EXCURSION 15B:
Roots of ignimbrite calderas: Batholithic plutonism, volcanism, and mineralization in the Southern Rocky Mountains, Colorado and New Mexico

Clark M. Johnson¹, James R. Shannon², and Christopher J. Fridrich³

¹Department of Geology and Geophysics, University of Wisconsin, Madison, Wisconsin 53706; ²Crown Resource Corporation, 820 16th Street, Suite 415, Denver, Colorado 80202; ³U.S. Department of Energy, Nevada Operations Office, Las Vegas, Nevada 89193

Introduction

The Questa, Mount Aetna, and Grizzly Peak calderas and associated volcanic and plutonic rocks provide a view of crustal magmatism from the surface through 4 to 8 km of crust. The petrologic relations between spatially and temporally related volcanic and plutonic rocks will be studied in the 28–19 Ma Latir volcanic field and associated Questa caldera. Deeply eroded ring-zone structures and brittle and ductile deformation are the focus of the trip through the 34–35 Ma Mount Aetna caldera in southern Colorado. Intra-caldera structures related to caldera collapse and resurgence, in addition to petrologic relations between high-level intrusive stocks and ash-flow magmatism, will be the topic of discussions at the 34 Ma Grizzly Peak caldera north of Mount Aetna. The Questa caldera occupies the eastern flanks of the Rio Grande rift in northern New Mexico, and the Mount Aetna and Grizzly Peak calderas occupy the western flank of the extreme northern part of the rift in central Colorado (Fig. 1).

Inasmuch as this trip focuses on the roots of calderas, we wish to comment on the usage of the terms “caldera” and “cauldron.”

Clough et al. (1909) originally used the term cauldron subsidence for a roughly circular structure formed by froundering of a cylindrical block of crust into an underlying magma body. Historically, the term cauldron has been applied to eroded volcanic collapse structures (e.g., Clough et al., 1909; Kingsley, 1931; Esher, 1932; Williams, 1941; Williams and Mc Birney, 1968; O'Ferdel, 1953, 1978; Reynolds, 1956; Hills, 1958; Turner and Bowden, 1979). Williams and Mc Birney (1968) stated that the phrase cauldron subsidence has been applied to all downdropped blocks enclosed by ring dikes. They recommended restriction of this phrase to ring complexes, or arcuate and circular intrusive bodies produced by erosion of a caldera.

In contrast, Smith and Bailey (1968) suggested that the term cauldron should include all volcanic subsidence structures regardless of shape or size, depth of erosion, or connection with surface volcanism. According to this usage, calderas are a type of cauldron. More recently, Lipman (1984) stated that a distinction between calderas and cauldrons, as defined by Williams and Mc Birney (1968), is not purposeful “because all transitions are present in the examples described.” However, four other papers in the same volume (Hildebrand, 1984; Yoshiida, 1984; Wunderman and Rose, 1984; Elston, 1984) used the term cauldron in their titles.

There is a growing problem with the terminology used for large silicic volcanic collapse structures. One of the focuses of this field excursion is to demonstrate that there are systematic and significant variations in the characteristics expressed by different erosional levels of these systems. Shannon (1988) suggested a new classification scheme which is most compatible with the historic application of the terms caldera and cauldron. He recommended that the phrase volcanoplutonic subsidence system (or structure) be used as the general descriptive phrase for all features produced by collapse of roof rocks into a magma chamber, regardless of shape, size, depth of erosion, structural level, or connection with surface volcanism. The term caldera (similar to Williams and Mc Birney, 1968) is used for a high-level, geomorphic and structural feature related to the volcanic depression produced by collapse into a subvolcanic magma chamber. The term cauldron (similar to Williams and Mc Birney, 1968) is used for the deeper subsurface analog which no longer retains its high-level topographic and structural expression. No distinction in the mechanism of formation is implied and most cauldrons are inferred to have had a related caldera on the surface. Possible exceptions are subterranean cauldron subsidences (Clough et al., 1909; Pitcher, 1978). Ring-dike complexes and ring complexes occur below the volcanic edifice, and differ from cauldrons in that they no longer retain synvolcanic volcanic rocks within the ring structure.

Usage of the terms “caldera” and “cauldron” in describing the three volcanoplutonic complexes covered by this trip follows that used in most of existing literature that covers the three complexes: “caldera” is used for the Questa and Grizzly Peak localities, and “cauldron” is used for the Mount Aetna locality. These usages do not imply that a fundamentally different level of erosion exists at any of the three localities.

Acknowledgments

Michelyn Hass and Paul Dombrowski are thanked for assistance in manuscript preparation and drafting, respectively.

The Latir volcanic field and Questa caldera:
Relations between volcanic and plutonic rocks
July 1–3, 1989
Leader: Clark M. Johnson

Summary

An exceptional cross section is exposed through precaldera and caldera-related volcanic rocks, resurgent plutons, and later intrusions of the Latir volcanic field and Questa

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FIGURE 1—Generalized geologic map of northern New Mexico and southern Colorado in the vicinity of the Rio Grande rift. Our trip focuses on the Latir volcanic field and Questa caldera in northern New Mexico, and the Mount Aetna and Grizzly Peak cauldrons/calderas in southern Colorado.
A caldera. This cross section is largely due to the combination of regional northeast tilting and dissection of the field by the Rio Grande rift (Lipman, 1983; Lipman and Reed, 1984, 1989; Figs. 2, 3). The majority of the precaldera volcanic rocks (28.5–26 Ma) have metaluminous, intermediate compositions, from olivine basaltic andesite (53 wt% SiO₂) to quartz latite (67 wt% SiO₂; Johnson and Lipman, 1988). The earliest rocks also include high-SiO₂ (75–77 wt%) rhyolites that whole-rock and mineral–chemical data indicate have fractionated from intermediate-composition magmas that did not reach the surface.

Inception of alkaline magmatism (alkaline dacite, comendite, and high-SiO₂ peralkaline rhyolite) correlates with initiation of regional extension approximately 26 Ma ago (Lipman, 1983; Hagstrum and Lipman, 1986). The Questa caldera formed 26 Ma ago upon eruption of the >500 km³ (possibly as much as 1000 km³) high-SiO₂ peralkaline Amalia Tuff.

Chemical and isotopic data indicate that all of the precaldera and caldera-related volcanic rocks evolved in an open system by crystal fractionation, magma mixing, and crustal assimilation (Johnson and Lipman, 1988). Probably all precaldera rocks evolved from mantle-derived basaltic magmas; few, if any, represent crustal melts.

Four resurgent plutons (Virgin Canyon, Cañada Pinabete, Rito del Medio, and Cabresto Lake) were emplaced within 1 Ma of caldera formation, possibly within several hundred thousands years (Lipman et al., 1986; Hagstrum and Lipman, 1986). The oldest intrusive unit, the peralkaline granite of the Virgin Canyon and Cañada Pinabete plutons (Figs. 3, 4), has chemical and isotopic compositions that are indistinguishable from those of the early ring-fracture dikes and late-erupted parts of the Amalia Tuff. Phenocryst compositions preserved in the peralkaline granite suggest that the Amalia Tuff magma initially formed from a trace-element–enriched, high-alkali metaluminous magma (Johnson et al., 1989; Czamanske and Dillet, 1988); isotopic data indicate that the parental magmas contained a large crustal component (Johnson and Lipman, 1989). High halogen fluxes from degassing alkali basalts that were injected into the lower part of the magmatic system during regional extension are interpreted as the driving force for establishing silicic peralkaline compositions.

Trace-element-rich metaluminous granites in the Virgin Canyon, Cañada Pinabete, and Rito del Medio plutons were intruded immediately after emplacement of the peralkaline granite; the most mafic metaluminous granites (71 wt% SiO₂) may have compositions that are similar to those of the magmas which were parental to the Amalia Tuff (Johnson et al., 1989). The relatively mafic (monzogranite to granite) Cabresto Lake pluton probably does not represent the compositions that are similar to parental magmas of the more silicic resurgent plutons of Virgin Canyon, Cañada Pinabete, and Rito del Medio.

Intrusions along the southern margin of the Questa caldera include 26–23 Ma granodiorite, syenogranite, and alkali feldspar granite. The two western plutons at Bear Canyon and Sulphur Gulch (Fig. 3) are composed of alkali feldspar granite which contains molybdenite mineralization (Leonardson et al., 1983). The easternmost intrusive complex near the town of Red River is composed of multiple intrusive units that may contain both precaldera and postcaldera rocks.

The youngest plutons of the Latir field are south of the Questa caldera, and include the 22–21 Ma Rio Hondo granodiorite to granite pluton, and the 20–19 Ma Lucero Peak granite pluton. The Lucero Peak pluton contains minor molybdenite mineralization on its eastern margin (Ludington, 1981). These plutons are relatively coarse-grained and were emplaced at deep structural levels, as much as 7 km below the Miocene surface.

Postcaldera volcanic rocks are not preserved in the Sangre de Cristo Mountains. The Amalia Tuff and postcaldera lavas are, however, preserved on an intralift horst (Timber and Brushy Mountains). The Cabresto Lake pluton and southern caldera-margin intrusions are chemically and temporally similar to lower sequence lavas in Timber and Brushy Mountains, and the youngest plutons of Rio Hondo and Lucero Peak are chemically and temporally similar to upper sequence lavas (Thompson et al., 1986; Johnson et al., 1989).

Comparison of mineralogic, chemical, and isotopic data of extrusive and intrusive rocks of the Latir field indicates dramatic differences in the evolution of crystal-poor magmas which erupt as volcanic rocks and crystal-rich magmas that solidify to form plutons, particularly those which form coarse-grained rocks. In contrast to the open-system evolution of the precaldera and caldera-related volcanic rocks, high-level evolution of the plutonic rocks largely involved closed-sys-

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**FIGURE 2**—Stratigraphy of volcanic and plutonic rocks of the Latir volcanic field and younger volcanic and sedimentary units. Silicic resurgent plutons include Virgin Canyon, Cañada Pinabete, and Rito del Medio. Southern caldera-margin intrusions include the Bear Canyon and Sulphur Gulch plutons and Red River intrusive complex. From Johnson et al. (1989).
tem crystal fractionation (Johnson et al., 1989). Coarse-grained plutons do not have isotopic gradients, despite emplacement into Proterozoic crust, indicating that assimilation at high levels in the crust did not occur (Johnson and Lipman, 1989). This contrasts with data from the volcanic rocks, particularly the Amalia Tuff.

Although major-element compositions of both extrusive and intrusive rock suites in the Latir field are broadly similar, and both suites have highly evolved rocks with low Ba and Sr and high Nb, Th, and U contents, highly evolved plutons are markedly depleted in rare-earth-element (REE) contents. Differences in abundance of REE-rich accessory minerals cannot explain these differences, because evolved rocks from both suites contain abundant, early formed accessory minerals such as sphene and apatite. The lower REE contents of the evolved plutonic rocks are instead interpreted as a result of filter-pressing of an evolved magma from a crystal-rich cumulate zone with residual accessory minerals. The relatively elevated REE contents of the volcanic rocks suggest decoupling of major- and accessory-mineral fractionation, and possibly repeated replenishment of the subvolcanic magma chambers (Johnson et al., 1989). The presence of a cumulate-rich zone probably reflects evolution during the waning stages of a magmatic center, when basalt inputs were low. Such a zone probably does not characterize magmatic systems beneath active volcanoes.

FIGURE 3—Generalized geologic map of the Latir volcanic field and the Questa caldera, emphasizing the postcaldera intrusive rocks, LVF, Latir volcanic field and associated intrusions; TM, Timber and Brushy Mountains; SJF, San Juan volcanic field; SLH, San Luis Hills; TPVF, Taos Plateau volcanic field. From Johnson et al. (1989).
First day: Santa Fe to Questa, New Mexico
Assembly point: JAVCEI Meeting, Santa Fe, New Mexico
Departure time: 14:00
Distance: approximately 90 miles
Stops: 1

The northern Rio Grande rift is represented by a series of en-echelon basins. Our route begins in the city of Santa Fe and continues north through the Española Basin to the town of Questa in the southern San Luis Basin. The Española Basin formed 3–7 Ma ago and is flanked by the largely Pliocene to Pleistocene Jemez and Cerros del Rio volcanic fields on the west and Proterozoic rocks in the Sangre de Cristo Mountains on the east (Manley, 1979, 1984; Baldridge, 1979). The Pliocene Taos Plateau volcanic field joins the basin on its northern end, approximately 20 mi north of the town of Española.

The Taos Plateau volcanic field is dominantly composed of tholeiitic mafic- and intermediate-composition lavas and occupies the southern part of the San Luis Basin (Lipman and Mehnert, 1975; Dungan et al., 1986). We will spend a large portion of the trip in the San Luis Basin, which represents the physiographic expression of the Rio Grande rift in northern New Mexico and southern Colorado. The Taos graben, which occupies the southern part of the basin, formed less than 5 Ma ago (Manley, 1984) and has been partially filled with large volumes of younger lavas. This contrasts with the largely sedimentary fill in the Española Basin.

The Taos graben is flanked on both sides by Proterozoic rocks which underlie the Sangre de Cristo and Tusas Moun-

FIGURE 4—Geologic map of the resurgent dome of the Questa caldera. Important units of the silicic resurgent plutons include the peralkaline granite and early and later metaterrigenous granites of Virgin Canyon and Cañada Pinabete, and medium- to coarse-grained, high-SiO₂ granite of Rito del Medio, which is slightly younger. The Cabresto Lake pluton is also related to caldera resurgence, but is petrologically distinct from the three silicic resurgent plutons. Detailed mapping by C. M. Johnson, P. W. Lipman, and J. C. Reed, Jr. Larger-scale mapping from Lipman and Reed (1989).
tains on the east and west sides of the Rio Grande rift, respectively. The Oligocene to Miocene Latir volcanic field occupies a large portion of the Sangre de Cristo Mountains between the town of Taos and the Colorado–New Mexico state line (Fig. 1). A large gravity low is coincident with the Latir volcanic field in the Sangre de Cristo Mountains and its inferred extent in the San Luis Basin, indicating that a large volume of low-density volcanic and plutonic rocks underlie the region (Keller et al., 1984; Cordell et al., 1986).

Mileage

<table>
<thead>
<tr>
<th>Mileage</th>
<th>Description</th>
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<tbody>
<tr>
<td>0</td>
<td>Santa Fe. Travel north on US-84.</td>
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<tr>
<td>27</td>
<td>Junction of US-84 and NM-68. Turn north onto NM-68.</td>
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<tr>
<td>45</td>
<td>Junction of NM-68 and NM-75. Continue north on NM-68.</td>
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<tr>
<td>58</td>
<td>STOP 1-1. View of the Taos Plateau volcanic field from picnic area. The Rio Grande Gorge (cut through the plateau-forming Servilleta Basalt) is directly north. The mountains in the far north are intermediate- and silicic-composition volcanoes of the Taos Plateau volcanic field. Proterozoic rocks and the southern plutons of the Latir volcanic field underlie the Sangre de Cristo Mountains visible on the east (right) side of the rift.</td>
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<tr>
<td>66</td>
<td>Junction of NM-68 and NM-522. Turn north on NM-522.</td>
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<tr>
<td>70</td>
<td>Town of Taos. Continue north through traffic light.</td>
</tr>
<tr>
<td>90</td>
<td>Town of Questa. Dinner and lodging.</td>
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**Second day: Precaldera volcanic rocks to postcaldera mesozonal plutons**

Assembly point: Sangre de Cristo Motel, Junction of NM-522 and NM-38

Departure time: 8:00

Distance: 147 miles

Stops: 13

The second day's route continues north from Questa along the east side of the Rio Grande rift, west of the Sangre de Cristo Mountains. We will examine the precaldera and caldera-related volcanic rocks of the Latir volcanic field, as well as later Miocene lavas and domes and the Pliocene Servilleta Basalt. After returning to Questa in mid-day, we will follow the Red River, which generally follows the southern caldera margin. Much of the mineralization associated with the Questa caldera is localized along the southern margin in the Bear Canyon and Sulphur Gulch plutons. The Red River intrusive complex, near the town of Red River (elev. 2640 m), is farther east on NM-38 (not covered in this road log). The Red River complex contains a complicated sequence of granodiorite, syenogranite, and alkali feldspar granite (26–24 Ma). A road log through the Red River complex and into the Cabresto Creek drainage can be found in Lipman and Reed (1984).

The last section of the second day road log travels south from Questa through progressively deeper portions of the volcanic field to the southern plutons of Rio Hondo and Lucero Peak. This section completes the traverse through a cross section of the field, from surface rocks in the north, to 2–4 km below the Miocene surface near Questa, to 7–8 km below the Miocene surface near Rio Hondo.

**Milestone**

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<td><strong>Town of Questa</strong> (elev. 2260 m). Junction of NM-522 and NM-38. Proceed north on NM-522 toward the town of Costilla. Major drainages to east are Cabresto Creek on the north (bisecting the Cabresto Lake pluton, 25 Ma) and Red River on the south (bisecting the southern caldera-margin plutons, 26–23 Ma). The ridge between Cabresto Creek and Red River is welded intracaldera Amalia Tuff. Alteration scars in general mark weathering of zones of high pyrite and/or zones of rock that are tectonically shattered by low-angle faulting (J. Meyer, pers. comm. 1988). The scar by Questa has low pyrite content, but is highly shattered by low-angle structures (Fig. 5). Guadalupe Mountain, a set of rhyodacite volcanoes (4.8 Ma) of the Taos Plateau volcanic field, may be seen on the northeast.</td>
</tr>
<tr>
<td>3.9</td>
<td><strong>New Mexico Port of Entry.</strong></td>
</tr>
<tr>
<td>6.8</td>
<td><strong>Junction with road to town of El Rito</strong> on right (east). Continue straight. The silicic resurgent plutons of Virgin Canyon, Cañada Pinabete, and Rito del Medio, precaldera volcanic rocks, and Proterozoic rocks occupy the hills directly east.</td>
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<td>16.6</td>
<td><strong>Junction with road to Cedro Canyon</strong> on right (east). Continue straight. The large cliff on the north side of the canyon is welded outflow Amalia Tuff, erupted from the Questa caldera 26 Ma ago (Fig. 6). The Amalia Tuff is underlain successively by alkaline dacite, olivine basaltic andesite, and xenocrystic andesite (lower slopes on the south side). The tuff is overlain conformably by tilted volcaniclastic sedimentary rocks that were eroded from the Latir field (volcaniclastic lower part of the Santa Fe Group), which are in turn overlain unconformably by weakly consolidated gravels consisting of Proterozoic clasts (upper part of the Santa Fe Group). The section is capped by the Servilleta Basalt of the Taos Plateau volcanic field.</td>
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<td>19.4</td>
<td><strong>Town of Costilla</strong> (elev. 2380 m). Junction of NM-196 and NM-522. Turn right (east) on NM-196 to town of Amalia.</td>
</tr>
<tr>
<td>21.4</td>
<td><strong>Cross Costilla Creek.</strong> Surrounding hills capped by Servilleta Basalt.</td>
</tr>
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<td>24.1</td>
<td><strong>STOP 2-1. Outflow Amalia Tuff overlain by Santa Fe Group.</strong> Included in the Santa Fe group are alkali basalt lavas (16 Ma) dipping northeast, interlayered with volcaniclastic sedimentary rocks and capped</td>
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**FIGURE 5—North view, just south of the town of Questa. The prominent hill with the alteration scar on the north side is >1 km of intracaldera Amalia Tuff.**
unconformably by Servilleta Basalt. The high hills directly east on northern side of Costilla Valley are mainly Proterozoic supracrustal rocks. One 8 Ma rhyolite center (elev. 2700–3000 m) intrudes the Proterozoic rocks. Rocks south of the Costilla Valley are mainly precaldera lavas of the Latir volcanic field, indicating that a major dip-slip fault is coincident with the valley. 0.9

25.0 Town of Amalia (elev. 2490 m). As road bends south, we are traveling through alkaline basalts (15 Ma) on north side of road. 2.7

27.7 Precaldera alkaline dacite. Exposed on south. (House addresses: 907–911 NM-196). 1.4

29.1 STOP 2-2. Precaldera augite andesite. Exposed on south. This unit contains abundant reversely zoned, high-Mg and Cr clinopyroxene phenocrysts that are interpreted as indicating late-stage mixing with basaltic magmas (Johnson and Lipman, 1988). 5.0

34.1 Junction with road to Latir Lakes (on south). Continue straight. An optional trip is to drive up Latir Creek (1 mi), turn right (west) up Lemos Creek for 1 mi to outcrops of Amalia Tuff and cognogenic peralkaline rhyolite lavas. 2.1

36.2 STOP 2-3. View of comendite, peralkaline rhyolite, and quartz latite. Carson National Forest Boundary (elev. 2710 m). High hills on south up to Ortiz Peak (elev. 3417 m) are underlain by voluminous comendite lavas and minor ash-flow tuffs that were erupted immediately prior to eruption of the Amalia Tuff (Fig. 7). Peralkaline rhyolite lavas cogenetic with the Amalia Tuff have been faulted down to the lower hills south of the road. Intrusive quartz latite crops out on the north side of the road, surrounded by Proterozoic supracrustal rocks. The intrusions are localized along faults paralleling the Costilla Valley and are cogenetic with voluminous extrusive units exposed in the core of the caldera in the Latir Lakes region (southwest). The quartz latite unit is probably similar to the magmas which were parental to the earliest units in the Latir volcanic field, the early rhyolites (Johnson and Lipman, 1988). The early rhyolite (28 Ma) lavas and ash-flow tuffs crop out in the eastern parts of the Latir volcanic field and include the Tuff of Tetilla Peak (28 Ma). Accessible outcrops include Comanche Point (elev. 2820 m), 2 mi east of Stop 2-3. A road log for the area east of this stop can be found in Lipman and Reed (1984). 11.2

Turn around and travel west on NM-196.

47.4 Town of Amalia. 5.6

53.0 Town of Costilla. Junction of NM-196 and NM-522. Turn left (south) toward Questa. Rhyodacite volcanoes of the Taos Plateau volcanic field are visible south on NM-522, including Ute Mountain (elev. 3094 m) at 2:00 and Guadalupe Mountain at 12:00 (Lipman and Mehnert, 1979). 2.7

55.7 Road to Cedro Canyon on left (east). Continue straight. 0.8

63.7 Milepost 33. North margin of the Questa caldera as marked by peralkaline ring-fracture dike cutting Proterozoic supracrustal rocks along north side of Jaracito Canyon (Fig. 8). The crest of the south slope of Jaracito Canyon is Virsylvia Peak (elev. 3839 m), the highest peak in view, and is part of the intracaldera resurgent uplift. 1.8

65.5 STOP 2-4. View of resurgent dome of the Questa caldera at junction of road to El Rito. Directly east, the silicic resurgent granite of Rito del Medio (Fig. 8) forms the prominent cliffs (top elev. 3170 m) on the north side of Rito del Medio Canyon. Most of this pluton is coarse-grained, high-SiO2 granite that contains abundant miarolitic cavities. Border phases include coarse-grained pegmatites and fine-grained, relatively mafic granite. The highest peak visible directly up Rito del Medio Canyon is Venado Peak (elev. 3881 m). The top of Virsylvia Peak is just visible immediately to the north. Both peaks are capped by precaldera andesite and volcanioclastic sedimentary rocks that are intruded by the Virgin Canyon pluton. The outermost and oldest unit in the Virgin Canyon pluton is peralkaline granite porphyry, which probably grades into the Jaracito Canyon ring-fracture dike. The peralkaline granite is intruded by a relatively mafic metaluminous granite, termed the early metaluminous granite. This is in turn intruded by a more silicic metaluminous granite, termed the later metaluminous granite. The Cañada Pinabete pluton, visible at 2:00 to the south, contains the same intrusive sequence as that exposed in Virgin Canyon (Johnson et al., 1989). 2.9

68.4 STOP 2-5. View of plutons along south margin of the Questa caldera from New Mexico Port of Entry. The Cañada Pinabete pluton occupies the
lower slopes directly east (elev. 2500–3800 m) and is mainly composed of later metaluminous granite, with early metaluminous and peralkaline granite exposed on its north and west margins. Cabresto Peak (elev. 3794 m) is prominent at 11:00 and is primarily precaldera quartz latite intruded by the Virgin Canyon pluton. Pinabeto Peak (elev. 3642 m) lies directly east and is composed of Proterozoic supracrustal rocks on its lower slopes, overlain by precaldera volcanic rocks of the caldera floor. Several kilometers of intracaldera resurgence are required to elevate these rocks relative to the thick intracaldera tuff exposed south of Cabresto Creek (alteration scars at 2:00). A portion of this apparent elevation difference may be related to tilting. Directly south is Flag Mountain (elev. 3641 m), the top of which is composed of Proterozoic plutonic rocks. The lower slopes of the mountain south of Red River comprise the dominant part of the Bear Canyon pluton and mark the southern margin of the Questa caldera. North at 10:30, the Platoro caldera (120 km distant) of the San Juan volcanic field can be seen, along with the intervening San Luis Hills (Oligocene volcanic rocks) within the rift. The Timber and Brushy Mountains horst block is southwest in the center of the rift (behind Guadalupe Mountain), where the only postcaldera Latir lavas are exposed (Thompson et al., 1986). Eroional remnants of the Latir field are found as far as 45 km west in the Tusas Mountains, on the west side of the Rio Grande rift, and merge with distal rocks of the San Juan volcanic field. 3.9

72.3 Town of Questa (elev. 2260 m). Junction of NM-522 and NM-38. Proceed east on NM-38 toward the town of Red River. The conical hill (Goat Hill, elev. 2947 m) directly ahead is altered intracaldera Amalia Tuff that contains lenses of caldera-collapse megabreccia (Fig. 5). The majority of intracaldera tuff has been tilted westerly about a north-northeast axis to nearly vertical. Approximately beneath this hill is the site of the underground Molycorp molybdenum mine. The timbered slope on the south side of Red River is the Bear Canyon pluton, the westernmost of the southern caldera-margin intrusions. The caldera floor near Questa lies beneath the surface (<2200 m). 2.0

74.3 STOP 2-6. Bear Canyon pluton at Eagle Rock campground (elev. 2300 m). This is the north end of the Bear Canyon pluton, which ends immediately north above the cliffs and intrudes intracaldera Amalia Tuff and precaldera andesite. The Bear Canyon pluton is a high-SiO2, mildly porphyritic granite that was intruded along the southern caldera margin 23–25 Ma ago. Subeconemic levels of molybdenite are concentrated in K-alteration zones within precaldera andesites above the aplite roof of the pluton. Drilling indicates that the Bear Canyon pluton connects with the Sulphur Gulch pluton (5 km east) at depth (Leonardson et al., 1983). Hydrogen- and oxygen-isotope data indicate that hot meteoric waters circulated along the southern caldera margin during cooling of the plutons that were in part related to the mineralization (Hagstrum and Johnson, 1986; Johnson and Lipman, 1989). 1.7

76.0 Good exposures of altered, chaotic, andesite caldera-fill on south side of Red River, indicating proximity of the southern caldera wall. 1.3

77.3 STOP 2-7. Rhyolite dike swarm at Columbine Canyon campground (elev. 2400 m). Vertical cliffs (top elev. 2700 m) on north side of road are part of a massive swarm of largely metaluminous, rhyolite porphyry dikes that trend east–west and cut Proterozoic intrusive rocks along the general trend of the south caldera margin (Fig. 9). The northermost dikes cut intracaldera Amalia Tuff and caldera-floor andesite, and some cut the Sulphur Gulch pluton. Low-angle structures with top-to-the-east offsets controlled the emplacement of these northermost dikes (J. Meyer, pers. comm. 1988). Low-angle faulting occurred between the time of caldera formation and cooling of the subvolcanic plutons, and is responsible for the near-vertical tilt of the intracaldera units. Greater than 100% extension has accompanied the faulting in some areas (Meyer, 1988).

The metaluminous dikes are associated with the southern caldera-margin intrusive activity and are not related to earlier caldera collapse or resurgence. Some dikes, however, are peralkaline rhyolite porphyry similar to the Amalia Tuff, indicating minor leakage of Amalia Tuff magma along the southern caldera margin. One peralkaline rhyolite dike that crops out south of the diabase contains pumice that
are flattened parallel to the dike margin; this dike may represent a vesiculating feeder dike to the Amalia Tuff (J. Meyer, pers. comm. 1988). Dark-colored dikes are pre-Mississippian diabase that cut Proterozoic intrusive rocks. Hydrogen- and oxygen-isotope data indicate that meteoric hydrothermal alteration occurred within the Tertiary rocks, as well as Proterozoic rocks (Hagstrum and Johnson, 1986; Johnson and Lipman, 1989). Molybdenum open pit (inactive) behind cliffs to north; the talus spoils are visible east along the road, where they fill Sulphur Gulch (Fig. 9). 1.6

78.9 STOP 2-8. Sulphur Gulch pluton. Ahead is Molybdenum mill. Hydrothermal minerals are similar to those in the Bear Canyon pluton (pyrite, alkali feldspar, fluorite, calcite, and quartz), and are generally restricted to the aplite. Molybdenum mineralization is concentrated along the contact with precaldera andesite within the caldera (Leonardson et al., 1983). The Sulphur Gulch pluton and associated dikes are 23–25 Ma old. Turn around and travel west on NM-38. 6.6

85.5 Town of Questa (elev. 2260 m). Junction of NM-522 and NM-38. Proceed south on NM-522 toward the town of Taos. Pliocene lavas of the Taos Plateau volcanic field can be seen to the west. The extensive flat regions are underlain by the Servilleta Basalt. 3.6

89.1 Road to Red River Fish Hatchery on right. Continue straight. Directly east (900) is Flag Mountain, which is underlain by Proterozoic intrusive rocks. The northern contact of the Rio Hondo pluton lies on the far side (east) of Flag Mountain. The southern contact of the Bear Canyon pluton occurs on the lower slopes (elev. 3000 m), marking the southern boundary of the Questa caldera. 6.2

95.3 STOP 2-9. View of Rio Hondo pluton and dike swarm at junction of road to San Cristobal. High peaks along this part of the Sangre de Cristo Range are, from north to south, Flag Mountain (elev. 3641 m), Lobo Peak (elev. 3693 m), and Gallina Peak (elev. 3318 m), all of which have upper slopes composed of Proterozoic intrusive and supracrustal rocks. The lower slopes (elev. 2500–3400 m) are underlain by granodiorite to granite of the Rio Hondo pluton (21–22 Ma). A massive dike swarm is associated with the Rio Hondo pluton (Reed et al., 1983; Lipman and Reed, 1989); aspen-covered slopes of Gallina Peak are underlain by rhyolite dikes that have completely obliterated the Proterozoic roof rocks of the Rio Hondo pluton. 3.3

98.6 Junction with road to Arroyo Hondo on south side of bridge. Turn left (east). 0.9

99.5 Town of Arroyo Hondo (elev. 2200 m). 3.3

102.8 Junction with NM-230. Turn left (north) toward town of Valdez. 0.7

103.5 Junction with east—west dirt road at edge of Rio Hondo Canyon. Turn right (east) and follow along southern rim of Rio Hondo Canyon. Town of Valdez in canyon bottom to the north. Note 60–120 m of dissection of the alluvial fans. 1.3

104.8 Junction with NM-150 at canyon edge. Continue straight (east), down canyon side. 1.0

105.8 Cross bridge over Rio Hondo (elev. 2320 m). 1.3

107.1 STOP 2-10. Highly sheared western margin of Rio Hondo pluton (21–22 Ma). Structural reconstruction indicates that we are 7–8 km below the Miocene surface. The majority of the Rio Hondo pluton is composed of granodiorite (64–70 wt% SiO2). The deepest exposed parts of the Rio Hondo pluton occur in Hondo Canyon. Only the upper and northern parts of the Rio Hondo pluton contain granite (up to 78 wt% SiO2). Hydrogen- and oxygen-isotope data indicate that widespread circulation of hot meteoric waters occurred during late-stage solidification of the pluton; hydrothermal circulation was dominantly concentrated along fractures zones that developed during deformation of the pluton on its margins (Fig. 10; Hagstrum and Johnson, 1986; Johnson and Lipman, 1989). 1.2

108.3 STOP 2-11. Mafic inclusions in Rio Hondo pluton. Pull out left and right past prominent outcrop on left (north). Mafic inclusion-rich, compositionally heterogeneous zones, as shown in this outcrop, are common in the lower parts of the Rio Hondo.
pluton (Fig. 11). Textural relations and chemical compositions of the coarse-grained inclusions suggest that they represent fragments of cognate mafic cumulates disrupted from the bottom of the Rio Hondo magma chamber (Johnson et al., 1989). Large volumes of hydrothermal fluids circulated through the highly fractured granodiorite at this outcrop, resulting in partial recrystallization of quartz; relatively massive granodiorite 0.2 km east of this outcrop has not undergone significant hydrothermal alteration. 1.5

109.8 Tertiary rhyolite dikes cutting Proterozoic amphibolite are exposed on north side of road as it curves left at Taos East Condominiums. 0.9

110.7 STOP 2-12. Rhyolite dikes of Rio Hondo pluton. Pull off 0.1 mi past outcrop as road curves left. Outcrops of rhyolite dikes can be traced up the canyon walls. The younger Lucero Peak pluton (21–19 Ma) crops out on the southern, upper slopes of Hondo Canyon. The Lucero Peak pluton does not cut the Rio Hondo pluton and is not cut by the Rio Hondo dike swarm. Turn around and travel west on NM-230. 4.9

115.6 Cross Rio Hondo Bridge. 1.0
116.6 Follow paved road as it turns left (south) to town of Arroyo Seco. 1.3

117.9 Town of Arroyo Seco (elev. 2330 m). Follow road as it turns right (west). 1.9

119.8 Junction with NM-230. Stay left (south). 2.1

121.9 STOP 2-13. View of Lucero Peak pluton from Stewart’s Studio. Directly east is the rounded top of Lucero Peak (elev. 3301 m). The rounded shape follows the pegmatite- and aplite-rich roof zone of the Lucero Peak pluton (Fig. 12). Proterozoic rocks underlie the highest terrain, including Wheeler Peak (elev. 4012 m, the highest point in New Mexico), which is behind Lucero Peak from this view. Pueblo Peak (elev. 3750 m) is seen south of Arroyo Seco canyon (occupying the prominent canyon south of Lucero Peak). This is a sacred mountain of the Taos Pueblo, and has not been mapped since 1920. It is presumably underlain largely by Proterozoic rocks, although the Lucero Peak pluton extends south of Arroyo Seco canyon for an unknown distance. 0.5

122.4 Junction of NM-150 with US-64/NM-522. Turn left (south) onto US-64/NM-522 toward the town of Taos. 2.3

124.7 Town of El Prado. Continue into the town of Taos. 1.9

126.6 Junction of US-64 and NM-522 in the town of Taos (traffic light). Following dinner in Taos, return to Questa by following NM-522 north. 20.0

146.6 Town of Questa (elev. 2260 m).

Third day: Silicic resurgent plutons of Rito del Medio and Virgin Canyon, and regional geology to Alamosa, Colorado

Assembly point: Sangre de Cristo Motel, Junction of NM-522 and NM-38
Departure time: 8:00
Distance: approximately 9 miles of hiking and 95 miles by vehicle
Stops: 2

Today's route involves a hike through the eroded resurgent dome of the Questa Caldera to examine the magmas that were present in the subcaldera magma chamber immediately following eruption of the Amalia Tuff. We will be hiking for most of the day, from approximately 2400 to 3600 m elevation. Bring plenty of water (stream waters contain giardia and should not be drunk) and a rain coat. Following the hike, we will travel by vehicle north past the northern margin of the Latir field (near the town of Costilla). Farther north, the Sangre de Cristo Mountains are almost exclusively underlain by Pennsylvanian, Permian, and Proterozoic rocks. Blanca Peak (elev. 4372 m), for example, dominates the skyline during our travel north to the town of Fort Garland. The town of San Luis (the oldest town in Colorado, established in 1851) lies near the northern end of the Taos Plateau volcanic field. Directly west of the town of San Luis are the alkaline and tholeiitic lavas of the San Luis Hills, which make up the northernmost exposed intrarift horst in the San Luis Basin. As is typical of the Timber...
and Brushy Mountains horst block farther south, the early rift San Luis lavas are not tilted, in contrast to younger lavas along the flanks of the Rio Grande rift. A gravity high is centered on the San Luis Hills horst, and extension of this high north of the town of Alamosa indicates (in addition to drilling data) that this horst system extends most of the length of the basin (Tweto, 1979a; Keller et al., 1984). Neogene maﬁc lavas within, and on the flanks of, the basin generally become more alkaline northward, possibly reﬂecting increasing crustal thickness (Lipman, 1969; Lipman and Meinert, 1975).

Mileage

0.0 Town of Questa (elev. 2260 m). Junction of NM-522 and NM-38. Proceed by vehicle north on NM-522. 3.9

3.9 New Mexico Port of Entry. 2.9

6.8 Junction with road to El Rito. Turn right (east) and drive 1.0 mi to sharp left at town of El Rito (elev. 2448 m). Turn left onto dirt road, drive approximately 0.5 mi to ﬁrst right that continues up (east) alluvial fan. Turn right (east) and drive as far as possible (0.5–1.0 mi, elev. 2500 m, depending on extent of private development). Park vehicles.

Hike dirt road up alluvial fan (east) 0.2–0.5 mi to prominent north–south dirt road following cliffs (elev. 2620 m). Walk south on road for approximately 0.5 mi until directly west of prominent cliffs of Rito del Medio granite. You have gone too far if you have crossed Rito del Medio Creek, which runs year-round.

0.0 Start hike at National Forest Service marker indicating trail to Latir Wilderness. Trail follows north side of Rito del Medio Creek once adjacent to prominent granite cliffs. Hike 0.8 mi to prominent granite cliffs of Rito del Medio granite. 0.8

0.8 STOP 3-1. Rito del Medio pluton (trail elev. 2900 m). Most of the Rito del Medio pluton consists of coarse-grained granite (76 wt% SiO₂) that is texturally similar to the coarser parts of the Cañada Pinabete pluton to the southwest. The Rito del Medio granite is considered to be a late-stage differentiate of the metaluminous granite of the Virgin Canyon and Cañada Pinabete plutons. The roof of the Rito del Medio pluton is at the top of the cliffs 270 m above, and is locally more maﬁc and ﬁne-grained, commonly associated with feldspar–quartz pegmatites and unidirectional solidiﬁcation textures. The pluton intrudes Proterozoic supracrustal rocks and precaldera volcanic rocks at high structural levels. Paleomagnetic data show that the Rito del Medio pluton is not tilted, in contrast to the Virgin Canyon pluton farther east, indicating that it is the youngest of the three silicic resurgent plutons (Hagstrum and Lipman, 1986).

The Rito del Medio granite is composed almost entirely of alkali feldspar and quartz, with minor biotite and plagioclase. A notable feature of the pluton is the occurrence of primary muscovite and hematite, which is interpreted as indicating loss of alkalies by late-stage volatile exsolution at relatively high oxygen fugacities (Dillett and Czarnanske, 1987).

Miarolitic cavities as large as 6 cm are common throughout the pluton, although the largest cavities are restricted to the interior of the pluton (Fig. 4). This may reﬂect inward crystallization and volatile saturation in the core. Cavities comprise up to 4.2 vol% of the granite. The cavities are partially ﬁlled with euhedral quartz, alkali feldspar, magnetite, hematite, muscovite, and ﬂuorite, indicating late-stage exsolution of a volatile-rich silicate ﬂuid during crystallization.

Continue up trail on north side of Rito del Medio Creek. Trail is steep for next 0.4 mi, then ﬂattens for 1.0 mi. 1.4

2.2 Junction with abandoned north–south logging road (elev. 3230 m). Turn right (south), and cross Rito del Medio Creek. Continue up (east) Rito del Medio Creek on south side. Cabresto Peak lies immediately south (elev. 3794 m) and is underlain by precaldera quartz latite on its upper part, indicating that the caldera ﬂoor is at elevations greater than 3800 m in this part of the resurgent dome. The break in slope on the west side of Cabresto Peak (elev. 3470 m) marks the Proterozoic–Tertiary unconformity. The roof of the Rito del Medio pluton on the south side of Rito del Medio Creek lies on the timbered shoulder west of this point (elev. 3350 m). Several trails follow the Rito del Medio Creek; the easiest are just above the creek gully, although they may be difﬁcult to ﬁnd. Following the creek gully is also possible. 1.0

3.2 STOP 3-2. Virgin Canyon pluton. Open meadow between Cabresto and Venado Peaks (elev. 3500 m). This cirque is at the base of Virgin Canyon (upstream to the east), and is in the southern part of the Virgin Canyon pluton. The southern cirque wall is entirely composed of precaldera quartz latite more than 300 m thick, which is intruded by peralkaline granite (25 Ma) of the Virgin Canyon pluton. The peralkaline granite is well exposed on the low ridge to the west at 3540 m (extreme northern ﬂank of Cabresto Peak), as well as high on the western ﬂank of Venado Peak (east of the meadow, elev. 3881 m) at 3690 m, where the granite intrudes precaldera andesite. The eroded caldera ﬂoor is probably at elevations greater than 4000 m in this part of the resurgent dome, indicating that possibly more than 2 km of the resurgence has occurred relative to the southern part of the caldera, near the range front at Goat Hill.

The peralkaline granite margin of the Virgin Canyon pluton varies from a few meters thick on the north side of Cabresto Peak, to approximately 30 m thick on the west side of Venado Peak. The peralkaline granite is at least 50 m thick on Virsylvia Peak (East Virsylvia Peak elev. 3839 m, West Virsylvia Peak elev. 3819 m), visible directly north. The peralkaline granite is intruded in both the Virgin Canyon and Cañada Pinabete plutons by a distinctive, more maﬁc (71–74 wt% SiO₂), metaluminous granite termed the early metaluminous granite. The early metaluminous granite is intruded in both plutons by a generally more silicic (75–78 wt% SiO₂) equigranular granite termed the later metaluminous granite (Fig. 13), which typically contains miarolitic cavities. The consistent sequence of these three units in the Cañada Pinabete and Virgin Canyon
plutons and the correlation of the Rito del Medio granite with the Cañada Pinabete pluton indicate that the units are not volumetrically small, isolated bodies, but large volumes of magma which underlay most of the resurgent dome of the Questa caldera.

Unlike the southern caldera-margin intrusions and the southern plutons of Rio Hondo and Lucero Peak, meteoric hydrothermal alteration of the resurgent plutons is minimal (Johnson and Lipman, 1989). This is interpreted to be a result of rapid cooling of the relatively fine-grained silicic resurgent intrusions.

Parts of the Virgin Canyon pluton have been tilted during major structural disruption which occurred immediately after caldera formation 26 Ma ago (Hagstrum and Lipman, 1986). The peralkaline granite continues the chemical and mineralogical trends of the Amalia Tuff, and is interpreted as the solidified remnants of the Amalia Tuff magma. Reflex biotite and calcic amphibole in the peralkaline granite suggest that the granite evolved from a metaluminous parental magma, possibly associated with high halogen fluxes and accompanying alkali enrichment (Czamanske and Diliet, 1988; Johnson et al., 1989). The early metaluminous granite in Virgin Canyon and Cañada Pinabete was probably derived by crystal fractionation of the early metaluminous granite, and continued fractionation likely produced the Rito del Medio granite. The Cabresto Lake pluton crops out south of Virgin Canyon and is the most mafic resurgent pluton. Chemical and isotopic data suggest, however, that the Cabresto Lake granite and monzogranite do not represent parental magmas to the more silicic resurgent plutons of Virgin Canyon, Cañada Pinabete, and Rito del Medio (Johnson et al., 1989).

Turn around and follow the Rito del Medio Creek trail west.

6.4 National Forest Service marker. Turn right on north–south dirt road and return to vehicles parked to the northwest (approximately 0.7–1.0 mi). Return to town of El Rito (1.0–1.5 mi southwest). Turn right (west) at pavement and travel 1.0 mi to NM-522. 3.6

10 Junction of El Rito road and NM-522. Turn right (north) toward Colorado. 13

23 Town of Costilla. Continue north on NM-522. 4

27 Enter Colorado. NM-522 becomes CO-159. 18

45 Town of San Luis, Colorado. Break for dinner. 16

61 Junction of CO-159 and US-160 at town of Fort Garland. Turn left (west) onto US-160 toward Alamosa. 25

86 Town of Alamosa. Overnight lodging.

The Mount Aetna cauldron:
Structures in deeply eroded ring zones
July 4–5, 1989
Leader: James R. Shannon

Summary
The Mount Aetna cauldron complex (Shannon, 1988), in the Sawatch Range, central Colorado (Fig. 14), consists of three main elements: (1) the 36.6 Ma Mount Princeton pluton, (2) the 34.4 Ma Mount Aetna cauldron, and (3) the 29.8 Ma, chemically evolved A-type granites (Fig. 15). These three elements represent the major Tertiary magmatic events in the south-central Sawatch Range. They occurred during a fundamental change from Laramide magmatism and compressional tectonism during the early Tertiary to Rio Grande rift-related magmatism and extensional tectonism during the middle Tertiary to Recent (Shannon et al., 1987a). The Mount Princeton pluton and Mount Aetna cauldron, together with the Bonanza and Grizzly Peak calderas (Fig. 14), represent different erosional and structural levels of volcanoplutonic subsidence systems.

The Mount Princeton pluton is an elliptical (24 × 34 km), compositionally and texturally zoned, flat-topped pluton. Compositional (granodiorite, quartz monzonite, and granite/plitite) and textural zonations in the roof-zone border unit of the pluton are interpreted as the complex record of crystallization during numerous volcanic ventings. A correlation between the low-silica rhyolite Wall Mountain Tuff (Epis and Chapin, 1974) of the ThirtyNine Mile volcanic field, east of the Rio Grande rift (Fig. 14), and the Mount Princeton pluton is suggested based on spatial relations and similar ages (Shannon, 1988). The Mount Princeton pluton was breached by erosion prior to collapse of the Mount Aetna cauldron, for which it provided a relatively uniform, massive-textured, and structurally isotropic host. The Mount Princeton pluton is interpreted to represent the plutonic roots of a caldera in which all evidence of the volcanic edifice and collapse structure has been completely removed by erosion.

The Mount Aetna cauldron consists of two collapse structures: a 13 × 27 km elliptical main cauldron and a nested, northern cauldron 12 km in diameter (Fig. 15). A 0.5 km thick sequence of gently south-dipping precollapse volcanic
rocks and syncollapse intracauldron tuff and megabreccia are preserved in the southern part of the main structure. The Mount Aetna intracauldron tuff is correlated with the Badger Creek Tuff (Epis and Chapin, 1974) of the Thirtynine Mile volcanic field (Fig. 14) and an intrusive tuff dike (Fig. 15) based upon spatial associations, similar ages, mineralogy, and chemistry (Shannon et al., 1988; Shannon, 1988). All are pheno-andesites (IUGS classification) and have rhyodacitic compositions. The above intracauldron features, as well as the outflow-sheet remnants clearly establish the Mount Aetna center as a classic example of the roots of an ash-flow caldera. All of the northern part of the cauldron, however, is eroded to a structural level below both caldera fill and precollapse lavas. This northern part has the features of a ring-dike complex: the cauldron structure is manifested as a system of ring shears and ring intrusions cutting across the Mount Princeton pluton country rocks. The caldera (cauldron) blocks that subsided into the Mount Aetna magma chamber collapsed as coherent units; they consisted of a minimum of 2 km thickness of Mount Princeton country rocks.

The Mount Aetna cauldron provides a rare opportunity to characterize ring-zone features at a relatively deep erosion level (Shannon and Epis, 1987; Shannon, 1988). The collapse structures are delineated by the distribution of five ring-zone features which are present in zones from 20 to 300 m wide. In general paragenetic sequence, these features are: (1) brittle–ductile ring shear, (2) microbreccias, (3) flinty crush rock, (4) intrusive breccias, and (5) ring dikes. The distribution and crosscutting relations of the various ring-zone features indicate at least two main collapse–resurgence cycles; the first related to the main cauldron and the second related to the northern cauldron. Collapse–resurgence cycles are defined as paired collapse and resurgence events (Shannon, 1988).

Collapse of the main cauldron formed dominantly outward-dipping (60°–80°) ring shear zones (Figs. 16, 17). The minerals in these shear zones were deformed by both brittle (feldspars) and ductile (quartz) processes. The resultant proto-and orthomylonite textures typically display S–C fabrics (Simpson and Schmidt, 1983). The initial ring shears exerted a strong structural control on subsequent ring-zone activity; the later-formed ring-zone features follow these initial shears in distribution and orientation. Thin seams of microbreccia were injected along the C-surfaces after ductile shearing. The change from ductile to brittle deformation may be related to rapid and fluctuating changes in strain rate during cauldron collapse.

Flinty crush rock, first described at the Glen Coe cauldron in Scotland (Clough et al., 1909) is present at a number of localities around the main collapse structure (Fig. 16a). It is a microfragmental intrusive rock resembling pseudota-
chylite and is present along the margins of ring dikes and as thin, irregular, discontinuous seams in the wall rocks (Figs. 17, 18). Flinty crush rock crosscuts ductile shears and is crosscut by the ring dikes. It is interpreted as a hybrid mixture of phryic magma and microbreccia and may represent the subtle remnants of conduits of ignimbrite vents along the ring zone (Shannon, 1988).

Dike-like bodies (0.5 cm–100 m) of intrusive breccia are common along the western, northwestern, and northern portions of the main collapse structure. They are matrix-supported and contain sub-rounded clasts of wall rock in a clastic, hydrothermally altered matrix. Rarely, the intrusive breccias are physically mixed with early ring-dike material. They are interpreted to have formed largely by fluidized flow in a medium of venting volcanic gas (and/or by phreatomagmatic processes) along the ring zone.

There are three textural varieties of porphyritic rhyodacitic to quartz monzonitic ring dikes. Type 1 dikes are fine-phenoocryst porphyritic rhyodacite which occurs as thin selvages on later ring dikes, as thin dikesets, and as mixtures with intrusive breccias. These dikes are considered to be relatively early, intruded during or after collapse of the main cauldron, but prior to resurgence of the main cauldron. Type 2 ring dikes are very coarse-phenoocryst porphyritic quartz monzonite. They are preferentially developed around the southern portion of the main cauldron and are continuous with an asymmetric (i.e., off-center) resurgent intrusion which cuts intracauldron tuff and microbreccia (Fig. 15). Type 2 dikes are interpreted to represent a magmatic resurgence event following collapse of the main cauldron.

Type-3 ring dikes are medium-phenocryst rhyodacite and are preferentially developed around the northern cauldron, but were also locally intruded along the (reactivated) main cauldron boundary. Type-3 ring dikes are interpreted as related to a magmatic resurgence event following collapse of the northern cauldron. This magmatic resurgence was also expressed by preferential uplift of the northern cauldron block (restored nearly to its original level). The remaining portion of the main cauldron block (i.e., the southern part) was apparently tilted to the south during this resurgence event.

Intrusive tuff dikes are present approximately 5 km outside of the northwestern ring zone (Figs. 15, 19). They are in cone-sheet orientation and cut Precambrian country rocks (Fig. 16b). The intrusive tuff dikes are interpreted to represent the conduits to ignimbrite eruptions (of Badger Creek Tuff) on the surface (Shannon et al., 1988; Shannon, 1988). These observations suggest that some tuff may be vented from cone-sheet-oriented structures outside of the main ring zone, and that at deep erosional levels vitroclastic textures
FIGURE 16—Distribution and orientation of brittle-ductile ring shears and flinty crush rock related to the main (a) and northern (b) cauldron ring zones, Mount Aetna cauldron, Colorado. From Shannon (1988).
related to explosive venting of tuff are more likely to be preserved in that distal setting in contrast to the main, highly dynamic ring zone.

Microstylolites are present in two different settings associated with the Mount Aetna cauldron (Shannon and Nelson, 1987; Shannon, 1988). They are not considered to be an integral ring-zone feature, but are particularly well developed in the ring zone of the northern collapse structure. The microstylolites are interpreted to be the result of hydrothermal pressure solution of crystalline silicate rocks (Shannon, 1988). They are present in flinty crush rock, intrusive breccia, ring dikes, and sheared wall rocks, and are interpreted as formed during the resurge of the northern cauldron block.

The occurrence of ductile shearing at the subvolcanic level (as shallow as 1–3 km) at Mount Aetna is probably related to the large thermal anomaly around the subcaldera magma chamber and to the capacity of the ring zones to act as thermal conduits once they form (Shannon and Epis, 1987; Shannon, 1988). Ductile-deformation processes may also be enhanced by hydrolytic weakening (Griggs, 1967; Yund and Tullis, 1980) related to the mechanical breakdown of hydrous minerals (biotite and hornblende) or introduction of meteoric and/or magmatic water into the ring zone (Shannon, 1988). S–C surfaces in the ring shear zones dominantly yield a sense of shear indicating the caldera (cauldron) blocks went down (Fig. 16a). In addition, ductile-deformation processes were apparently not active, or of minimal importance, during the resurgence stage of each collapse–resurgence cycle.

Following caldera formation by about 4 Ma, the Mount Aetna area was the site of renewed magmatic activity associated with the shift to an active extensional tectonic setting (Shannon et al., 1987a). Topaz rhyolites (Nathrop topaz rhyolites) and chemically evolved A-type (anorogenic) granite and rhyolite intrusions (Mount Aetna granites) are present in a 36 km long, N50E-trending belt which is, in part, coincident with the southeastern margin of the Mount Aetna cauldron (Fig. 15). These rocks, together with granites associated with Climax-type porphyry Mo deposits represent a subgroup of A-type granites (distinguished by trace-element signatures) that is associated with the Rio Grande rift province in Colorado (Shannon et al., 1987b; Shannon, 1988).

Faulting related to development of the upper Arkansas axial graben segment of the Rio Grande rift began at about 28–29 Ma (Tweto, 1979b; Shannon et al., 1987a; Shannon, 1988). Formation of the graben was also associated with asymmetric uplift of the western Sawatch Range marginal-block uplift (Figs. 14, 20). This resulted in relatively deep erosion of the Mount Aetna cauldron complex in the Sawatch Range, in contrast to the Mosquito Range (eastern marginal block uplift) which retains remnants of outflow ash-flow tuff from the inferred Mount Princeton caldera (Wall Mountain Tuff) and the Mount Aetna cauldron (Badger Creek Tuff), and extrusive topaz rhyolites (Nathrop topaz rhyolites).

**Fourth day: Alamosa to Buena Vista, Colorado, and the Mount Aetna cauldron**

- **Assembly point:** Alamosa
- **Departure time:** 7:00
- **Distance:** 182 miles
- **Stops:** 6

Our route traverses the eastern flanks of the San Juan volcanic field and continues north into the Sawatch Range. The Platoro caldera (30 Ma), the oldest and southernmost
caldera of the San Juan volcanic field (Steven and Lipman, 1976) can be seen at 9:00 (southwest) during the drive between the towns of Alamosa and Monte Vista. Farther north, the low hills directly west of the highway are the eroded remnants of the intermediate-composition Summer Coon volcano, which is several million years older than the Platoro caldera.

The route turns east at the town of Saguache, then curves north and skirts the eastern side of the Bonanza caldera (36 Ma) and associated volcanic rocks at the northern end of the San Luis Basin (Varga and Smith, 1984). Although the Bonanza caldera has been previously grouped with the San Juan volcanic field, its close temporal and spatial relations with the older Mount Aetna and Grizzly Peak calderas suggest that it is more appropriately grouped with the Sawatch Range calderas (Fig. 14). While traveling north of the town of Villa Grove, the high peaks (Mt. Shavano, Mt. Princeton) of the Sawatch Range can be seen to the north over Poncha Pass. Along the east side of the upper Arkansas Valley, the mid-Tertiary ash-flow tuffs of the ThirtyNine Mile volcanic field overlies Permian, Pennsylvanian, and Proterozoic rocks in the southern Mosquito Range. The Mount Aetna caldera and Mount Princeton pluton are emplaced into Proterozoic rocks in the Sawatch Range, and these can be seen to the west.

The relationship of the Mount Aetna caldera to the older Mount Princeton pluton, the ThirtyNine Mile volcanic field, the Eocene–Oligocene erosion surface, and the Rio Grande rift will first be discussed, followed by examination of a variety of ring-zone features (brittle–ductile ring shears, flinty crush rock, microbreccias, ring dikes and microstrolites) near St. Elmo.

### Mileage

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<thead>
<tr>
<th>Mileage</th>
<th>Event</th>
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<tr>
<td>85</td>
<td><strong>Poncha Pass</strong> (elev. 2750 m).</td>
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<tr>
<td>118</td>
<td><strong>Town of Buena Vista</strong> (elev. 2425 m). Brief rest/coffee stop. Travel south on US-24.</td>
<td>2</td>
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<td>120</td>
<td><strong>Junction of US-285 and US-24.</strong> Johnson Village. Turn left (east) on US-285. After approximately 2.1 mi, turn left (north) to scenic overview.</td>
<td>2.1</td>
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<tr>
<td>122.3</td>
<td><strong>STOP 4-1. Overview of regional geologic and tectonic setting of the Mount Aetna caldera and vicinity</strong> (Figs. 14, 15). The timing of magmatic and tectonic events in the Sawatch Range and extreme northern Rio Grande rift are summarized in Table 1. The Wall Mountain Tuff and Badger Creek Tuff are preserved as valley fill on the Eocene–Oligocene erosion surface (Epis and Chapin, 1975) on Triad Ridge, to the southeast. The Badger Creek Tuff has been correlated with the Mount Aetna intracaldera tuff based upon spatial associations and similarities in chemistry, mineralogy, and age determinations. Turn around and drive west on US-285.</td>
<td>2.2</td>
</tr>
<tr>
<td>124.5</td>
<td><strong>Junction of US-285 and US-24.</strong> Johnson Village.</td>
<td>5.8</td>
</tr>
<tr>
<td>130.3</td>
<td><strong>Junction of US-285 and CO-162.</strong> Town of Nathrop. Turn right (west) on CO-162 (Chalk Creek Road). Route enters the Sawatch Range and crosses the Mount Aetna caldera (Fig. 16).</td>
<td>4.6</td>
</tr>
<tr>
<td>134.9</td>
<td><strong>Mount Princeton Hot Springs.</strong></td>
<td>11.2</td>
</tr>
<tr>
<td>146.1</td>
<td><strong>Junction of CO-162 and Hancock Road.</strong> Turn left (south) on Hancock Road. Route follows upper Chalk Creek along the western caldera margin.</td>
<td>5.6</td>
</tr>
<tr>
<td>151.7</td>
<td><strong>STOP 4-2. Overview of the Mount Aetna intracaldera volcanic rocks.</strong> The Mount Aetna caldera is one of the most deeply eroded collapse structures which still retains some of the classic features typically associated with higher-level caldera systems. The precollapse lavas of the Mount Aetna caldera mark the floor of the caldera, upon which the intracaldera Badger Creek Tuff and multilithic megabreccias were deposited. Ring-zone features (e.g., ring shears, flinty crush rock, microbreccias, and ring dikes) in the south are developed in a zone separating intracaldera volcanic rocks, including megabreccias, from the Mount Princeton quartz monzonite. The remainder of the day will concentrate on the parts of the ring zone, caldera, and Mount Princeton pluton that are below the level of the caldera floor. Turn around and drive north on Hancock Road.</td>
<td>5.7</td>
</tr>
</tbody>
</table>
| 157.4 | **STOP 4-3. Ring shear in caldera block.** Saint Elmo at junction with Hancock Road. Park in pull-out on south side of CO-162 just east of CO-162.

### Table 1—Summary of events and timing in the Sawatch Range, central Colorado.

<table>
<thead>
<tr>
<th>Event</th>
<th>Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sawatch uplift</td>
<td>Laramide to 45 Ma</td>
</tr>
<tr>
<td>Eocene–Oligocene erosion surface</td>
<td>&gt;36 Ma</td>
</tr>
<tr>
<td>Mount Princeton pluton/Wall Mtn. Tuff</td>
<td>36.6 Ma</td>
</tr>
<tr>
<td>Bonanza caldera</td>
<td>36 Ma</td>
</tr>
<tr>
<td>Mount Aetna caldera/Badger Creek Tuff</td>
<td>34.4 Ma</td>
</tr>
<tr>
<td>Grizzly Peak caldera</td>
<td>34 Ma</td>
</tr>
<tr>
<td>Evolved granites and rhyolites</td>
<td>29–30 Ma</td>
</tr>
<tr>
<td>Beginning Rio Grande rift faulting</td>
<td>28–29 Ma</td>
</tr>
<tr>
<td>Opening of upper Arkansas graben</td>
<td>&lt;28 Ma</td>
</tr>
<tr>
<td>Uplift of Sawatch Range block</td>
<td>&lt;20 Ma</td>
</tr>
</tbody>
</table>
Hancock Road intersection. Outcrops on south and north side of CO-162 (west of parking area) show that a subtle but continuous ring shear is developed in the caldera block approximately 0.75 km inside of the main ring zone. A narrow (<1.0 m), steeply outward-dipping zone of brittle–ductile shearing and intrusive breccia cuts Mount Princeton quartz monzonite. A short distance to the north, the Mount Princeton quartz monzonite is unaffected by ring shearing and is typical of the caldera block far from the ring zone. These relations indicate that the caldera block collapsed as an essentially coherent unit with little or no internal disruption. Drive west on CO-162 to town of Saint Elmo. 0.2

157.6 Saint Elmo. 0.4

158.0 STOP 4-4. Northern ring zone. Turn right (north) and then left (west) on Tincup Pass Road. Park at Poplar Gulch trailhead. Hike approximately 0.5 km to landslide, then up scree slope to base of cliffs.

The most accessible outcrop that displays many of the ring features is at this stop (Fig. 21). The important relations to observe are the outward inclinations of all ring-zone features and their cross-cutting relation (Figs. 17, 18). All ring features at this stop dip outward at angles ranging from approximately 30 to 80°.

In general, ring shears have well developed S–C fabrics. Fig 16 (a, b) shows that S–C fabrics in ring shears around the main collapse structure indicate that the caldera block has been faulted down. The occurrence of ductile deformation at depths as shallow as 1–3 km is highly unusual. This is probably related to heating of the ring zone, possibly assisted by hydrolastic weakening.

Flinty crush rock was first described from the Glen Coe caldera in Scotland (Clough et al., 1909) and is present in the ring zone around the main collapse structure of the Mount Aetna caldron (Fig. 16a). Based on observations at Mount Aetna, a new mechanism of formation for flinty crush rock is suggested, involving injection of phytic magma with a cataclastic component during ring shearing. Flinty crush rock may represent the subtle remnants of magmatic venting from the ring zone during caldera collapse.

Two varieties of ring dike are present at this stop: evidence (non-fragmental textures) suggests that non-explosive, forceful emplacement of the majority of ring dikes occurred during magmatic resurgence stages. Chlorite microstylolites in the flinty crush rock and ring dikes are important because they indicate pressure solution of silicate minerals by the action of hydrothermal fluids. They crosscut all ring-zone features and are interpreted to have formed during resurgence of the northern caldron block. Return to Saint Elmo. 0.4

Saint Elmo. (drive east on CO-162). 8.3

166.7 Junction of CO-162 and Quarry Road. Turn north (left) on Quarry Road. 0.3

167.0 STOP 4-5. Cauldron block of Mount Princeton quartz monzonite. The younger structures and porphyritic rhyolite dikes related to northern Rio Grande rift tectonism and magmatism are well exposed here. The high-angle, brittle, rift-related faults with associated zeolitic alteration contrast with the brittle–ductile ring shears in terms of the style of deformation.

Porphyritic, high-SiO₂ rhyolite dikes contain microphenocrysts of garnet and have high incompatible-element (Rb, Nb) contents. They, together with lamprophyre (kersantite and spessartite) dikes, represent a rift-related, bimodal, magmatic association. Turn around and return to CO-162. 0.3

167.3 Junction of CO-162 and Quarry Road. Turn east on CO-162. 3.8

171.1 Mount Princeton Hot Springs and junction of CO-162 and CO-321. Turn north (left) on CO-321. 0.7

171.8 STOP 4-6. Overview of southern Mosquito Range and extreme northern Rio Grande rift. Pull over at turnout at sharp 180° turn. This stop provides an overview of major tectonic elements in an opposite view from that of Stop 4-1. The Eocene–Oligocene erosion surface that preserves remnants of outflow Wall Mountain Tuff and Badger Creek Tuff and extensive topaz rhyolites represents a geologic datum that was disrupted by the younger Rio Grande rift. The relation between ignimbrite calderas/cauldrons and continental rifts will be explored using the relation of the Sawatch Range calderas/cauldrons and the northern Rio Grande rift. 9.8

181.6 Town of Buena Vista (elev. 2425 m).

Fifth day: Northern ring zone of the Mount Aetna cauldron

Assembly point: Buena Vista
Departure time: 8:00
Distance: Approximately 35 vehicle miles and 5 hiking miles
Stops: 4

This section concentrates on ring-zone features (brittle–ductile ring shears, intrusive breccias, ring dikes) exposed in the northern ring zone on Sheep Mountain. We will also examine an intrusive tuff dike in Grassy Gulch, which provides compelling evidence for an ignimbrite vent.

Mileage

0.0 Town of Buena Vista (elev. 2425 m). Junction of US-24 and CO-306. Travel west on CO-306. 7.1
7.1 Junction of CO-306 and CO-344. Travel south on CO-344 (South Cottonwood Creek Road). 3.3

10.4 STOP 5-1. Overview of the Mount Aetna cauldron and northern ring zone. Pull out on the north side of Cottonwood Lake. View to south of the northern flank of Mount Princeton consists entirely of Mount Princeton quartz monzonite of the Mount Aetna cauldron block. Sheep Mountain to the north contains the northern ring zone of the Mount Aetna cauldron. High-angle, brittle, rift-related faults with associated zeolitic alteration and bimodal (ryolite and lamprophyre) dikes are also present on Sheep Mountain. 0.8

11.2 Junction of CO-344 and CO-443. Continue southwest on CO-344. 4.8

16.0 Junction of CO-344 and Grassy Gulch Road. Park vehicles and walk north (approximately 1 mi) on Grassy Gulch Road. 1.2

17.2 STOP 5-2. Intrusive tuff dike at Grassy Gulch. Brock and Barker (1965, 1972) provided preliminary descriptions of an intrusive welded-tuff dike in Grassy Gulch (Mount Harvard 15 min. topographic quadrangle) and suggested that it was a feeder to an extrusive ash-flow tuff. Further studies have shown that this dike consists of relatively non-welded but well-indurated tuff which contains abundant crystals and pumice fragments (Fig. 19). This dike has been correlated with the Badger Creek extra- and intracaldera tuff, based upon spatial relations, mineralogy, chemistry, and age determinations, and is believed to be a cone-sheet dike that ventilated the Mount Aetna magma chamber outside the main ring zone (Shannon et al., 1988; Shannon, 1988). The dike is subparallel to, and approximately 5.5 km away from, the main ring zone. Ring shearing has not been observed in the adjacent Precambrian wall rocks. This dike is unusual in that it provides a rare, unequivocal example of an intrusive tuff vent. Return to vehicles and drive east on CO-344. 5.7

22.9 Junction of CO-344 and CO-443. Turn north on CO-443. Park at valley edge. 0.4

23.3 STOP 5-3. Outer northern ring zone and intrusive breccia exposed near Sheep Mountain. Hike approximately 1 mi up dirt road to Porphyry Gulch. At switchbacks, hike directly up hill to the east. Caution: the talus slope is steep and dangerous. We will examine the northern ring zone of the Mount Aetna cauldron. A large (up to 100 m thick) intrusive breccia body cuts early formed brittle-ductile ring shears and contains a multitude, transported clasts of the Mount Princeton pluton and Precambrian rocks. S-C fabrics in the Mount Princeton wall rock indicate downward movement of the cauldron block.

Ring-zone features dip predominantly steeply outward here. Intrusive breccias which were asymmetrically developed along the northern ring zone are interpreted to represent a major episode of venting of volcanic gases, and only rarely with a magma component. Return to vehicles and drive south on CO-443. 0.4

23.7 Junction of CO-344 and CO-443. Turn east on CO-344. 2.8

26.5 STOP 5-4. Ring dike exposed near Sheep Mountain. Park in bend in road, cross creek, hike up scree slope to base of cliffs. The inner portion of the northern ring zone is well exposed at this stop. Early brittle-ductile ring shears are cut by a ring dike (type 3) which is approximately 50 m thick and generally dips steeply outward. The dike has dark and narrow chilled margins. Chlorite microstylolites and devitrification textures are common in the dike margins. S-C fabrics indicate downward movement of the caldera block. Return to vehicles and drive to Buena Vista via CO-344 (north) and CO-306 (east). 8.4

34.9 Town of Buena Vista (elev. 2425 m).

The Grizzly Peak caldera: Structure, stratigraphy, and resurgence in an eroded caldera

July 6–7, 1989
Leader: Christopher J. Fridrich

Summary

The 34 Ma, 17 × 23 km Grizzly Peak caldera lies on the crest of the Sawatch Range about 30 km north of the more deeply eroded Mount Aetna cauldron (Figs. 14, 22). Sufficient intracaldera tuff is preserved in portions of the Grizzly Peak caldera for resolution of intracaldera stratigraphy as well as the geometry of collapse and resurgence structures (Fridrich, 1987). In more strongly uplifted and less deeply collapsed areas, erosion has exposed resurgence intrusions and deep-seated structures of the ring-fracture zones (Figs. 23, 24).

Volcanic and shallow intrusive features of the Grizzly Peak caldera document evolution of the magmatic center from precaldera through post-resurgent stages. Precaldera intrusions, alteration zones, and lavas were emplaced along

FIGURE 22—Location map of the Grizzly Peak caldera in the vicinity of the Sawatch Range. Y and Z are remnants of the outflow sheet of the Grizzly Peak Tuff. X is the precaldera dike swarm. North is to top of page.
FIGURE 23—Geologic map of the Grizzly Peak caldera. Units, from oldest to youngest: 8, precaldera rocks (not divided); 7, precaldera alteration zone; 6, precaldera lavas; 5, Grizzly Peak Tuff; 4, caldera-collapse breccia; 3, resurgent intrusions; 2, late- and post-resurgent intrusions; 1, Quaternary rocks. ABC line marks cross section in Fig 24.
a 20 km radius semicircular fracture swarm in and around the site of the future caldera (Fig. 22; Fridrich et al., 1988). Activity in this early dome field culminated in the caldera-forming eruption of the Grizzly Peak Tuff. Much of the tuff ponded in the >600 km³ depression, filling the asymmetric caldera to a compacted thickness locally >2.7 km, including intercalated rock-avalanche breccias shed from ring-fault scarps. Following collapse, the caldera was uplifted to form a complexly faulted resurgence dome (Fig. 24). A belt of post-resurgence intrusions across the center of the caldera formed during the waning stages of the magmatic center.

Caldera subsidence at Grizzly Peak formed a fault-bounded depression having the shape of an asymmetric bowl. The bowl-like shape is due to faulting of the caldera floor downward in steps across wide ring-fracture zones and to slumping of ring-fault scarps. Asymmetry of collapse is manifested mainly by an inner ring-fracture zone dividing the caldera block into two major segments that collapsed to different depths (Figs. 23, 24).

Welding zonation of the intracaldera tuff is that of a single cooling unit. The only observed cooling breaks are envelopes of quenching around wedges of caldera-collapse breccia that were cold upon incorporation in the accumulating tuff. There are no sediments or lavas intercalated in the unit, no erosional breaks, no soil horizons, and no lithic fragments in the tuff or clasts in the breccias of any other tuff unit; there are none of the features that are indicators of multicyclic caldera activity. The Grizzly Peak Tuff is the product of a single eruption.

The intracaldera tuff is offset and shows thickening across the inner ring-fracture zone. The tuff is not brittlely deformed in the collapse fault zones; it is welded across these faults and to their scarps. Field evidence that collapse faults were active while the intracaldera tuff was still hot is one of the criteria used to distinguish collapse structures from later-formed resurgence structures.

Caldera resurgence was accomplished partly by emplacement of a composite laccolith now exposed in the core of the resurgence dome in the northern caldera segment. Room for the resurgence intrusions was created largely by >1 km of uplift of their common roof along a vertical, piston-like fault that forms the walls of the composite laccolith where the fault is preserved. A portion of the roof of basal intracaldera tuff remains at the current level of erosion on the north side of the laccolith. Normal faults in surrounding intracaldera tuff are radial to the intrusion-cored piston block.

Each of the resurgence intrusions is concentrically zoned from leucocratic granodiorite margins to a mafic granodiorite/quartz monzodiorite core. This type of zonation is the reverse of the silicic-coreward zoning found in intrusions that fractionally crystallize during inward solidification. Reverse zoning in these intrusions evidently formed by rearrangement of a vertically graded magma column by the flow dynamics of magma emplacement and is therefore inferred to be analogous to the zoning found in ash-flow tuffs (Fridrich and Mahood, 1984).

Compositional zoning of the Grizzly Peak Tuff, defined by fiamme (collapsed pumice lumps), is a step function rather than a continuous gradient. Seven petrographic groups of fiamme each have distinct compositions separated by compositional gaps. As the same clusters are found in collections of fiamme from widely separated stratigraphic levels, step-function zoning must be intrinsic to the chamber rather than a consequence of the tapping process. Fridrich and Mahood (1987) interpreted the seven fiamme groups as seven separately convecting layers in a density-stratified reservoir tapped by eruption of the Grizzly Peak Tuff.

The Grizzly Peak Tuff is zoned from high-silica rhyolite at the base to low-silica rhyolite at the eroded top. Two horizons of heterogeneous tuff in the caldera fill contain fiamme of dacite to mafic latite along with the rhyolitic fiamme that make up the rest of the tuff. The total zonation,
from 57 to 77% SiO₂, is one of the largest gradients documented in a single volcanic unit, excluding those that have large compositional gaps. Occurrence of the two heterogeneous tuff horizons under caldera-collapse megabreccias suggests that these horizons represent surging of magma from exceptionally deep levels of the chamber in association with two large caldera-collapse events (Fridrich and Mahood, 1987).

Major-element trends of the Grizzly Peak Tuff can be modeled by crystal fractionation using observed phenocrysts. The trends of several trace elements are strongly non-linear with differentiation, hence late-stage mixing can be eliminated as a significant factor in generation of the compositional gradient. Inferences in trace-element trends correlate with observed changes in phenocryst mineralogy and composition, indicating control by crystal–liquid equilibria. The abundance of some trace elements increases too strongly with differentiation to fit the major-element crystal-fractionation model, suggesting the zonation is the result of a combination of processes (Fridrich, 1987; Fridrich and Mahood, in prep.). Oxygen-, strontium-, neodymium-, and lead-isotopic compositions indicate that substantial crustal contamination occurred, but crustal melting is ruled out as a source for the tuff because the tuff extends to compositions that are too mafic (Johnson and Fridrich, 1987, and in prep.).

Compositional trends defined by the zoned resurgent intrusions can be modeled as mixing lines between the compositions of the fiamme groups found in the tuff. Fridrich (1987) inferred from this result that magma mixing had progressively diminished compositional zonation in the subcaldera chamber during resurgences.

“Quenched blob” inclusions of phenocryst-poor latite porphyry in the resurgent intrusions have a chemical signature that is distinct from those of fiamme in the Grizzly Peak Tuff. These latite inclusions probably represent a new infusion of mafic magma from the roots of the system into the high-level magma chamber during resurgences. Continued insurgence of the new latite, after solidification of the subcaldera magma chamber, formed the dominantly latitic post-resurgent intrusions, which commonly include boulder-size inclusions of a granite interpreted on chemical grounds and field evidence as the subcaldera granite.

In addition to the intrusions that are clearly resurgent in age and those that are clearly post-resurgent, there is another set of small stocks emplaced in the caldera intermediate in age between those two groups. These late-resurgent (?) intrusions are spatially associated with stockwork veining and alteration resembling that found in porphyry-type Cu–Mo ore deposits, but do not contain commercial mineralization.

Sixth day: Cross section through intracaldera fill and resurgent intrusions

**Assembly point:** Buena Vista

**Departure time:** 8:00

**Distance:** 125 vehicle miles and approximately 5 hiking miles

**Stops:** 8

After driving north from Buena Vista through the Arkansas Valley graben, we will travel west to the northeastern margin of the Grizzly Peak caldera at Independence Pass to examine the stratigraphy of the intracaldera tuff as well as major resurgence faults. Our route continues farther west, then southeast to see internal contacts and compositional zoning in the resurgent intrusions in the north-central part of the caldera.

**Mileage**

0.0 Town of Buena Vista (elev. 2425 m). Travel north on US-24. 17.4

17.4 Town of Granite. 2.6

20.0 Junction of US-24 and CO-82. Turn west (left) onto CO-82, the road to Aspen. 2.5

22.5 STOP 6-1. View of extracaldera intrusions from Fisherman’s parking for Twin Lakes Reservoir. The pyramidal peak on the massif to the northwest is Mount Elbert, the highest peak (4400 m) in Colorado. A composite rhyolite porphyry stock on the first spur south of Mount Elbert crops out as a large area of white rock. This intrusion is part of a large extracaldera swarm of dikes and stocks forming an arc extending from the northeast perimeter of the caldera clockwise to the southeast perimeter and probably beyond under glacial cover (Fig. 22). These dominantly rhyolitic intrusions predate the caldera by no more than 3 Ma, based on K–Ar dates and the presence of clasts of these porphyries in the caldera-collapse breccias. 22.9

45.4 Independence Pass (elev. 3700 m). Start hike. From here we will hike 2.5 mi south (300 m elevation gain). Bring lunch, rock hammer, and clothes appropriate for rain and cold wind, regardless of how nice it may look now. Gloves or warm pockets and a warm hat are recommended. 0.2

0.2 STOP 6-2. View of core and margin of the Grizzly Peak caldera. Looking southeast, the southeastern caldera margin can be seen starting at East Red Mountain which appears as a large red, yellow, and white scar ending abruptly at the caldera-margin fault along its eastern side.

From East Red Mountain, the caldera margin turns northeast across Star Mountain, forming the prominent V-shaped contact near its top. The caldera margin dips inward there at 75°, separating wall rocks of gray uniform Precambrian gneiss from brownish, strongly layered caldera-collapse breccias inside the “V.” On the ridge west of Star Mountain is a prominent outcrop of tuff breccia that has a compositionally mixed appearance like a fruitcake. Both of these peaks are stops on tomorrow’s tour.

From Star Mountain, the caldera margin proceeds northeast approximately at treeline, crossing the ridge we are on at the saddle ahead. 0.6

0.8 STOP 6-3. Caldera margin. The margin here is a high-angle contact between welded ash-flow tuff and Precambrian St. Kevin granite (in place). 0.6

1.4 Small fault separating mixed vitrophyric tuff and breccia to the north from uninterrupted caldera-collapse breccia to the south. 1.1

2.5 STOP 6-4. Overview of resurgent intrusions and type section of the Grizzly Peak Tuff. In the distance, note the Pennsylvanian red beds that dominate the Elk Mountains to the west of the Sawatch Range. Remnants of outflow Grizzly Peak Tuff have only been recognized on the northern flank of Mount Sopris, the northwesternmost gray peak in the Elk
Mountains, and east of the Sawatch Range in the Rio Grande rift, just south of the Twin Lakes Dam which we passed this morning.

The margin of the composite laccolith which comprises the resurgent intrusions of the Grizzly Peak caldera crops out as the vertical contact that bisects Grizzly Peak, straight ahead, into dark tuffs and intercalated breccias on the east side and light gray granodiorite porphyry on the west side (Fig. 25). From there the contact winds to the northeast to the base of the peak we are standing on, where it makes a right-angle turn to the northwest. The largely vertical contact that surrounds the resurgent intrusions is the piston fault (Figs. 23, 24, 26).

The valleys immediately to our left and right follow two of the resurgence faults that are radial to the intrusion-cored piston block. Other resurgence faults are visible in the valley below Grizzly Peak (Fig. 25).

The ridge to our right is largely a remnant of the roof of the resurgent intrusions. This tilted section of high-silica rhyolite tuff is the basal third of the type section of the Grizzly Peak Tuff, shown as the vertical bar on the right side of the upper section in Fig. 24. The middle third of the type section is the medium-silica rhyolite tuff forming the east side of Grizzly Peak. The upper third is the low-silica tuff exposed in the rust-colored peak immediately southeast of this overlook. This total section is 2.7 km thick. It is an incomplete section of a single cooling unit; the base is not exposed and the top is eroded. Return to vehicles. 2.5

45.4 Independence Pass. Continue west on CO-82. 8.9

54.3 Junction of CO-82 and the Lincoln Creek Road. Turn left onto the Lincoln Creek Road. 1.6

55.9 STOP 6-5. Precambrian wallrocks at Middle Grottos of Lincoln Creek. Precambrian migmatites, unusually well exposed here, comprise a major portion of the wallrocks of the caldera. 2.8

58.7 STOP 6-6. Roadcut through high-silica rhyolite tuff just inside the northwestern caldera margin. 2.0

FIGURE 25—Overlook of Grizzly Peak from end of Independence Pass trail, showing layer-cake stratigraphy of caldera block. On the left, the cliff-forming unit is the Grizzly Peak Tuff, and the slope-forming unit is intracaldera breccia. The resurgent intrusions occupy the right side of the photo. The foreground consists of thick tuff, downfaulted relative to the background. The layering is composed of horizons of boulders (up to 3 m) that are strewn along flow-unit horizons. There are, however, no cooling breaks.

60.7 Grizzly Reservoir dam. Stretch your legs while the leader gets the keys to the gate. Drive across the dam and then left up the New York water-diversion canal service road. Turn around at the big bend in the road at Tabor Creek (1.8 mi) and backtrack 0.2 mi to the contact between tan-pink welded tuff and gray granodiorite porphyry. 2.0

62.7 STOP 6-7. Cut through the resurgent intrusions on NY Canal. After examining the tuff-granodiorite contact, we will walk 0.4 mi each way across a lobe of one of the resurgent intrusions. Note the gradational internal changes in texture, mineralogy, and color index. The zoning is from 69 wt% SiO₂ at the margin to 58 wt% SiO₂ in the core. The core of the intrusion has a flow foliation and contains abundant inclusions; both are uncommon near the intrusion’s margins. These, and other features we will see, provide important constraints on the origin of reverse concentric zoning in these intrusions.

Before leaving, collect a sample of the leucocratic granodiorite at the margin of the outermost resurgent intrusion, which is bluish or tan rather than the greenish gray of the later-emplaced interior intrusion. Return toward Lincoln Creek Road stopping on the south side of the Grizzly Reservoir dam. 1.4

64.1 STOP 6-8. Core rock of resurgent intrusions at Grizzly Reservoir dam. Walk down the spillway to see the more mafic core rock of the outermost resurgent intrusion. Cross the dam. 0.2

64.3 Return to Buena Vista by the same roads taken in. 60.7

125.0 Buena Vista (elev. 2425 m).

Seventh day: Margin of the Grizzly Peak caldera

Assembly point: Buena Vista
Departure time: 8:00
Distance: 79 vehicle miles and 7 hiking miles (elevation gain of 550 m)
Stops: 5
Our route follows a ridge in the northeastern portion of the caldera margin to examine some of the best exposures of caldera-collapse breccia at Grizzly Peak.

**Mileage**

0.0 **Town of Buena Vista** (elev. 2425 m). Travel north on US-24. 20.0

20.0 **Junction of US-24 and CO-82.** Turn west (left) onto CO-82. 14.2

34.2 **South Fork Lake Creek Road.** Turn left. 2.0

36.2 **Caldera-margin.** The contact is expressed here as a change from ruggedly polished, nearly continuous outcrop to scattered crumbly knobs separated by trees and grass. The caldera wall here is composed of the Twin Lakes Granodiorite, whereas the caldera fill is megabreccia with a matrix of crushed rock and tuff. 1.2

37.4 **McNasser Gulch.** Turn right onto the road to Sherman mine in McNasser Gulch. 2.2

39.6 **STOP 7.1. Caldera-collapse megabreccia at the Sherman mine.** This Au–Ag–Pb–Zn mine has never been a profitable venture, but has produced small volumes of ore with Au grades as high as 5 ounces per ton. The thin and highly discontinuous quartz–sulfide veins mined here are developed in fractures running through one of the major caldera-collapse megabreccias of the caldera. At depth, these fractures are filled with calcite and chlorite. It is only within the upper 50–100 ft below the capping layer of welded tuff that the vein mineralogy changes first to simple quartz–pyrite and then to quartz–multiple sulfides–native gold.

Note the shattered appearance of the megabreccia wallrocks around the veins being mined. Internal shattering in clasts in the megabreccias makes the clast size appear to be much smaller than it actually is. True clast size is shown by continuity of original structures such as dikes. Prebrecciation structures are offset and rotated to varying degrees across the seams of crushed and sheared rock formed by the shattering, resulting in a jigsaw-puzzle appearance.

Backtrack down the McNasser Gulch Road to intercept a faint hiking trail that climbs the ridge to the north. 0.4

40.0 **Invisible trailhead for a nearly invisible trail.** Start hike. Park along the side of the road. From here, we will hike almost directly north to the saddle between Ouray Peak and the garnet-covered ridge on the east flank of Grizzly Peak. Bring a lunch, rain gear, warm clothes, and hiking boots. 0.9

0.9 **STOP 7.2. Resurgence fault at saddle between McNasser and Graham Gulches.** This saddle follows a major resurgence fault, the throw of which is greater than the local topographic relief. The rocks to the west are medium-silica rhyolite tuffs interlayered with extensive breccia sheets. The rocks to the east, on the other hand, are mostly wedges of breccias with masses of low-silica rhyolite tuff banked against them. Climb over to the east side of Ouray Peak, the double knob just to the east. 0.4

1.3 **STOP 7.3. Megabreccia and quenched tuff at Ouray Peak.** The tuff that caps this peak shows well-developed welding zonation up from the breccia layer it was deposited on (Fig. 27). This cooling break is only a local one; where breccia wedges pinch out in the intracaldera tuff, the envelopes of quenched tuff around them pinch out as well.

The first breccia under the tuff that caps the peak is a megabreccia with only minor tuff matrix. This matrix takes the form of seams of tuff that appear almost to be dikes because they show evidence of internal fluidized flow, namely size sorting developed inward from contacts (Bagnold effect). The tuff seams are not dikes; they are rootless. The tuff matrix in the breccias was fluidized at the time of deposition and is therefore intrusive; the tuff matrix continued moving upward after the remaining breccia came to rest.

About 12 m below, we pass into an underlying breccia. This breccia has abundant tuff matrix and the dominant clast is the pinkish-tan St. Kevin’s granite from the north side of the caldera. The dark-colored breccia above is derived from the Denny Creek Granodiorite, which is from east of the caldera.

Hike east to the next major knob on this ridge. 0.7

2.0 **STOP 7.4. Tuff breccia at Fruitcake Hill.** The tuff breccia making up this hill is the only one in the caldera that is nearly matrix-supported (Fig. 28). It also differs from other breccias in the caldera in having well-developed size sorting and rounding of the boulder-like clasts. In the rest of the caldera, rock types that are not found together in the caldera walls are not mixed together in the breccia. This breccia is the exception; rock types from all along the north and east caldera walls are intimately mixed here. Cruson (1973) interpreted this feature as a possible breccia pipe and pyroclastic vent. In support of his interpretation, this distinctive tuff breccia crops out in a nearly round area 1 km in diameter, with high-angle contacts on at least two sides. 1.5

3.5 **STOP 7.5. Megabreccia lenses at Star Mountain.** The consistency in foliation attitudes across Star Mountain make it appear that the mountain is a mass
of Precambrian rock in place. As we now look at the cliff-like, northeastern face of Star Mountain, it is clear that this mountain is composed of megabreccia.

The breccia is a composite of numerous lenses laminated together along zones of concentrated shearing. Some lens-like contacts coincide with lithology changes. Each lens may have started out as a giant boulder that caved off the wall of the caldera in a collapse event. This breccia has no real matrix; it is just a mass of giant boulders that have been brittlely deformed into interlocking lens shapes. The fact that this brittle deformation of the boulders did little to disrupt the attitudes of metamorphic foliations within the rock is an interesting clue to the physical nature of the breccia emplacement process.

Before we leave, inspect the caldera margin contact immediately to the northeast. Return to the vans by the path taken in. 3.5

7.0 Trailhead. Return to Buena Vista by the roads taken in. 39.2

79.2 Buena Vista (elev. 2425 m).

54.3 Junction of CO-82 and the Lincoln Creek Road. Turn left onto the Lincoln Creek Road. 6.8

61.1 Portal campground. Start hike. Drive just beyond the campground and park. From here we will walk up the remainder of the Lincoln Creek Road, which is strictly a four-wheel-drive road from here on. Bring lunch, rock hammer, rain gear, and warm clothes. 3.9

3.9 Below Mount Garfield cirque. At this point, we turn off the road and bushwack uphill into the lower part of the cirque on the south side of Mount Garfield. Four-wheel-drive vehicles park here. 0.6

4.5 STOP A-1. Lower heterogeneous tuff horizon at Mount Garfield cirque. On both the north and south sides of the cirque, moderately dipping, black welded tuff is plastered on this side of the ridge against a contact which truncates the nearly flat-lying tuffs and breccias and an altered porphyry sill that make up the body of the ridge. This contact may be one side of a 3 km long fissure vent that cuts through the lower half of the caldera fill in the center of the caldera (Fridrich, 1987).

The black tuff is the lower heterogeneous tuff horizon. Compositions of individual flows in this subunit of the Grizzly Peak Tuff range from high-silica rhyolite to mafic latite. The entire range can be found in single large slabs of bulk tuff (Fig. 29).

Supplemental log A: To the center of the Grizzly Peak caldera

Assembly point: Buena Vista
Departure time: 8:00
Distance: 122 vehicle miles and 9 hiking miles with an elevation gain of 600 m
Stops: 1

Our route takes us to the center of the Grizzly Peak caldera to examine the compositional zoning of the Grizzly Peak Tuff defined by fiamme in the lower heterogeneous tuff horizon of the caldera fill, as well as post-resurgent intrusions and a feature interpreted as a possible fissure vent.

Mileage

0.0 Town of Buena Vista (elev. 2425 m). Travel north on US-24. 20.0

20.0 Junction of US-24 and CO-82. Turn west (left) onto CO-82. 25.4

45.4 Independence Pass. Continue west on CO-82. 8.9

FIGURE 29—Welded tuff of the lower heterogeneous tuff horizon subunit of the caldera fill. Collapsed and devitrified pumice lumps in this rock range in color from light to black, and from high-silica rhyolite to mafic latite (75–57 wt% SiO2) in composition.
The altered sill above is one of the late-resurgent intrusions; alteration of the sill is similar to that which is characteristic of porphyry systems that do not contain commercial mineralization.

The dikes on the north side of this cirque are part of a large radial swarm of dikes around a post-resurgent stock in the valley below. The more mafic of the dikes commonly contain large engulfed granite boulders (Fig. 30). No outcrop has been found of this granite, which is chemically dissimilar to all other silicic rocks in the central Sawatch Range, except the Grizzly Peak rhyolite. Return to the vehicles. 4.5

9.0 Parking area. Return to Buena Vista by the route taken in. 61.1

122.0 Buena Vista (elev. 2425 m).

Supplemental log B: To the top of East Red Mountain

Assembly point: Buena Vista
Departure time: 8:00
Distance: 80 vehicle miles (4WD vehicle required), or 74 vehicle miles and 6 hiking miles with 800 m elevation gain

Stops: 2

This trip goes to a prominent overlook on the eastern margin of the Grizzly Peak caldera to see a precaldera alteration zone, welded-tuff dikes that were vents for the caldera-forming eruption, and, looking into the caldera, four major faults along which the northeastern quadrant of the caldera collapsed a minimum of 4 km.

Mileage

0.0 Town of Buena Vista (elev. 2425 m). Travel north on US-24. 20.0
20.0 Junction of US-24 and CO-82. Turn west (left) onto CO-82. 14.2
34.2 South Fork Lake Creek Road. Turn left. 2.7
36.9 Signpost without a sign. Turn left, proceed 15 m, then turn right on a road marked with a brown plastic stick labeled 382. To walk, stay left at the brown plastic stick and park immediately. Cross South Fork Lake Creek on the wooden footbridge 30 m ahead. 0.2

37.1 Road crossing of South Fork Lake Creek. Stop and check conditions before crossing. 0.1

37.2 Locked green gate. Turn left and, after 6 m, go through green gate that is made to appear locked but is not. The drive to the top of East Red Mountain is about 2.8 mi from here, but the upper part of the road is dangerously washed out and is usually blocked by snowdrifts until later summer. 1.3

38.5 STOP B-1. Caldera floor. Park and walk off the road on the right side to see the basal contact of the Grizzly Peak Tuff inside the caldera. We may have to walk from here even in the lightest snow year. 1.5

40.0 STOP B-2. Caldera faults and welded-tuff dikes. Top of East Red Mountain. From here, we can see four major faults related to caldera subsidence which separate the northeastern quadrant of the caldera from rocks outside the caldera. In the field, we will discuss the constraints on their throws (Fig. 31).

On the east side of the mountain is a cornice of snow which, if sufficiently melted, will allow us to see a welded-tuff dike emplaced in the outer ring fracture of the Grizzly Peak caldera. There are four welded-tuff-dike segments emplaced along the ring-fracture zone in this area; they cover most of the compositional range of the intracaldera rhyolite tuffs. Only the most mafic of these dikes, the one with vitrophyric margins on both sides, is unshaped. The most silicic of the four dikes is most sheared.

The East Red alteration zone is developed around a swarm of northeast-trending quartz porphyry dikes. Sharp truncation of this zone by the caldera-margin ring fault clearly establishes the alteration as pre-caldera in age.

Return to Buena Vista by the roads taken in. 40.0

80.0 Buena Vista (elev. 2425 m).

Eighth day: Buena Vista to Denver, Colorado

Assembly point: Buena Vista
Departure time: 8:00
Distance: 149 miles
Stops: None

We will return to Denver in time for late afternoon and evening flights from Stapleton International Airport. After traveling north out of the northern end of the Rio Grande rift, we will intersect the northeastern end of the Tertiary Colorado Mineral Belt near the Climax molybdenum mine. After turning east on I-70, or trip will continue mainly through Precambrian rocks (1.0–1.8 Ga) of the Colorado Front Range.

Mileage

1 Town of Buena Vista. Travel north on US-24. 17
17 Town of Granite. 3
38 Town of Leadville. 1
39 Junction of US-24 and CO-91. Turn right (east) on CO-91. 12

51 Climax molybdenum mine. 12

63 Junction of CO-91 and I-70. Turn right (east) on I-70 toward Denver. 41

104 Junction of US-40 and I-70. Continue on I-70 east. Stay on I-70 through Denver; follow signs to Stapleton International Airport. 45

149 Turnoff for Stapleton International Airport. Mileage approximate. Turn south to airport.

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