Miocene Cache la Poudre River

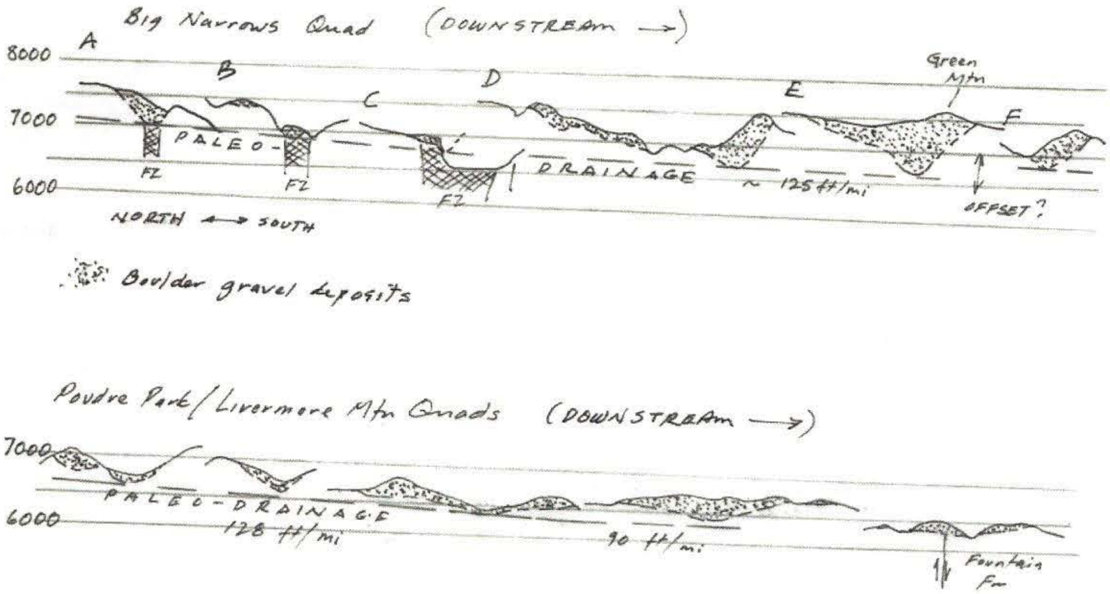


Fig. 5 – Serial downstream sections through the boulder gravel deposits of the late Oligocene-Miocene Cache la Poudre River showing paleogradients

The fact that the paleocanyon is now filled with coarse bouldery fluvial deposits is puzzling. Initially, the river had to be energetic enough to cut the canyon. Then, the river system had to be capable of moving such large-caliber material. And yet it seems it must have been simultaneously aggrading (depositing while losing energy). The general rarity of sorting or bedding in these fluvial channel gravels suggests deposition was either on-going, or that finer grained, better sorted deposits of lower flow velocities were repeatedly flushed downstream by higher-velocity, boulder-transporting events.

West of here, similar fluvial gravels are interbedded with the rhyolite ash-flow erupted from the Braddock Peak complex at about 27.7 Ma (late Oligocene) and locally contain abundant clasts eroded from the volcanic edifice. The gravels here are probably the downstream equivalents of those late Oligocene-Miocene(?) gravels. Steven and others (1997) noted that these mid-Tertiary paleodrainages trend more easterly and northeasterly than the drainages of the middle Oligocene White River Group deposits east of the Front Range, and they inferred a change in tilt direction at this time. One suggestion is that these high-level fluvial gravel deposits are the mountain-bound remnants of the Ogallala Formation alluvial fan complexes on the Colorado Piedmont, although the Ogallala is not known to be much older than about 17 Ma on the Piedmont.

Note the contrast of this paleochannel with the modern Cache la Poudre River in the canyon to the south (fig. 4 and 6). The river is deeply incised in the Proterozoic basement and yet it preserves a strongly meandering path similar to many of the other major streams that drain the Front Range. These meandering paths suggest the drainage was established on a more gently tilted surface (probably on an eastward-declining alluvial fan complex) and then superimposed during younger uplift of the Proterozoic basement.

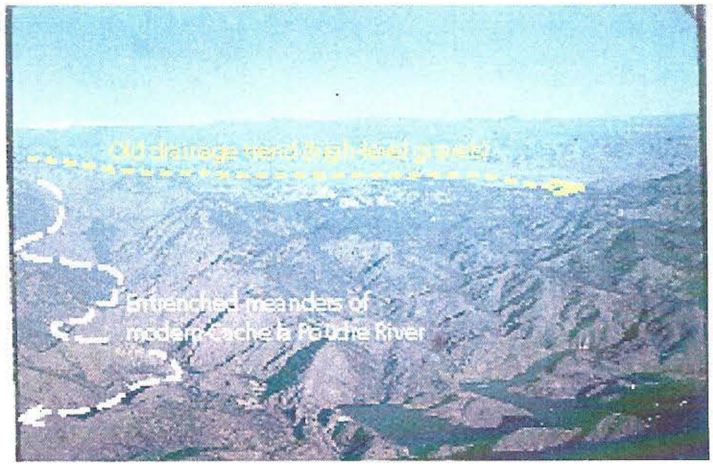


Fig. 6 – Aerial photograph (by Bill Braddock, 1976) of the confluence of the Cache la Poudre River and its North Fork at Seaman Reservoir (right foreground) showing the modern and Miocene(?) drainages; snow-covered Medicine Bow Mountains on left horizon

TRAVEL: Retrace roads to the paved Red Feather Lakes Road (CR 74E) and TURN LEFT (WEST). About 6 mi west, TURN LEFT (SOUTH) on unpaved CR 68C in the direction of the Delatour Boy Scout Camp and Shambala Buddhist Center

The road passes for several miles through medium and coarse-grained porphyritic biotite granites within the Log Cabin batholith, one of several large intrusions of Silver Plume-type granite emplaced at about 1,400 Ma.

TRAVEL: After about 4 mi, pass the entrance to the Delatour Camp and continue west another 6 mi to a triangle road junction adjacent to a power-line transformer site (Goddell Corner, no sign). TURN LEFT (SOUTH) on CR 69 and climb about 0.7 mi before dropping down on many switchbacks into the canyon of the Cache la Poudre River at Rustic.

TURN RIGHT (WEST) on CO 14 toward Cameron Pass

At about 6 miles west, the valley floor becomes substantially wider and flat-bottomed upstream from the Pinedale-age terminal moraine at Home (note sign for the "Home Moraine Campground" on the south side of the highway). The Home moraine was pushed all the way down to about 7600 ft elevation (far lower than most Front Range terminal moraines that end at about 8200 ft) because of the large catchment area in the headwaters of the Cache la Poudre drainage (see Madole and others, 1998).

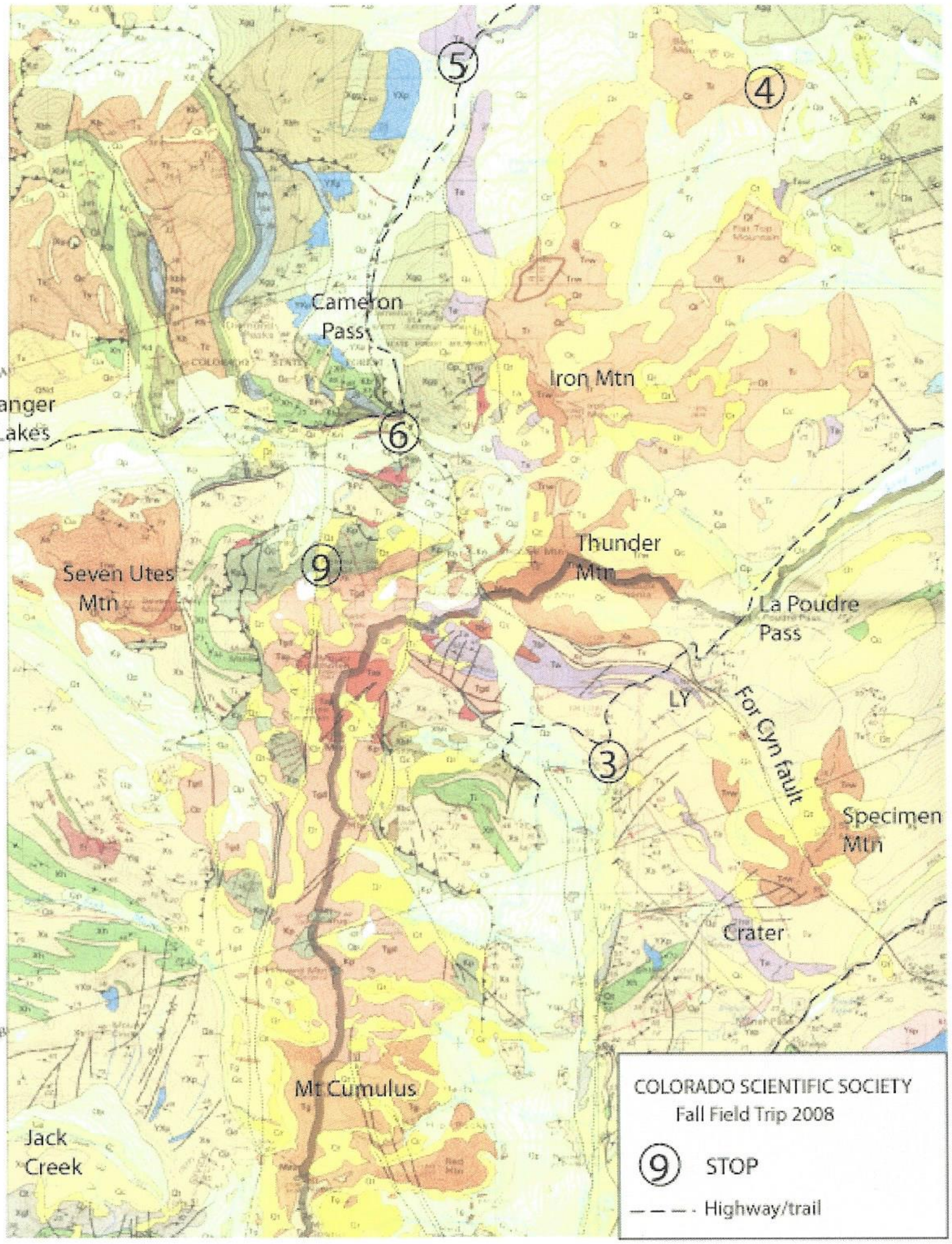
The highway (CO 14) passes upstream through a crystalline complex of Early Proterozoic banded granite gneisses and hornblende gneisses that likely formed from volcanic rocks erupted about 1780 Ma to 1760 Ma. These gneisses are intruded by fine grained, homogeneous granite of the Rawah batholith that invaded at about 1725 Ma to 1715 Ma. Complex relationships among these rocks are well exposed in roadcuts adjacent to Poudre Falls.

TRAVEL: About 12 miles up the canyon from the Home moraine, pass the turn-off to Chambers Lake and the road to Glendevey.

About 3 miles uphill from the Glendevey Road turnoff, TURN LEFT (SOUTH) on a good dirt road to Long Draw Reservoir and Long Draw Campground (USFS). Stay on this road, bearing RIGHT at the turn-off to Peterson Lake, for about 13 miles.

Just beyond the Peterson Lake turn-off, the road climbs through a pair of switchbacks. Note the well bedded, yellowish-brown, clay-rich deposits in the roadcuts. These sediments have been loosely correlated with the middle Oligocene White River Group. We can only say here that they seem to be older than the volcanic rocks.

From the parking area west of the west end of Long Draw Reservoir, a trail leads about 200 yds to La Poudre Pass at 10,175 ft. (we will have NPS permission to drive further west on September 6, but you would normally have to walk from here). See geologic map (fig. 7).



Geologic map of Rocky Mtn Natl Park (Braddock and Cole, 1990)

Fig. 7 – Geology of the northern Never Summer Mountains

La Poudre Pass is the Continental Divide here (in the bottom of a valley, no less!) and also marks the boundary with Rocky Mountain National Park to the west. We will drive a couple of miles west along the Grand Ditch maintenance road through a section of tilted late Oligocene volcanic rocks, turn around, and walk back east along the ditch road.

YOU'RE IN THE PARK NOW, SO NO HAMMERS AND NO COLLECTING.

LUNCH STOP!

The Grand Ditch water-diversion structure was constructed starting in the 1880's to intercept water from the Upper Colorado (Grand) River drainage basin on the western slope of the Divide and convey it into Long Draw Reservoir. From there, the water is released down the Cache La Poudre River for agricultural use on the Colorado Piedmont during the summer. It was constructed primarily by Chinese and Mexican laborers and about 8 miles were completed by 1890. In 1936, the Ditch was extended another 6 miles, and today, it spans nearly 17 miles to collect snowmelt from both west and east slopes of the Never Summer Mountains.

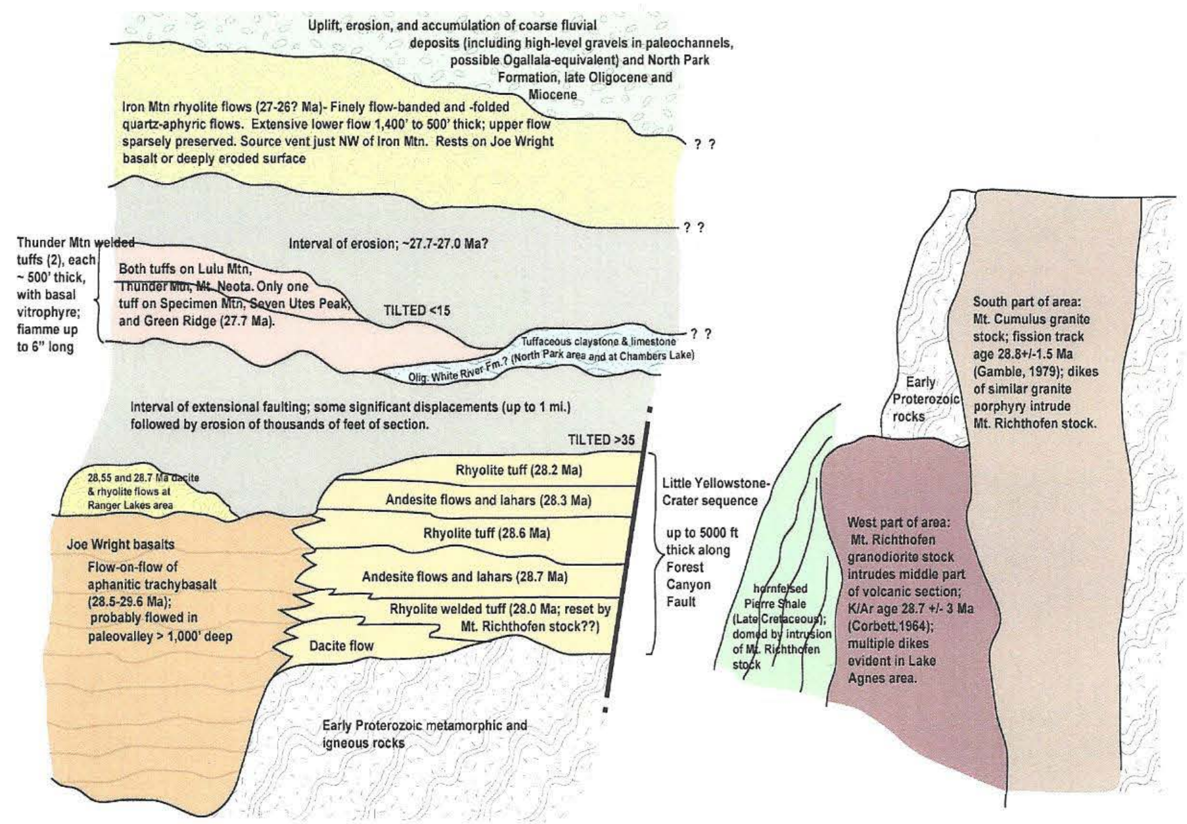
STOP 3 -- "Big Bend" on Grand Ditch; Overview of Little Yellowstone volcanic section:

This vantage provides a panorama of the tilted Oligocene volcanic rocks preserved in a half-graben to the southeast across the area known as Little Yellowstone for its semblance to volcanic terrains in the first National Park. The volcanic section is tilted against the major Forest Canyon fault that crosses the skyline just south of Specimen Mountain (brownish high peak) and crosses the Grand Ditch about a mile north of here where the first volcanic rocks were encountered on the drive to this location.

Inferred stratigraphic relations and radiometric ages are summarized in fig. 8. The volcanic geology is highlighted in serial geologic sketch maps in fig. 9.

SCHEMATIC STRATIGRAPHIC SEQUENCE for VOLCANICS of the BRADDOCK PEAK COMPLEX
based on field relations

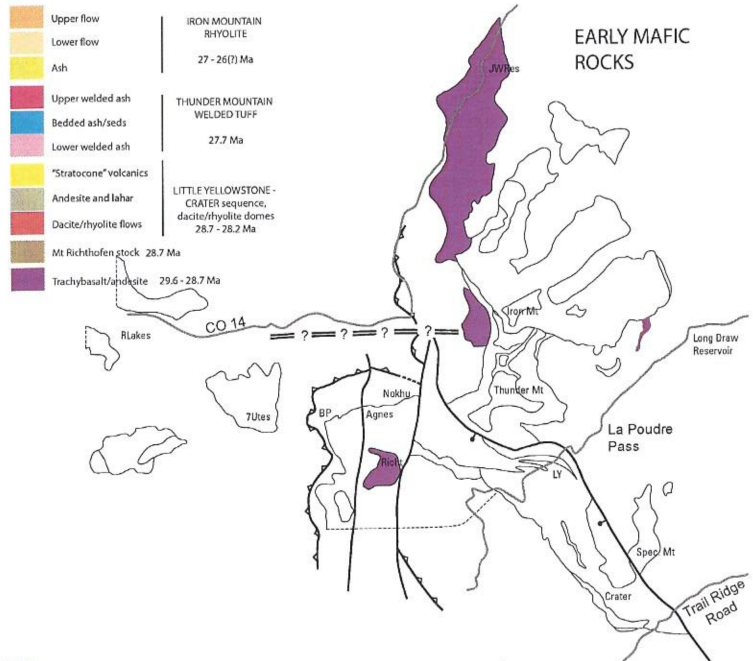
by ED LARSON, BILL BRADDOCK, & MIKE O'NEILL

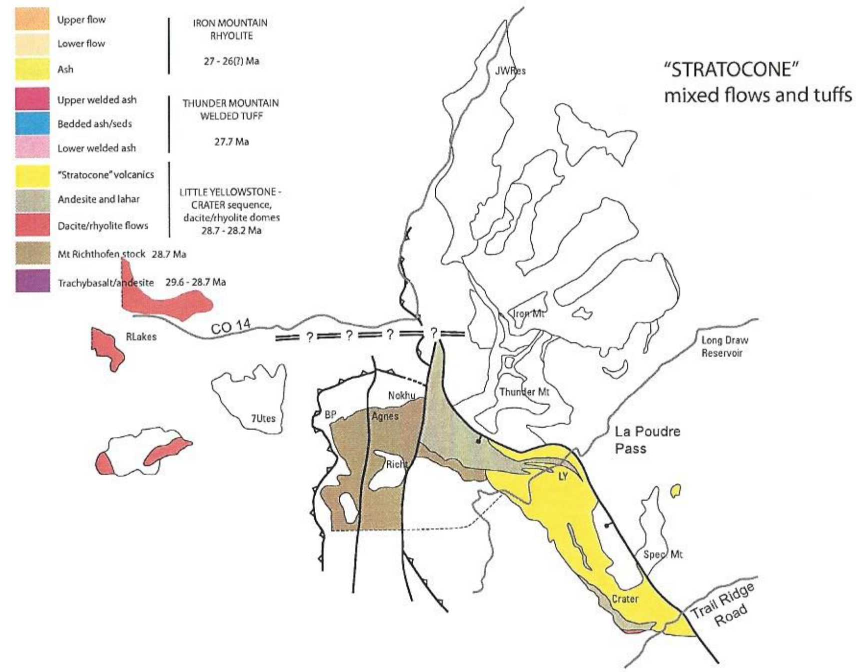


$^{40}Ar/^{39}Ar$ radiometric dates from USGS (Kathy Knox, CU MS thesis, 2005) and unpub. data (NM Tech lab)

Fig. 8 – Stratigraphic relations in the Braddock Peak complex

Little Yellowstone Canyon: The area of light-colored rock exposed in the valley below is a colorful sequence of dominantly rhyolitic rocks including bedded ash-fall tuffs, lava flows, flow breccias, and a welded tuff with dark basal vitrophyre. These same rock types occur along the Grand Ditch north of here and are interbedded with three tongues of calcalkaline andesite and associated laharic breccias. The Little Yellowstone sequence is over a mile thick and is thought to have accumulated on the flank(s) of a stratovolcano that was active from about 28.8 Ma to 28.2 Ma and perhaps to ~28.0 Ma. The sequence dips 35° to 50° northeastward into the Forest Canyon (normal) fault against Proterozoic basement rocks


EARLY MAFIC ROCKS
Upper flow
Lower flow
Ash
IRON MOUNTAIN RHYOLITE
27 - 26(?) Ma
Upper welded ash
Bedded ash/seds
Lower welded ash
THUNDER MOUNTAIN WELDED TUFF
27.7 Ma
"Stratocone" volcanics
Andesite and lahar
Dacite/rhyolite flows
LITTLE YELLOWSTONE - CRATER sequence, dacite/rhyolite domes 28.7 - 28.2 Ma
Mt Richthofen stock 28.7 Ma
Trachybasalt/andesite 29.6 - 28.7 Ma
JWRes
Iron Mt
Thunder Mt
CO 14
RLakes
Long Draw Reservoir
Nokhu
Agnes
BP
7Utes
Richt
La Poudre Pass
LY
Spec Mt
Crater
Trail Ridge Road


"STRATOCONE"
mixed flows and tuffs
Upper flow
Lower flow
Ash
IRON MOUNTAIN RHYOLITE
27 - 26(?) Ma
Upper welded ash
Bedded ash/seds
Lower welded ash
THUNDER MOUNTAIN WELDED TUFF
27.7 Ma
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Dacite/rhyolite flows
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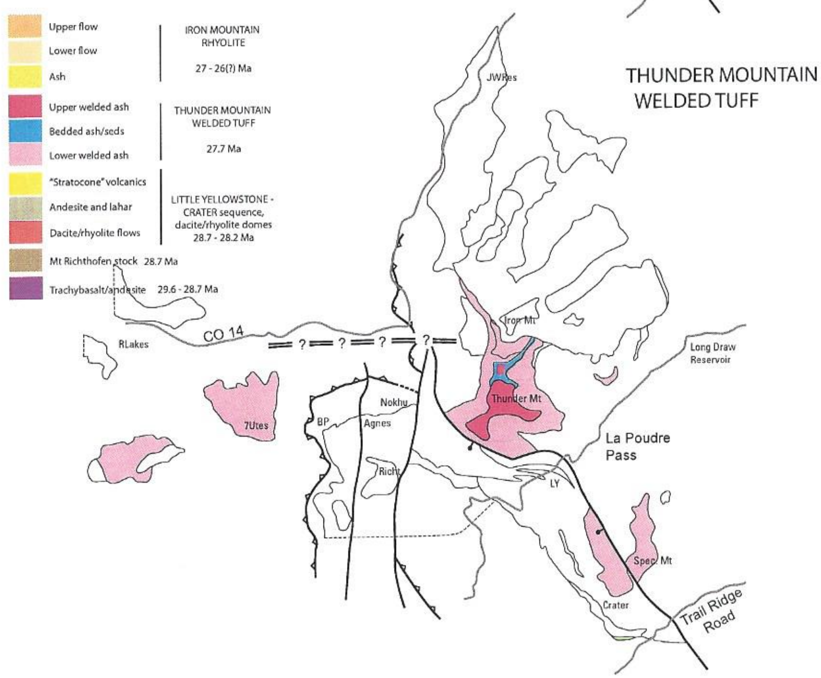
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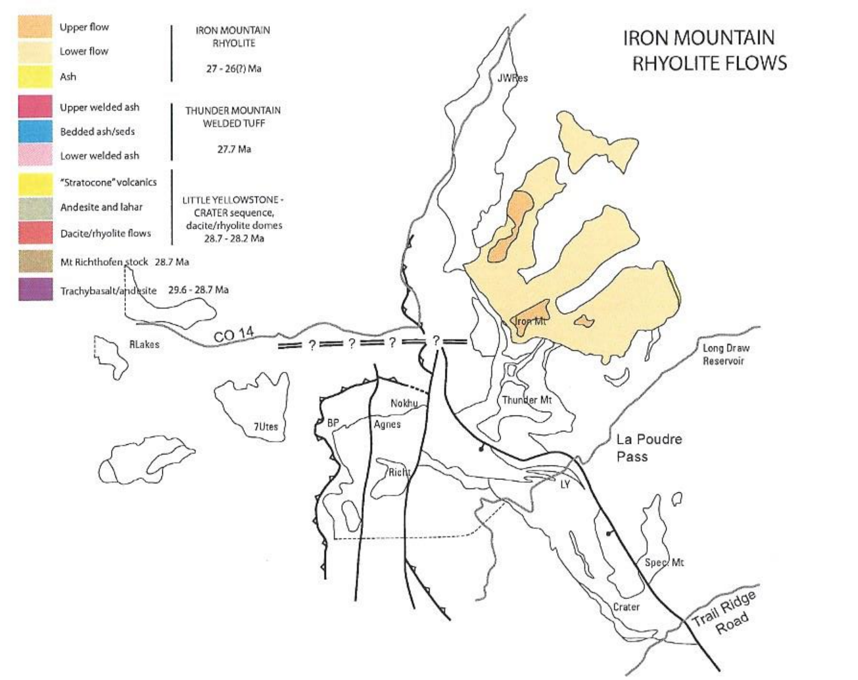
IRON MOUNTAIN RHYOLITE FLOWS
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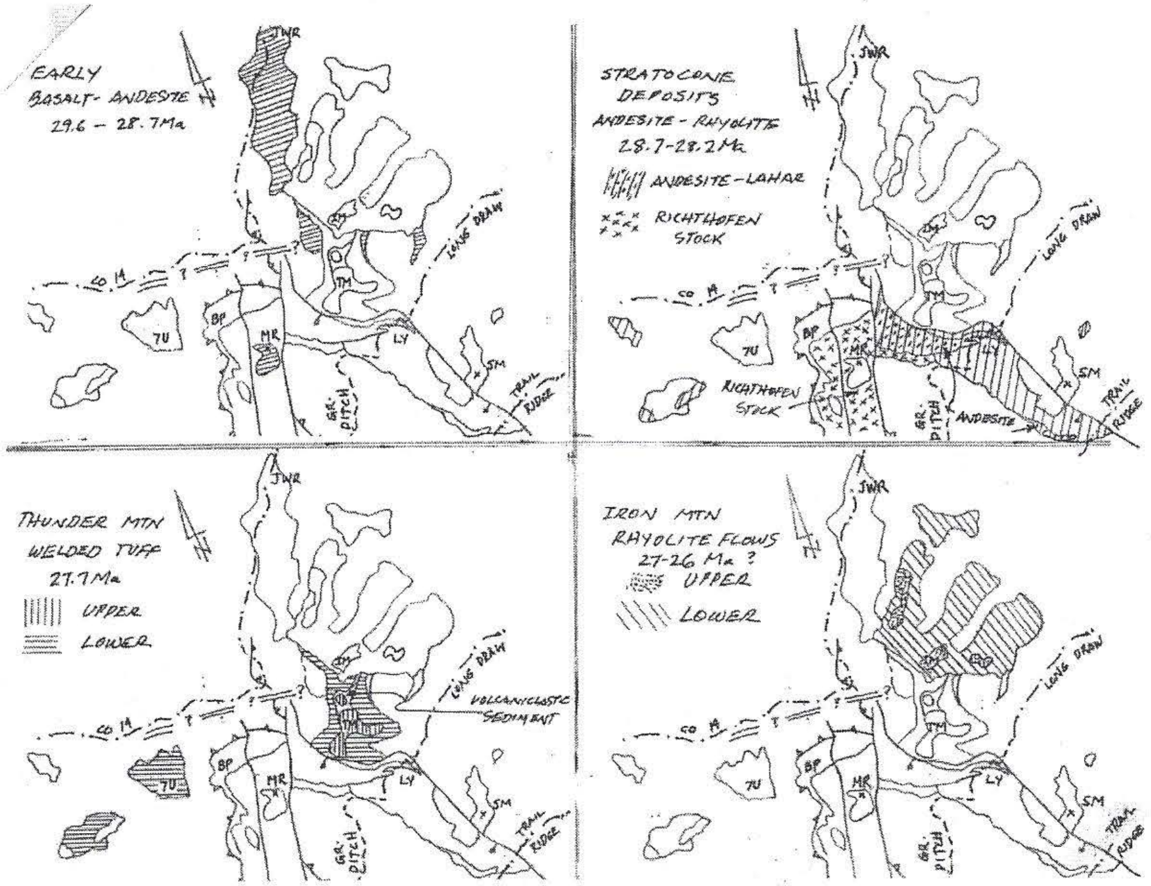


Fig. 9 – Sequential geologic sketch maps showing eruptive/intrusive phases of the Braddock Peak complex

$Ar^{40/39}$ dates from samples in the Ditch section are in minor disagreement with the observed stratigraphic order. The lowest sample in the section was a crystal-rich quartz-sanidine rhyolite collected here (at the Big Bend) that yielded an age of 28.0 Ma from sanidine. Dates of 28.85 Ma and 28.35 Ma were obtained on amphibole from the middle and upper andesite units, respectively, stratigraphically higher in the section (fig. 7 and 8).

Volcanic rocks along the Grand Ditch continue along strike to the southeast, across the Little Yellowstone valley and up to the skyline. The equivalent volcanic section south of the skyline summit of Specimen Mountain (in the region shown erroneously as The Crater on topographic maps) displays the heterogeneous stratocone sequence (fig. 11 and 12). From the base upward, the section displays a dacite flow (age in progress), a thin rhyolite tuff, a prominent flow of andesite with conspicuous laharic debris-flows, and a rhyolite welded tuff with a basal vitrophyre (28.2 Ma). Most of the higher section is obscured by talus.

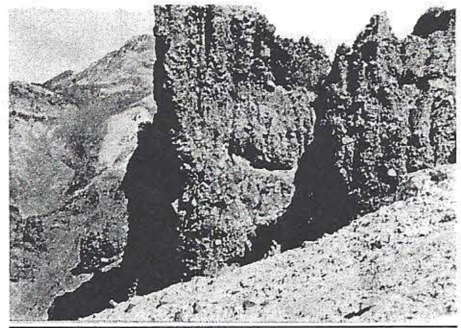


Fig. 10 – Willis Lee photograph (1916) of laharic breccia in the area of The Crater south of Specimen Mountain

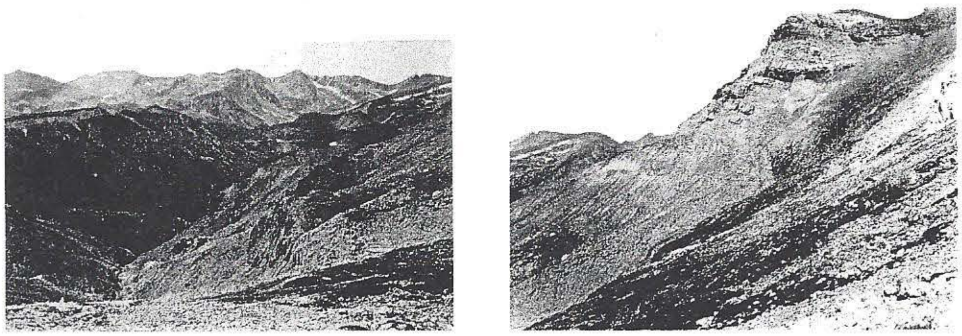


Fig. 11 – Willis Lee photographs (1916) looking west and down into the area of The Crater (left); and looking north along the headwall of The Crater at bedded volcanic ash, breccia, and dark vitrophyre (right)

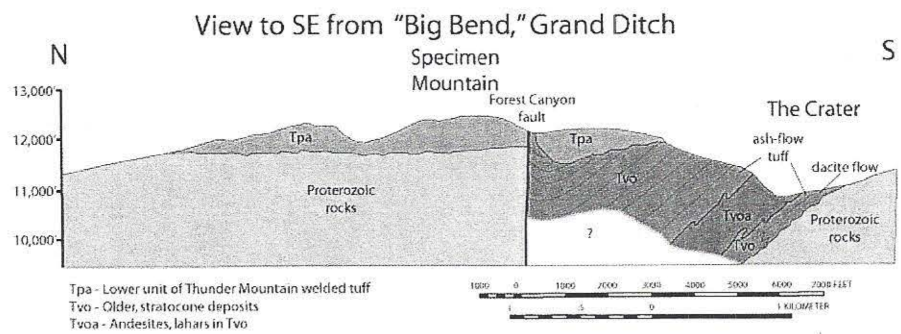


Fig. 12 – Sketch section of the Little Yellowstone-Crater section and Specimen Mountain, viewed southeast from the Grand Ditch

Specimen Mountain (fig. 7 and 12) is capped by a largely devitrified rhyolitic welded tuff that contains abundant phenocrysts of smoky quartz and sanidine and common collapsed pumice fragments (dark fiamme up to 6 inches). This unit is informally known as the Thunder Mountain tuff, named for that peak one mile north of here (see below). It is several hundred feet thick on Specimen Mountain and has a dark basal vitrophyre as much as 5 ft thick that is discontinuous along strike. The welded tuff contains numerous lithic fragments up to about 4 inches of various rock types, but many are hornfelsed Cretaceous Pierre Shale that may have come from the Never Summer Mountains to the west.

The Thunder Mountain tuff was erupted across an irregular erosion surface that records nearly complete stripping of older volcanic rocks from the block northeast of the Forest Canyon fault. This erosion also beveled the older stratocone sequence in the downthrown block southwest of the fault. The Thunder Mountain tuff south of the fault is tilted about 15° to 20°, less than the underlying stratocone deposits, indicating tilting and erosion prior to eruption. Further tilting/faulting occurred following eruption.

DISCUSSION: Let's return to the problem of evaluating the four available radiometric dates, three from the Grand Ditch section and one from the Crater (fig. 8). The prominent welded tuff, about 1/3 of the way up in the Crater section, has been dated at 28.2 Ma (sanidine). Although this unit is petrographically very similar to the welded tuff at the Big Bend, it has not been physically traced along strike to that locality. The only reason this date is under scrutiny is that it limits the time span between its eruption and the eruption of the Thunder Mountain tuff that caps Specimen Mountain to ~0.5 million years. During this interval, there would have occurred, in succession, continued accumulation of several thousand feet of stratocone deposits, normal-fault displacement of a least a mile, and substantial erosion. Some portion of the erosion, of course, could have occurred concomitantly with the faulting. Is 0.5 million years sufficient for this succession of events?

If we accept this date of 28.2 for the tuff in the Crater section and the sequence of events, it means that all three dates from the Ditch section are unacceptable: the Big Bend welded tuff being too young, and the andesite dates too old. Less than a mile to the west of the Big Bend, field relations along Box Creek show the Mount Richthofen granodiorite intruded the stratocone sequence. Certainly, then, there is the distinct possibility that the 28.0 Ma date reflects later reheating by the stock. As for the 'too-old' andesite dates, we would invoke the specter of excess argon in a mineral (hornblende) that commonly provides wobbly data.

Verification that stratocone building began a little earlier than 28.2 Ma is available from volcanic rocks near Ranger Lakes, in the northwest part of the area. Three radiometric dates, obtained on sanidine from a dacite and two rhyolites are, in order, 28.7, 28.55, and 28.55 Ma. Unfortunately, these lavas cannot be physically correlated with the Little Yellowstone section.

So, finally, in spite of all of the discrepancies in the available age data, our best guess is that the building of a stratovolcano began by ~28.7 Ma and continued to some time after 28.2 Ma. It is abundantly clear from the foregoing discussion that there is a need for additional 40/39 dates, particularly from sanidine-bearing rocks.

Regional relations of the Thunder Mountain tuff

This crystal-rich rhyolitic welded tuff consists of two ash-flow units at Thunder Mountain and at nearby Mount Neota and Lulu Mountain. The time break between the two eruptive events was probably short because the basal vitrophyre of the upper unit is typically the only evidence to separate the two. About 100 ft of volcaniclastic sediment (poorly to well stratified bedded tuff, lithic fragments, pumice, and crystals) is preserved between the ash-flows at a single locality in the flat, broad saddle between Thunder Mountain and Iron Mountain (fig. 9). A single ash-flow unit is preserved at Specimen Mountain, and a thick section at Seven Utes Mountain (4 miles west of here; >600 ft) also appears to be a single cooling unit and contains abundant fragments of volcanic, sedimentary, and Proterozoic rock.

At Thunder Mountain and nearby peaks, each of the ash-flow units is about 500 ft thick. Based on close similarities in phenocryst content, the units are considered to have erupted from the same magma chamber. Phenocrysts 1-3 mm in size make up 15 to 25% of the rock and consist of sanidine, smoky quartz (commonly doubly terminated), oligoclase, and a trace of biotite. Volcanic lithic fragments are present as are flattened pumice clasts. Non-volcanic lithic fragments are common in both eruptive units (locally 15 to 20% of the rock) and include Proterozoic rocks as well as some Phanerozoic sediments, especially Pierre Shale. The groundmass consists of devitrified shards.

The age of the Thunder Mountain tuff is inferred to be 27.7 Ma based on an $Ar^{40/39}$ age from quartz-sanidine-bearing distal outflow tuff on Green Ridge, 25 miles north. Gamble (1979) obtained a zircon fission-track age of about 27.6 Ma from "flow" rock at Specimen Mountain.

The Thunder Mountain pyroclastic flows are geologically significant inasmuch as several investigators, especially Bill Braddock, suggested a caldera might have developed during their eruption. No caldera or obvious caldera remnant has yet been located in the Braddock Peak intrusive-volcanic complex.

Jim Cole has looked at regional gravity data that suggest the area of the Mount Cumulus stock might be a source of the welded tuff. An oval gravity low (>15 mgal) covers an area of 4 x 7 mi beneath the stock, a blind granite porphyry body to the west, and the westward edge of the Never Summer thrust at Jack Creek. The Mount Cumulus granite is, like the Thunder Mountain tuff, a high-silica granite that has a porphyritic phase with quartz and feldspar phenocrysts. Similar-looking granite porphyry dikes at Lake Agnes will be viewed at Stop 9 (Day 2).

Because of considerable structural dislocation and extensive deep erosion, however, questions of the location (and existence) of a caldera will likely linger long into the future.

TRAVEL: Return to La Poudre Pass and drive back out the access road. About 0.5 mile downhill from the Peterson Lake turnoff past little Trap Lake, TURN LEFT (SOUTH) to the Trap Lake Trailhead and park.

STOP 4 – Iron Mountain rhyolite flow

Here, we examine rhyolitic lava flows that were produced during the last known volcanic episode of the Braddock Peak complex. Prior to the lava eruption, the region was again deeply eroded. All of the Thunder Mountain welded tuffs were removed northward of an imaginary east-west-trending line running along the northern side of Neota Valley.

The center of volcanism was located about one-half mile northwest of Iron Mountain, and the rhyolite flows are informally designated the Iron Mountain rhyolite. From this vent, viscous magma flowed about 3 miles to the north, northeast, and east, inundating the surface topography (fig. 7).

The Iron Mountain rhyolite is divisible into two flows (fig. 9). The lower one, which makes up most of the unit, is as thick as 1400′ near the vent but diminishes to about 500′ at the distal margins. Here at Trap Lake, the lower unit is characterized by 5-10% fine-grained (1/32″-1/16″) crystals of sanidine, quartz, oligoclase, and biotite, in a flow-banded matrix. The flow lamina are very thin (~1/32″ and less) and are contorted into flow folds at various scales (amplitudes of 1/8″ to 40′). The rock is aphanitic, contains no lithic fragments, and shows tan, pink, and red to maroon hues.

The upper flow is only preserved on Iron Mountain (~400′ thick) and on some topographic uplands that radiate north and east from that peak. The base is marked by a pyroclastic layer: a 5-10′-thick vitrophyre containing rhyolite fragments and fiamme up to 6″ in longest dimension. The upper flow is commonly darker in color than the lower flow, and is more evenly laminated and lacks large flow folds. Both flows are similar in mineralogy and grainsize. No age is available (yet) for the Iron Mountain rhyolite.

In a few places, a light-colored unit up to 40′ thick underlies the basal vitrophyre: it is composed of fragments of aphanitic rhyolite, flattended pumice, and blebs of obsidian.

TRAVEL: Return to the Long Lake access road and continue about 2 miles to the junction with CO 14. TURN LEFT (WEST) and continue uphill for about 2 miles to a parking area next to Joe Wright Reservoir.

STOP 5 – Joe Wright basalt

Low roadcuts on the northwest side of the highway expose the monotonously uniform flow-on-flow sequence of mafic-alkalic volcanic rocks that may be as much as 1000′ thick. Individual flows, which are not conspicuously marked by vesiculation or breccia zones, vary from about 20′ to 40′ thick. These rocks consistently display an aphanitic groundmass with minor microphenocrysts of plagioclase (up to 5%). They include rocks with 54-60% silica and 6-7% total alkalies, and are referred to as trachybasalts and trachyandesites. The flow sequence is best observed along CO 14 all the way up nearly to Cameron Pass.

The present distribution suggests that the flows erupted into a depression, perhaps a stream valley that declines northward from the Braddock Peak complex (fig. 9). Some flow remnants occur farther east near Long Draw Reservoir, so some flows may have covered broader areas or there may have been multiple stream valleys that conveyed basalt.

Two dates have been obtained from the middle part (29.8 Ma) and upper part (28.5 Ma) of the sequence near here. The older date has a large analytical error; this sample produced a plateau age of about 28.8 Ma, which may be closer to the true age. These numbers overlap with some of the early dacite and rhyolite flows farther west near the Ranger Lakes (fig. 8). Other samples are in process to define the onset of basalt volcanism.

TRAVEL: Continue southwest on CO14 over the summit of Cameron Pass at about 10,275 ft. About one mile below the pass, the highway makes a prominent bend to the right following the trend of the upper Michigan River. Park on the right-hand side of the road just past the prominent red sedimentary rocks on the right-hand roadcut.

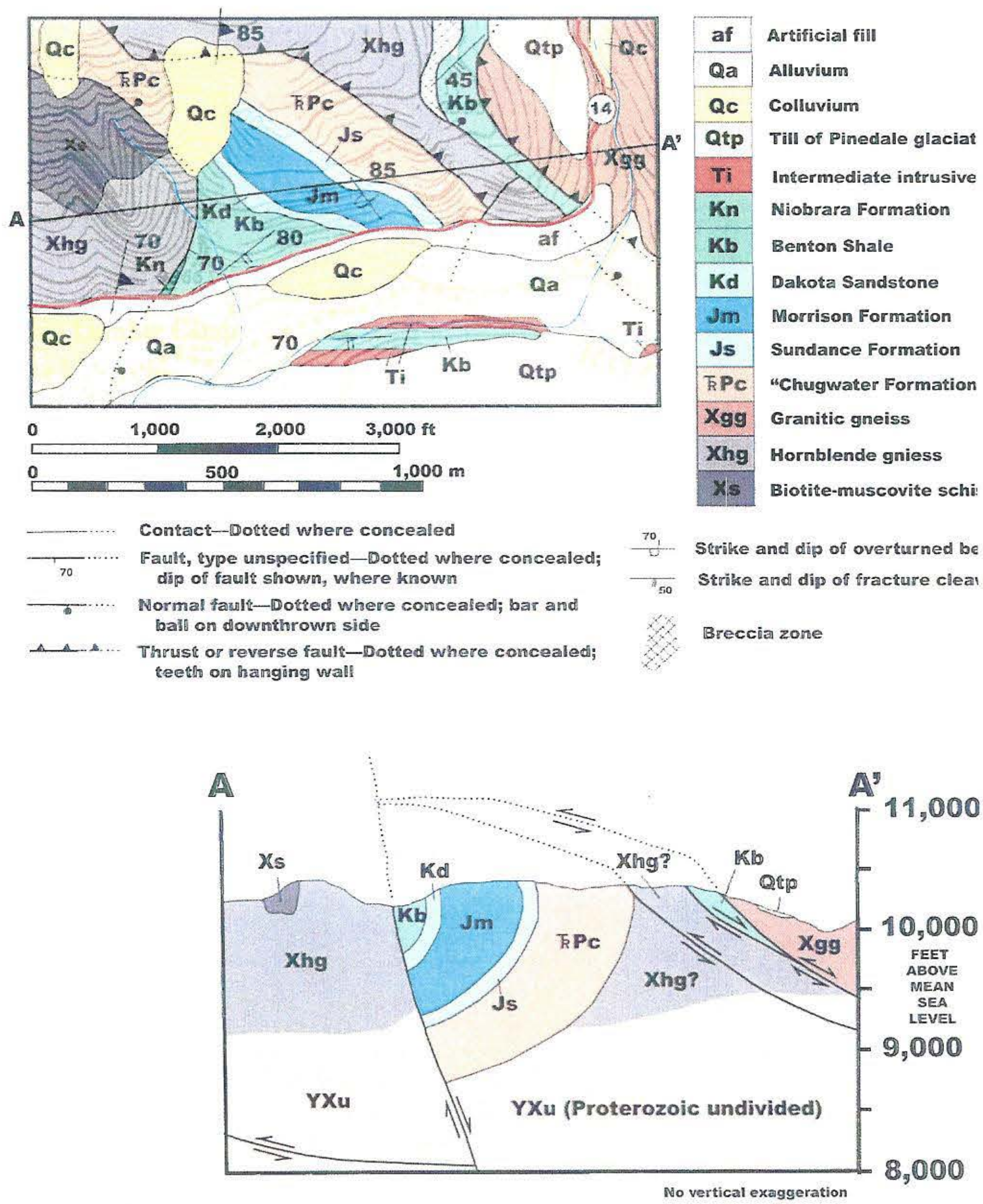
STOP 6 – SEVERAL TOPICS

STOP 6a. – Panoramic view of Nokhu Crags, Mount Richthofen, and Braddock Peak (looking south into the Lake Agnes glacial valley). The rugged Nokhu Crags on the left are composed of Cretaceous Pierre Shale that is deformed and baked by intrusion of the Mount Richthofen granodiorite stock. Temperatures appear to have locally exceeded 500° C (sanidine hornfels facies). The Pierre Shale here comprises the lower plate of the Eocene Never Summer overthrust sheet that placed Proterozoic gneiss over Paleocene-Eocene Coalmont Formation. In the Crags area the Pierre Shale dips at 70° - 80° because both it and the thrust were domed up around the margins of the stock. Farther south at Mount Cirrus (~12,800′), nearly flat-lying baked remnants of shale form the roof of the stock.

The highest peak in this view is Mount Richthofen whose summit consists of a dark gray andesite porphyry phase that is older than the main granodiorite that makes up the medium gray lower slopes. The singular peak on the right side of the Lake Agnes valley consists of baked Pierre Shale and is slated to be officially named Braddock Peak (by the end of 2008; see guidebook cover photo and Overview section).

STOP 6b – Iron Mountain west face. The rusty-colored peak east of here at the head of the Michigan River valley is Iron Mountain (12,265′; fig. 7). The source of the Iron Mountain rhyolite flows is probably just north of the summit. The west face of the peak shows the two flow units separated by a dark vitrophyre ledge. The lower slopes show dark basalt that can be traced northward and down the paleoslope to the Joe Wright Reservoir exposures (Stop 4).

STOP 6c – Thrust and normal-fault structure on the north side of CO 14. This stop affords the opportunity to examine the beautifully exposed section of non-volcanic rocks along CO 14, and elements of the west-verging thrust structure. All units from the Triassic and Permian Chugwater Formation of Braddock and Cole (1990) to the Cretaceous Niobrara Formation are represented, although the beds are overturned westward and the units have been thinned by faulting and shearing. In the interpretation shown on the map and cross-section (fig. 13; modified from Kellogg and others, 2008), both thrust and normal faults cut the rocks, juxtaposing Early Proterozoic gneiss against the sedimentary rocks. The two contrasting types of faults indicate that the area has been deformed during both Eocene Laramide contraction and Oligocene and younger extension. All pre-Permian rocks in this area have been eroded during uplift of the ancestral Front Range during the late Paleozoic.



Modified from Kellogg, Ruleman, Shroba, and Braddock (2008)

Fig. 13- Geologic map and cross section showing Eocene and younger fault relations along CO 14 west of Cameron Pass.

STOP 6d – Michigan River tear(?) fault. The east-west valley below to the south marks a significant change in geology. For example, the Pierre Shale of the Nokhu Crags is at least 4,000′ thick, and yet the entire Pierre is missing from the section north of CO 14. The Paleocene-Eocene Coalmont Formation rests on the upper-middle part of the Pierre in the footwall of the Never Summer thrust to the south, but the Coalmont rests directly on the Lower Cretaceous Benton Shale to the north. The flat-lying Never Summer thrust to the south is replaced by the steeper thrust displayed on the north side of CO 14 that dips >45° east. Folds in the faulted Phanerozoic section north of the highway and beneath the roof thrust have no counterparts to the south of the valley.

Gorton (1953) and Ward (1957) mapped in this area and both showed a buried/concealed transverse fault beneath the surficial valley deposits as a way of accounting for the discrepancies north and south of the valley. Exposures to the east at the head of the Michigan River valley are not good enough to establish the existence of a fault in the Proterozoic rocks, and Oligocene volcanics cover most of the landscape far to the east.

TRAVEL: Continue west on CO 14 through the bustling metropolis of Gould and then across the terraced landscape between the Michigan and Illinois Rivers for about 20 mi to Walden.

Walden is the county seat of Jackson County that incorporates most of North Park and the flanks of the surrounding ranges: Medicine Bow Mountains, Rabbit Ears Range, and Park Range. The North Park basin was settled in the late 1800's when the main economic activity was haying. Coal was mined from the Coalmont Formation for several decades and shipped out of North Park by rail to Wyoming. Market conditions changed, the mines closed, and the rail lines were dismantled in the mid 1900's.

Exploration for oil and gas was active for several decades following WWII, but no major fields were discovered in the folded structures of the Coalmont Formation and underlying marine shales. Renewed exploration in 2008 may have located commercial oil in fracture-controlled reservoirs in Lower Cretaceous formations.

Walden and Jackson County support growing tourism related to various outdoor activities, including hunting, fishing, bird watching, winter snowmobiling, ORV riding on two dune fields on the flanks of the Medicine Bow, and moose viewing (moose were re-introduced to the region in the 1970's and are thriving). Traditional ranching and farming continue to maintain the year-round economy.

OVERNIGHT IN WALDEN WITH AFTER-DINNER DISCUSSION SESSION

DAY 2 TRAVEL: Depart Walden eastbound on CO 14 in the direction of Cameron Pass. At about 4.5 miles, TURN RIGHT on County Road 21 (dirt) marked by a blue and yellow road sign. Continue south about 6 miles to the crest of the east-wet ridge, and then descend about 0.3 mi toward the broad Deer Creek valley. TURN LEFT (EAST) on a fair dirt track north of the creek and proceed about 0.5 mi to the base of the pink cliffs.

<u>STOP 8 -- Owl Ridge exposure of Oligocene-Miocene section.</u> Walk up the slope to the north that exposes the uppermost part of the Coalmont Formation, a section of light-colored tuffaceous claystones correlated with the White River Group, pinkish beds of volcanic ash from the Braddock Peak complex, and

overlying fluvial sands and gravels of the North Park Formation. The entire stratigraphic section dips about 25° to the northeast here on the southwest limb of the northwest-trending North Park syncline. This fold is younger than the folds that deform the Paleocene-Eocene Coalmont Formation across the basin and has a slightly different trend. It is curious because it suggests contractional deformation at a time when extensional faulting was active in the northern Never Summer Mountains (STOP 3, Day 1).

The principal interest at this stop is the pink, poorly welded, pumice-rich rhyolitic tuff (15-20′ thick) that rests unconformably on beds of the White River Formation (Montagne, 1957; Tweto, 1976). Pumice fragments in the tuff, which reach maximum dimensions of ~8″, are slightly flattened parallel to bedding and reversely graded. Crystals common to both the pumice fragments and groundmass are smoky quartz, sanidine, and oligoclase. Gypsum is a common secondary mineral phase, occurring in void cavities and seams. As yet, there is no radiometric date for this pyroclastic unit, but one is in the works. Based on stratigraphic relations, chemistry, and mineralogy, we consider this unit to be an outflow phase erupted during the Thunder Mountain pyroclastic event at 27.7 Ma. The fact that only one tuff is present here (18 miles west of Braddock Peak), and only one at Green Ridge (22 miles north), suggests the Thunder Mountain tuff was erupted in one major pulse.

Fluvial sands and gravels above the welded tuff belong to the North Park Formation. Clasts here are mostly volcanic rocks that probably came from the Braddock Peak complex and the late Oligocene volcanic rocks of the Rabbit Ears Range to the south. Proterozoic granite, pegmatite, and gneiss are typical but much less common at this stratigraphic level.

The fluvial gravels observed at STOP 2 (Day 1) west of Livermore appear to be related to the North Park Formation. Both deposits locally rest on welded tuff correlated with the Thunder Mountain tuff, and both record energetic transport of coarse grained material that includes clasts of the late Oligocene volcanic edifices. Integrated studies are planned in the next few years to investigate the uplift, erosion, and sedimentation histories of these rocks (coordinated by Jim Cole).

TRAVEL: Backtrack west to County Road 21 and continue south on this main dirt road toward Rand. TURN LEFT (EAST) at the sign pointing toward Gould. Continue about 7.5 miles to the junction with the CO 14 paved road. TURN RIGHT (EAST) and continue 4 miles toward Cameron Pass.

Yellow-brown outcrops on the left (north) are rhyolite flows dated at 28.55 Ma (Knox, 2005).

Pass the Moose Visitor Center on CO 14 and continue for about 2 miles. At the sign for the Colorado State Forest Campground (Upper Michigan River), TURN RIGHT (SOUTH) on the entry road. STOP at the self-service fee-entry station, pay the day-entry fee, and affix the valid entry sticker to your windshield.

Follow signs to the Lake Agnes Trailhead and park.

Hike up the Lake Agnes trail about one mile (about 600 ft elevation gain) to the lovely alpine tarn, Lake Agnes.

STOP 9. Lake Agnes - - At this stop we take a close look at the northern margin of the granodioritic Mount Richthofen stock, its contact with the hornfelsed Pierre Shale (including the Nokhu Crags), and the late-stage dikes that cross-cut the pluton margin.

The granodioritic Mount Richthofen stock is the older of the two plutons comprising the ~150 km^2 Never Summer "batholith". The younger Mount Cumulus stock is restricted spatially to southern margin of the batholith and, unlike the Mount Richthofen stock, consists largely of granite and quartz-K feldspar rhyolite porphyry. Whole-rock K-Ar and zircon fission-track ages demonstrate that the plutons are largely contemporaneous with the volcanic activity (~28.5 Ma) but, because we have no modern high precision U-Pb zircon ages, the precise crystallization ages of these stocks are not known.

Geochemical data from the stocks are also few and far between. Knox (2005) provided a few whole-rock analyses of both plutons, and compositions are consistent with their mineralogy. The Mount Richthofen stock has considerably lower wt % SiO_2 (~65%) than the Mount Cumulus body (~77%).

No depth of intrusion estimates are available, but the fact that the northern end of Mount Richthofen intrudes Tertiary andesite porphyry suggests very shallow depths of emplacement (<5 km). The contact between the andesite porphyry (dark gray) and the Mount Richthofen stock (medium gray) is visible about half-way up the north flank of Mount Richthofen and is clearly visible from Lake Agnes. The bases of the plutons are not exposed, but it seems likely that at least the Mount Richthofen stock is a laccolith.

New studies of the Tertiary intrusive igneous rocks in the Never Summer Mountains are underway at University of Colorado. The main thrust of this work is to try to test the genetic relationship between the intrusive rocks with intermediate to silicic volcanic rocks erupted in the region. Some recent models have suggested that high silica rhyolites, such as the Thunder Mountain ash flow tuffs, could represent melt extraction from high-level crystal "mushes" that are left behind and recrystallize to form epizonal batholiths. The Never Summer Mountains provide opportunities to test this model, given the relative simplicity (i.e. small volume) and good exposures of both extrusive and intrusive igneous rocks. The CU studies are beginning with geochemical and isotopic studies of dikes and border lithologies of the Mount Richthofen stock to try and assess models for silicic melt extraction from epizonal crystal mushes, and to try to directly link the Thunder Mountain ash flow tuffs to specific intrusive rocks. For example, along the southern margin of the Mount Richthofen stock just west of Lake Agnes, a fine-grained quartz-K-feldspar intrusive rock clearly has intermingled with coarse- grained portion of the pluton (Fig. 14). Is the fine grained lithology an example of crystal-poor melt extracted from the crystal mush represented by the coarser portions of the pluton? Radiogenic isotope studies are in progress to test this possibility, although such geochemical studies are hampered by the pervasive deuteric alteration of the border zones of the pluton.

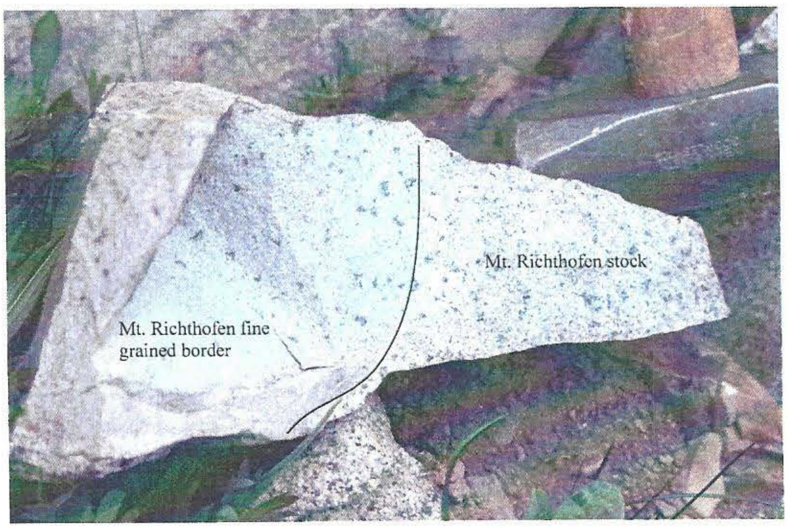


Fig. 14- Photo of intrusive rock lithologies present along the northern margin of the Mt. Richthofen stock.

Also present along the border zone of the Mount Richthofen stock at Lake Agnes are at least two generations of felsic dikes that appear to cross cut both the pluton and surrounding country rock. One of these contains abundant smoky quartz phenocrysts(?), akin to the Thunder Mountain ash flow tuffs but distinct from the fine grained, smoky quartz-free border lithologies of the Mount Richthofen stock. Do these represent feeder dikes for the large volume pyroclastic eruptions? Where were these dikes sourced? The Mount Cumulus granite? We will take a look at these dikes and let you formulate your own opinion!

TRAVEL: Hike back to Lake Agnes trailhead and return to CO 14. TURN RIGHT (EAST) and continue over Cameron Pass, down the canyon of the Cache la Poudre River, and out to Fort Collins.

REFERENCES

Abbott, J.T., 1976, Geologic map of the Big Narrows quadrangle, Larimer County, Colorado: U.S. Geological Survey, Geologic Quadrangle Map GQ-1323, scale 1:24,000.

Braddock, W.A., and Cole, J.C., 1990, Geologic map of Rocky Mountain National Park and vicinity: U.S. Geological Survey Miscellaneous Investigations Series Map I-1973, scale 1:50,000.

Chevillon, C.V., 1973, Petrology and structural geology of the Mount Cindy-Bearpaws Peaks area, Never Summer Mountains, Jackson County, Colorado: Buffalo, New York, State University of New York at Buffalo Masters thesis, 107 p.

Cole, J.C., and Braddock, W.A., 200x, Geologic Map of the Estes Park 30' x 60' quadrangle, north-central Colorado: U.S. Geological Survey Scientific Investigations Map 200x-xxxx, about 50 p., scale 1:100,000.

Corbett, M.K., 1968, Tertiary volcanism of the Specimen-Lulu-Iron Mountain area, north-central Colorado, *in* Epis, R.C. (ed.), Cenozoic volcanism in the southern Rocky Mountains: Colorado School of Mines Quarterly, v. 63, no 3, p. 1-37.

Gamble, Bruce, 1979, Petrography and petrology of the Mount Cumulus stock, Never Summer Mountains, Colorado: Boulder, Colorado, University of Colorado Masters thesis, 60 p.

Gorton, K.A., 1953, Geology of the Cameron Pass area, Grand, Jackson, and Larimer Counties, Colorado, *in* Wyoming Geological Association Guidebook, 8th Annual Field Conf., Laramie Basin, Wyoming and North Park, Colorado, 1953, p. 87-98

Hail, W.J., Jr., 1965, Geology of northwestern North Park, Colorado: U.S. Geological Survey Bulletin 1188, 133 p.

______ 1968, Geology of southwestern North Park and vicinity, Colorado: U.S. Geological Survey Bulletin 1257, 119 p.

Izett, G.A., 1968, Geology of the Hot Sulphur Springs quadrangle, Grand County, Colorado: U.S. Geological Survey Professional Paper 586, 79 p., scale 1:48,000.

______, 1975, Late Cenozoic sedimentation and deformation in northern Colorado and adjoining areas, *in* Curtis, B.F. (ed.), Cenozoic history of the southern Rocky Mountains: Geological Society of America Memoir 144, p. 179-210.

Kellogg, K.S., C.A. Ruleman, and Shroba, R.R., 2008, Geologic map of the Clark Peak quadrangle, Jackson and Larimer Counties, Colorado: U.S. Geological Survey Scientific Investigations Map 3010, scale 1:24,000.

Kinney, D.M., 1970, Preliminary geologic map of the Gould quadrangle, North Park, Jackson County, Colorado: U.S. Geological Survey Open-File Report 70-182, scale 1:48,000.

______ 1971, Preliminary geologic map of southwest third of the Kings Canyon quadrangle, North Park, Jackson County, Colorado: U.S. Geological Survey Open-File Report 71-171, scale 1:48,000.

Knox, K.L., 2005, The Never Summer igneous complex: Evolution of a shallow magmatic system: Boulder, Colorado, University of Colorado Masters thesis, 54 p.

Lee, W.T., 1917, The geologic story of the Rocky Mountain National Park, Colorado: U.S. national Park Service Publication, 89 p.

Madole, R.F., VanSistine, D.P., and Michael, J.A., 1998, Pleistocene glaciation in the Upper Platte River drainage basin, Colorado: U.S. Geological Survey Geologic Investigations Map I-2644, scale 1:250,000.

Metzger, C.W., 1974, Geology, mineralization, and geochemistry of the Upper Illinois River drainage basin, Grand and Jackson Counties, Colorado: Golden, Colorado School of Mines Master's thesis, 92 p.

Montagne, J. de la, 1957, Cenozoic structural and geomorphic history of northern North Park and Saratoga Valley, Colorado and Wyoming, *in* Rocky Mountain Association of Geologists, Guidebook to the geology of North and Middle Parks basin, Colorado, 1957, p. 36-42

Montagne, J. de la, and Barnes, W.C., 1957, Stratigraphy of the North Park Formation in the North Park area, Colorado, *in* Rocky Mountain Association of Geologists, Guidebook to the geology of North and Middle Parks basin, Colorado, 1957, p. 55-60

O'Neill, J.M., 1981, Geologic map of the Mount Richthofen quadrangle and the western part of the Fall River Pass quadrangle, Grand and Jackson Counties, Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I-1291, scale 1:24,000.

Pearson, R.C., Braddock, W.A., Flanigan, V.J., and Patten, L.L., 1981, Mineral resources of the Comanche - Big South, Neota - Flat Top, and Never Summer Wilderness Study Areas, north-central Colorado: U.S. Geological Survey, Open-File Report OF-81-578, scale 1:48,000.

Scott, G.R., and Taylor, R.B., 1986, Map showing late Eocene erosion surface, Oligocene-Miocene paleovalleys, and Tertiary deposits in the Pueblo, Denver, and Greeley 1° x 2° quadrangles, Colorado: U.S. Geological Survey Miscellaneous Investigations Map I-1626, scale 1:250,000.

Steven, T.A., Evanoff, Emmett, and Yuhas, R.H., 1997, Middle and Late Cenozoic tectonic and geomorphic development of the Front Range, Colorado, *in* Bolyard, D.W., and Sonnenberg, S.A. (eds.), Geologic history of the Colorado Front Range: Rocky Mountain Association of Geologists, p. 115-124.

Tweto, Ogden, 1976, Geologic map of the Craig 1° x 2° quadrangle, Colorado: U.S. Geological Survey Miscellaneous Investigations Map I-972, scale 1:250,000

Ward, D.E., 1957, Geology of the Middle Fork of the Michigan River, Jackson County, Colorado, *in* Rocky Mountain Association of Geologists, Guidebook to the geology of North and Middle Parks basin, Colorado, 1957, p. 70-74