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Photographic Essay: Geologic Map of the Bonanza Caldera Area, Northeastern San Juan Mountains, Colorado

By Peter W. Lipman

Photographic essay to accompany

Scientific Investigations Map 3394

U.S. Department of the Interior
U.S. Geological Survey

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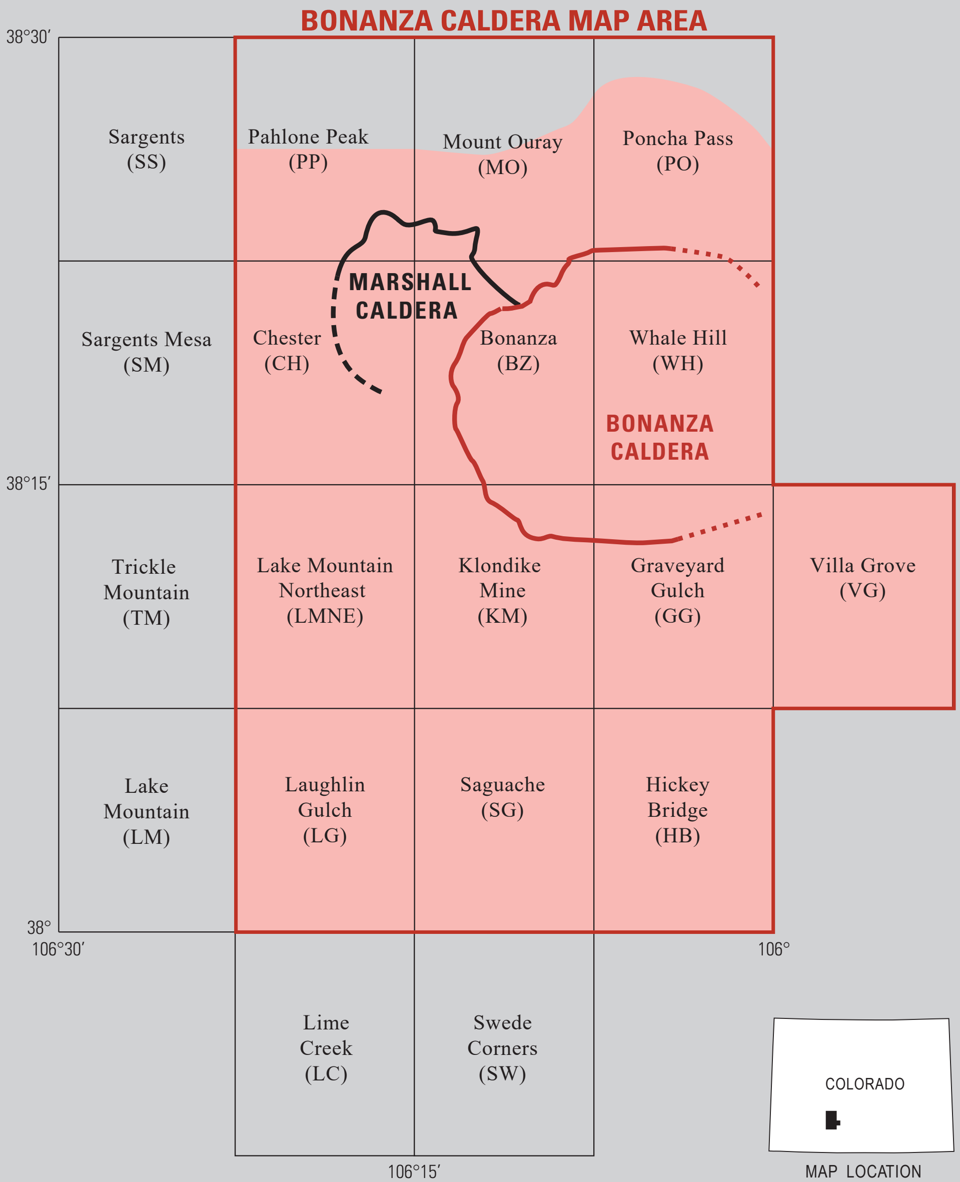
Contents

This photographic essay, containing 144 annotated images and explanatory captions, supplements the description and interpretation of rock units, caldera structures, and other volcanic features of the Bonanza caldera area presented in the map pamphlet. The individual photographs are grouped in 20 sections, based on stratigraphic units in the map area, caldera and intrusion structures, associated mineralization, notable geographic features, and participating research associates. Photo groups and individual photographs are referenced in the pamphlet text. All photographs were taken by Peter Lipman during 2006–2012.

See associated pamphlet, geologic map, figures, and tables 5 and 6 at https://doi.org/10.3133/sim3394. Cited chemical analyses are from table 5 and cited $^{40}Ar/^{39}Ar$ ages are from table 6 (tables at https://doi.org/10.3133/sim3394). Abbreviations for topographic-quadrangle names are defined in the index map. For major volcanic units, phenocryst percentages are listed, with principal phases in order of abundance: bi, biotite; cpx, clinopyroxene; pl, plagioclase; qtz, quartz; sn, sanidine. SiO_2, silica (silicon dioxide). Elements: Ag, silver; Cu, copper; Pb, lead; Zn, zinc.



Index map showing Bonanza Caldera mapped area (orange) and locations of labeled USGS 7.5' topographic quadrangles (gray outlines) in and adjacent to the map area. Abbreviations below quadrangle names are used throughout the publication to discuss areas of the map. Modified from figure 3 on sheet 1.

1. Bonanza

The town of Bonanza, the only settlement within outcropping parts of Bonanza caldera, was a thriving boomtown in the 1880s but at present has only a few year-round residents.

Photo 1.1*A*. Entry sign to town of Bonanza; along Bonanza road. Photo site: lat 38°17.3′ N., long 106°08.25′ W.

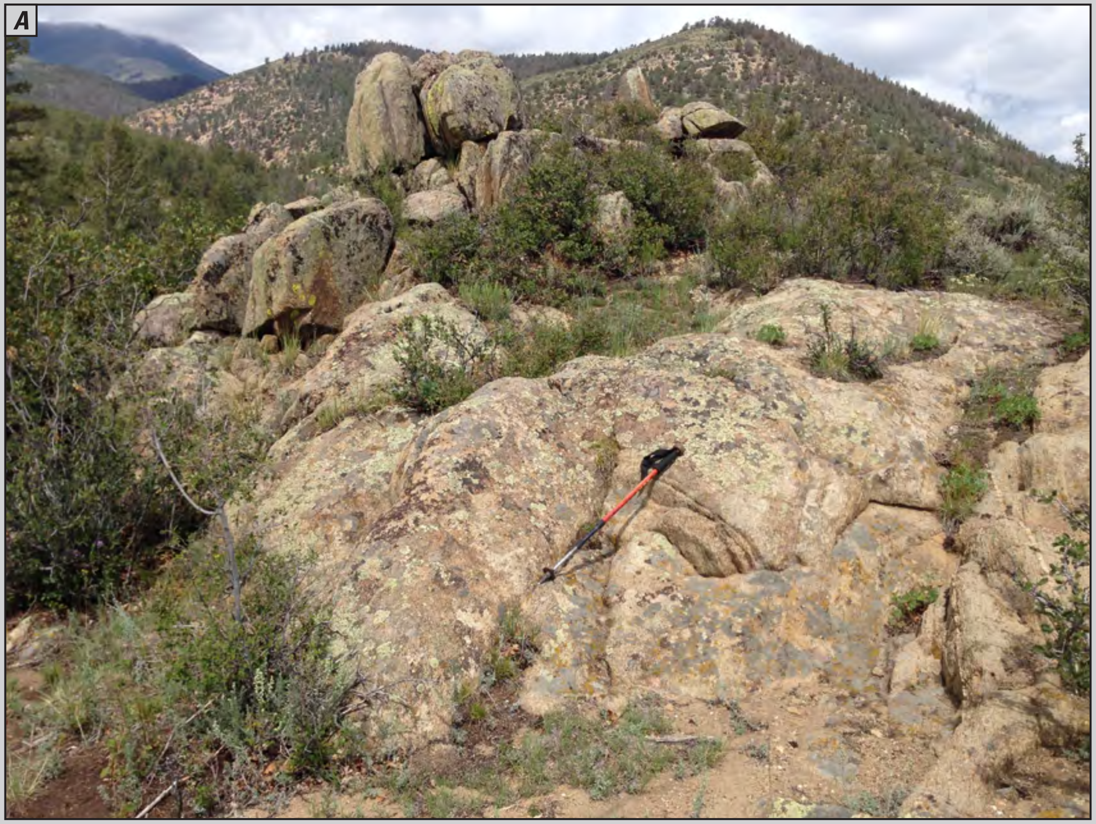
Photo 1.1*B*. Town of Bonanza: year-round population two (in 2014). Photo site: lat 38°17.7′ N., long 106°08.5′ W.

Detailed mapping of the geologically complex Bonanza area would have been far less successful without the immensely helpful and enjoyable collaborations with several able associates (who are imaged in several of the photographs).

Photo 2.1. Bill McIntosh (left) and Matt Zimmer (center right), from the New Mexico Bureau of Geology and Mineral Resources, made annual field trips for geochronologic sampling, providing the numerous $^{40}Ar/^{39}Ar$ ages that have been critical to constraining the Bonanza-area eruptive sequence and interpretations of volcanic processes. They are coauthors of an interpretive journal article on the Bonanza caldera area (Lipman and others, 2015). Andrea Sbisà (center left), at time of Bonanza fieldwork a graduate student at University of Trieste, Italy, provided much-appreciated month-long assistance during each of three core summers of field mapping (2008–2010). View is to east, from hill 12,011′ on the crest of the Whale Hill resurgent dome (WH), toward the distant Sangre de Cristo Mountains across the San Luis Valley segment of the Rio Grande rift. Photo site: lat 38°17.3′ N., long 106°05.8′ W.

3. Pre-Tertiary Rocks

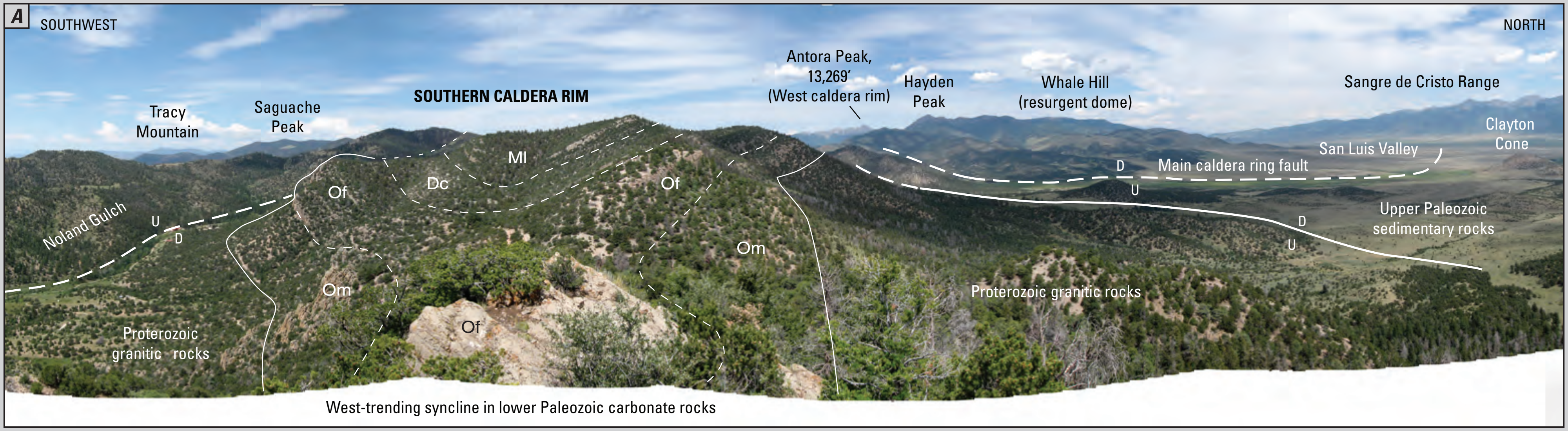
Precambrian crystalline rocks and overlying Paleozoic and rare lower Tertiary sedimentary deposits are widely distributed along margins of the map area, beneath the Oligocene volcanic rocks.



Photos 3.1*A*,*B*. **Precambrian rocks (Proterozoic)** are texturally and compositionally variable granitoid rocks, intruding into diverse metasedimentary and metavolcanic country rocks.

***A*.** Typical outcrop of granitic gneiss at mouth of Peterson Creek (WH: lat 38°17.20′ N., long 106°01.60′ W.).

***B*.** Foliated granodiorite, Kerber Creek road (sample 14L-23; GG, lat 38°12.97′ N., long 106°04.63′ W.).



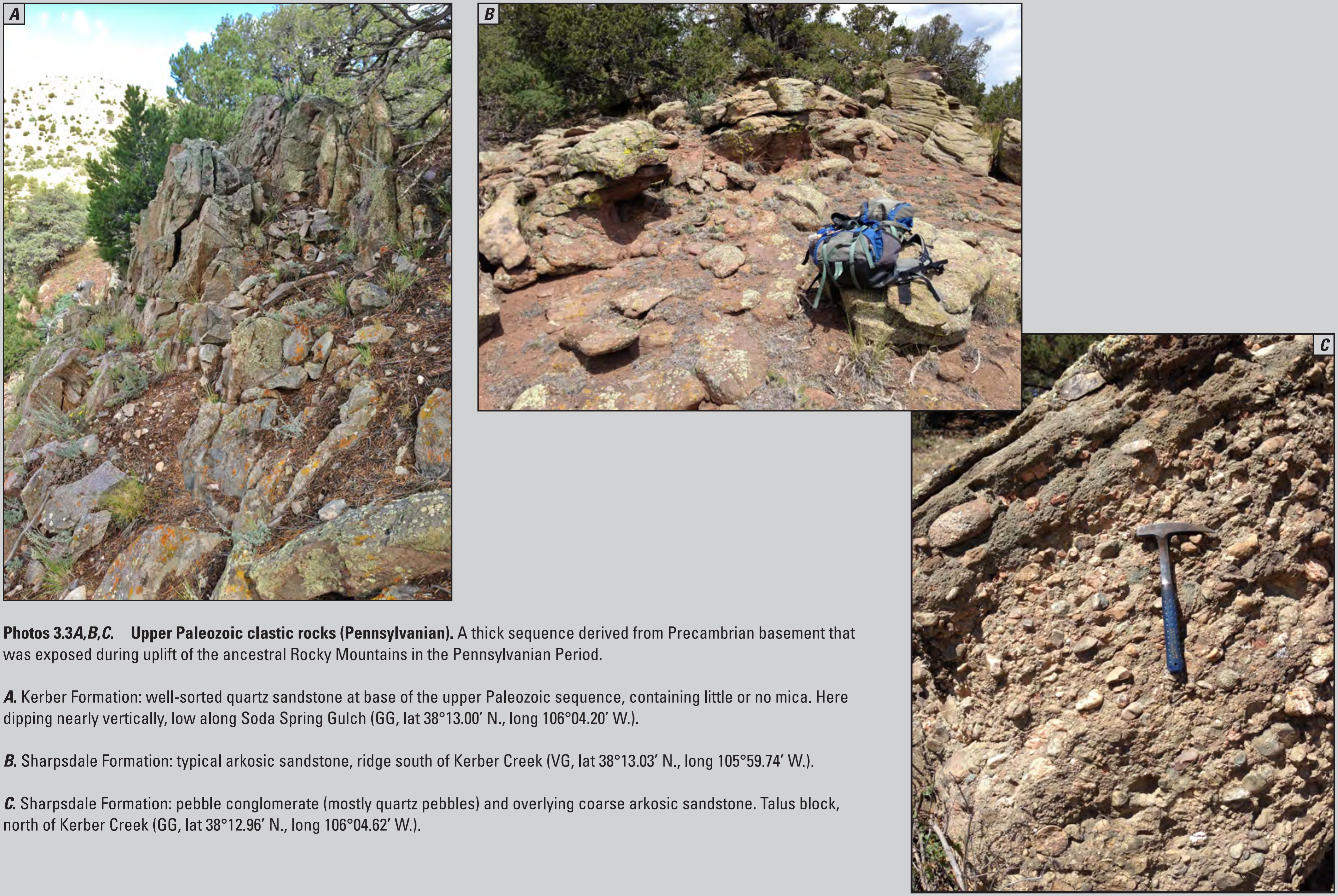
Photos 3.2*A,B,C*. Lower Paleozoic carbonate rocks. The Paleozoic strata are particularly helpful for interpreting the structure of Bonanza caldera, because they provide far more detailed stratigraphic resolution than the overlying volcanic units.

***A*.** Synclinal fold in lower Paleozoic carbonate rocks, along southern topographic rim of Bonanza caldera, and view toward south end of Whale Hill resurgent dome. Synclinal axis of lower Paleozoic carbonate rocks, underlain by Precambrian granite, trends east-west. This structure may be a remnant of an early Tertiary (Laramide) fold, because Oligocene volcanic rocks were deposited directly on the Precambrian nearby to the south and west. The easterly trend is anomalous for Laramide structures, however, and alternatively the syncline may be, at least in part, a hinge structure at the south margin of resurgent uplift in Bonanza caldera. The primary caldera ring fault follows Kerber Creek and projects eastward into the San Luis Valley, but several additional down-to-the-north normal faults accommodated peripheral caldera subsidence as far south as Noland Gulch. Dc, Dyer Formation; Of, Fremont Dolomite; Ml, Leadville Limestone; Om, Manitou Limestone. Movement shown along faults: D, down; U, up. View to west, from 9,400′ high point along ridge, west margin of VG quadrangle. Photo site: lat 38°11.6′ N., long 106°59.8′ W. .

Photos 3.2*A,B,C*—Continued. **Lower Paleozoic carbonate rocks.** The Paleozoic strata are particularly helpful for interpreting the structure of Bonanza caldera, because they provide far more detailed stratigraphic resolution than the overlying volcanic units.

B. Lower Paleozoic carbonate section, on north slope of hill 9532; viewed from Kerber Creek (GG). Upper cliff is Fremont Dolomite (unit Of, Upper Ordovician), capped by Dyer Formation (unit Dc, Devonian); lower cliff is Manitou Limestone (unit Om, Lower Ordovician), with talus of Harding Quartzite (unit Oh, not labeled) on bench above. Underlying slope consists of disaggregated Precambrian granitic rocks (unit p€g). Photo site: lat 38°13.4′ N., long 106°00.3′ W.

C. Well-bedded Manitou Limestone (Ordovician), north slope of Noland Gulch (GG). Photo site: lat 38°11.4′ N., long 106°08.25′ W.



Photos 3.3*A,B,C*. Upper Paleozoic clastic rocks (Pennsylvanian). A thick sequence derived from Precambrian basement that was exposed during uplift of the ancestral Rocky Mountains in the Pennsylvanian Period.

***A*.** Kerber Formation: well-sorted quartz sandstone at base of the upper Paleozoic sequence, containing little or no mica. Here dipping nearly vertically, low along Soda Spring Gulch (GG, lat 38°13.00′ N., long 106°04.20′ W.).

***B*.** Sharpsdale Formation: typical arkosic sandstone, ridge south of Kerber Creek (VG, lat 38°13.03′ N., long 105°59.74′ W.).

***C*.** Sharpsdale Formation: pebble conglomerate (mostly quartz pebbles) and overlying coarse arkosic sandstone. Talus block, north of Kerber Creek (GG, lat 38°12.96′ N., long 106°04.62′ W.).

4. Jacks Creek Volcano

Jacks Creek is a symmetrical central volcano (LMNE), about 10 km in diameter at present-day outcrop level, consisting mainly of outward-dipping andesitic flows and breccia that overlie rhyolite near the volcano core. Radial dikes of andesite to rhyolite are well exposed on its south and east flanks.

Photo 4.1. Andesitic lava flows and interleaved laharic breccias, east flank of Jacks Creek volcano. View to north from Middle Creek access road (LMNE). Photo site: lat 38°11.0′ N., long 106°19.0′ W.

Photo 4.2. East-trending dike of mafic dacite (sample 09L-34A, 62.6% SiO_2), which appears to feed into a slightly more silicic dacite flow that caps the ridge (sample 09L-34B, 66.5% SiO_2). View of this striking exposure is to east, across Middle Creek, from Middle Creek access road (LMNE). Photo site: lat 38°11.9′ N., long 106°18.1′ W.

Photo 4.3. Fine-grained dacite dike (sample 07L-57, 68.48% SiO_2), about 1 m wide. Typical exposure, a low rubble ridge rising above colluvium-mantled slope. Groundmass $^{40}Ar/^{39}Ar$ age: 34.51±0.63 Ma (table 6). Middle Creek access road (LMNE, lat 38°11.64′ N., long 106°19.06′ W.).

Photo 4.4. Central vent and intrusion. Pyroclastic-breccia-vent fill and intrusion of silicic dacite-rhyolite (sample SRM-2, 72.7% SiO_2; LMNE, lat 38°11.57′ N., long 106°20.99′ W.). Sanidine $^{40}Ar/^{39}Ar$ age: 34.29±0.06 Ma (table 6).

5. Rawley Volcanic Complex

The Rawley volcanic complex is an assemblage of dominantly andesite-dacite lavas erupted from a cluster of central volcanoes, within which Bonanza caldera subsequently formed.

Photo 5.1. Andesite flows on inner west caldera wall. Coherent stratigraphic sequences of west-dipping precaldera andesitic lava flows (units Tra, Trap) of the Rawley complex, along the east ridge of Windy Point, as viewed from south (BZ). Photo site: lat 38°18.2′ N., long 106°12.6′ W.

Photo 5.2. Complexly columnar-jointed dacite flow, suggesting emplacement into water or on wet sediment along axis of paleovalley. Junction of Little Kerber Creek and Lucky Boy Gulch (KM, lat 38°13.10′ N., long 106°09.05′ W.).

Photos 5.3*A,B,C,D*. **Variably welded crystal-poor ignimbrite**, dipping steeply west, in caldera-wall section of Rawley lavas, northeast slope of Flagstaff Mountain (BZ). Based on steep dips, initial impression was a tuff dike or surficial fracture fill, perhaps rhyolitic Bonanza Tuff intrusive into the Rawley lava sequence, but the welding zonation (see photo *A*) and well-sorted and finely bedded upper zone (see photo *D*) suggest origin as a small ignimbrite deposited within the dominant lava sequence of the Rawley complex. The steep dips could have resulted from rotation of a large slab that slumped downward along the caldera wall.

***A*.** View to south. Light-gray rocks in lower center and upper right are partly welded tuff that probably was originally glassy; tan-brown central zone, in middle of image, appears to have been a zone of primary devitrification. Unit is about 20 m thick, striking ~N. 20° W., dipping 50–70° W., and wedging out before reaching the skyline ridge crest. Photo site: lat 38°16.6′ N., long 106°11.8′ W.

***B*.** Closer view of lower partly welded zone, at bottom center of photo 5.3*A* (sample 14L-24, 75.80% SiO_2), showing conspicuous flattened pumice lenses (fiamme). Hiking pole is ~0.9 m long. Location: lat 38°16.61′ N., long 106°11.83′ W.

***C*.** Steeply dipping upper contact of light-gray partly welded ignimbrite against andesite lavas higher in caldera-wall section.

***D*.** Thinly bedded fine ash at top of partly welded pumiceous tuff (upper contact, shown in photo *C*).

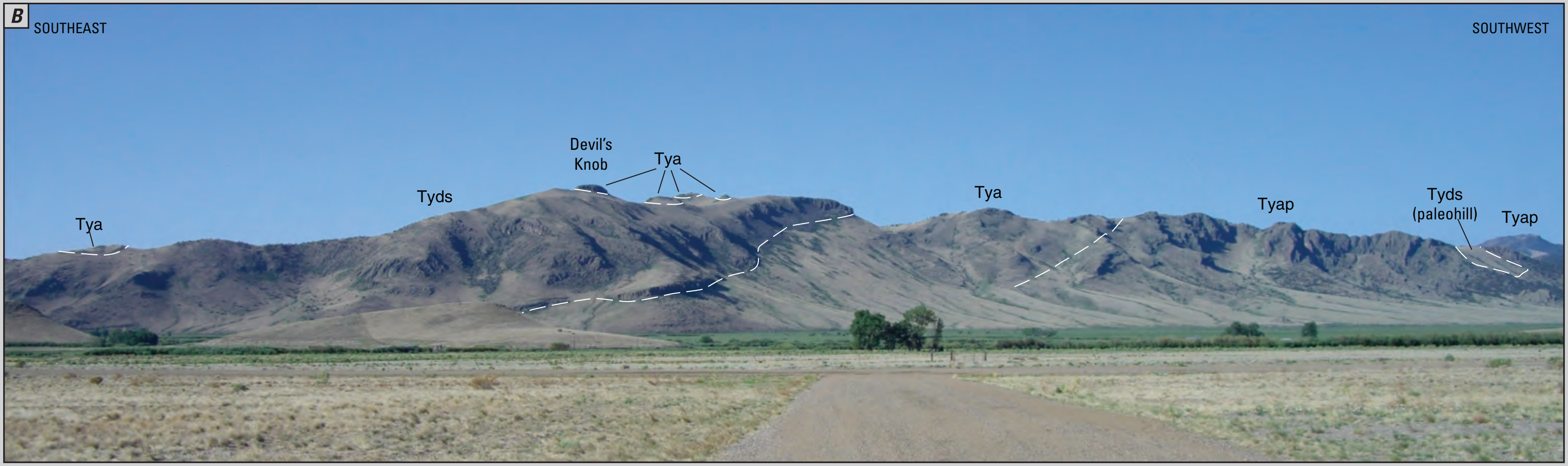
6. Tracy Volcano

Tracy volcano is a large compositionally diverse stratovolcano, centered south of the Saguache Valley, from which lavas were erupting concurrently with the Bonanza caldera cycle.

Photos 6.1*A,B*. Panoramas of northwest and northeast volcano flanks. Tracy volcano is the youngest and largest well-defined central volcano of the Conejos Formation in the map area, with an east-west extent of at least 15 km at exposed levels. Outflow Bonanza Tuff laps out against lower andesite lavas along the northern flank of this volcano, but thick upper flows of mafic dacite overlie distal Bonanza Tuff.

A. Northwest flank, Tracy volcano, view to southwest from Saguache Valley. The northwest flank of Tracy volcano, at left and center, contains a well-stratified thick flow sequence of mafic dacite (unit Tydu) that overlies flows of andesite (unit Tya) and plagioclase andesite (unit Tyap). Bonanza Tuff (unit Tbd) interfingers and wedges out between the andesite and overlying dacite of the Tracy edifice just east of Laughlin Gulch, and the southerly inferred continuation of the horizon delimiting the Bonanza eruption is indicated by the black-dashed line. CS, rhyolite lava dome at Campo Santo.

The present-day Saguache Valley coincides closely with an Oligocene paleovalley between Tracy volcano to the south and the composite highland of the Rawley volcanic complex to the north, within which Bonanza caldera formed. Fill of the paleovalley, well displayed on Houghland Hill, includes dacitic Bonanza Tuff (unit Tbd); an overlying complex succession (too thin to distinguish on photo) of local andesite and rhyolite flows (units Tba, Tbr), Saguache Creek Tuff (unit Tsc), and interleaved river gravels (units Tdc, Tsav); then Fish Canyon (unit Tfc) and Carpenter Ridge (unit Tcr) Tuffs from the central San Juan caldera cluster; and capping basalt flows (21.81 Ma) of the Hinsdale Formation (unit Thb). Photo site: lat 38°05.3′ N., long 106°11.0′ W.



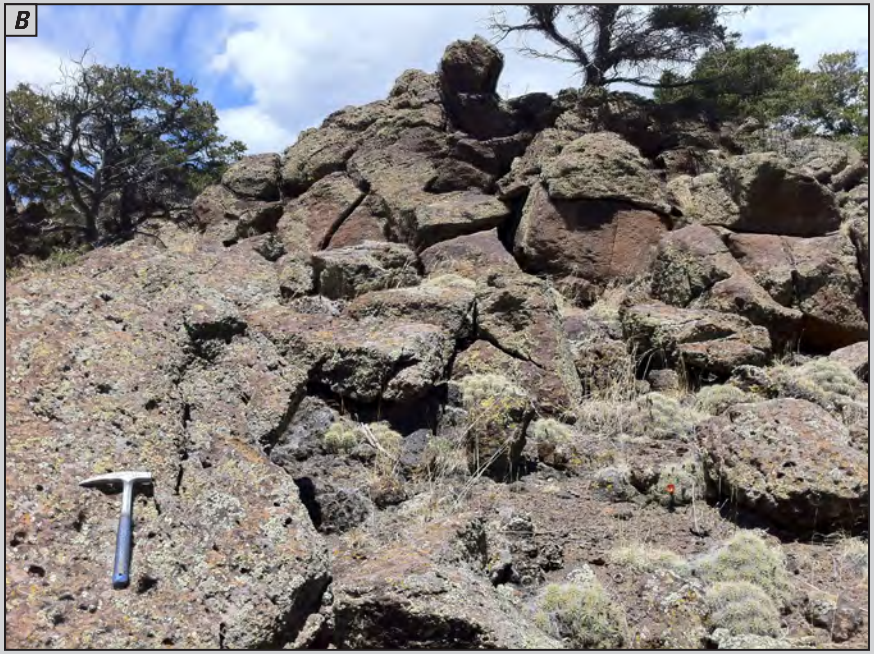
Photos 6.1*A,B*—Continued. **Panoramas of northwest and northeast volcano flanks.** Tracy volcano is the youngest and largest well-defined central volcano of the Conejos Formation in the map area, with an east-west extent of at least 15 km at exposed levels. Outflow Bonanza Tuff laps out against lower andesite lavas along the northern flank of this volcano, but thick upper flows of mafic dacite overlie distal Bonanza Tuff.

B. Northeast flank, Tracy volcano (Devils Knob ridge), view to south from Saguache Valley (SG). The rugged east-west ridge between the Saguache Valley and North Tracy Canyon provides spectacular exposures of andesitic and dacitic lavas on the northeast flank of Tracy volcano. In upward stratigraphic sequence: (1) the top of a paleohill (right side of view) of small-phenocryst dacite (unit Tyds), forming a widespread unit (33.55 Ma) in North Tracy Canyon and to the south along the east flank of the volcano; (2) overlying plagioclase andesite (unit Tyap), forming rugged cliffs of lavas and flow breccias; (3) multiple thin flows of aphanitic to finely porphyritic andesite (unit Tya); (4) thick upper unit of small-phenocryst dacite (unit Tyds), preserved only on the distal northeast flank of the exposed edifice; (5) small ridge caps of fine-grained andesite (unit Tya), including Devils Knob. Photo site: lat 38°05.9′ N., long 106°10.1′ W.

Photos 6.2*A*,*B*. Fine-grained andesite flows (unit Tya). Texturally diverse flows of aphanitic to finely porphyritic andesite (unit Tya, 56–61% SiO_2).

A. Multiple relatively thin flows of fine-grained andesite (unit Tya), forming ledges on slopes north of North Tracy Canyon (SG). Photo site: lat 38°03.2′ N., long 106°11.45′ W.

B. Angular flow breccia, fine-grained andesite (unit Tya) along Devils Knob ridge (SG, lat 38°03.38′ N., long 106°12.07′ W.). View to north across Saguache Valley, toward Sargents Mesa (left) and Bonanza caldera area (right).



Photos 6.3*A*,*B*,*C*. **Plagioclase-andesite flows** (unit Tyap). Distinctive coarsely porphyritic dark-gray lavas (56–60% SiO_2) characterized by tabular phenocrysts of plagioclase as much as 1 cm across (unit Tyap).

A. Plagioclase-andesite flow (unit Tyap), with basal flow breccia overlain by massive flow interior (sample 11L-35, 61.11% SiO_2). Plagioclase andesite is typically more vesicular than fine-grained andesite and is characterized by more irregular rougher outcrop surfaces (compare with photo 6.2*B*). North Tracy Canyon (SG, lat 38°03.15′ N., long 106°13.15′ W.).

B. Typical rough-textured vesicular surface, massive central zone of plagioclase-andesite flow interior, North Tracy Canyon (SG). Photo site: lat 38°13.35′ N., long 106°13.2′ W.

C. Characteristic porphyritic texture, plagioclase andesite (unit Tyap). Distinctive coarsely porphyritic dark-gray lavas (58–61% SiO_2; 15–25% pl>>cpx), characterized by tabular phenocrysts of plagioclase as much as 1 cm across.

Photos 6.4*A,B,C,D*. **Small-phenocryst dacite** (unit Tyds). Thick flows of petrographically distinctive, finely porphyritic, light-gray dacite (unit Tyds; 66–68% SiO_2, 5–10% pl>bi). Much of the small-phenocryst dacite is flow layered and characterized by schistose-like hackly fracturing on fine scale, a reflection of aligned-groundmass plagioclase microlites that define a felty trachytic fabric.

A. Thick flow of small-phenocryst dacite on hill 8612, north of lower Tracy Canyon. Jointed light-colored rocks in center of photo are a small patch of well-bedded centimeter-size angular blocks and chips of fine-grained dacite in a sandy matrix, dipping gently but banked against the massive dacite exposures on hill 8612. These bedded deposits are interpreted as caldera-wall volcaniclastic deposits (unit Tydt) banked along the east wall of a central caldera of Tracy volcano, later filled by a thick sequence of andesite flows (unit Tyca). Photo site: lat 38°01.5′ N., long 106°12.2′ W.

B. Characteristic schistose-like hackly fracturing along flow layering in the small-phenocryst dacite. Photo site: lat 38°01.7′ N., long 106°11.8′ W.

Photos 6.4*A,B,C,D*—Continued. **Small-phenocryst dacite** (unit Tyds). Thick flows of petrographically distinctive, finely porphyritic, light-gray dacite (unit Tyds; 66–68% SiO_2, 5–10% pl>bi). Much of the small-phenocryst dacite is flow layered and characterized by schistose-like hackly fracturing on fine scale, a reflection of aligned-groundmass plagioclase microlites that define a felty trachytic fabric.

C. Exceptionally developed flow layering in the small-phenocryst dacite. Photo site: lat 38°02.5′ N., long 106°11.6′ W.

D. Crudely bedded caldera-wall talus (unit Tydt), derived from the small-phenocryst dacite, near the westward bend of North Tracy Canyon (SG). The breccia consists of monolithologic dacite blocks, ranging in size from centimeters to meters, in a matrix of microbreccia of the same composition. Photo site: lat 38°03.0′ N., long 106°12.8′ W.

Photo 6.5. Dacite of Red Rock Canyon, containing blebs of andesite. Reddish-brown to gray crystal-rich dacite (sample 06L-73, 65.01% SiO_2) characterized by locally abundant small inclusions of incompletely mingled fine-grained andesite. In some outcrops, angular andesite inclusions in flow-foliated matrix dacite appear misleadingly similar to lithic-bearing welded tuff. Lower San Juan Creek (lat 37°57.96′ N., long 106°11.99′ W.). Two samples have $^{40}Ar/^{39}Ar$ ages of 33.46±0.08 and 33.50±0.09 Ma (biotite plateaus), providing constraints for early growth of Tracy volcano.

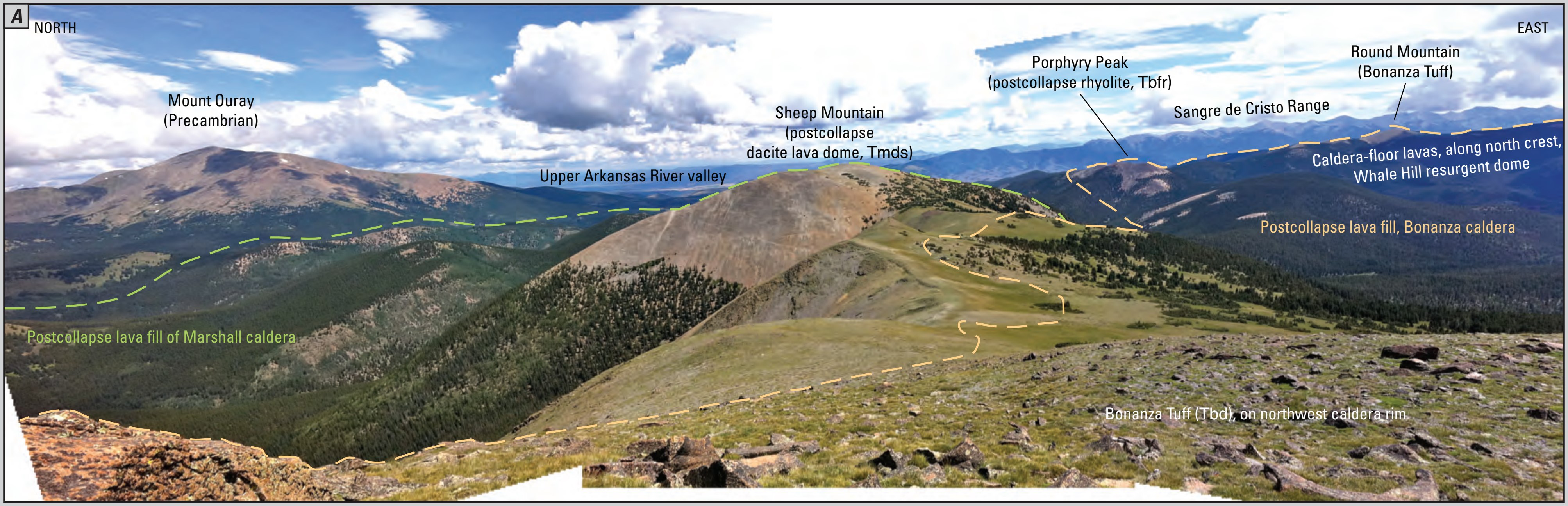
Photos 6.6*A*,*B*. Radial dikes of Tracy volcano. Numerous dikes of andesite to rhyolite that radiate eastward from an axial stock of granodiorite and intergradational andesite.

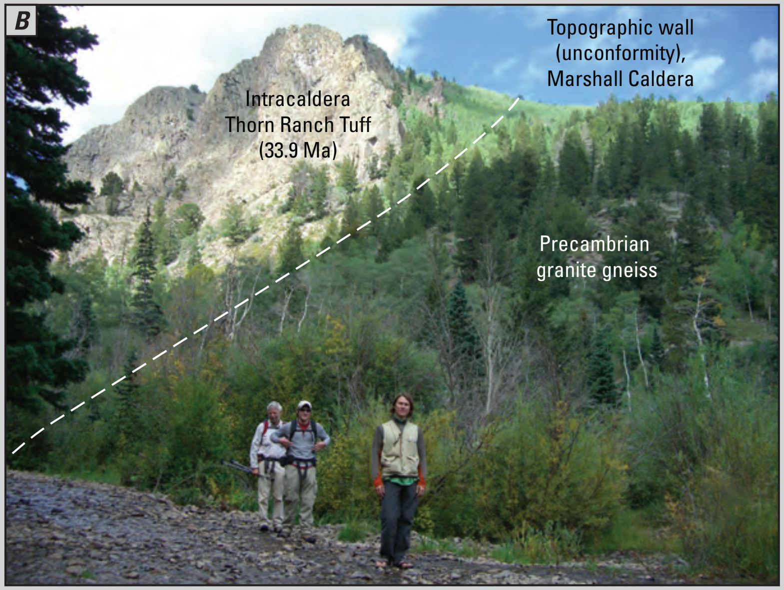
A. Exceptionally prominent andesite dike (unit Tyia), east side of lower North Tracy Canyon (SG). Most dikes of Tracy volcano are andesite, but they typically form subdued exposures that are most evident along ridge crests where host rocks offer a distinct contrast. The light-gray small-phenocryst dacite (unit Tyds) on the sparsely vegetated east flank of Tracy volcano provides an especially contrasting host that helps delimit the extent of these dikes. Many dikes lack outcrops but are marked by trains of andesite boulders, in places also by small pinyon pines aligned along dike trends. Photo site: lat 38°02.1′ N., long 106°12.4′ W.

B. Well-exposed andesite dike, cutting through andesite flow breccia along Devils Knob ridge (SG). View to north, across Saguache Valley toward Saguache Peak (KM), a high remnant of the Rawley volcanic complex on the south rim of Bonanza caldera. Photo site: lat 38°03.5′ N., long 106°`12.7′ W.

7. Thorn Ranch Tuff and Marshall Caldera

The Thorn Ranch Tuff erupted at 33.9 Ma from Marshall caldera just northwest of Bonanza, and features of this caldera system provide an important stratigraphic framework for interpreting the younger volcanic activity.





Photos 7.1*A,B*. Remnants of caldera wall. Marshall caldera was the source for the Thorn Ranch Tuff, a regional ignimbrite that is widely preserved east of the Upper Arkansas segment of the Rio Grande rift.

A. Northeast Marshall and northwest Bonanza calderas, viewed from the north flank of Antora Peak (BZ). Postcollapse andesite and dacite lavas of Marshall caldera bank out against Proterozoic granitic and metamorphic rocks on south slopes of Mount Ouray (13,921 ft), which represents a remnant of the original topographic rim for this caldera. Along the northwest margin of Bonanza caldera, dacitic intracaldera Bonanza Tuff (unit Tbd) wedges out against the lava fill of Marshall caldera, most spectacularly against the 33.89-Ma dacite lava dome (unit Tmds) of Sheep Mountain (12,228 ft) that directly overlies intracaldera Thorn Ranch Tuff (unit Ttr), beyond the present view, on the north slope of Sheep Mountain. To the east within Bonanza caldera, resurgently domed caldera-floor andesite lavas are capped by a small surviving scab of intracaldera Bonanza Tuff on Round Mountain (12,036 ft), all silhouetted against the Sangre de Cristo Range across the east side of the San Luis Valley segment of the Rio Grande rift. In the distance to the north is the upper Arkansas River valley, another segment of the Rio Grande rift, linked to the San Luis segment by a transfer zone across Poncha Pass. Photo site: lat 38°11.95′ N., long 106°12.7′ W.

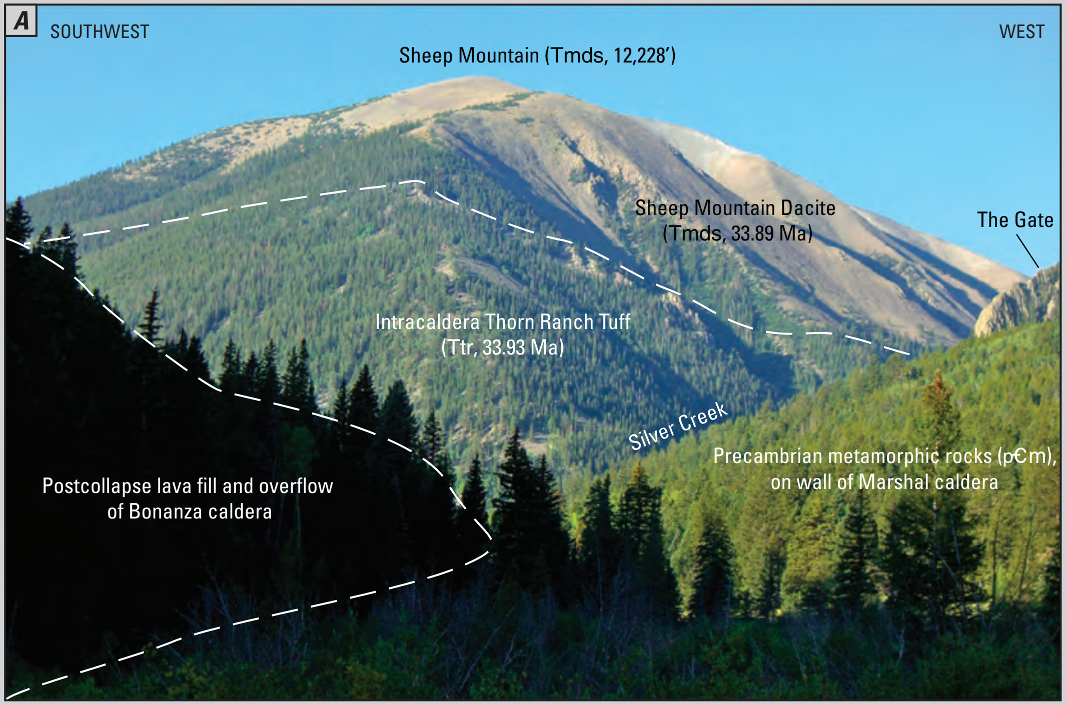
B. Topographic wall of Marshall caldera, at The Gate. Densely welded Thorn Ranch Tuff (unit Ttr), more than 300 m thick with no base exposed, is depositionally banked against Precambrian granitic gneiss (p€m) at this prominent topographic feature in upper Silver Creek (MO). Left to right in image: Bill McIntosh, Matt Zimmerer, Andrea Sbisà. Photo site: lat 38°21.8′ N., long 106°10.75′ W.

Photos 7.2*A*,*B*,*C*. Thorn Ranch Tuff (unit Ttr).

A. Densely welded intracaldera tuff at The Gate (BZ, lat 38°21.82′ N., long 106°10.85′ W.). Pocket knife is 8 cm long.

B. Welded intracaldera tuff, containing characteristic fragments of Proterozoic rocks (here, foliated granitic gneiss) at The Gate (BZ, lat 38°21.82′ N., long 106°10.85′ W.).

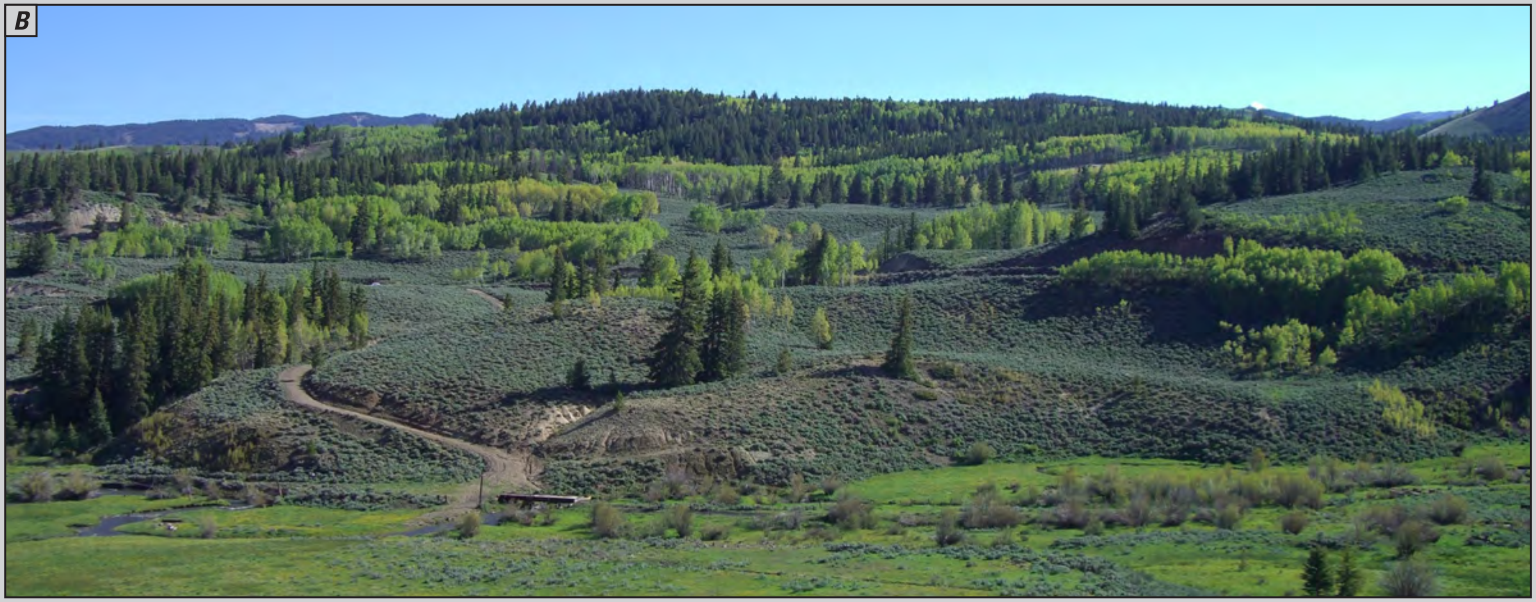
C. Thorn Ranch megabreccia (unit Ttrm): partly welded intracaldera tuff encloses large blocks of Precambrian granite (pꞒg) and smaller fragments of andesite (a). Marshall Pass road (PP, lat 38°23.24′ N., long 106°15.88′ W.).



Photos 7.3*A*,*B*. Fill of the Marshall caldera.

A. Northeast margin of Marshall caldera, viewed from ridge east of Silver Creek (BZ). Sheep Mountain is a large dacite lava dome (unit Tmds), forming initial postcollapse fill, with a $^{40}Ar/^{39}Ar$ age of 33.89 Ma (table 6) that is indistinguishable within uncertainties from the intracaldera Thorn Ranch Tuff (unit Ttr) that it directly overlies. Photo site: lat 38°22.7′ N., long 106°10.7′ W.

***B.* Stair-step slumps of andesite to dacite lava flows** (units Tma, Tmd) and interlayered Pitch-Pinnacle Formation (unit Tmp, bedded tuffaceous sediments) that filled and overflowed Marshall caldera. View to north, across Marshall Creek, from mouth of Tank Seven Creek (CH). Photo site: lat 38°21.3′ N., long 106°19.8′ W.



Bonanza caldera was the source of the compositionally complex Bonanza Tuff, erupted at 33.12 Ma. As interpreted here, Bonanza is a large resurgent caldera, with morphologic features well preserved on its western side, but its eastern margin is largely concealed beneath the San Luis Valley segment of the Rio Grande rift.

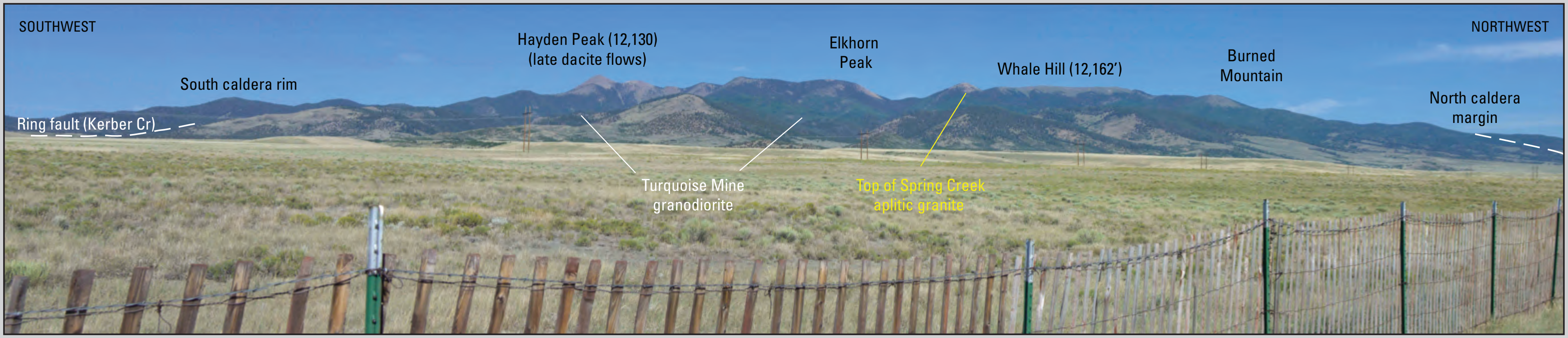
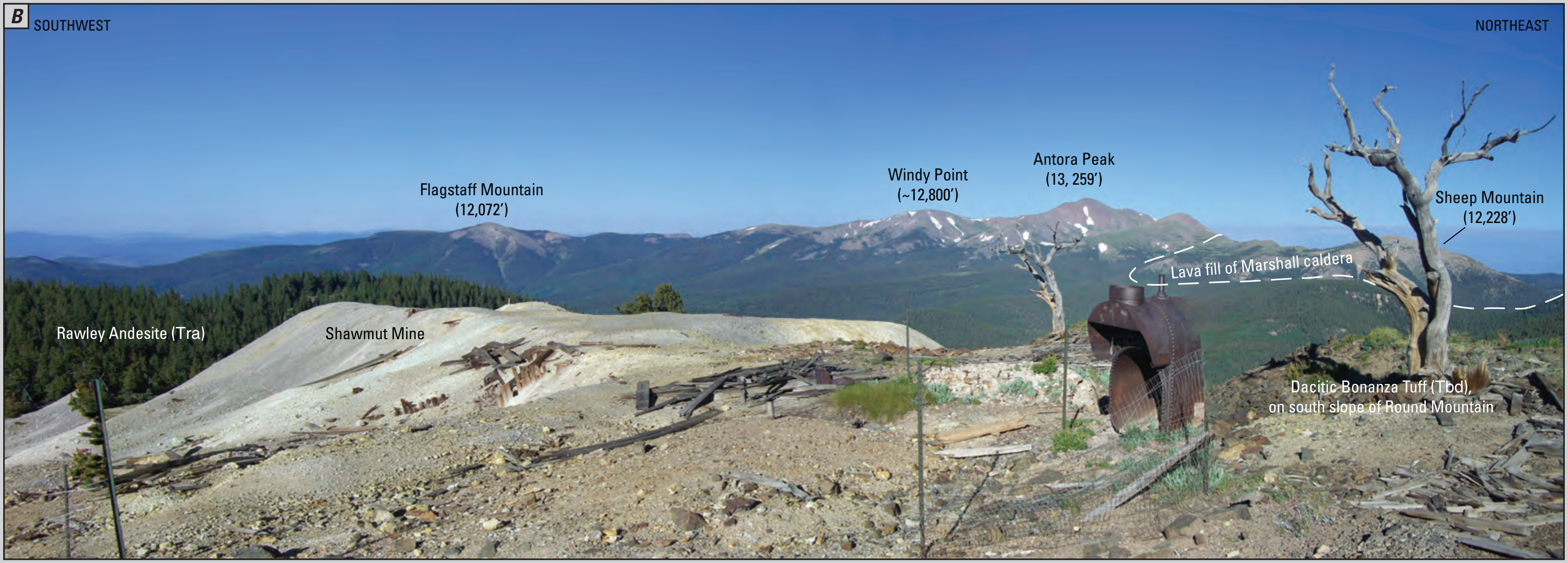


Photo 8.1. Bonanza caldera, from the San Luis Valley. The skyline profile is the crest of an elliptical resurgent dome, eroded approximately to stratigraphic level of caldera-floor andesitic lavas (units Tra, Trap) within Bonanza caldera. Broad flat-topped Whale Hill and northeast-sloping Burned Mountain are stripped upper surfaces of the caldera floor, locally capped by small erosional remnants of intracaldera tuff. The eastern hillside slopes from this view approximate the outward-dipping flanks of the resurgent dome. Hayden Peak is capped by thick flows of crystal-poor dacite (unit Tbdh; 69%–70% SiO_2; 32.7–32.8 Ma), which appear to have filled a deep valley or graben (erosional, structural?) high on the resurgent dome. The Turquoise Mine granodiorite (54%–67% SiO_2; 33.06±0.21 Ma) and aplitic granite of Spring Creek (73%–77% SiO_2; 33.26±0.07 Ma) are compositionally contrasting shallow plutons exposed at roof level. Within analytical uncertainties, they are essentially indistinguishable in age from Bonanza Tuff and are inferred to be upper parts of a much more extensive composite resurgent intrusive complex, having a broad compositional range comparable to that of the postcollapse andesite to rhyolite lavas of the Bonanza cycle (fig. 6, sheet 2). Photo site: lat 38°16.1′ N., long 105°57.9′ W.

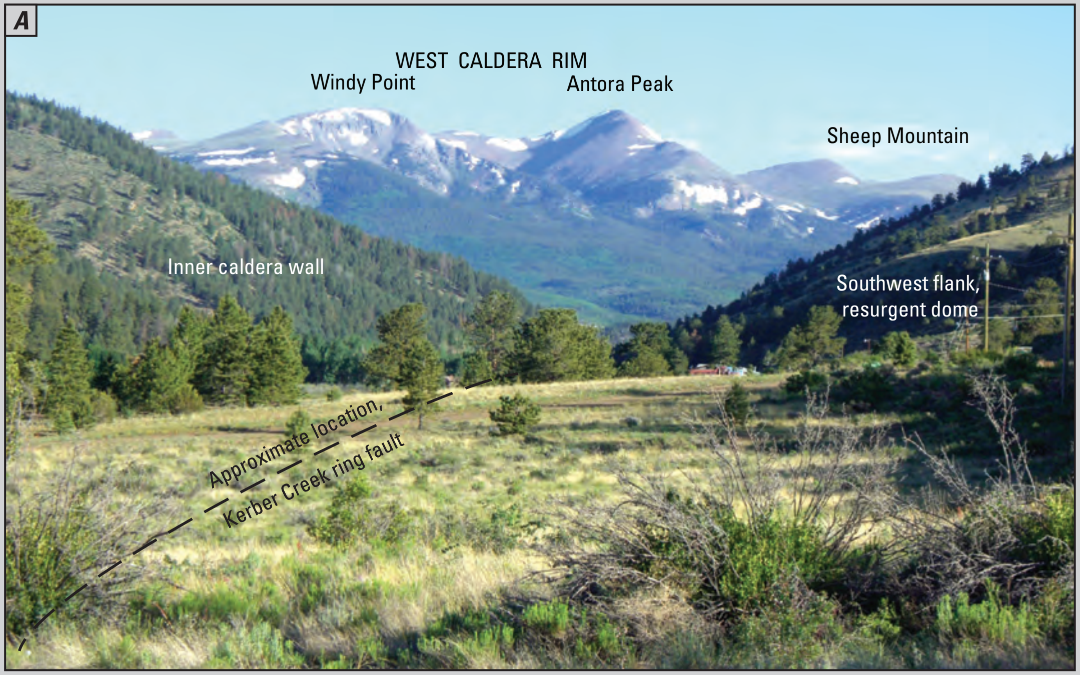
Photos 8.2*A*,*B*. **Panoramic views of western Bonanza caldera.** The high arcuate ridge between the Kerber Creek drainage to the east and tributaries of Middle Creek to the west marks the eroded west margin of Bonanza caldera, interpreted as exhumed remnants of the original caldera topographic rim.

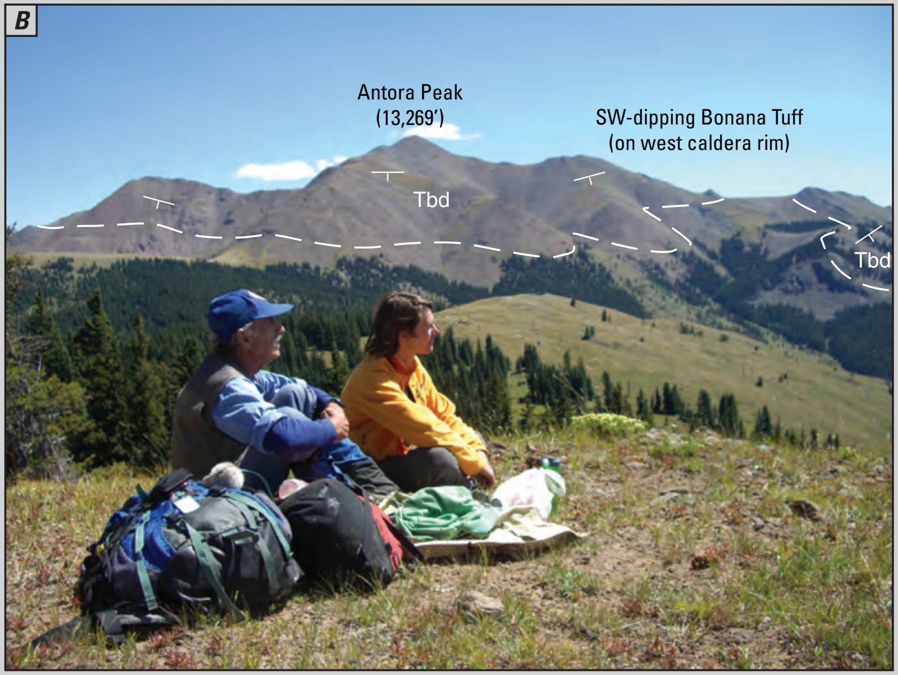
***A*.** Western Bonanza caldera and west flank of the resurgent dome, viewed from 11,490' knob along ridge between Eagle and Elkhorn Gulches (west slope of Hayden Peak, lat 38°16.91′ N., long 106°06.80′ W.). Erosional remnants of Bonanza Tuff, which discontinuously cap the high ridge from north of Antora Peak to Flagstaff Mountain and as far south as the ridgecrest between Grayback and Euclid Gulches, are high points along the west caldera rim. Kerber Creek and its tributaries form deep valleys between the west rim and the flank of the Whale Hill resurgent dome. West-dipping intracaldera Bonanza Tuff is as much as 2.5 km thick, as exposed along the long ridge north of Elkhorn Gulch and continuing across Kerber Creek to beyond lower Brewery Creek. In foreground (with, left to right, Matt Zimmerer, Andrea Sbisà, and Bill McIntosh) are talus exposures of intrusive Eagle Gulch Dacite (Teg), which forms an irregular sill between caldera-floor lavas and intracaldera Bonanza Tuff.



Photos 8.2*A*,*B*—Continued. **Panoramic views of western Bonanza caldera.** The high arcuate ridge between the Kerber Creek drainage to the east and tributaries of Middle Creek to the west marks the eroded west margin of Bonanza caldera, interpreted as exhumed remnants of the original caldera topographic rim.

B. West rim of Bonanza caldera, viewed from Round Mountain (on crest of Whale Hill resurgent dome, lat 38°20.40′ N., long 106°07.40′ W.). Erosional remnants of Bonanza Tuff, which discontinuously cap the high ridge from north of Antora Peak to Flagstaff Mountain and beyond, define remnants of the west topographic rim of the caldera. Most of the Bonanza Tuff is densely welded dacite (unit Tbd), but lower rhyolite (unit Tbrl) is preserved locally along the rim, varying from weakly welded to fluidal and rheomorphic (unit Tbrr). Round Mountain is a small remnant of dacitic Bonanza Tuff (Tbd), overlying caldera-floor andesite (unit Tra) along the north crest of the resurgent dome (fig. 16, sheet 1). The Shawmut Mine, which was initially located in 1885 and still accessible in the 1920s (Burbank, 1932, p. 60, 122–124, pl. 30), is reported to have worked a N. 30° E. sulfide-rich quartz vein, carrying Pb, Zn, Cu, and Ag, that represents the north end of a wide mineralized zone extending from the vicinity of the Rawley Mine. The deep valley of Kerber Creek lies between the west rim and the central ridge of the resurgent dome capped by Round Mountain. Sheep Mountain, a dacite dome (unit Tmds; 33.89 Ma) within the northeast margin of Marshall caldera, has been partly truncated by collapse of Bonanza caldera.





Photos 8.3*A,B*. West rim of Bonanza caldera. The high arcuate ridge from Flagstaff Mountain north to Antora Peak and beyond is capped by discontinuous erosional remnants of thick Bonanza Tuff (mainly dacite, unit Tbd). These areas of densely welded tuff bank thickly against older andesite (units Tra, Trap) on the caldera wall, where they are interpreted mainly to constitute high remnants of ponded intracaldera ignimbrite. In places, the ignimbrite is continuous across the present-day topographic ridge, into more widespread proximal outflow outcrops of the tuff to the west, suggesting that the ridge approximates the erosionally modified location of the original topographic rim of Bonanza caldera.

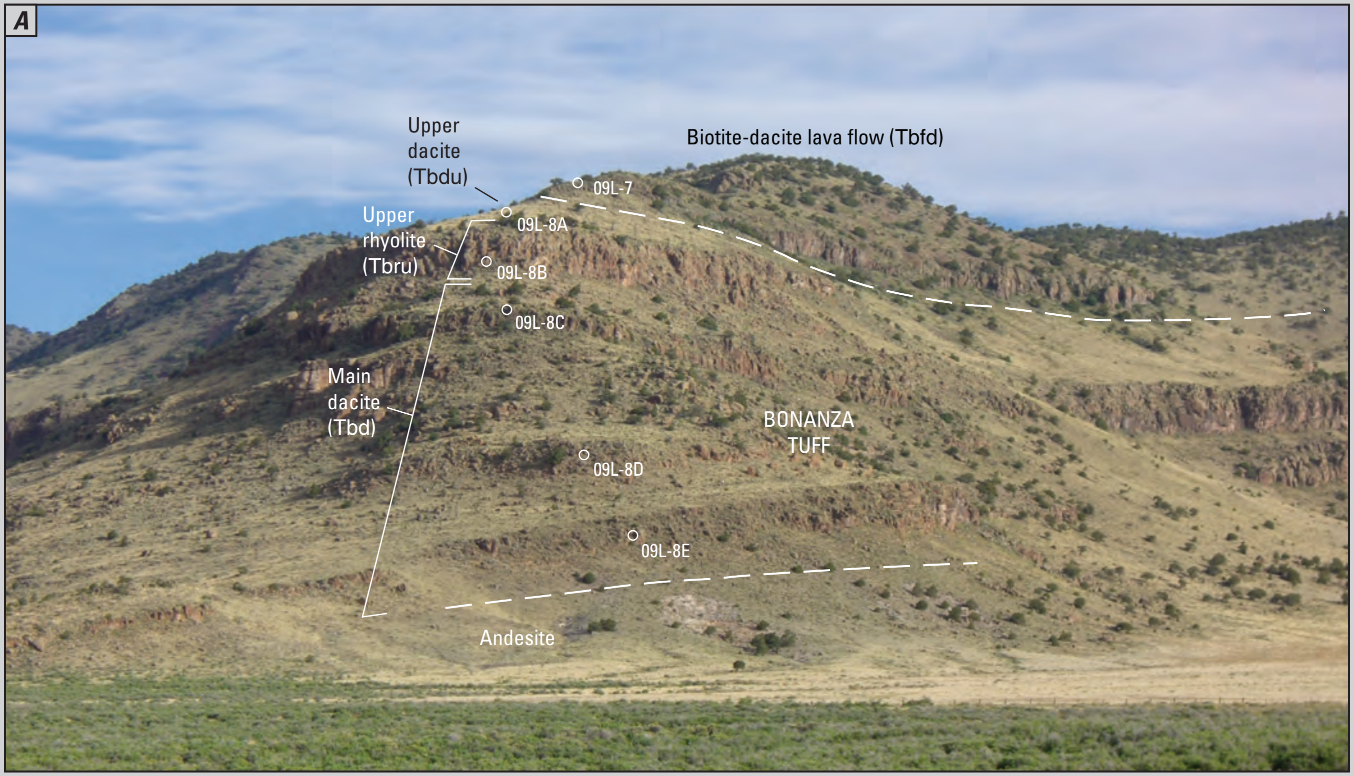
A. West rim viewed to northwest, up valley of Kerber Creek. In distance, Antora Peak (center, 13,269') is capped by densely welded dacitic Bonanza Tuff (33.12 Ma), while Windy Point (left, 12,800') exposes thin layer of basal rhyolitic Bonanza Tuff that has undergone local rheomorphic flowage (unit Tbrr). Lower slopes of both high points are west-dipping sequence of interlayered andesitic lava flows and volcaniclastic rocks that make up the erosionally modified inner wall of Bonanza caldera. Sheep Mountain (unit Tmds; right distant skyline, 12,228') is pre-Bonanza dacitic lava dome (33.89 Ma) that partly fills the older Marshall caldera, source of the 33.91-Ma Thorn Ranch Tuff (unit Ttr). On left (southwest) side of Kerber Creek, timbered slopes are lower portions of southwest caldera wall; right side of creek is a dip slope on flanks of the postcollapse resurgent dome. The valley of Kerber Creek coincides with the main ring fault, along which more than 3 km of subsidence was accommodated during eruption of the Bonanza Tuff and concurrent caldera collapse. Photo site: lat 38°15.1′ N., long 106°07.5′ W.

B. West rim as viewed from the northwest, at hill 11,697' along the Continental Divide (BZ). Thick dacitic Bonanza Tuff (Tbd; above white-dashed line) laps out against precaldera fill of the Marshall caldera and lava flows of the Rawley complex. Gentle west to southwest dips (10–20°) of foliation in the Bonanza Tuff appear primarily to record regional tilting associated with Rio Grande rift extension along the southern terminus of the Sawatch structural block. Alternatively, these tilts could, in part at least, reflect broad resurgence of Bonanza caldera, continuing west beyond the caldera margin. In image: Lipman and Andrea Sbisà. Photo site: lat 38°20.85′ N., long 106°15.1′ W.

Photo 8.4. Possible northeast caldera margin, at Round Hill. At Round Hill (PO), sanidine-bearing dacite laps unconformably against Proterozoic metamorphic rocks without intervening older volcanic rocks. The dacite has yielded an isotopic age indistinguishable from that of the Bonanza Tuff, suggesting that it may be a caldera-filling lava, wedging out low against a small remnant of the northeast topographic wall as exposed within the northern San Luis Valley, surrounded by sedimentary fill of the Rio Grande rift. Photo site: lat 38°23.5′ N., long 106°03.5′ W.

9. Bonanza Tuff

The Bonanza Tuff is an unusual ignimbrite sheet, characterized by exceptionally large and complex lateral and vertical variations in chemical and phenocryst compositions, including multiple alternations from dark crystal-rich silicic andesite and dacite to light-colored crystal-poor rhyolite.

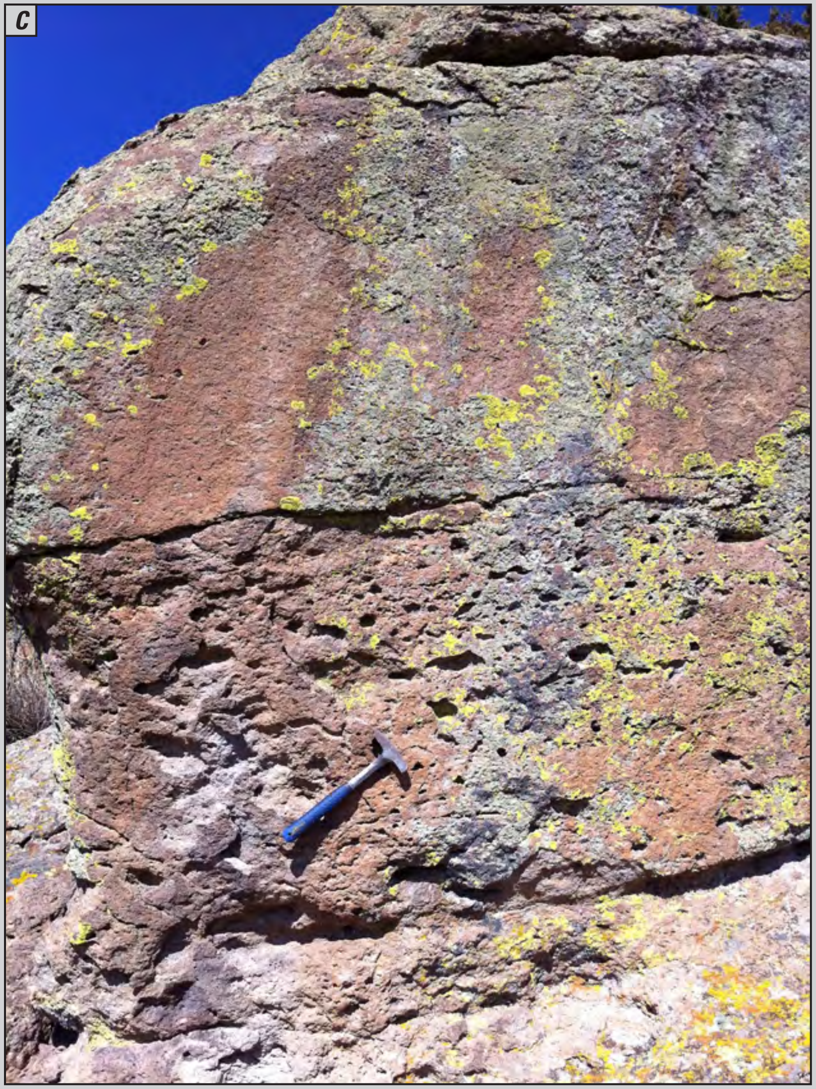


Photos 9.1*A,B,C*. Findley Ridge reference section. Outflow Bonanza Tuff that contains several alternations of rhyolite and dacite and multiple partial welding/cooling breaks is well exposed along the ridge on the west side of Findley Gulch (KM). The section is exceptionally thick (~175 m), because it is banked against the flank of a large paleovalley. This proximal site has been cited and sampled repeatedly as a reference section for the Bonanza Tuff (Bruns and others, 1971; Varga and Smith, 1984; McIntosh and Chapin, 2004).

A. Complex compositional and welding zonations in Bonanza Tuff at Findley Ridge. Circles indicate locations of newly analyzed samples (samples 09L-8A,B,C,D,E, table 5). Variable dips in cliff-forming zones of densely welded tuff reflect differential compaction in proximity to margin of the paleovalley. The lower rhyolite (unit Tbrl) is absent in this paleovalley section but crops out below the main dacite in exposures 6 km to the southwest. The ridge-capping dacite lava flow (unit Tbfd, sample 09L-7) is imaged in photo 13.1*B*. Photo site: lat 38°07.4′ N., long 106°11.2′ W.

B

C



Photos 9.1*A,B,C*—Continued. **Findley Ridge reference section.** Outflow Bonanza Tuff that contains several alternations of rhyolite and dacite and multiple partial welding/cooling breaks is well exposed along the ridge on the west side of Findley Gulch (KM). The section is exceptionally thick (~175 m), because it is banked against the flank of a large paleovalley. This proximal site has been cited and sampled repeatedly as a reference section for the Bonanza Tuff (Bruns and others, 1971; Varga and Smith, 1984; McIntosh and Chapin, 2004).

B. Large black near-glassy scoriaceous pumice lenses, within mafic dacite of Bonanza Tuff, low in Findley Ridge section: samples 11L-9A,B; 61.8, 63.4% SiO_2 (lat 38°07.74′ N., long 106°11.80′ W.; approximately same site as sample 09L-8D, table 5).

C. Abrupt contact within welded dacite, between relatively pumice-poor tuff and underlying tuff that contains larger flattened pumice blocks. Boundary is inferred to record instability in eruptive discharge or fluctuation in emplacement kinematics. Approximately same site as sample 09L-8B, table 5 (lat 38°07.85′ N., long 106°11.97′ W.).

Photos 9.2*A,B,C*. **Western outflow Bonanza Tuff,** consisting mainly of densely welded dacite (unit Tbd).

A. Typical outcrops of densely welded dacite. Crude slabby jointing reflects orientation of compaction foliation. Along broad paleovalley followed by Jacks Creek (LMNE, lat 38°12.08′ N., long 106°22.30′ W.).

B. Close-up of compaction foliation in densely welded dacitic tuff, small canyon 0.5 km north of Jacks Creek Cemetery (LMNE, lat 38°12.09′ N., long 106°21.07′ W.). In addition to near-glassy dark-gray crystal-rich pumice fiamme (analyzed samples 09L-33, table 5), sparse light-gray crystal-poor pumice (not analyzed) appears to record minor intermixed rhyolite.

C. Steep primary dip in densely welded dacitic tuff, where banked against a paleovalley margin along Middle Creek, 1.3 km south of mouth of Bear Gulch (LMNE, lat 38°13.04′ N., long 106°18.05′ W.). In image, Matt Zimmerer.

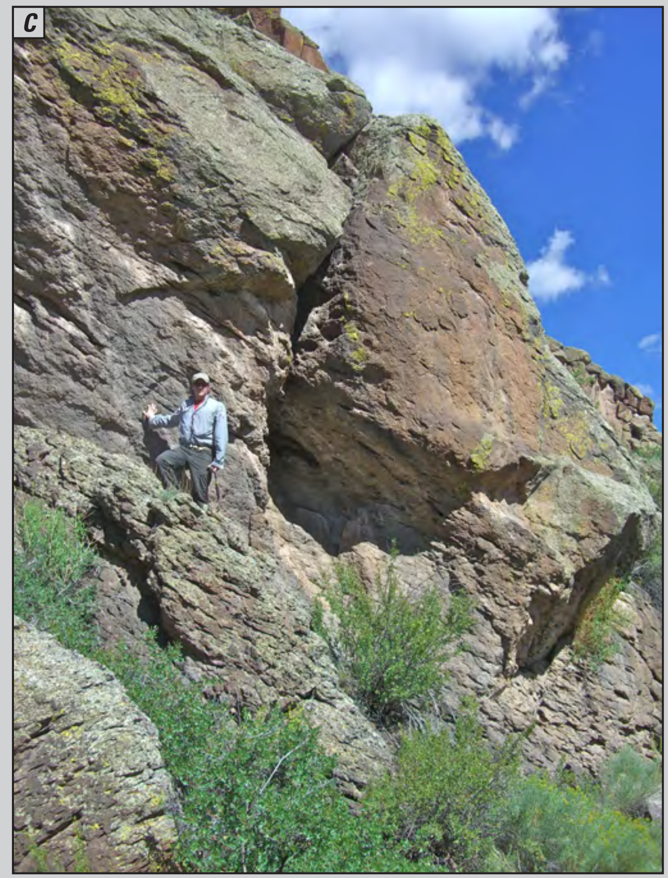
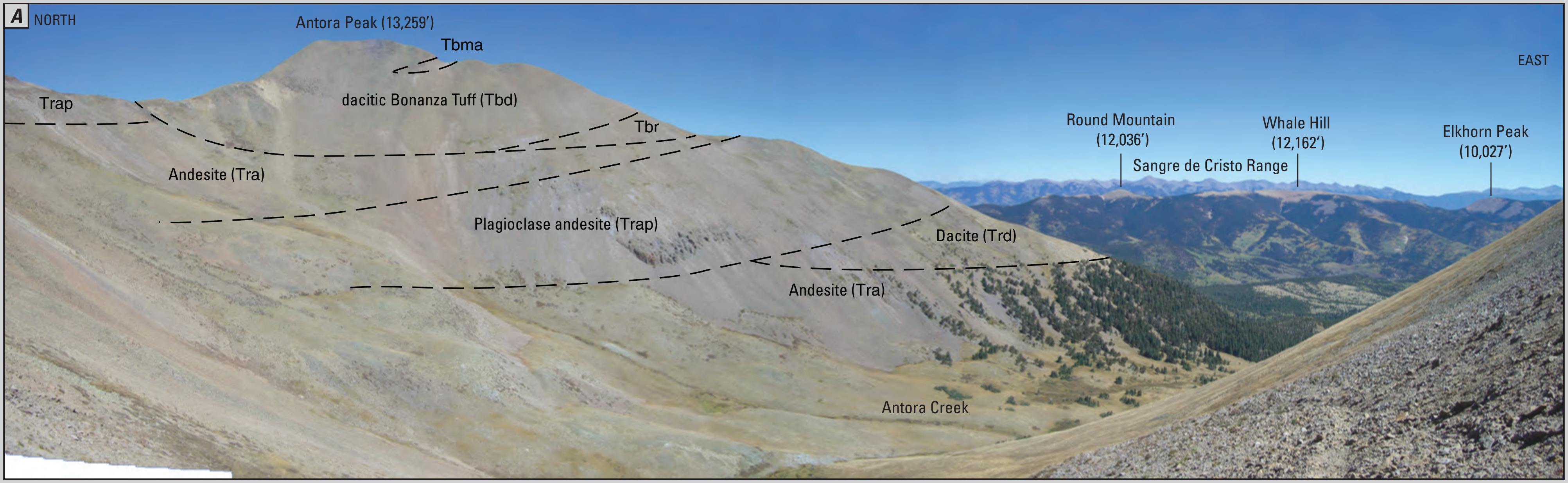
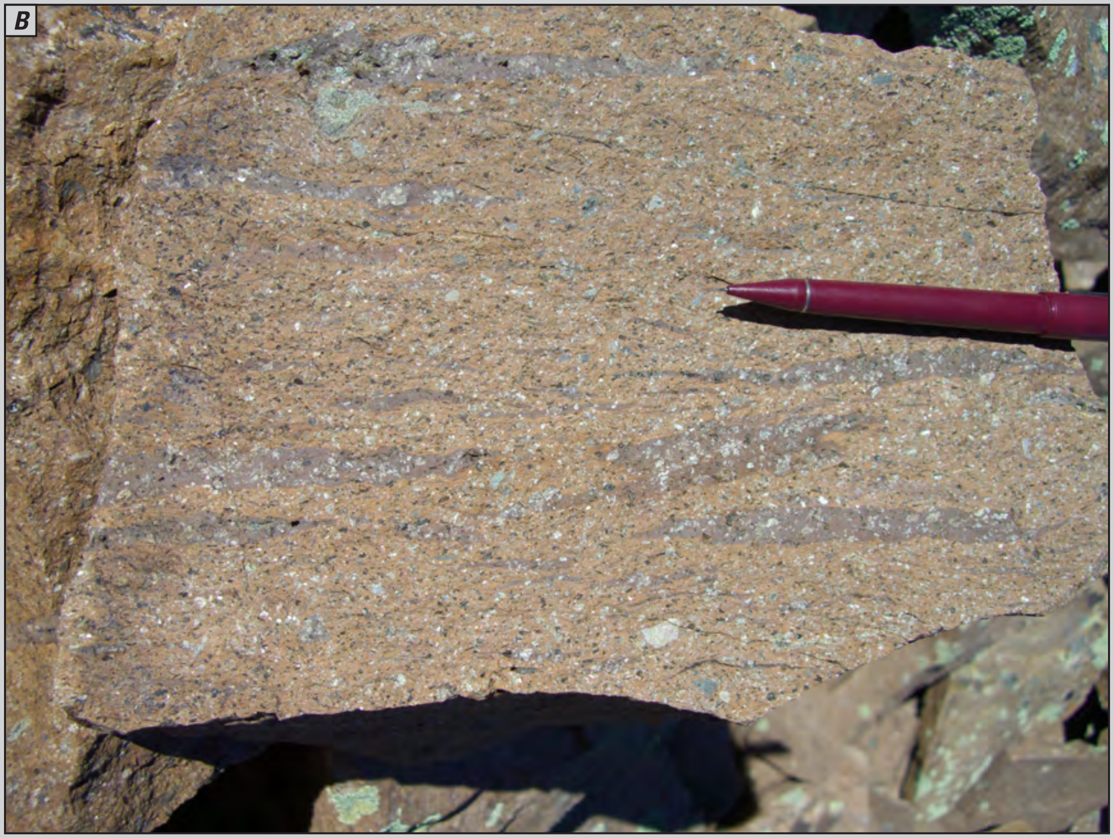


Photo 9.3. Eastern outflow Bonanza Tuff. Reference section of thick paleovalley fill at Two Creek (Jack Hall Mountain quadrangle, about 30 km northeast of Bonanza caldera), viewed from south. Thick section of lower rhyolite (unit Tbrl) includes three cliffs of densely welded tuff, separated by vapor-phase-crystallized zones of less-welded tuff (sample 08L-33A,B,C,D,E, 71.6–74.6% SiO_2). Thin zone (5–10 m) of crystal-rich dacite (unit Tbd: sample 08L-33E, 66.8% SiO_2), partly obscured by old landslide debris (unit Qfo) of porphyritic dacite lava from ridge crest to east of image, is overlain by slope-wash debris of virtually nonwelded upper rhyolite (unit Tbru: sample 09L-5B, 76.4% SiO_2). Prior to recognition of correlation with the Bonanza Tuff, this section was previously described as the type section for the Gribbles Park Tuff of Epis and Chapin (1974). At north margin of paleovalley, Ordovician Manitou Limestone (unit Om) and Harding Quartzite (unit Oh) overlie Precambrian metamorphic rocks (unit p€m). Photo site: lat 38°36.15′ N., long 105°46.5′ W.



Photos 9.4*A,B,C*. Intracaldera dacitic Bonanza Tuff. Constitutes the volumetric bulk of the caldera-filling ignimbrites but alternates multiple times with rhyolitic tuff and lenses of landslide breccia.

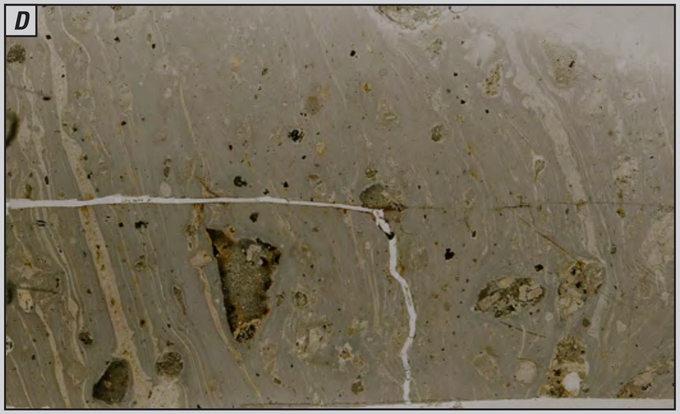
A. Antora Peak on the west rim of Bonanza caldera, from head of Antora Creek (BZ). This incomplete section of Bonanza Tuff, with its top eroded, consists mainly of densely welded massive dacite (unit Tbd); it is more than 300 m thick on the northwest flank of Antora Peak and is interpreted to be banked against andesite and dacite (units Tra, Trd) of the Rawley volcano, high on the original topographic rim of the caldera. A thin basal zone of rhyolitic Bonanza Tuff (unit Tbr) along the east ridge of Antora Peak wedges out to the west, as does a small lens of andesite landslide breccia (unit Tbma) higher within the thick dacitic Bonanza Tuff. Across Kerber Creek to the east, the elongate Whale Hill resurgent dome within Bonanza caldera is silhouetted against the crest of the Sangre de Cristo Range, farther east across the San Luis Valley segment of the Rio Grande rift. The nearly flat tops of Whale Hill and its northern continuation as Manitou Mountain are a stripped surface, underlain by andesitic lavas of the caldera floor, while Round Mountain and the north crest of Elkhorn Peak are capped by thin remnants of basal intracaldera Bonanza Tuff (dacitic). View northeast, across and down Antora Creek, from saddle between Windy Point and Antora Peak (BZ). Photo site: lat 38°18.9′ N., long 106°13.1′ W.



Photos 9.4*A,B,C*—Continued. **Intracaldera dacitic Bonanza Tuff.** Constitutes the volumetric bulk of the caldera-filling ignimbrites but alternates multiple times with rhyolitic tuff and lenses of landslide breccia.

B. Typical densely welded dacite (unit Tbd) on northwest slope of Antora Peak. Flattened pumice lenses are 5–15 cm long in cross section; pumices have crystal sizes and mineral modes little different from the fragmental welded-ash matrix, indicating limited breakage or winnowing during eruption and proximal emplacement. Photo site: lat 38°19.7′ N., long 106°13.2′ W.

C. Large light-gray pumice lenses (to >1 m) in dacite (unit Tbd); in addition to extreme flattening, the pumice lenses are elongate in the foliation plane, defining a down-dip lineation. Mining road that traverses from Squirrel Creek into Rawley Gulch (BZ, lat 38°18.91′ N., long 106°08.52′ W.).



Photos 9.5*A,B,C,D*. Intracaldera rhyolitic Bonanza Tuff. Multiple zones of light-gray crystal-poor rhyolite interleave with the volumetrically dominant dacite, defining complex compositional and welding zonations within the thick intracaldera ignimbrite.

***A*.** Basal contact of lower rhyolite (unit Tbrl), just south of Windy Point (BZ, lat 38°18.55′ N., long 106°12.83′ W.). The rhyolitic tuff is welded to its base, in contact with andesite (unit Tra) near the rim of the west caldera wall, without intervening bedded airfall tuff. In image: Andrea Sbisà.

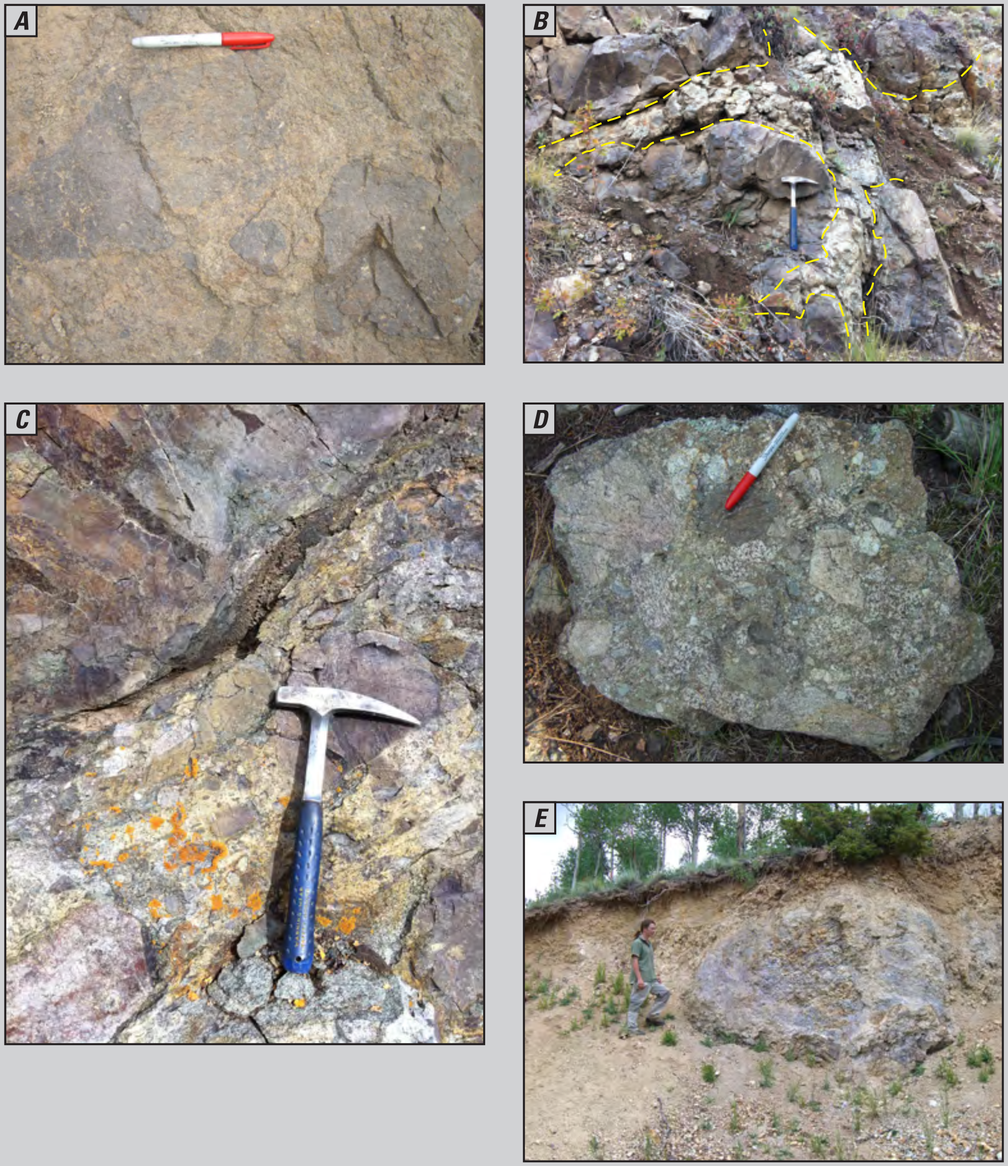
***B*.** Slabbly jointing in rheomorphic tuff (unit Tbrr), southwest slope of Windy Point (BZ, lat 38°18.53′ N., long 106°12.86′ W.). Rock texture appears lava-like, but many small angular fragments of dark andesite are discernable (five are circled).

***C*.** Weakly weathered surface on hand sample of lower rhyolite, showing fluidal welding despite containing abundant andesite fragments. Antora Meadows (BZ, lat 38°18.44′ N., long 106°12.94′ W.).

***D*.** Fluidal crystal-poor lower rhyolite (Tbrr) in thin section (analyzed sample 08L-09, 69.9% SiO_2, table 5). Pumice lenses have flowed rheomorphically to near-lava-like textures, but small fragments of andesite document pyroclastic origin. Field of view is 20 x 35 mm. Head of Spring Creek (WH, lat 38°19.76′ N., long 106°05.42′ W.).

10. Caldera-Collapse Landslide Breccia

Interfingered with the alternating zones of rhyolite and dacite ignimbrite within Bonanza caldera are many irregular lenses of brecciated precaldera rocks, both mesobreccia and much larger masses of little-broken massive lava, which are interpreted as landslide debris derived from caldera walls that had become oversteepened during subsidence.



Photos 10.1*A,B,C,D,E*. Lithic-rich and landslide-breccia facies. Small angular lithic fragments, mainly andesite and typically only a few centimeters across, are characteristic of the Bonanza Tuff, especially the intracaldera dacite of this ignimbrite. Scattered larger fragments are enclosed in the dacite locally, and masses of andesite megabreccia of mappable scale have textures indicative of origin by landsliding from the caldera walls during severe subsidence events.

A. Abundant large andesite clasts (to 50 cm at this location) in intracaldera dacitic Bonanza Tuff (unit Tbd), on a scale not present in the outflow ignimbrite. Kerber Creek road, just west of mouth of Soda Springs Gulch (GG, lat 38°12.80′ N., long 106°04.28′ W.).

B. Typical caldera-collapse mesobreccia (unit Tbma), delineated by dashed lines. Equant rounded block of andesite in center of photo, about 0.7 m in diameter, surrounded by light-gray matrix of rhyolitic Bonanza Tuff and additional andesite fragments. The light color of the tuff indicates that it was originally only weakly welded and probably glassy, due to quenching against the abundant clasts of wall-rock andesite. Roadcuts, Rawley Gulch (BZ, lat 38°18.51′ N., long 106°08.52′ W.).

C. Closer view of mesobreccia texture (same location as photo *B.*), showing wide range of andesite-clast sizes dispersed in lighter-colored tuffaceous matrix.

D. Talus block of mesobreccia (unit Tbmu), displaying diverse clast compositions, including mixed volcanic and Precambrian fragments. Along Alder Creek road (WH, lat 38°21.75' N., long 106°03.90' W.).

E. Isolated large block (3–4 m) of brecciated andesite, floating in partly welded Bonanza Tuff, all variably bleached by supergene alteration. Exposure is within the 2.5-km-thick section of intracaldera ignimbrite that is preserved on the tilted west flank of the resurgent dome. Lower Squirrel Creek road, just south of Rawley drainage portal (BZ, lat 38°18.55' N., long 106°08.77' W.). In image: Andrea Sbisà.

Photos 10.2*A,B,C*. Transition from Bonanza megabreccia to caldera floor. Relatively good exposures on the slopes above Kerber Creek, along southwest flank of the resurgent dome (GG), document obscure transitions between caldera-floor andesite lavas and clast-dominated megabreccia. The presence of megabreccia with local matrix of dacitic Bonanza Tuff at the base of the thick intracaldera ignimbrite accumulation, directly in contact with caldera-floor lavas, documents that initial caldera collapse was delayed until after eruption of the bulk of the lower rhyolitic Bonanza Tuff.

A. Local matrix of dacitic tuff in fractured andesite lava; arroyo east of lower Sawmill Gulch (GG, lat 38°13.54' N., long 106°05.62' W.).

B. Tuffaceous matrix, between texturally contrasting blocks of fine-grained and plagioclase-phyric andesite (units Tra, Trap); arroyo east of lower Sawmill Gulch (GG, lat 38°13.58' N., long 106°05.63' W.).

C. Base of lens of weakly welded dacitic Bonanza Tuff (unit Tbd), near poorly constrained contact between in-place andesite lavas of the caldera-floor and overlying caldera-collapse megabreccia. Arroyo east of lower Sawmill Gulch (GG, lat 38°13.56' N., long 106°05.58' W.). In image: Andrea Sbisà.

Photos 10.3*A,B,C*. Rheomorphic lower Bonanza Tuff, enclosing diverse masses of precaldera andesite, ridge west of upper Schoolhouse Gulch along Big Tree Lane (GG). In roadcut exposures (fig. 15, sheet 2), scattered steep lenses of rhyolitic Bonanza Tuff are spatially associated with a sheet-like erosional remnant of flow-layered rhyolite, interpreted as rheomorphic lower Bonanza Tuff (unit Tbrr) despite its fluidal lava-like fabric. Where contacts with adjacent caldera-floor andesite are well exposed, especially at the south end of the main body, masses of andesite ranging in size from several meters across to centimeter-size chips are enclosed by fluidal rhyolite that is locally flow folded. In striking contrast to the weakly welded matrix tuff associated with most caldera-collapse breccias at Bonanza (photos 10.1*B*,*C*) and elsewhere (Lipman, 1976), the texture of the rhyolite along Schoolhouse Gulch is strikingly lamellar and fluidal adjacent to andesite clasts, even in thin-section scale.

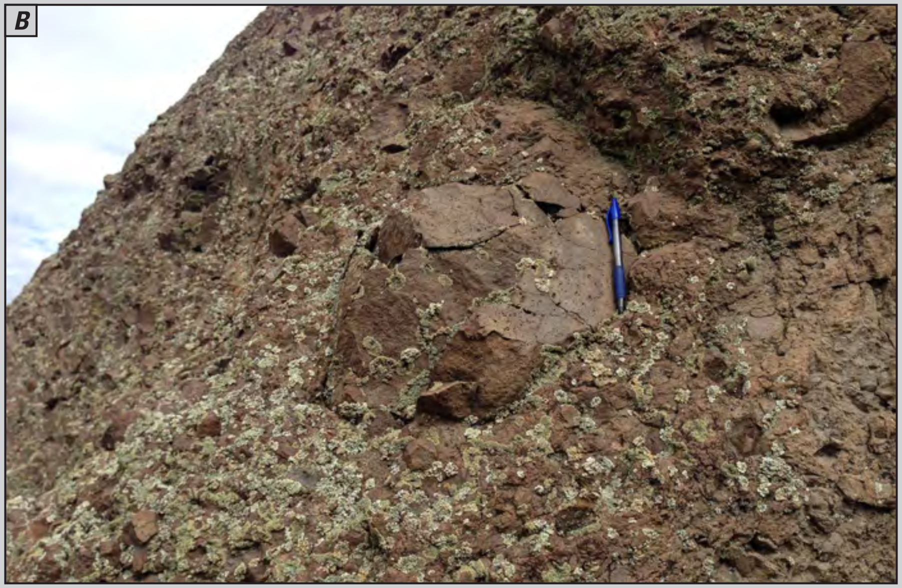
A. Highly irregular blocks (outlined in orange; dashed where approximate) of andesite laharic breccia, enclosed within flow-laminated rheomorphic rhyolite tuff. Although flow laminated, the rhyolite contains centimeter-size angular andesite fragments (hiking pole, ~0.9 m). GG, lat 38°14.58' N., long 106°05.27' W.

B. Closer view of contact (dashed line) between block of andesite laharic breccia and enclosing dense rhyolite that remains fluidal at the contact. Several small fragments of andesite enclosed in the fluidal rhyolite are circled. Hiking pole, ~0.9 m. GG, lat 38°14.60' N., long 106°05.26' W.

C. Well-exposed contact between massive andesite lava and enclosing slabby fluidal rhyolite. GG, lat 38°14.76' N., long 106°05.33' W.

11. Caldera-Collapse Structures

Andesitic and dacitic lavas of the caldera floor that are adjacent to inferred ring faults along Kerber Creek and Columbia Gulch to the south are locally severely shattered. Angular blocks mostly less than 1 m across are juxtaposed, with only minor pulverized matrix. In many exposures, finely shattered fragments fit together without large-scale rotation or other movement. These breccias grade into less-shattered lava laterally, away from mapped ring faults.



Photos 11.1*A*,*B*,*C*. Shatter breccia adjacent to ring fault along Kerber Creek.

A. Brecciated caldera-floor andesite (unit Trax) along margin of resurgent dome, adjacent to valley of Kerber Creek (location of inferred concealed ring fault); distant ridges form the eroded topographic rim of caldera (upper left). White rectangle shows location of photo *B*. GG, lat 38°13.30' N., long 106°05.39′ W. In image: Andrea Sbisà.

B. Crushed fragments fit closely together, without abundant fine-grained matrix or evidence for major shearing (location shown in photo *A*).

C. Detail of outcrop, containing more abundant fine-grained matrix than displayed by photo *B* (GG, lat 38°13.41′ N., long 106°05.53′ W.).

Photos 11.2*A*,*B*,*C*. Shatter breccia adjacent to satellitic ring fault along Columbia Gulch. All photographs from same locality (GG, lat 38°13.04′ N., long 106°18.05′ W.).

***A*.** Outcrop of brecciated andesite (unit Trax), containing steeply dipping zones of more intense fracturing. In image: Andrea Sbisà.

***B*.** Closer view of steep fracture containing finely pulverized andesite within broader zone of more coarsely shattered breccia.

***C*.** Tightly fractured andesite, with many fragments fitting together without abundant fine-grained matrix.

12. Ignimbrite Fracture Fills

Within the near-floor megabreccia, much of the matrix tuff is weakly welded, lithic rich, and exposed mainly as fragments on slopes (photo 10.1), but some dike-like outcrops of tuffaceous crack fills are strongly welded and have steeply dipping fiamme.

Photos 12.1*A,B,C,D*. Discontinuous dike-like bodies of steeply dipping Bonanza Tuff, interpreted as filling dilatant fractures in upper part of caldera-floor lava and megabreccia sequence. Fracture-fill origin is supported by areal distribution; confined to within or closely adjacent to megabreccia low in the intracaldera section. All photos: lower slopes between Sawmill and Big Tree Gulches (GG).

A. View to southwest, up the valley of Kerber Creek, which follows the main caldera ring fault. Crack fill is rib of densely welded rhyolitic tuff (unit Tbrf), with near-vertical contact between fracture-filling tuff and country rock of andesitic lava (unit Tra), on lower flank of resurgent dome. High distant ridges are eroded topographic rim of caldera. This and some nearby crack fills are semi-parallel to the northwest trend of the adjacent Kerber Creek ring fault, but others are at high angles. GG, lat 38°13.95' N., long 106°06.94' W. In image: Andrea Sbisà.

B. Outcrop of near-vertical fluidal-textured rhyolitic rib (unit Tbrf). Rectangle indicates location of photo *C*.

Photos 12.1*A,B,C,D*—Continued. **Discontinuous dike-like bodies of steeply dipping Bonanza Tuff,** interpreted as filling dilatant fractures in upper part of caldera-floor lava and megabreccia sequence. Fracture-fill origin is supported by areal distribution; confined to within or closely adjacent to megabreccia low in the intracaldera section. All photos: lower slopes between Sawmill and Big Tree Gulches (GG).

C. Sparse andesitic fragments document fragmental nature, even where tuff is strongly altered or fluidal in texture.

D. At another rib, steeply dipping foliation is well defined by flattened-pumice fiamme in the rhyolitic tuff (73.13% SiO_2). Sample 10L-9; GG, lat 38°13.92' N., long 106°05.92' W.

Photos 12.2*A,B*. Dike-like body of crack-filling Bonanza Tuff, upper Elk Horn Ranch road. Discontinuous north-trending fracture fill of rhyolite (unit Tbrf) characterized by angular fragments of andesite and vertically dipping, fluidal flow-layered foliation.

A. View to north, along ridge above Elkhorn Ranch road. Outcrop is crack-fill of rhyolite tuff (unit Tbr). Surrounding slopes and road cuts beyond outcrop consist entirely of andesite (unit Tra). Near head of Big Tree Gulch (GG, lat 38°19.50' N., long 106°05.67' W.; samples 12L-2A,B; 72.9%, 75.6% SiO_2).

B. Detailed view of textures in rhyolite fracture fill, showing angular andesitic fragment in near-vertical flow-layered rheomorphic tuff. Same location as photo *A*.

Photos 12.3*A,B*. Dike-like fracture fill, with conspicuous flattened pumice fiamme that dip steeply. Along Elk Horn Ranch subdivision road, at 9,600', west side of upper Sawmill Gulch (GG, lat 38°14.59' N., long 106°05.73' W.).

A. Roadcut view; rhyolitic tuff (sample 07L-37, 73.13% SiO_2) is steep body about 3 m wide, between two contrasting textural types of andesite. Hiking pole, ~0.9 m long.

B. Closer view, showing steeply dipping fiamme in rhyolitic tuff.

13. Postcollapse Lavas, Bonanza Caldera Cycle

After the ignimbrite eruption and concurrent caldera subsidence, compositionally diverse lavas ranging from andesite to high-silica rhyolite filled the caldera to overflowing and spread across adjacent slopes.

Photos 13.1*A*,*B*,*C*. Postcaldera andesite and Bonanza Tuff. Sparsely porphyritic dark-gray lava flows (unit Tba), previously described as upper andesite (Varga and Smith, 1984), overlie proximal outflow Bonanza Tuff widely around southwest flank of Bonanza caldera.

A. On ridge west of lower Dry Gulch (LMNE, KM), andesite flows directly overlie the Bonanza ignimbrite, within which partly welded upper rhyolite (unit Tbru) grades downward into dacite (unit Tbd). Along debris-mantled base of ridge, andesite flows of the Rawley complex (unit Tra) are locally exposed beneath the Bonanza Tuff. Photo site: lat 38°08.0′ N., long 106°15.0′ W.

B. Flow-layered small-phenocryst dacite (sample 09L-7, 66.1% SiO_2; lat 38°07.90′ N., long 106°12.02′ W.), which caps the thick paleovalley-filling section of Bonanza Tuff on the ridge west of Findley Gulch (KM; see photo 9.1*A*). In image, Valibone Memeti.

C. Along side valley west of Middle Creek (LMNE), postcaldera andesite (unit Tba) occupies a steep paleovalley partly coincident with present-day Middle Creek, where it is banked against dacitic Bonanza Tuff (unit Tbd) and underlying dacitic flows of the Jacks Creek volcano (units Tjd, Tjds). Photo site: lat 38°12.9′ N., long 106°18.1′ W.

Photos 13.2*A*,*B*. **Upper dark malpais andesite** (unit Tbam). A distinctive local unit of massive dark-gray to black vesicular lava flows and proximal breccia that overlies Bonanza Tuff west of upper Middle Creek (CH, lat 38°15.98′ N., long 106°18.12′ W.).

A. Massive cliffs of crudely bedded chaotic breccia and spatter (unit Tbab), cropping out west of Middle Creek (CH), appear to be the east flank of an eruptive cone. Interlayered with lesser volumes of lava with irregular shapes.

B. Blocks in the breccia tend to be subequant and crudely sorted.

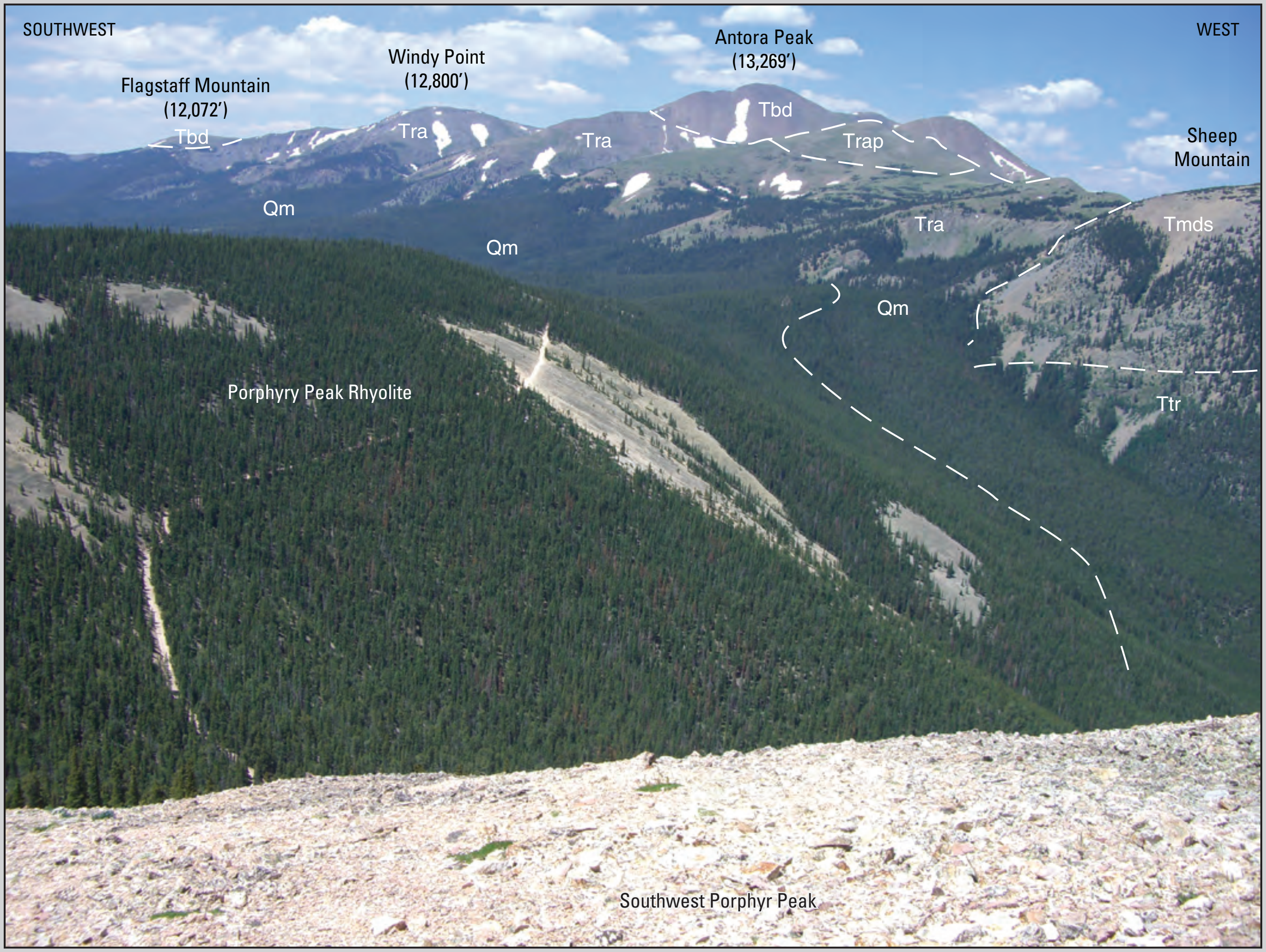


Photo 13.3. View from southwest summit of Porphyry Peak, toward west rim of Bonanza caldera. Thick Porphyry Peak Rhyolite (unit Tbfr), exposed as talus in foreground and along the historic Otto Mears Toll Road, constitutes upper lava-flow fill in Bonanza caldera. These lavas are crystal-poor silicic rhyolite (72.3–76.0% SiO_2; 5–10% phenocrysts of sn, qtz>pl>bi), chemically similar to the granitic Spring Creek intrusion (units Tas, Tgs) on the east flank of the resurgent dome. The skyline ridge defines eroded remnants of the caldera's topographic rim, along which dacitic Bonanza Tuff (unit Tbd) is plastered against andesitic lavas (units Tra, Trap) of the Rawley volcanic complex. These lavas in turn onlap Thorn Ranch Tuff (unit Ttr) and overlying Sheep Mountain Dacite (unit Tmds) within the older Marshall caldera. Lower timbered slopes are widely mantled by glacial moraine (unit Qm). Photo site: lat 38°21.05′ N., long 106°09.35′ W.

Photo 13.4. Hayden Peak from the south. Areally restricted erosional remnants of distinctive massive gray lava flows (unit Tbdh) of sparsely porphyritic silicic dacite (69.2–70.5% SiO_2) occupy upper slopes of Hayden Peak and extend along ridge to north (WH). Exposed largely as talus on steep slopes. Deposited on lower rhyolitic Bonanza Tuff (unit Tbrl) and caldera-floor lavas of the Rawley complex, mainly andesite (unit Tra), in a deep paleovalley or possibly along an obscure fault-bounded keystone graben of the caldera resurgent dome. On the lower south slope of Hayden Peak, a thick rhyolite flow complex (unit Trfr) caps the caldera-floor andesite flows on the southwest-dipping flank of the resurgent dome; these lavas are locally overlain by small erosional remnants of dacitic Bonanza Tuff (unit Tbd). View to north, up Greenback Gulch (WH). Photo site: lat 38°15.0′ N., long 106°07.4′ W.

14. Resurgent Intrusions, Bonanza Caldera Cycle

Compositionally and texturally diverse intrusions varying from gabbro to silicic granitic rocks intruded and uplifted the caldera floor and lowest ignimbrite fill. The scattered surface exposures of the intrusions are inferred to represent an irregular roof zone of a more continuous composite resurgent complex at slightly greater depth.

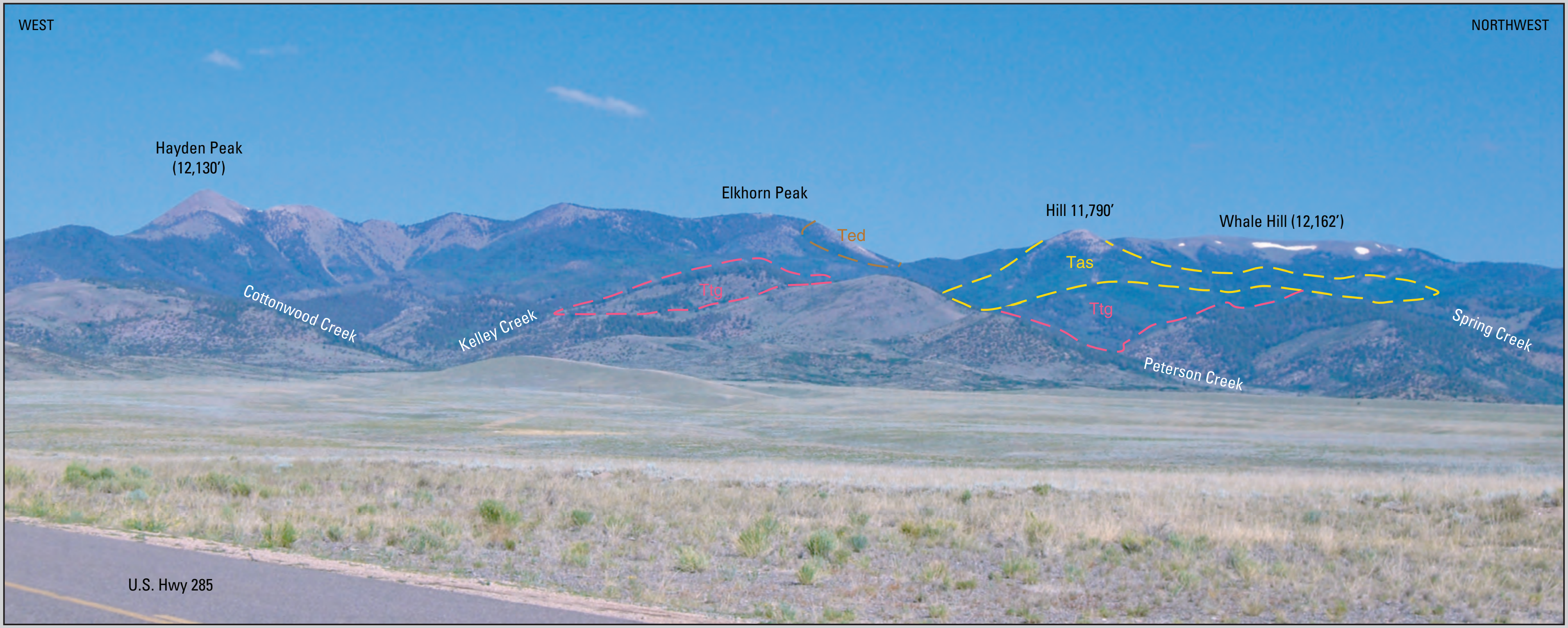


Photo 14.1. Intrusions, east flank of Bonanza resurgent dome. Panorama of resurgently uplifted caldera floor. Valleys on east flank of the Bonanza resurgent dome have eroded down into several compositionally diverse intrusions that are exposed at near-roof levels. These include the granodiorite to intrusive andesite of the Turquoise Mine pluton (units Ttg, Tta) and aplitic and porphyritic granite of the Spring Creek intrusion (units Tas, Tgs). A sill-like body of Eagle Gulch Dacite (unit Ted) is exposed at its northeast termination on the north slope of Elkhorn Peak. The compositional range of these intrusions is comparable to that of the postcollapse andesite to rhyolite lavas of the Bonanza cycle. Wall rocks for the intrusions are precaldera andesite and dacite lavas of the Rawley volcanic complex, forming the floor of Bonanza caldera. The nearly flat crests of Whale Hill and Elkhorn Peak are close to the surface on which intracaldera Bonanza Tuff accumulated. The outward-dipping slopes viewed from this vantage approximate tilts on flanks of the resurgent dome. Hayden Peak is underlain by a thick sequence of postcollapse dacitic lavas (unit Tbdh), probably filling a paleovalley. Panoramic view from U.S. Hwy 285, in the San Luis Valley (WH). Photo site: lat 38°17.9′ N., long 105°59.2′ W.

Photos 14.2*A,B,C*. Turquoise Mine intrusion (~33.0 Ma?). Texturally variable light-gray granodiorite and darker intrusive andesite form a composite intrusion about 3 x 7 km across, extending from the head of Peterson Creek, across several drainages to the southwest, to at least as far as the southeast ridge of Hayden Peak.

A. Medium-grained granodiorite (unit Ttg) that forms much of the intrusion varies from equigranular to finely porphyritic (62.4% SiO_2), consisting mainly of plagioclase, biotite, chloritized pyroxene, and small interstices of quartz and alkali feldspar. Ridge between Peterson and Kelley Creeks, hill 10,056; sample 08L-4B (WH, lat 38°17.63' N., long 106°03.71' W.).

B. Aplitic granodiorite (unit Ttg; 67.0% SiO_2) is a relatively minor phase, forming irregular pods up to a few meters across within dominant volumes of the coarser granodiorite (unit Ttg). Ridge between Peterson and Kelly Creeks, hill 10,056; sample 08L-4A (WH, lat 38°17.63' N., long 106°03.71' W.).

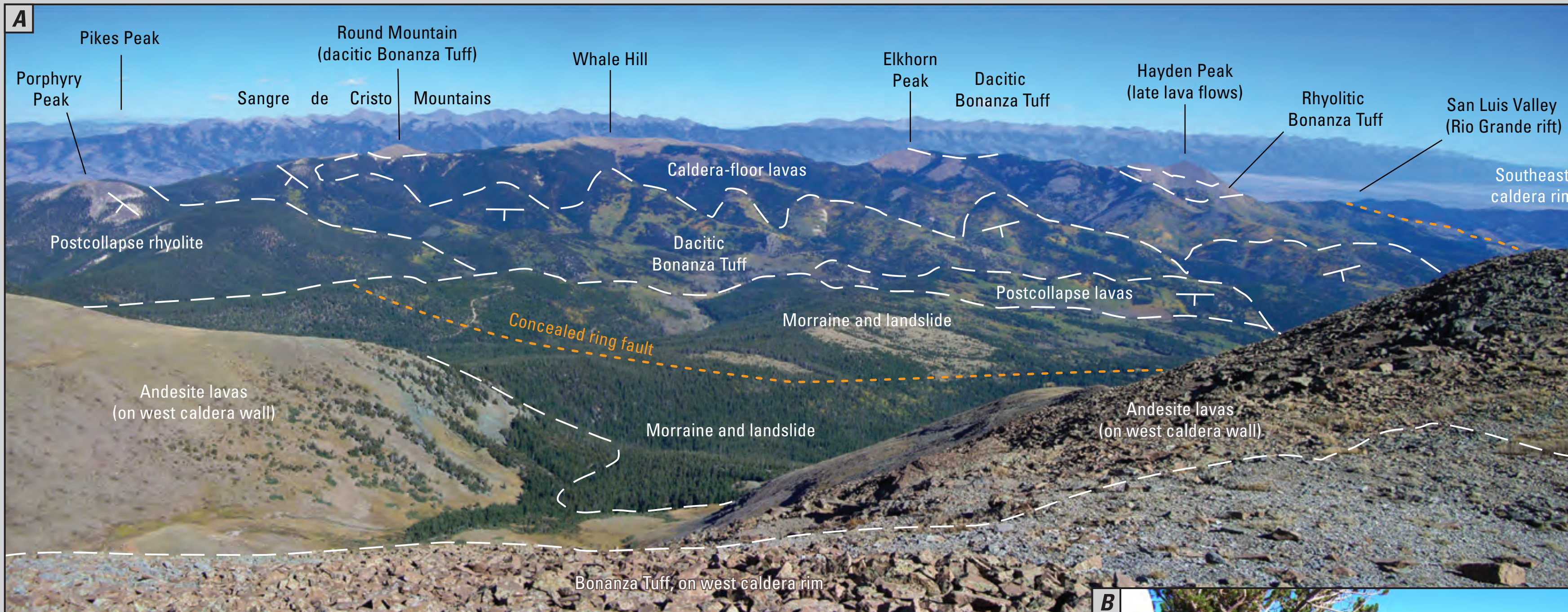
C. Intrusive andesite phases (unit Tta) are relatively unaltered dense dark-gray rocks, characterized by closely spaced rectilinear joints, that form bold outcrops. In places, the andesite is in sharp contact with granodiorite; elsewhere, contacts appear to be gradational. Sample 08L-41 yielded $^{40}Ar/^{39}Ar$ ages (whole-rock) of 33.06±0.21 Ma (plateau) and 32.83±0.21 Ma (isochron). Ridge between Peterson and Kelley Creeks (WH, lat 38°17.62' N., long 106°03.52' W.).

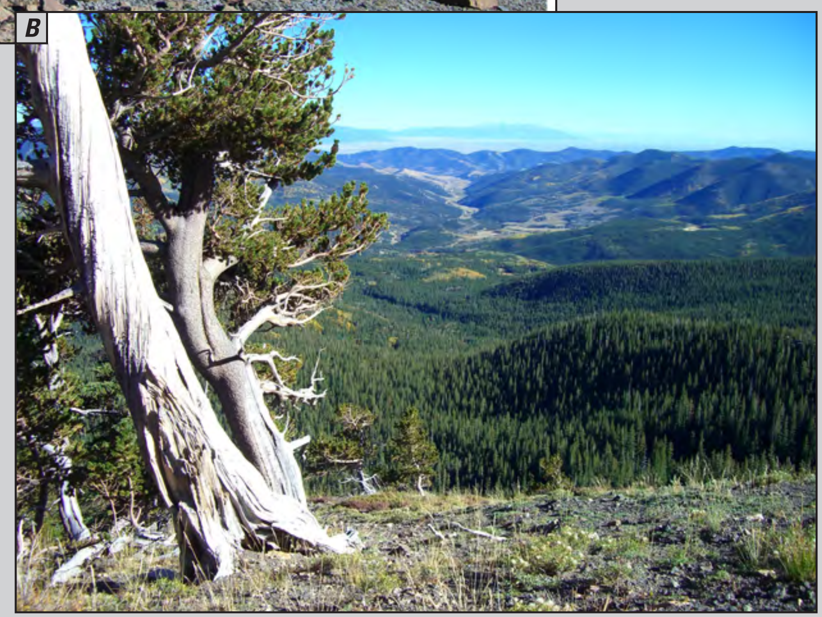
Photos 14.3*A,B*. Silicic intrusions into the core of the Whale Hill resurgent dome. These include the Spring Creek intrusion, exposed near roof level on the east slopes of Whale Hill, and the Eagle Gulch Dacite, a sill-like body intruded near the contact between basal intracaldera Bonanza Tuff and underlying caldera-floor lavas on the southwest flank of the resurgent dome.

***A*.** Spring Creek intrusion of aplitic granite (~33.0 Ma) on hill 11,790 south of upper Spring Creek (WH). Margins are aplitic granite and rhyolite porphyry (unit Tas), especially along roof contacts. Grades into coarser porphyritic granite (unit Tgs) in pluton interior. The aplitic granite is light gray, containing 5–15% phenocrysts of K-feldspar and quartz, 74.4–76.6% SiO_2. Outcrops are rare, and the steep slopes are dominated by angular talus. Photo site: lat 38°18.7′ N., long 106°05.2′ W.

***B*.** Eagle Gulch Dacite (unit Ted), forming typical talus slope. A northeast-trending elongate body about 8 km long, it consists of light-tan to gray dacite that is compositionally and texturally uniform (67.4–68.1% SiO_2). Exposed mainly as blocky talus slopes, the Eagle Gulch Dacite contains 10–15% phenocrysts of altered plagioclase, K-feldspar, and biotite that are everywhere silicified, thermally recrystallized, and otherwise altered. View west from upper Elkhorn Gulch, toward Antora Peak on eroded topographic rim of Bonanza caldera. Photo site: lat 38°16.95′ N., long 106°06.85′ W.

After the ignimbrite eruption and emplacement of caldera-filling lava flows, the caldera floor was arched into an exceptionally large and steep-sided resurgent dome with its crest along Whale Hill.

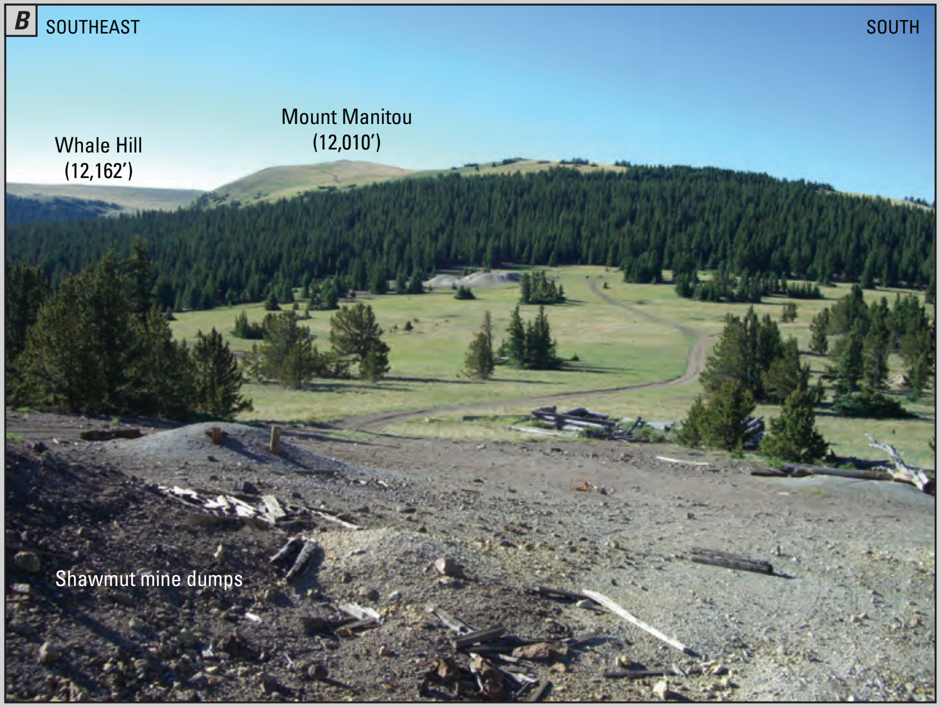


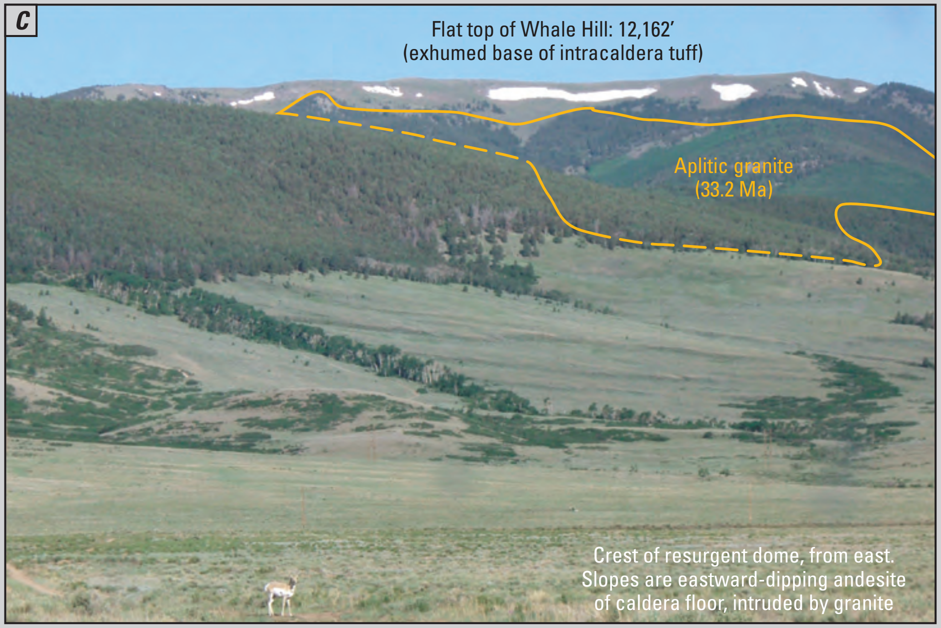


Photos 15.1*A*,*B*. Whale Hill resurgent dome and south caldera margin, viewed from west. The long high ridge between the Kerber Creek drainage to the west and the San Luis Valley to the east, from Hayden Peak north across Whale Hill to Round Mountain, marks the eroded anticlinal crest of the Whale Hill resurgent dome within the Bonanza caldera.

A. Panorama of resurgent dome. View is to east from west caldera rim, across Whale Hill toward the San Luis Valley segment of the Rio Grande rift (compare with photo 8.1). West-dipping intracaldera Bonanza Tuff, on the timbered slopes on the west flank of the dome, is a sequence of interfingering dacite, rhyolite, and interleaved landslide breccia as much as 2.5 km thick, overlain by ~1 km of caldera-filling lava flows. The composite caldera-fill section is as much as 3.5 km thick, dipping 45–55° on flanks of the resurgent dome (fig. 14*A*, sheet 2). Photo site: lat 38°18,9′ N., long 106°13.3′ W.

B. South caldera rim and ring fault (just to south of photo 15.1*A*). View from southeast ridge of Antora Peak, down Kerber Creek, toward San Luis Valley and distant Sangre de Cristo Range. Meadows and open valleys in middle distance are underlain by concealed ring faults of Bonanza caldera; dark-shadowed ridges in upper right are high points along eroded south topographic rim, from Ute Pass eastward to the San Luis Valley. Southwest flanks of the Whale Hill resurgent dome are partly visible behind old tree-line pine. Photo site: lat 38°17.25′ N., long 106°12.6′ W.





Photos 15.2*A*,*B*,*C*. Along crest of the Whale Hill resurgent dome. The long, gently rolling ridge from Elkhorn Peak north to Whale Hill, Mount Manitou, Round Mountain, and Burnt Mountain (WH) marks the exhumed approximate surface of the caldera floor, from which intracaldera Bonanza Tuff has largely been stripped by deep subsequent erosion (see photo 8.1).

A. Caldera-floor remnant of dacitic intracaldera Bonanza Tuff (unit Tbd) at Round Mountain (12,036'), deposited directly on intracaldera andesitic lava flows (unit Tra), as exposed along crest of resurgent dome (WH). Dumps of the Shawmut Mine are at left of image (compare with photo 8.2*B*). Photo site: lat 38°20.2′ N., long 106°07.4′ W.

B. Whale Hill and Mount Manitou, from Round Mountain (WH). Rolling tree-lined uplands are stripped surface of caldera-floor andesitic lavas (units Tra, Trap) along crest of resurgent dome, from which intracaldera Bonanza Tuff (unit Tbd) has been erosionally stripped except at Round Mountain. View to southeast from Shawmut Mine. Photo site: lat 38°20.4′ N., long 106°07.4′ W.

C. Whale Hill and Spring Creek resurgent intrusion, viewed from the east (WH). Aplitic granite of this intrusion (unit Tas, 73–77% SiO_2), exposed at roof level, intrudes caldera-floor andesitic lavas of the Rawley complex (unit Tra) just below the crest of the resurgent dome defined by Whale Hill. The skyline profile marks the caldera-floor surface from which Bonanza Tuff has been erosionally stripped, except at Round Mountain (photos 8.2*B*, 14.1*A*). Photo site: lat 38°19.8′ N., long 106°00.6′ W.

Photos 15.3*A,B,C,D*. Steeply dipping intracaldera Bonanza Tuff, on northeast flank of resurgent dome. On this flank of the dome, multiple alternations of rhyolite and dacitic Bonanza Tuff that interfinger with caldera-collapse landslide megabreccia have dips of foliation as steep as 90°.

A. Rheomorphic Bonanza rhyolitic tuff (unit Tbrr) that is flow- and shear-layered, dipping about 65° to east, interleaved between dacitic Bonanza (unit Tbd) to east (right) and megabreccia of plagioclase andesite (unit Tbmp) in valley to left, on southeast side of hill 9312 (WH, lat 38°21.53' N., long 106°03.57' W.; sample 12L-1A, 78.3% SiO_2).

B. Upper contact of rheomorphic rhyolite depicted in photo *A*, grading upward into dacitic Bonanza Tuff (unit Tbd) to right (photo *C*). Flow layering in rheomorphic rhyolite dips about 75° to east.

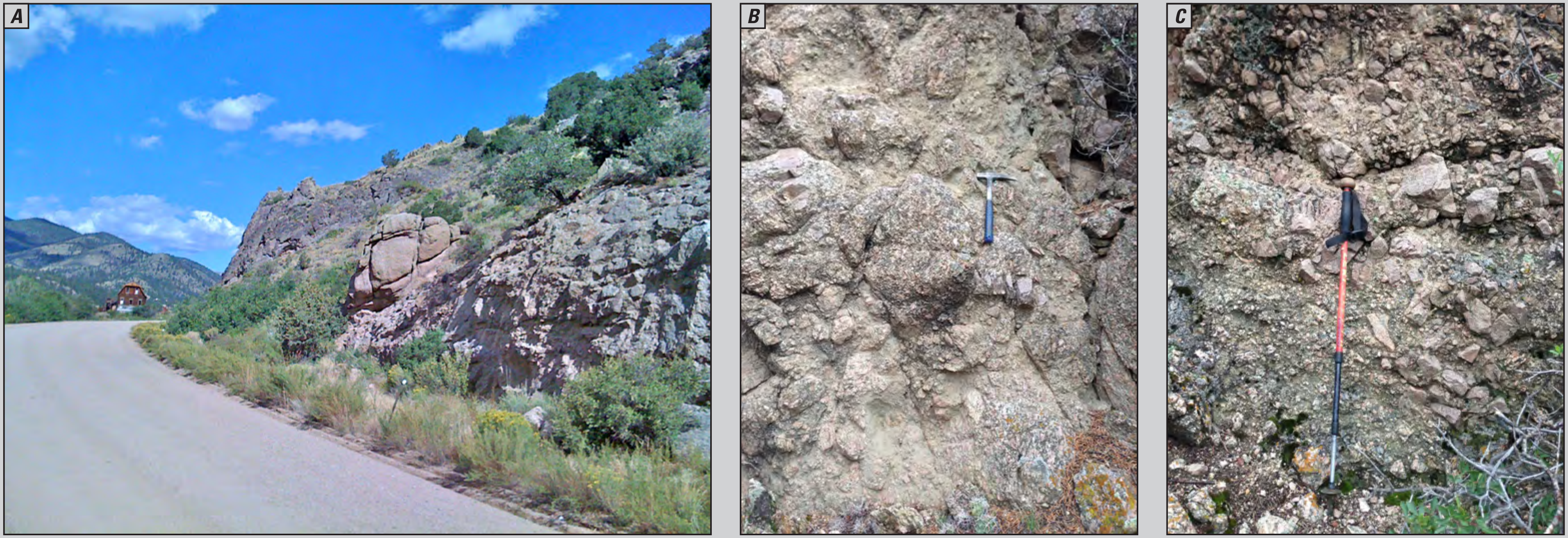
C. Large andesitic clast in dacitic Bonanza Tuff (unit Tbd), just to right (east) of photo *B*.

D. Steeply dipping foliation in dacitic Bonanza Tuff (unit Tbd), to right (east) of photo *C*.

Photo 15.4. Intracaldera Bonanza Tuff at Soda Springs Gulch (GG), dipping steeply on southwest flank of resurgent dome. Dips are conformable with underlying Paleozoic strata, exposed on ridge at left of image. Train of andesite megablocks between Upper Paleozoic Sharpsdale Formation (unit ℙs) and intrusive dacite are interpreted to be caldera-collapse landslide breccia (compare with photo 16.3*A*). Dacite may be an irregular sill-like intrusion, rather than precaldera lava flow (alternatively, monolithologic landside megabreccia?). p€, Precambrian granite; Ls, Limestone; Fm, Formation. Photo site: lat 38°12.9′ N., long 106°04.7′ W.

16. An Additional Complexity

Especially problematic to interpret have been distinctive shattered breccias of Proterozoic granodiorite gneiss (unit p€g) and their relations to adjacent Paleozoic and Tertiary rocks, which crop out in small areas along both sides of Kerber Creek near the junction with Little Kerber Creek (GG). These rocks are tentatively interpreted as caldera-collapse breccias (unit Tbmc) but with many uncertainties.

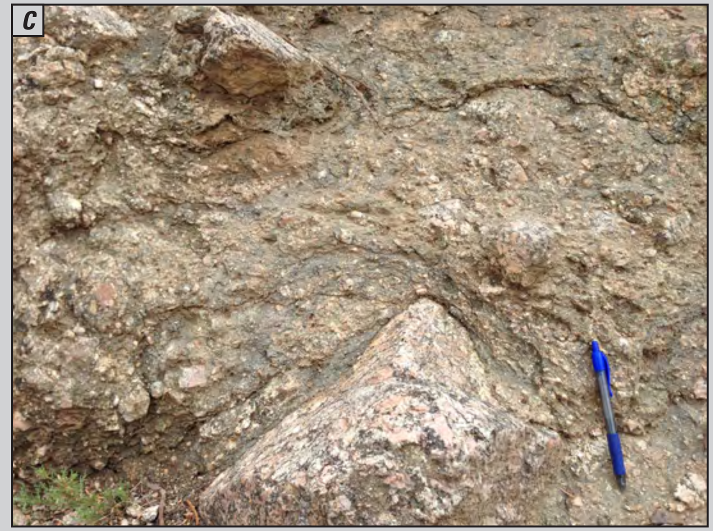


Photos 16.1*A,B,C*. Shattered Precambrian granitic gneiss. Rotated blocks of foliated gneiss as much as several meters across are juxtaposed, many with only minor matrix of pulverized granodiorite. Others have matrix apparently derived from rhyolitic Bonanza Tuff (unit Tbr) or disaggregated Sharpsdale Formation (unit ℙs), fragments of which overlie (and may underlie) the zone of Precambrian-clast breccia. Photo site: lat 38°12.95′ N., long 106°04.85′ W.

A. Roadcut outcrops of brecciated granodiorite gneiss, adjacent to dacite lava (unit Trd) of the Rawley complex. In center of image, a large weather-rounded block of gneiss several meters across is surrounded by more finely brecciated granodiorite. At first view, the dacite appears to overlie the breccia, but alternatively the breccia may have been deposited against the dacite along a paleovalley slope or may be in fault contact.

B. Variably fractured granodiorite gneiss—some blocks fitting together, others surrounded by more finely shattered matrix. Photo site: lat 38°12.95′ N., long 106°04.8′ W.

C. Finely shattered coarse angular fragments of Precambrian granodiorite gneiss, underlain by zone of smaller fragments with a higher proportion of green-gray pulverized matrix. Hiking pole is ~0.9 m in length. Photo site: lat 38°12.95′ N., long 106°04.88′ W.



Photos 16.2*A,B,C,D*. Rotated clasts in pulverized Precambrian matrix. Same outcrops as depicted in photo 8.1. Photo site: lat 38°12.95′ N., long 106°04.88′ W.

A. Large rounded blocks of granodiorite gneiss, with divergent foliation orientations, in matrix of more finely shattered gneiss.

B. Matrix-supported rounded block of granodiorite gneiss.

C. Isolated fragments of granodiorite gneiss in pulverized matrix.

D. Closer view of green-gray arkosic matrix that is interpreted as finely pulverized granodiorite, based on mineral and chemical affinities. Chapstick case is 6.5 cm in length.

Photos 16.3*A,B,C*. Brecciated and shattered clasts of Upper Paleozoic Sharpsdale Formation (unit ℙs). Brecciated sedimentary rocks and adjacent small outcrops displaying divergent bedding orientations (commonly steep), exposed in small arroyos just west of Soda Springs trail. These exposures are to the east, and probably beneath, the brecciated Precambrian rocks. The quality of outcrops varies with seasons; best exposed after heavy rainfall.

A. Large fragments of fine-grained calcareous sandstone, with divergent steep dips. GG, lat 38°12.97' N., long 106°04.48' W.

B. Small exposure of lithologically diverse sandstone fragments of Sharpsdale Formation. Light-colored breccia matrix above and left of hammer appears to be nonwelded rhyolitic tuff. GG, lat 38°12.90' N., long 106°04.50' W.

C. Closer view of textures and tuffaceous matrix of breccia in photo *B*.

Photos 16.4*A,B,C,D*. Volcanic clasts and matrix, associated with brecciated Precambrian rocks. Intermixed with the breccias of pre-Tertiary rocks are a few large andesite clasts (unit Tra) and locally exposed matrix of nonwelded rhyolitic tuff (unit Tbrn?).

***A*.** White nonwelded tuff (rhyolitic Bonanza Tuff?; sample 13L-1, 73.8% SiO_2) forming indurated matrix to blocks of granodiorite gneiss in a rare small outcrop surrounded by surficial debris. The tuff also encloses centimeter-size fragments derived from the gneiss. Float of the tuff in adjacent areas suggests that volcanic matrix is much more extensive than suggested just by this small contact outcrop. Pen is 13 cm long. Photo site: lat 38°12.95′ N., long 106°04.59′ W.

***B*.** Large block of shattered andesite, derived from the Rawley volcanic complex, on top of brecciated granodiorite gneiss and adjacent to nonwelded rhyolitic tuff (see photo 16.3*C*). Hiking pole is ~0.9 m in length. GG, lat 38°12.94′ N., long 106°04.59′ W.

C

D

Photos 16.4*A,B,C,D*—Continued. **Volcanic clasts and matrix, associated with brecciated Precambrian rocks.** Intermixed with the breccias of pre-Tertiary rocks are a few large andesite clasts (unit Tra) and locally exposed matrix of nonwelded rhyolitic tuff (unit Tbrn?).

C. Andesite megablocks (to 10 m) on slope mantled with small sandstone fragments derived from the Sharpsdale Formation (unit IPs), which is inferred to form matrix for the andesite blocks. In the absence of large-displacement faults (for which evidence is lacking), the entire breccia complex, including andesite, Paleozoic sandstone, and Precambrian gneiss, projects to lie above the Bonanza Tuff (at right of photo) that dips steeply on the southwest flank of the resurgent dome (see photo 14.3). View to north, from the Soda Springs trailhead, along the Bonanza road (GG). Photo site: lat 38°12.9′ N., long 106°04.45′ W.

D. Smaller clasts of brecciated andesite, surrounded by fragmented sandstone of the Sharpsdale Formation (delineated by dashed lines), form small outcrop along the Soda Springs trail just upslope from the image in photo *A*. Higher portions of slope consist entirely of disaggregated blocks of Sharpsdale Formation and a few intermixed clasts of Proterozoic gneiss; no source is available for the andesite clasts, other than an essentially in-place origin. Photo site: lat 38°12.95′ N., long 106°04.4′ W.

17. Post-Bonanza Ignimbrites and Lavas

After completion of Bonanza eruptions, ignimbrites from younger San Juan calderas and locally erupted lavas largely to entirely blanketed the region, and scattered remnants of this cover have survived erosion.

Photo 17.1. Volcanic fill, paleo-Saguache Valley. View to west, up Saguache Valley. Houghland Hill is a near-horizontal layered sequence of regional ignimbrites that ponded along axis of the Saguache paleovalley, between Tracy volcano to the south and the composite highland of the Rawley volcanic complex to the north, within which Bonanza caldera formed. The exposed sequence on Houghland Hill is from 33.12-Ma Bonanza Tuff at base, up through 32.2-Ma Saguache Creek, 28.0-Ma Fish Canyon Tuff (forming prominent mid-slope cliff), and 27.55-Ma Carpenter Ridge Tuff to capping flow of 21.8-Ma Hinsdale Basalt. Fluvial gravels form thin lenses between the ignimbrite sheets, and postcaldera andesite flows overlie the Bonanza Tuff along southeast slopes of the hill. The south flank of the paleovalley is defined by thick lava flows of mafic dacite on Sierra de la Lola, erupted from the Tracy volcano, against which the valley-fill ignimbrites wedge out. North flank of the paleovalley, to right of Colorado Hwy 114, is defined by andesitic lavas low on the southwest slope of the Rawley volcanic complex, overlain by thick Bonanza Tuff and upper andesite-dacite flows of the Bonanza caldera cycle. Photo site: lat 38°06.4′ N., long 106°11.2′ W.

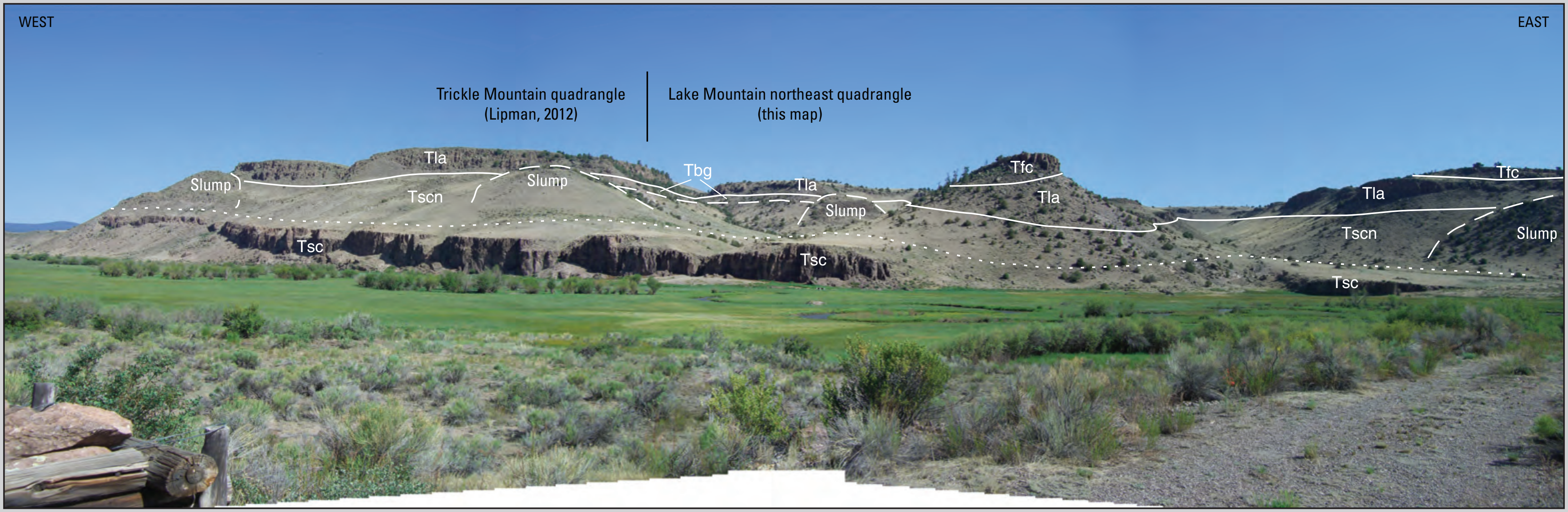


Photo 17.2 Post-Bonanza stratigraphy, southeast flank of Trickle Mountain. View north across Saguache Creek (southwest corner of LMNE), showing interfingering between local volcanic units (andesite of Lone Tree Gulch, unit Tla; tuff of Big Dry Gulch, unit Tbg) and regional ignimbrites (Saguache Creek and Fish Canyon Tuffs) along axis of Saguache paleovalley. The andesite of Lone Tree Gulch consists of dark-gray flows of sparsely porphyritic vesicular andesite (59% SiO_2, 30.2 Ma) and a local sequence of lava flows that overlie densely welded lower and nonwelded upper zones of the Saguache Creek Tuff (units Tsc, Tscn) and are onlapped by Fish Canyon Tuff (unit Tfc) along the paleo-Saguache Valley. From a distance, both Fish Canyon Tuff and andesite of Lone Tree Gulch form dark-gray columnar-jointed cliffs of misleadingly similar appearance. Detailed relations among weakly welded underlying tuffs and local lenses of volcanic conglomerate (too thin and discontinuous to map) are obscured by widespread landslides and slumps from the upper cliff-forming units. Dotted contact, gradational contact between unit Tsc and unit Tscn. Photo site: lat 38°07.35′ N., long 106°22.3′ W.

Photos 17.3*A,B,C*. **Saguache Creek Tuff** (unit Tsc) is a crystal-poor rhyolitic ignimbrite, erupted from the North Pass caldera at 32.2 Ma.

***A*.** Base of Saguache Creek Tuff, here welded nearly to its base; lower dark zone is vitrophyre about 2 m thick, overlain by red-brown devitrified tuff that grades upward into less-welded tuff (unit Tscn). This ignimbrite is underlain by weakly indurated cross-bedded ash (wind-blown dunes?). Roadcut along Colorado Hwy 114 (sample 99L-20A; LMNE, lat 38°08.69′ N., long 106°20.50′ W.).

***B*.** Central zone of lithophysal gas cavities, developed widely within densely welded Saguache Creek Tuff. Roadcut along Colorado Hwy 114 (LG, lat 38°07.32′ N., long 106°22.28′ W.).

***C*.** Closer view of lithophysal cavities.

Photos 17.4*A,B*. **Fish Canyon Tuff** (unit Tfc). Large regional ignimbrite of compositionally uniform crystal-rich dacite, erupted from the La Garita caldera at 28.02 Ma.

***A*.** Typical outflow Fish Canyon Tuff. High crystal content, moderate welding, and coarse jointing yield grussy-weathering rounded outcrops and sandy soils. Spanish Creek access road (TM, lat 38°11.16′ N., long 106°29.35′ W.).

***B*.** Slabby bee-hive weathering in upper partly welded Fish Canyon Tuff. Along road between Mill Creek and Laughlin Gulch (LG, lat 38°04.52′ N., long 106°19.73′ W.).

Photo 18.1. Northern San Luis Valley segment of Rio Grande rift. Flat-floored valley is underlain by sedimentary fill of the Rio Grande rift zone, including the Miocene Dry Union Formation (unit Tdu) and younger alluvial-fan deposits (units Qfo, Qf). The San Luis valley segment of the rift zone is an asymmetrical graben, with its major bounding fault on the east side, against the Sangre de Cristo Range. The resurgently uplifted core of the Bonanza caldera forms the west flank of the valley; volcanic units dip eastward without major fault disruption, at least at exposed levels. In the center distance beyond village of Villa Grove, Mount Princeton is a mid-Tertiary granitoid intrusion in the Sawatch Range that bounds the west side of the Upper Arkansas segment of the rift zone. Along the Upper Arkansas segment, the main bounding fault is on the west side of the rift valley and the east flank is more gentle, an asymmetry opposite to that of the San Luis segment. This change in rift-zone geometry is accommodated along a structural transfer zone at Poncha Pass. View to north from U.S. Hwy 285 (VG). Photo site: lat 38°14.8′ N., long 105°58.8′ W.

Photos 18.2*A,B,C,D*. Dry Union Formation (unit Tdu). Erosional remnants of little-consolidated gravel and boulder deposits in sandy matrix that constitute exposed fill of the Upper Arkansas and northern San Luis Valley segments of the Rio Grande rift zone. Clasts are dominantly intermediate-composition Tertiary lavas and Precambrian crystalline rocks, in varied proportions. Present along the eastern mountain front, at northeast margin of the map area (PO), where physically continuous with more widespread and better exposed deposits of this unit north of Poncha Pass.

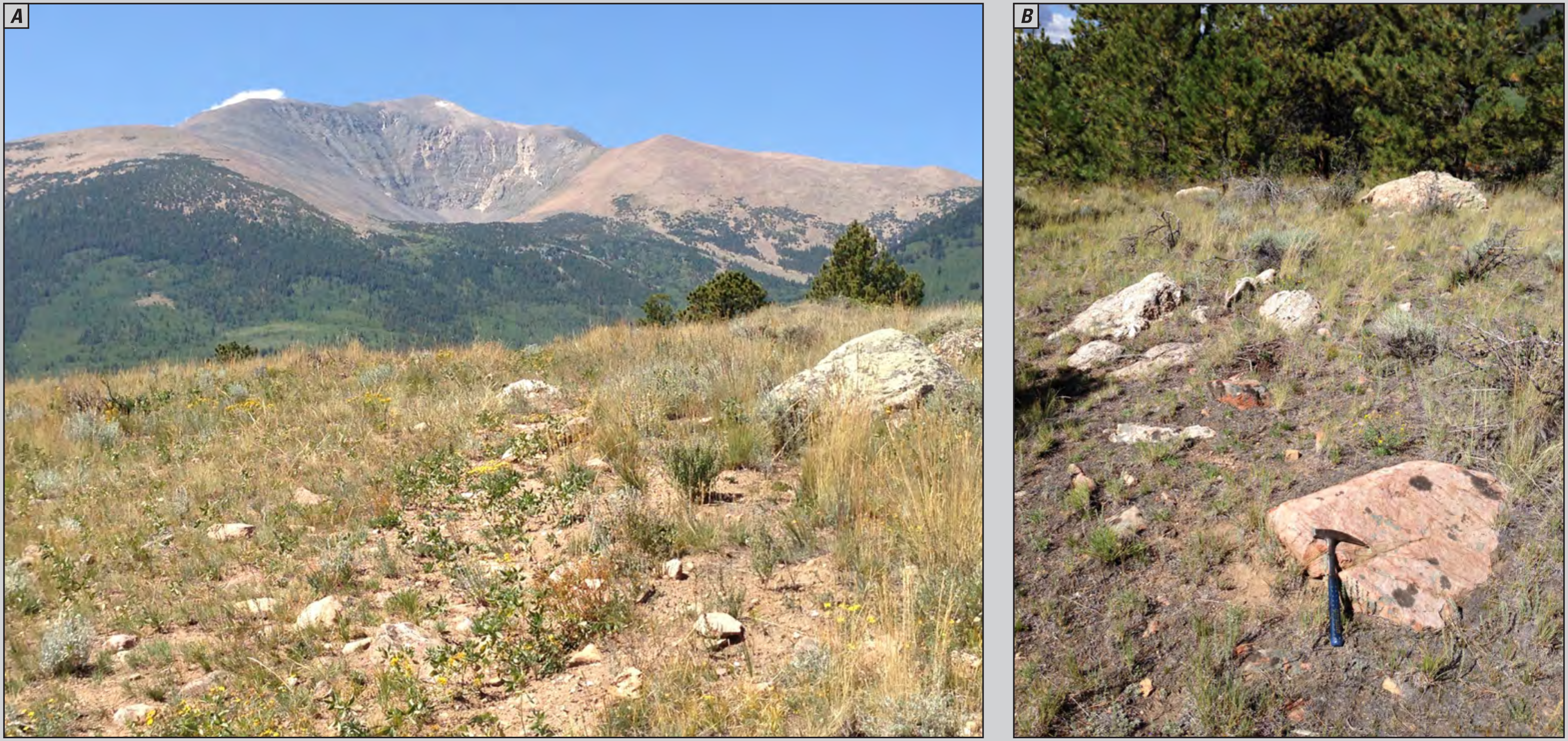
A. West-tilted Dry Union Formation, southern margin of Upper Arkansas segment. Moderately rounded to well-rounded andesite and dacite boulders and smaller clasts in sandy matrix (unit Tdua); a rare artificial exposure of this weakly consolidated alluvial-fan deposit. Roadcut along Poncha Creek (PO, long 38°26.64′ N., long 106°06.78′ W.).

B. Closer view of photo *A*. Poorly sorted conglomerate, probably typical of this weakly indurated deposit that constitutes alluvial fill of the San Luis and Upper Arkansas segments of the Rio Grande rift zone but forms no natural outcrops within map area. Hiking pole, ~0.9 m long.

Photos 18.2*A,B,C,D*—Continued. **Dry Union Formation** (unit Tdu). Erosional remnants of little-consolidated gravel and boulder deposits in sandy matrix that constitute exposed fill of the Upper Arkansas and northern San Luis Valley segments of the Rio Grande rift zone. Clasts are dominantly intermediate-composition lavas of Tertiary age and Precambrian crystalline rocks, in varied proportions. Present along the eastern mountain front, at northeast margin of the map area (PO), where physically continuous with more widespread and better exposed deposits of this unit north of Poncha Pass.

C. Basal depositional contact of Dry Union Formation. Mixed volcanic and sparse Precambrian clasts (unit Tdua), exposed above fine-grained andesite of the Conejos Formation (unit Tca) in excavation along roadbed of old Marshall Pass narrow-gage railway. Mouth of Beaver Creek (MO, lat 38°25.06′ N., long 106°04.59′ W.). Hiking pole, ~0.9 m long.

D. High-level alluvial fan, northwest of Villa Grove. One of several dissected alluvial fans along the east flank of the resurgent core of Bonanza caldera, tentatively interpreted as southerly remnants of the Miocene Dry Union Formation (unit Tdu) standing higher than the main Quaternary alluvial fan (unit Qf). Alternatively, these slopes of volcanic cobbles and sand may be older Quaternary fan deposits (unit Qfo). View to southwest, from U.S. Hwy 285. Photo site: lat 38°17.1′ N., long 106°00.3′ W.



Photos 18.3*A*,*B*. **Proximal upper boulder conglomerate.**

***A*.** Coarse unconsolidated boulder conglomerate, containing clasts as much as several meters in diameter, is a high-energy proximal fan deposit flanking the east slopes of Mount Ouray. This deposit is interpreted as an upper facies of the Dry Union Formation that records rapid late uplift and energetic erosion of the Sawatch block, after near-complete removal of Tertiary volcanic cover. Alternative interpretation as exceptionally large dissected deposit of old glacial moraine derived from the prominent Devils Armchair cirque on the east slope of Mount Ouray seems less likely; comparably large and low-altitude moraine (to below 9,000', along ridge between Beaver and Grays Creeks) appears to be absent on the east slope of Antora Peak or along other cirque valleys of the Sawatch Range to the north. View to west, toward Mount Ouray, from northwest of O'Haver Lake (MO). Photo site: lat 38°26.0′ N., long 106°09.4′ W.

***B*.** Typical outcrop of boulder conglomerate. Photo site: lat 38°26.0′ N., long 106°09.4′ W.

19. Faults of the Rio Grande Rift System

The Rio Grande rift is a linked system of Tertiary fault-bounded basins that resulted from extension as the mid-Tertiary ignimbrite volcanism waned. Rift faulting was focused along the crest of the Rocky Mountains from northern Mexico to central Colorado, including the San Luis and upper Arkansas Valleys in proximity to the Bonanza area. Many rift-related faults are poorly exposed and difficult to constrain with precision in the Bonanza map area.

Photo 19.1. High-angle contact, interpreted as normal fault between andesite lava of the Conejos Formation (unit Tca) to left (west) of water tank and sheared Proterozoic metamorphic rocks (unit p€m) to right. Alternative interpretation as steep depositional contact seems less plausible, because lava sequence dips only gently westward (10–15°) on low hills just west of linear contact with the Precambrian rocks. Northwest of Poncha Pass (at Boy Scout Camp; PO, lat 38°25.65′ N., long 106°05.85′ W.).

Photo 19.2. Peterson Creek fault. Altered andesite and rhyolite of the Rawley complex (units Tra, Trfr) on the Bonanza caldera floor are displaced down against Precambrian granite gneiss (unit p€g), along a north-trending fault that is well exposed at the mouth of Peterson Creek. This fault appears to continue south beyond Clayton Cone (VG) but is concealed beneath surficial deposits. View to north from Peterson Creek road (WH). Photo site: lat 38°17.25′ N., long 106°01.95′ W.

Large areas of volcanic rocks in the area that became the Bonanza mining district were affected by intense propylitic, argillic, and acid-sulfate alteration, especially in proximity to subvolcanic intrusions. Vein mineralization was localized along fractures on the west flank of the Whale Hill resurgent dome, most with only modest net displacement.

Photo 20.1. Rawley vein, 300-ft level (BZ, lat 38°19.50′ N., long 106°07.55′ W.). The Rawley vein, developed at multiple levels along Rawley Gulch, was the leading producer in the Bonanza district. Production of base and precious metals (Pb, Zn, Ag) peaked between 1915 and 1930, with a mild resurgence during World War II that continued into the 1950s.

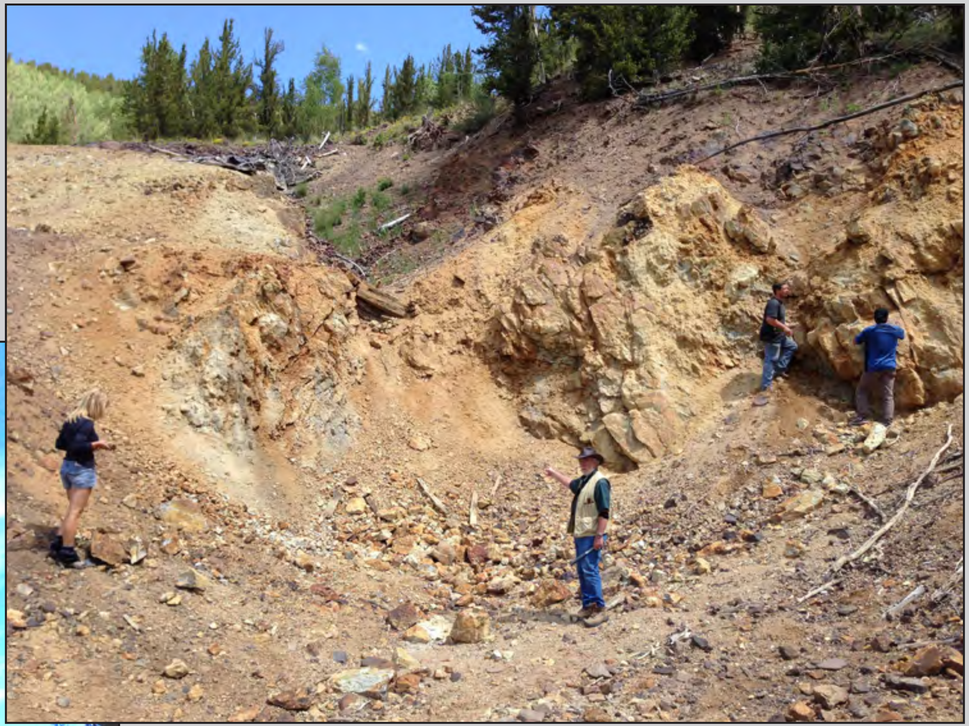


Photo 20.2 Cocomonga head-frame (BZ, lat 38°18.78′ N., long 106°08.97′ W.). The Cocamonga and associated Bonanza mines, along upper Kerber Creek, were the second most productive working in the Bonanza district. Photo site: lat 38°18.95′ N., long 106°08.95′ W.

Photo 20.3. Villa Grove Turquoise Mine (WH, lat 38°17.90′ N., long 106°03.20′ W.), along the eastern contact between granodiorite of the Turquoise Mine intrusion (unit Ttg) and caldera-floor andesite (unit Tra) of the Rawley volcanic complex, was mined for copper as early as the 1890s but only developed for turquoise in 1936. The mine produced high-quality turquoise, essentially free from veining and having a sky-blue color. Peak production was in the 1940s (Cappa and Wallace, 2007); the mine is currently (2015) inactive. View to north, from ridge between Peterson and Kelly Creeks. Photo site: lat 38°17.5′ N., long 106°03.5′ W.

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