Geologic Map of the Central San Juan Caldera Cluster, Southwestern Colorado

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Wheeler Geologic Monument (Half Moon Pass quadrangle) provides exceptional exposures of three outflow tuff sheets erupted from the San Luis caldera complex. Lowest sheet is Rat Creek Tuff, which is nonwelded throughout but grades upward from light-tan rhyolite (~74% SiO_2) into pale brown dacite (~66% SiO_2) that contains sparse dark-brown andesitic scoria. Distinctive hornblende-rich middle Cebolla Creek Tuff contains basal surge beds, overlain by vitrophyre of uniform mafic dacite that becomes less welded upward. Uppermost Nelson Mountain Tuff consists of nonwelded to weakly welded, crystal-poor rhyolite, which grades upward to a densely welded caprock of crystal-rich dacite (~68% SiO_2). White arrows show contacts between outflow units.

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GEOLOGIC SETTING

Andesitic to rhyolitic volcanic rocks of the central San Juan volcanic field, along with associated base- and precious-metal epithermal veins, are classic examples of large-volume continental volcanism and ore deposits. They have been studied intermittently since early in the twentieth century (Emmons and Larsen, 1913; Cross and Larsen, 1935; Larsen and Cross, 1956), culminating with the detailed study of the Creede mining district by Steven and Ratté (1965, 1973) and regional field and volcanological studies (Lipman and others, 1970; Steven and others, 1974; Steven and Lipman, 1976). While much had previously been learned about the evolution of several complex caldera clusters from which at least 22 major ash-flow sheets (each 150–5,000 km^3) were erupted at 30-26 Ma, recent mapping and other research initiated in support of the Creede Scientific Drilling Project (Bethke and Lipman, 1987; Bethke and Hay, 2000) has provided major new insights for the regional stratigraphic sequence, duration of volcanism, eruptive processes, magmatic evolution, and regional structure in the central part of the volcanic field.

Many of the major map units and caldera features of the central San Juan area are described more completely by Lipman (2000). The present geologic map constitutes basic documentation for interpretations developed in that report, which provides additional information for understanding regional volcanism and structure.

VOLCANISM

The San Juan Mountains are the largest erosional remnant of a composite volcanic field (fig. 1, sheet 3) that covered much of the southern Rocky Mountains in middle Tertiary time (Steven, 1975). The San Juan field consists mainly of intermediate-composition lavas and breccias, erupted about 35–30 Ma from scattered central volcanoes (Conejos Formation) and overlain by voluminous ash-flow sheets erupted from caldera sources (Lipman and others, 1970). At about 26 Ma, volcanism shifted to a bimodal assemblage dominated by trachybasalt and silicic rhyolite, concurrent with the inception of regional extension during establishment of the Rio Grande rift.

Preserved rocks of the San Juan field now occupy an area of more than 25,000 km^2 and have a volume of about 40,000 km^3. They cover a varied basement of Precambrian to lower Tertiary rocks along the uplifted and eroded west margin of the Late Cretaceous to early Tertiary (Laramide) uplifts of the Southern Rocky Mountains and adjoining portions of the San Juan Basin on the eastern Colorado Plateau (fig. 1). The San Juan field is one of many loci of Tertiary volcanic activity—including the Sierra Madre Occidental, Trans-Pecos, Mogollon-Datil, Absaroka, Challis, and Lowland Creek fields—that developed along the east Cordilleran margin of the North American plate, probably in a complex response to changing subduction geometry along its west margin.

In the central San Juan Mountains (fig. 2, sheet 3), eruption of at least 8,800 km^3 of dacitic-rhyolitic magma as nine major ash flow sheets (individually 150–5,000 km^3) was accompanied by recurrent caldera subsidence between 28.3 Ma and about 26.5 Ma (Ratté and Steven, 1967; Lipman and others, 1989; Lipman, 2000). Voluminous andesitic-dacitic lavas and breccias were erupted from central volcanoes prior to the ash-flow eruptions, and similar lava eruptions continued within and adjacent to the calderas during the period of more silicic explosive volcanism (Lipman and others, 1978). Exposed calderas vary in size from 10 to 75 km in maximum dimension, the largest calderas being associated with the most voluminous eruptions (table 1). Caldera-subsidence features that likely accompanied initial explosive eruption of the Masonic Park Tuff are entirely concealed beneath younger rocks and structures in the central San Juan region. The giant La Garita caldera (35 x 75 km) collapsed in at least three successive northward-migrating segments during eruption of the Fish Canyon Tuff at 27.6 Ma (fig. 2). After collapse of La Garita caldera, seven additional explosive eruptions and calderas of variably smaller size formed inside La Garita depression during about one million years (table 1). In one sense, the younger caldera systems constitute large postsubsidence volcanoes associated with a La Garita megacaldera cycle. Even the incompletely understood Cochetopa Park caldera, mainly lying north of the map area, appears to have been the site of at least modest subsidence during Fish Canyon eruptions of the La Garita cycle.

Erosional dissection to depths of as much as 1.5 km has exposed diverse features of intracaldera ash-flow tuff and interleaved caldera-collapse landslide deposits that accumulated to multi-kilometer thickness within concurrently subsiding caldera structures. The calderas display a variety of postcollapse resurgent uplift structures, and caldera-forming events produced complex fault geometries that localized late mineralization, including the epithermal base- and precious-metal veins of the well-known Creede mining district (Steven and Ratté, 1965; Wetlaufer and others, 1979; Foley and others, 1993; Barton and others, 2000). Most of the central San Juan calderas have been deeply eroded, and their identification has been dependent on detailed geologic mapping (fig. 3, sheet 4). In contrast, the primary volcanic morphology of the symmetrically resurgent Creede caldera has been exceptionally preserved because of rapid infilling by moat sediments of the Creede Formation, which were preferentially eroded during the past few million years.

The ash-flow tuffs and calderas of the central San Juan region (fig. 4, sheet 4) have been widely recognized as exceptional sites for study of explosive volcanic processes (Steven and Ratté, 1965; Ratté and Steven, 1967; Steven and others, 1969; Steven and Lipman, 1976). The geologic mapping reported here provides a framework for diverse volcanologic, geochronologic, and petrologic studies that are generating new insights into processes of pyroclastic eruption and emplacement, geometric interrelations between caldera subsidence and resurgence, the petrologic diversity of sequential ash-flow eruptions, recurrent eruption of intermediate-composition lavas after each caldera-forming event, associated regional fault development, volume relations between ash-flow eruptions and associated calderas, the emplacement of subvolcanic batholiths, and involvement of mantle-derived mafic materials in magma-generation processes (Lipman and others, 1989, 1996, 1997; Lipman, 2000; Riciputi and others, 1995; Bachmann and others, 2002; Schmitz and Bowring, 2001; Parat, 2001).

Lavas, volcaniclastic sedimentary rocks, and intrusions emplaced concurrently with ash-flow tuffs in the central San Juan Mountains are here interpreted as defining multiple caldera cycles, based on affinities of geographic distribution and stratigraphic sequence, isotopic age and paleomagnetic pole positions, and petrologic character (tables 1, 2). Interpretation of some units remains ambiguous, however, especially assignment of certain lavas to the late stages of one cycle versus inception of the next one. The revised interpretations of caldera geometry and regional volcanic history (fig. 5, sheet 4) build upon the earlier syntheses (Lipman and others, 1970; Steven and Lipman, 1976), utilizing general concepts of caldera geometry and eruptive cycles summarized by Smith and Bailey (1968) and Lipman (1984, 1997a). These overview papers provide a useful framework for detailed interpretations of the map relations depicted here.

Briefly, many large ash-flow calderas such as those in the San Juan field form at sites of preceding volcanism that records shallow accumulation of caldera-related magma. Large eruptions (>50–100 km^3 of ash-flow magma) cause caldera collapse concurrently with volcanism, as indicated by thick intracaldera ash-flow fill and interleaved collapse slide breccias. Volumes of intracaldera and outflow tuff tend to be subequal; correlation between them is commonly complicated by contrasts in abundance and size of phenocrysts and lithic fragments, degree of welding, devitrification, alteration, and even chemical composition of magmatic material. Structural boundaries of calderas commonly are single ring faults or composite ring-fault zones that dip steeply. Scalloped topographic walls beyond the structural boundaries of most calderas are due to secondary gravitational slumping during subsidence. The area and volume of caldera collapse are roughly proportional to the amount of erupted material. Postcollapse volcanism may occur from varied vent geometries within ash-flow calderas; ring-vent eruptions are most common in resurgent calderas, reflecting renewed magmatic pressure. Resurgence within calderas may result in a symmetrical dome or more geometrically complex forms. In addition to resurgence within single calderas, broader magmatic uplift occurs within some silicic volcanic fields, reflecting isostatic adjustment to emplacement of associated subvolcanic batholiths. Large intrusions related to resurgence are exposed centrally or along the margins of some deeply eroded calderas. Hydrothermal activity and mineralization accompany all stages of ash-flow magmatism, becoming dominant late during caldera evolution. Much rich mineralization formed millions of years later than caldera collapse, where the caldera served primarily as a structural control for late intrusions and associated hydrothermal systems.

STRUCTURE

Structural features of the central San Juan Mountains (fig. 6, sheet 4) involve complex interactions between diverse localized faulting associated with volcanism, especially the large calderas, and effects of west-southwest-directed regional extension associated with inception of the Rio Grande rift zone (Lipman, 2000, fig. 14). Many faults are exposed within the map area, but erosion levels are insufficient to expose any ring faults directly related to caldera collapse, such as those well exposed within the Lake City and Silverton calderas in the western San Juan Mountains (Steven and Lipman, 1976). A distinctive area of rectilinear faulting, within and adjacent to the southern segment of the enormous La Garita caldera, appears to have accommodated early piecemeal-style collapse, probably initiated during precursor eruption of the Pagosa Peak Dacite (Lipman, 2000); some of these faults localized continued subsidence in the southern segment during subsequent eruptions of Fish Canyon Tuff.

Several fault clusters are related to resurgent uplift of caldera floors. Especially conspicuous is the Deep Creek graben along the keystone crest of the steep-sided Snowshoe Mountain dome within the Creede caldera (Steven and Ratté, 1965). Other resurgent structures include the graben faults of the Creede mining district that were also initiated as keystone faults on the elliptical resurgent uplift within the Bachelor caldera (Steven and Lipman, 1976), faults bounding trap-door-style uplift of the San Luis Peak block within the caldera associated with eruption of the Nelson Mountain Tuff, and probably also the faults that cut intracaldera Fish Canyon Tuff in the uplifted block of La Garita Mountains.

Another group of structures are linear grabens and other faults (fig. 6) adjacent to calderas that appear largely to have initially been established during segmented subsidence of La Garita caldera, then passively buried by younger tuff sheets and lava flows. These include the Los Pinos and Cochetopa grabens that connect La Garita Mountain segment to the Cochetopa caldera across the Continental Divide at the north margin of the map area, some faults of the Clear Creek graben to the west of the central segment, and perhaps initial faulting along the Rio Grande graben to the southeast of the central segment. The southwestern bounding faults of the Clear Creek graben appear to have controlled a subparallel segment of La Garita caldera-wall unconformity, along which Carpenter Ridge Tuff and younger units are depositionally banked against steep slopes without major later faulting. In contrast, northeastern bounding faults from Bristol Head to Spring Creek Pass (sheets 1, 2) had continued later movement, after eruption of the Nelson Mountain Tuff. Much of the structure beneath the heavily moraine-mantled floor of the Clear Creek graben, previously interpreted as a complex of graben faults (Steven, 1967), is here alternatively interpreted as a weakly faulted synclinal sag, in which caldera-filling ash-flow sheets banked with varied dips and hinging of foliation against the combined graben and caldera-wall paleotopography within La Garita caldera. To the southeast (Wolf Creek Pass quadrangle), the Pass Creek fault zone runs between the central caldera cluster and the Platoro caldera complex (southeast of map area), involving displacements younger than Fish Canyon Tuff and modest associated hydrothermal alteration (Lipman, 1975, p. 110-111).

During late stages of San Juan volcanism, the Rio Grande rift zone became active within the present-day San Luis Valley area to the east of the San Juan Mountains (fig. 1), but only a few northwest-trending faults within the map area have appropriate geometry and timing to clearly reflect such regional tectonism (Lipman and Mehnert, 1975). Northwest-trending faults of the Rio Grande graben cut basaltic lava flows of the Hinsdale Formation dated at about 24 Ma south of South Fork, and the late movement along the Bristol Head master fault of the Clear Creek graben suggests that faults localized by and initially active during formation of La Garita caldera also were influenced by regional stresses associated with initial southwestward-directed extension along the Rio Grande rift zone.

METHODS OF STUDY

Geologic mapping, initiated to characterize the geologic setting for the Creede Scientific Drilling Project (Bethke and Lipman, 1987), was gradually expanded to cover the entire central caldera cluster as multiple stratigraphic, structural, geochronologic, and volcanologic problems emerged. New field studies by Lipman totaled about 55 weeks, mainly between 1986–89 (in part, jointly with David A. Sawyer) and 1995–99 (in part, jointly with Olivier Bachmann and Michael Dungan). Additional assistance in fieldwork was provided by Douglas Yager (1989), Christian Huber (1997), Olivier Roche (1998), and Charles Perring (1999). Small parts of the present map area were recompiled from published sources, such as the detailed mapping of the Creede district by Steven and Ratté (1965, 1973); all areas that required significant reinterpretation were remapped (fig. 3). Fieldwork and primary map compilation were at a scale of 1:24,000, using 7.5′ topographic quadrangle maps as base materials (fig. 3); these data are included as digital files in the accompanying CD-ROM. In total, 208 map units were distinguished.

The database was compiled using ArcInfo GIS software and the ALACARTE interface (Wentworth and Fitzgibbon, 1991), mainly by Joel Robinson, with supplemental contributions by Dillon Dutton, Tracey Felger, and David Ramsey. The geologic map data were transferred to the 1:50,000-scale county map series by GIS methods in order to provide a more legible base than would have been possible by photo reduction of the 1:24,000-scale quadrangle maps. A drawback of the county map series, however, is that some areas, compiled from older 1:62,500-scale topographic maps, do not register precisely with the more recent 1:24,000 topography. Thus, some contacts of geologic units, especially where near horizontal, do not precisely fit the generalized contours at the 1:50,000 scale. The improved readability of the base, especially for steep mountain areas, is considered to be more important for most potential users than this drawback. In the Description of Map Units, references to locations on the map and the accompanying database are by abbreviations of the 7.5′ quadrangle names (fig. 3); for example, the Creede quadrangle is referenced (CR).

Volcanic rock names are used in general accord with the IUGS classification system (Le Bas and others, 1986); in particular, the term “silicic dacite” is now used in place of quartz latite. Most of the volcanic rocks constitute a high-K assemblage that is transitional between subalkaline and alkaline suites, similar to those at other Tertiary volcanic fields in the southern Rocky Mountains. For simplicity and continuity with previous usage, such modifiers as “high-K” or “trachy” are omitted from most rock names. Names, divided on the basis of percent SiO_2, are <52, basalt; 52–57, basaltic andesite; 57–62, andesite; 62–66, dacite; 66–70, silicic dacite (quartz latite); 70–75, rhyolite; >75, silicic rhyolite (all compositions for bulk-rock analyses recalculated to 100% volatile-free, all FeO as Fe_2O_3). Phenocryst assemblages serve to distinguish many of the major tuff sheets (table 2). Cited chemical and petrographic data are from Ratté and Steven (1967), Lipman (1975), Whitney and Stormer (1985), Whitney and others (1988), Webber (1988), Askren and others (1991), Yager and others (1991), Riciputi (1991), Riciputi and others (1995), Bachmann and others (2000), and Lipman (unpub. data). All published and new major-oxide and trace-element analyses (about 1,000 samples) for the central caldera cluster, compiled by stratigraphic unit as determined for the current map, have been tabulated in a separate report (Lipman, 2004); locations of analyzed samples are plotted in the digital map release. Sanidine compositions, initially determined from x-ray cell parameters (Lipman, 1975) and later by electron-microprobe analysis (Lipman and Weston, 2001; Lipman, unpub. data), have also provided useful discriminants to test correlations among some tuff sheets. Mineral-chemical data for other phenocrysts (biotite, augite) show less variation among central San Juan tuff units.

Revised values for pre-1977 K-Ar radiometric ages for San Juan rocks are taken from the compilation by Hon and Mehnert (1983), which utilizes the presently accepted IUGS decay constants. Recent $^{40}Ar/^{39}Ar$ dates, all incremental-heating plateau ages unless otherwise indicated, are mainly from Lanphere (1988, 2000, and unpub. data). All other $^{40}Ar/^{39}Ar$ ages are adjusted to the calibrations of Lanphere (1988); these result in Oligocene ages about 1 percent younger than those reported for San Juan rocks by some other labs (for example: Kunk and others, 1985; Balsley and others, 1988; Lipman and others, 1996). Age determinations from within the study area (49 localities; in total, 61 mineral and whole-rock ages) are plotted on the geologic map. Interpreted preferred ages (table 1; some unit descriptions) are influenced by stratigraphic relations, supplemented by additional age determinations from beyond the present map area; interpretive problems with ages for some units are discussed in Lipman (2000).

Cited paleomagnetic-pole directions for the central San Juan rocks are partly from published sources (Tanaka and Kono, 1973; Diehl and others, 1974; Lipman, 1975; Elwood, 1982) but include many recently determined values (Rosenbaum and others, 1987, unpub. data; L. Brown, unpub. data)

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DESCRIPTION OF MAP UNITS

[Locations are indicated by 7.5′ quadrangle names (abbreviated in fig. 3). For major volcanic units, phenocryst percentages and pricipal phases in order of abundance are listed: pl, plagioclase; sn, sanidine; qz, quartz; bi, biotite; cpx, clinopyroxene; hbl, hornblende. Sanidine composition includes percent (subscript): Ab, albite; An, anorthosite; Cs, celsian; Or, orthoclase]

SURFICIAL DEPOSITS

Qal **Alluvium (Holocene)**—Silt, sand, gravel, and peaty material in valley bottoms. Locally includes small deposits of colluvium and talus (units Qc, Qt) at margins of valley bottoms

Qc **Colluvium (Holocene)**—Poorly sorted silt- to boulder-sized material on slopes and in steep valleys. Locally includes small alluvial, talus, landslide, and glacial moraine deposits

Ql **Landslide deposits (Holocene and Pleistocene)**—Lobate accumulations of poorly sorted soil and rock debris on slopes marked by hummocky morphology and downslope-facing scarps. Derived from bedrock and glacial deposits. Includes small earth-flow, block-slump, and block-slide deposits

Qf **Alluvial fan deposits (Holocene)**—Generally poorly sorted material, ranging in size from silt to boulders, which grades into modern colluvium in upper parts of drainages. Only large low-angle fans are shown; smaller steep fan deposits are mapped with colluvium (Qc). Fan deposits largely predate outwash of Pinedale glaciation and are mostly derived from unglaciated drainages

Qt **Talus (Holocene)**—Angular rock fragments as much as 1 m in diameter forming talus cones, talus aprons, and scree slopes. Locally well sorted. Grades into colluvium (Qc) as sand and silt content increases

Qlo **Older landslide deposits (Pleistocene)**—Landslide deposits in which original hummocky morphology has become subdued due to erosion and sedimentation, and eroded landslide features forming high-standing erosional remnants

Qfo **Older alluvial fan deposits (Pleistocene)**—High-standing erosional remnants of dissected alluvial fans

GLACIAL DEPOSITS

Qr **Rock glacier (Pleistocene)**—Glacier-shaped deposit of angular rock fragments, generally lacking fine-grained material on upper surface

Qg **Glacial outwash gravel (Pleistocene; Pinedale glaciation)**—Moderately sorted to well-sorted stratified terrace and fan deposits consisting of sand, gravel, and well-rounded boulders

Qm **Moraine and till (Pleistocene; Pinedale glaciation)**—Terminal and lateral moraines, thick valley-bottom till. Poorly sorted and generally unstratified clay, silt, and sand containing cobbles and boulders; characterized by hummocky or ridgy topography. Some till has been mapped with colluvium (Qc)

Qmo **Older moraine and till (Pleistocene; pre-Pinedale glaciation)**—Deposits preserved as local erosional remnants

Qgo **Older glacial outwash gravel (Pleistocene; pre-Pinedale glaciation)**—Deposits preserved as local erosional remnants of high-standing outwash terraces

POSTCALDERA VOLCANIC ROCKS

Hinsdale Formation (Miocene)—The Hinsdale Formation is an assemblage of basaltic-andesite lavas erupted from widely scattered vents and volumetrically subordinate silicic rhyolite erupted as lava domes and tuffs. These rocks, emplaced intermittently between about 26 Ma and 14 Ma in the central San Juan Mountains, constitute a bimodal volcanic suite that accompanied regional extension along the Rio Grande rift zone (Lipman and Mehnert, 1975). Occurs mainly in southeastern and northwestern parts of map area (sheets 1, 3)

Thb **Basaltic flows**—Mesa-capping erosional remnants of fine-grained dark-gray lava flows of silicic alkalic olivine basalt (trachybasalt) and basaltic andesite (52–57% SiO_2). Small sparse olivine phenocrysts, partly altered to rusty brown iddingsite, are typical. No obvious eruptive vents or concentrations of vent scoria were identified within the surviving erosional remnants of this unit within the map area. A conspicuous circular undrained depression in basalt along the flat crest of Fish Canyon Ridge (northwest corner, MM) appears to be a preserved lava drain-out feature, rather than a vent; no scoria, cinders, or oxidized rocks are present. K-Ar whole-rock ages (Steven and others, 1995) are 21.90±0.61 Ma (Elk Mountain, LH), 22.48±0.63 Ma (Copper Mountain, SC), and

23.13±0.64 Ma (ridge between Pierce and Elliot Creeks, LH). Thickness 0–125 m

Thr **Rhyolite lava, tuff, and intrusion**—Light-gray to white flow, volcanic neck, and pyroclastics (BR) of silicic alkalic rhyolite (76–77% SiO_2) containing a few percent phenocrysts (microperthitic sodic sn, qz, bi). K-Ar age on relict obsidian nodules (Apache tears), 22.4±0.9 Ma (Lipman and others, 1970; Hon and Mehnert, 1983)

Thbi **Basaltic intrusion**—Fine-grained dark-gray dike of silicic alkalic olivine basalt, exposed only in small cut bank of Rio Grande 4 km southeast of Creede (CR)

Tlp **Los Pinos Formation (Miocene and Oligocene)**—Weakly to nonindurated volcanic conglomerates and tuffaceous sedimentary rocks, poorly exposed beneath capping basaltic lava flows of the Hinsdale Formation on Heart Mountain (MH). Derived largely from adjacent constructional highlands of the Pagosa Peak Dacite and Huerto Andesite. Unit is much more widespread southeast of the map area (Lipman, 1975). Thickness, 0–25 m

OLIGOCENE VOLCANIC ROCKS

ROCKS OF THE CREEDE CALDERA CYCLE

The near-pristine morphology of the Creede caldera, which formed during eruption of the Snowshoe Mountain Tuff (fig. 5*A*, sheet 4), is spectacularly preserved for an Oligocene volcano, because erosion by the Rio Grande has preferentially removed weakly indurated caldera-filling sediments during the past few million years (Steven and Ratté, 1965). Definitive evidence of relations between rocks of the Creede caldera and the San Luis caldera complex has been frustratingly elusive, despite detailed mapping and abundant (but inconsistent) geochronologic data; the Creede caldera is tentatively interpreted as younger, based on diverse field and petrologic evidence (Lipman, 2000, p. 39, table 7)

Creede Formation—Moat sediments. After caldera collapse, sectors of the Creede caldera basin that were not filled by lava flows of Fisher Dacite were occupied by a shallow lake (Steven and Ratté, 1965; Barton and others, 2000), and tuffaceous sedimentary deposits of the Creede Formation accumulated within the lake and on lower slopes of adjacent caldera walls (Larsen and Crossey, 1996; Heiken and others, 2000). Original thickness of these untilted strata is at least 1,200 m, as indicated by a 700-m-elevation range in preserved surface exposures and an additional 500 m penetrated in Creede Scientific Drill Hole CCM-2 (CR; Hulen, 1992). Duration of sedimentation of the Creede Formation is estimated to have been 0.34 m.y. (Lanphere, 2000), between about 26.8 and 26.5 Ma

Tc **Fine-grained sedimentary deposits**—Finely laminated shale and well-bedded tuffaceous sandstone, representing shallow- to deep-water deltaic and lake deposits in the moat of the Creede caldera

Tcg **Conglomerates**—Coarse alluvial-slope wash and stream conglomerates along margin of the caldera north of Creede (Creede paleochannel of Steven and Ratté, 1965; Creede alluvial fan of Heiken and others, 2000) and on west side of resurgent dome. North of Creede, the cobbles and boulders include intracaldera Carpenter Ridge Tuff, Wason Park Tuff, andesite of Bristol Head, and phenocryst-rich dacite interpreted as derived from the Nelson Mountain and probably Rat Creek Tuffs (Lipman and Weston, 2001)

Tct **Travertine and calcareous tufa**—Widely distributed mounds and irregular bodies of porous bedded carbonate, interfingering with the sedimentary deposits, represent deposits of mineral springs active during filling of the Creede caldera moat

Tcaf **Dacitic ash-flow tuff**—Local nonwelded dacitic tuff, containing 10–25% phenocrysts (pl>bi, hbl, cpx), interbedded with sedimentary Creede Formation in lower Goose Creek (LH) and in the Creede Scientific Drill Holes. Probably distal pyroclastic deposits associated with eruptions of Fisher Dacite. Thickness, 0–15 m

Tcl **Landslide breccia**—Small exposures of monolithologic breccia at mouth of Elliot Creek (tributary of lower Goose Creek, LH), consisting of crystal-rich dacitic welded tuff, interbedded with sedimentary Creede Formation. Probably derived from Blue Creek Tuff on the east caldera wall. These small outcrops provide unique evidence for prolonged instability of the Creede caldera wall. Thickness, 0–10 m

Fisher Dacite—Postcaldera flows and domes of thick viscous lava erupted along the east to southwest margins of the Creede caldera, both before and after resurgent uplift of the caldera floor. Flows interfinger with and overlie sediments of the Creede Formation. Boundaries with South River Volcanics along south margin of the caldera are poorly constrained except where separated by Snowshoe Mountain Tuff, because lithologies overlap among these two caldera-filling lava assemblages. Maximum exposed thickness, >950 m, from Goose Creek to Copper Mountain

Tfl **Dacite lava flows**—Thick flows and domes of massive and flow-layered porphyritic dacite (62–66% SiO_2; 25–35% pl>>bi, hbl>cpx, sparse large sn). Flow layering dips gently within lower parts of flows, but steep ramp layers are common in upper parts, as illustrated by mapped foliations along the erosional upper surface of the Wagon Wheel Gap flow. The McCall Creek flow (BC, CR, SC) is a silicic dacite (67–70% SiO_2) that appears to have erupted early ($^{40}Ar/^{39}Ar$ age (bi), 26.63±0.09 Ma) onto the flat caldera floor prior to resurgence. Topographically high flows on Copper and Fisher Mountains are younger ($^{40}Ar/^{39}Ar$ ages (bi, sn), 26.2–26.4 Ma) and appear to postdate resurgence. Contacts are shown between some individual lava flows within unit. On high east side of Wagon Wheel Gap flow, an upper flow unit is marked by a subhorizontal vitrophyre zone, overlying steep flow ramps in a lower unit

Tfb **Flow breccia**—Traction breccia at margins of dacitic lava flows and domes. Only sufficiently thick to map locally, such as at forks of Bellows Creek (WW)

Tfa **Andesitic lava flows**—Local thin flows of sparsely porphyritic fine-grained andesite (56–61% SiO_2) that overlie discontinuous lenses of outflow Snowshoe Mountain Tuff southeast of South River Peak (SR). In places difficult to distinguish from lithologically similar underlying basaltic andesites of South River Volcanics (Tsrm); in real terms, these exemplify continuity of regional intermediate-composition volcanism, punctuated by a major event of explosive volcanism and caldera formation. K-Ar whole-rock age, 26.3±0.2 Ma

Tfv **Volcaniclastic rocks**—Bedded polylithic breccia, conglomerate, and finer-grained volcanic sediments derived from high-standing masses of Fisher Dacite, mainly representing deposition by synvolcanic mudflows. Accumulated as clastic aprons on flanks and between penecontemporaneous volcanoes south and west of Fisher Mountain

Tfi **Intrusions**—Dikes and plugs of porphyritic dacite, commonly with steep flow layering. A large body along the northwest Creede caldera margin (northeast corner, BH) alternatively may be a thick valley-filling lava flow, either Fisher Dacite or premonitory to the San Luis caldera complex. Correlation of dikes in Blue Creek and Miners Creek is uncertain; alternatively possibly related, respectively, to eruption of dacite flows of McClelland Mountain (Tmd) and the dacite of McKenzie Mountain (Tmcd)

Snowshoe Mountain Tuff—Product of caldera-forming eruption. Dacitic welded tuff (62–67% SiO_2, 35–45% pl>>bi>cpx>>hbl, sn, qz), forming thick densely welded accumulation within Creede caldera and thinner weakly welded outflow deposits locally preserved on high mesas, commonly where capped by basaltic lavas of the Hinsdale Formation southeast of caldera. Small erosional remnants designated as this unit on Palmer Mesa (ME) and west of Stone Cellar Campground (SA) may alternatively constitute late-erupted dacitic cooling subunits of the Nelson Mountain Tuff (Equity facies, Tnde), which is difficult to distinguish by petrologic characteristics. Both these units are characterized by similar phenocryst modes and relatively potassic sanidine compositions (Or_{68-70}). Snowshoe Mountain Tuff exposed on west slopes of Fisher Mountain (SC) represents early caldera-filling deposits, within a scallop in south caldera wall, that were truncated by continued subsidence (Lipman, 2000, fig. 13). Remnant magnetic polarity, normal

Tsp **Partly welded tuff**—Tan to gray weakly indurated tuff. Preserved as small erosional remnants of outflow sheet ($^{40}Ar/^{39}Ar$ age (bi), 27.08±0.25 Ma); mappable widely near top of intracaldera accumulation and locally along partial cooling breaks deeper within the caldera. Multiple cooling breaks especially well developed on east flank of resurgent dome ($^{40}Ar/^{39}Ar$ age (bi), 26.69±0.21 Ma). Thickness, 0–100 m

Ts **Densely welded tuff**—Red-brown to gray massive tuff forming bulk of intracaldera resurgent dome; no base exposed. Slopes north of Spar City are intensely shattered and brecciated but apparently in place and resulting from resurgent uplift (Steven and Ratté, 1973) rather than deposits of early landsliding from the south caldera wall. $^{40}Ar/^{39}Ar$ age (bi), 26.86±0.12 Ma. Thickness, 0 – >1,700 m

Landslide breccia member—Local lenses of chaotic landslide debris of precaldera rocks, interleaved with upper parts of intracaldera Snowshoe Mountain Tuff and banked against lower slopes of Creede caldera wall

Tsl **Mixed lithologies**—Poorly exposed massive breccia containing abundant andesitic clasts, probably derived mainly from the andesite of Bristol Head (Tba). Previously mapped as Huerto Andesite (Steven and Ratté, 1965) or Conejos Formation (Steven and others, 1974), but sparse fragments of Wason Park Tuff (Tw) demonstrate a younger age for the breccia. Virtually nonindurated matrix of crystal-rich biotite-bearing tuff locally obscurely exposed in roadcuts appears to be nonwelded Snowshoe Mountain Tuff. Preserved mainly against lower western caldera wall, along Hwy 149, south of Fir Creek (BH)

Tslw **Breccia with clasts of Wason Park Tuff**—Dominantly large chaotic blocks of Wason Park Tuff (Tw) along ridge between Soda and Leopard Creeks (LH); clasts of Wason Park and Blue Creek Tuffs (Tbc) beneath capping flow of Fisher Dacite (or upper slide breccia of dacitic lava?) on northwest ridge of Ute Peak (WW)

Tslc **Breccia with clasts of Carpenter Ridge Tuff**—Finely broken landslide breccia dominantly derived from Willow Creek and Campbell Mountain welding zones (Tcbw, Tcbc) on north caldera wall. Well exposed along northwest flank of resurgent dome, especially at Point of Rocks (CR) where previously interpreted as a flow-brecciated rhyolitic lava dome (Steven and Ratté, 1965, 1973). Also present as small poorly exposed patches capping some downdropped blocks within the Deep Creek graben, across the center of the resurgent dome. Several horizons of similar slide breccia near the top of intracaldera Snowshoe Mountain Tuff were penetrated in Creede Scientific drill holes (Hulen, 1992). Fragments in these landslide masses have unaltered plagioclase phenocrysts and near-magmatic K_2O/Na_2O ratios, rather than the extreme K-metasomatic alteration and clay pseudomorphs after plagioclase that characterize exposures of these welding zones on the northwest to northeast caldera walls, indicating that the potassic alteration of the welded tuffs within the Bachelor caldera postdated formation of the Creede caldera

Tslf **Breccia with clasts of Fish Canyon Tuff**—Small patches of monolithologic breccia containing shattered blocks of Fish Canyon Tuff (Tfc) as much as several tens of meters across. Best exposed in lower Leopard and lower Blue Creeks (WW, LH)

Tslm **Breccia with clasts of Masonic Park Tuff**—Thick unstratified monolithologic breccia containing shattered blocks of Masonic Park Tuff (Tmp) as much as several tens of meters across. Best exposed in lower Leopard Creek (LH)

Tsld **Breccia with dominant clasts of dacitic lava**—Large shattered blocks of porphyritic dacite, beneath Wagon Wheel Gap flow of Fisher Dacite along Rio Grande (WW). Probably derived from dacite flows of McClelland Mountain (Tmd), on eastern caldera wall

Tsla **Breccia with clasts of andesitic lava**—Blocks of fine-grained andesite lava from multiple sources (Conejos Formation, South River Volcanics, andesite of Bristol Head?), interleaved with upper parts of intracaldera tuff especially along west flank of resurgent dome and against western caldera wall. In places, also contains subordinate fragments of intracaldera Carpenter Ridge Tuff and Wason Park Tuff

ROCKS OF THE SAN LUIS CALDERA COMPLEX

The San Luis caldera complex (fig. 5*A*, sheet 4) is the composite source for three successive large ash-flow eruptions and associated overlapping caldera-subsidence events that successively produced the Rat Creek, Cebolla Creek, and Nelson Mountain Tuffs (Lipman and others, 1989; Lipman, 2000). After each ash-flow eruption, the associated caldera was variably filled by andesitic to rhyolitic lavas. Available isotopic ages are in the general range 26–27 Ma, but in detail, some are inconsistent with the mapped stratigraphic sequence (Lipman, 2000, fig. 11), even when analyzed in replicate (M.A. Lanphere, unpub. data, 1988–99)

Rocks of the Nelson Mountain caldera cycle

The Nelson Mountain Tuff is the most voluminous outflow deposit erupted from the San Luis caldera complex, and its eruption was followed by growth of large postcaldera volcanoes on its east and west flanks, roughly concurrent with resurgent uplift of the caldera interior. Fieldwork in progress (2002) suggests that the polycyclic Cochetopa caldera, which lies mainly north of the map area, last subsided passively during early stages of the Nelson Mountain eruption, then was flooded by later-erupted Nelson Mountain Tuff from vents within the San Luis complex

Baldy Cinco Dacite—Western postcaldera volcano. Lava flows, volcaniclastic rock, and intrusions forming an eroded stratocone at southwest margin of San Luis caldera complex (BC). Dominant characteristic rock type is gray dacite, containing large sanidine phenocrysts. Contacts are shown between some major lava flows within unit. Maximum preserved thickness, >300 m

Intrusions—Texturally and compositionally diverse intrusive rocks (BC) defining the core of the eroded Baldy Cinco volcano in upper Rough Creek and the intrusive root of a possible second volcanic center at the head of Mineral Creek ($^{40}Ar/^{39}Ar$ age (sn), 25.69±0.17 Ma)

Tbir **Rhyolite**—Dike and plug (or vent dome) of sparsely porphyritic flow-layered gray to tan rhyolite (72–74% SiO_2; 10–15% pl>sn>bi). Resembles Mineral Mountain Rhyolite, but intrudes and overlies Nelson Mountain Tuff in upper Rough Creek (BC)

Tbi **Porphyritic dacite**—Gray to tan massive dacite. The largest intrusions are a high-standing elliptical stock (3 km in long dimension) of coarsely porphyritic dacite at the head of Mineral Creek (65–66% SiO_2; 10–15% pl>large sn>qz, bi) and a severely hydrothermally altered and pyritized porphyry body in upper Rough Creek (62–65% SiO_2; 20–25% pl>>bi>cpx, hbl)

Tbia **Andesite**—Fine-grained dense dark-gray andesite as small irregular intrusions (east of upper Rough Creek) and possible lava flows low in section northeast of Baldy Cinco. Alternatively, lavas could be western outliers of andesitic Stewart Peak Volcanics (Tsa)

Tbf **Lava flows**—Gray to tan porphyritic dacite (65–66% SiO_2; 15-25% pl>large sn>bi, cpx), forming bulk of the preserved Baldy Cinco volcano ($^{40}Ar/^{39}Ar$ ages (sn); 26.45±0.16 Ma, 3 km northeast of Baldy Cinco; 25.95±0.07 Ma, north slope of upper Miners Creek)

Tbv **Volcaniclastic rocks**—Crudely bedded mudflow deposits and coarse breccias derived mainly from coarsely porphyritic dacite lava flows and domes; most widespread low in Baldy Cinco edifice, on outer west flank of caldera complex

Stewart Peak Volcanics—Eastern postcaldera volcano. Lava flows and associated volcaniclastic rocks, filling eastern moat area of Nelson Mountain caldera and constituting outward-dipping erosional remnants of a large stratocone centered on upper Spring Creek (SL). Andesitic compositions are most common, especially low in unit; flows and breccias of porphyritic dacite become abundant high in some sections. Boundaries between some dacite flows are obscure; individual flows may be as much as 200 m thick; andesitic flows tend to be thinner (10–50 m). Several individual flows and domes (north of Nelson Mountain and west of San Luis Pass; SL) are mingled nearly aphyric dark-gray andesite and more porphyritic light-gray dacite. Contacts are shown between some major lava flows within unit. Thickness, 0 – >500 m

Tsir **Resurgent intrusions**—Equigranular to porphyritic fine- to medium-grained hypabyssal granitic rocks (mainly granodiorite, 61–65% SiO_2), intrusive into intracaldera Nelson Mountain Tuff (Equity facies, Tnde) on west and northwest slopes of San Luis Peak

Tsi **Porphyritic dikes and sills**—Widely scattered gray dacitic-andesitic intrusions (59–64% SiO_2, 5–20% pl>>hbl, cpx). Dacitic compositions are most common, especially in larger bodies. Andesite dikes locally intrude dacite bodies

Mafic dacite—Light-gray to tan rocks (62–66% SiO_2, 20–35% large phenocrysts of pl>cpx, bi; some contain hbl in place of cpx)

Tsd **Lava flows**—A single widespread flow caps Continental Divide at head of Mineral Creek (BC); also a common rock type high on southeast flanks of the Stewart Peak volcano. $^{40}Ar/^{39}Ar$ ages (bi), 26.49-26.86 Ma (five samples)

Tsdv **Volcaniclastic rocks**—Mudflow deposits and coarse breccias derived from porphyritic dacite lava domes

Porphyritic to fine-grained andesite—Dark-gray rocks (58–62% SiO_2, 15-30% pl>>cpx; sparse bi and (or) hbl in some flows). Finely porphyritic to aphanitic rocks form volumetrically minor local flows, especially low in unit

Tsa **Lava flows**—Most voluminous lava type in unit, especially on northern preserved flanks of Stewart Peak volcano

Tsv **Volcaniclastic rocks**—Mainly mudflow deposits derived from andesitic volcanic centers

Tss **Tuffaceous sedimentary rocks**—Pale-yellow to tan fine-grained volcaniclastic rocks, forming poorly exposed discontinuous lenses between Nelson Mountain Tuff and overlying intracaldera lava flows and tuffs. Includes finely laminated lacustrine sediments, tuffaceous sandy fluvial beds, and local bedded carbonate deposits. Mostly poorly exposed as float in landslides and in small gullies. Thickness, 0–30 m

Nelson Mountain Tuff—Product of caldera-forming eruption. Regional ash-flow sheet and thick intracaldera fill; grades upward in composition from rhyolite to dacite (73–63% SiO_2). Map subunits are primarily compositional and welding zones, rather than strictly sequential stratigraphic units. Normal magnetic polarity, with relatively steep inclination becoming nearly vertical high in some sections (Lipman, 2000, fig. 10). Apparent $^{40}Ar/^{39}Ar$ ages (sn) on outflow tuff at several localities, as young as 26.1 Ma, are inexplicably younger than either seemingly correlative intracaldera Equity facies or some stratigraphically overlying lava flows (Lipman, 2000, fig. 11 and discussion therein)

Tndn **Nonwelded to partly welded dacite**—Uppermost proximal Nelson Mountain Tuff, both within and locally outside the San Luis Peak caldera complex. Yellow-tan to gray, porous, vapor-phase-crystallized to glassy. Grades down into more welded dacitic Nelson Mountain Tuff (Tnd, Tnde). Crystal rich; phenocrysts similar to welded dacite (Tnde). Thickness, 10–50 m

Tnde **Welded mafic dacite (Equity facies)**—Dacite and mafic dacite, welded zone; dense dark-gray devitrified main part of the intracaldera Nelson Mountain Tuff (63–66% SiO_2; 25–45% pl>>bi, cpx>sn, hbl, qz). Characterized by relatively potassic sanidine compositions (Or_{68-70}). Dashed lines indicate locally conspicuous welding boundaries within caldera; thick parts commonly have propylitic alteration. Within caldera on slopes adjacent to Bondholder Meadow (SP), includes basal zone, as much as 100 m thick, that is characterized by scattered rhyolitic pumice fragments and is obscurely transitional into silicic dacite (Tnd). Essentially all of this unit south of the Continental Divide occupies a broad paleovalley in the southern wall of the source caldera, as indicated by underlying Carpenter Ridge Tuff exposed in the triangular intrusion-uplifted area called the “Equity block” (fig. 6, sheet 4) and penetrated in numerous mining-exploration drill holes. The paleovalley was structurally controlled by north-trending keystone graben faults (northern extensions of Amethyst and Bulldog Mountain faults) in the Bachelor caldera resurgent dome. Thin outflow deposits present only as uppermost partly welded tuff near the caldera (for example, on Nelson Mountain, Snow Mesa); grade downward into silicic dacite tuff (Tnd). Most mafic dacite of the Equity facies is petrologically similar to Snowshoe Mountain Tuff (Ts). $^{40}Ar/^{39}Ar$ ages (sn); 27.06±0.16, 26.68±0.15, 26.77±0.17 Ma. Thickness, 20–50 m in outflow sheet; within caldera, thickness increases from <200 m southward to >1,200 m with no base exposed, indicating asymmetrical caldera subsidence

Tnd **Welded silicic dacite and transitional rhyolite-dacite**—Transitional rhyolite-silicic dacite welded zone (67–72% SiO_2; 15–25% pl>sn, bi>cpx, qz). Characterized by less potassic sanidine compositions (Or_{64-67}) than mafic dacite of the Equity facies (Tnde). Forms brownish-gray main cliff-forming welded caprock of outflow Nelson Mountain Tuff, commonly with black vitrophyre (3–5 m) near base. Contains pumice lenses of both crystal-poor rhyolite and crystal-rich dacite. Grades downward into rhyolite (Tnr). Thickness, 20–50 m outside caldera; not mapped separately within caldera

Tnr **Welded to partly welded rhyolite**—Light-gray and tan to light-reddish-brown welded tuff (71–74% SiO_2; 5–15% pl> sn>bi>>cpx). Dark-gray pumice fiamme, characterized by flattening ratios <10:1, are commonly glassy and set in orange-brown devitrified matrix, forming colorful “halloween” rock (glassy black pumice lenses in devitrified red-brown matrix). Locally intensely zeolitized or argillically altered. Best exposed along Saguache Creek (SA), where tuff ponded in northern moat of La Garita caldera and at least four welded zones are separated by less welded tuff. Grades into less welded tuff (Tnn). Thickness, 0–200 m

Tnn **Nonwelded to partly welded rhyolite and silicic dacite**—Gray porous pumiceous tuff containing common small angular fragments of andesitic lava. In most sections, originally glassy; now widely argillized or zeolitized. Some thick accumulations are vapor-phase crystallized, even where nonwelded. Commonly poorly exposed due to weak induration and to cover by talus from welded caprock (Tnd). Flow-unit partings, locally marked by thin crystal-rich surge beds and accretionary lapilli, are present in some well-exposed sections. Phenocrysts (typically 5–10% pl, sn>bi) are similar to welded rhyolite (Tnr). Thickness, 10–250 m; greatest in upper Miners Creek (BC) where ponded within Rat Creek caldera and in Cathedral-Mineral Creek area (MM) where ponded within Cebolla Creek caldera

Tnns **Nonwelded surge-bedded rhyolite**—Poorly exposed nonwelded tuff characterized by exceptionally developed bedding, marked by concentrations of crystals and small lithic fragments, resulting from sequential emplacement of pyroclastic surges. Phenocryst phases (pl, sn>bi) are similar to welded and nonwelded rhyolite (Tnr, Tnn). Mapped as separate unit in Cañon Nieve area (northwest corner, PT). Thickness, 0–75 m

Tnxp **Nonwelded crystal-poor rhyolite**—Poorly exposed nonwelded fine-grained glassy and zeolitic rhyolitic tuff, lacking large pumice or common lithic fragments and containing <5% sn, pl>bi. Exposed only on lower south-facing slopes of upper Miners Creek (BC). Contact with overlying Nelson Mountain Tuff (Tnn) not exposed; possibly related to Mineral Mountain Rhyolite (Tmmt) rather than to Nelson Mountain Tuff(?). Thickness, 0–100 m

Landslide breccia lenses—Local landslide deposits, interleaved with intracaldera Nelson Mountain Tuff, that were derived from oversteepened caldera walls during eruption-related subsidence

Tnlr **Breccia lenses with clasts of Mineral Mountain Rhyolite**—Fragments of sparsely porphyritic rhyolitic lava as much as several tens of meters across, in a matrix of comminuted rock fragments. Interleaved with Equity facies of Nelson Mountain Tuff west of Bondholder Meadow (SP). Derived from lava flows of Mineral Mountain Rhyolite (Tmm) exposed along the north margin of the Nelson Mountain caldera. Thickness, 0–100 m

Tnld **Breccia lenses with clasts of dacitic lavas**—Fragments of porphyritic dacite as much as several tens of meters in diameter, set in a matrix of comminuted rock fragments. Best exposed at the head of East Willow Creek, just south of the Continental Divide (SL). Probably derived from nearby precaldera dacite of East Willow Creek (Twl) on the southeast Nelson Mountain caldera wall. Thickness, 0–100 m

Tnlf **Breccia lenses with clasts of Fish Canyon Tuff**—Fragments of intracaldera Fish Canyon Tuff (La Garita Member, Tfg) as much as several tens of meters in diameter, set in a matrix of finely comminuted Fish Canyon Tuff. Best exposed south of Stewart Creek (SP). Derived from La Garita Mountains along east caldera wall. Thickness, 0–100 m

Rocks of the Cebolla Creek caldera cycle

Eruption of the compositionally distinctive Cebolla Creek Tuff caused subsidence of a large caldera, now largely concealed beneath the Nelson Mountain caldera and flanking postcollapse volcanoes

Tst **Tuff and travertine**—Poorly exposed bedded tuff of uncertain origin within caldera at head of East Willow

Creek (SL); may be correlative with tuffaceous sediments of Mineral Mountain Rhyolite (Tmmt). Also small irregular body of porous bedded carbonate, interfingering with local sediments (Tmmt) along lower Mineral Creek (MM) and representing deposits of mineral springs active during filling of the Cebolla Creek caldera

Mineral Mountain Rhyolite—Bulbous flows of phenocryst-poor flow-laminated rhyolitic lava, interpreted as post-subsidence fill of the Cebolla Creek caldera. $^{40}Ar/^{39}Ar$ age (bi), 27.00±0.19 Ma on Mineral Mountain

Tmm **Crystal-poor rhyolite flows and domes**—Light-gray flow-laminated to massive phenocryst-poor lava (72-75% SiO_2; 2–5% pl>>bi>sn). Carapace breccias and steeply dipping ramp structures are well developed at flow tops. Thick perlitic glass zones at some flow margins may reflect interaction with wet sediments or shallow lake deposits. Individual flows are as much as 200 m thick; total thickness, >900 m

Tmmt **Crystal-poor tuff and tuffaceous sediments**—Thin beds of crystal-poor white tuff, probably deposited by combined tephra-fall, surge, and aqueous processes. Overlies Cebolla Creek Tuff (Tcc) and flanks of Mineral Mountain lavas in lower Mineral Creek and east of Pasture Creek (MM). Thickness, 0–50 m

Tmmi **Dacitic-rhyolitic intrusion(?)**—Compositionally varied dike or local flow (65–72% SiO_2; 5–25% pl>sn>bi), poorly exposed along Mineral Creek

Tcma **Local andesitic lava flows**—Small exposures of finely porphyritic plagioclase andesite, which underlie silicic lavas of Mineral Mountain Rhyolite along Mineral Creek, tentatively grouped as lithologically atypical parts of the lava fill of the Cebolla Creek caldera. These poorly exposed rocks could alternatively be anomalously mafic Mineral Creek Dacite (Tmid) or, perhaps, even high-standing Conejos Formation lavas (Tca) along the western topographic wall of the Cebolla Creek (and La Garita?) caldera. Thickness, >15 m

Dacite of East Willow Creek—Flow-layered gray dacitic lava flow and flow breccia (65–66% SiO_2; 25–30% pl>>bi, hbl>cpx, qz, sn) overlying intracaldera Cebolla Creek Tuff (Tccd) at the head of East Willow Creek and across the Continental Divide to the north (SL). Normal magnetic direction, similar to that of Cebolla Creek Tuff. Thickness, 0–75 m

Twl **Dacite lava**—Flow layered, gray, devitrified

Twlb **Carapace breccia**—Consists of angular blocks, mostly glassy

Cebolla Creek Tuff—Caldera-forming eruption. Distinctive compositionally uniform ash-flow sheet of mafic dacite, characterized by abundant phenocrystic hornblende relative to augite and by lack of sanidine. Basal crystal- and lithic-rich surge beds, about 1 m thick, present in many sections, are well exposed along Cebolla Creek (MM) and at Wheeler Geologic Monument (HM). Previously mapped as part of the Nelson Mountain or Rat Creek Tuffs (Steven, 1967; Steven and Ratté, 1973; Steven and Bieniewski, 1977). Weakly welded deposits were widely eroded prior to eruption of Nelson Mountain Tuff, which directly overlies older units in many places within general distribution area of the Cebolla Creek. Distinctive normal magnetic direction (Lipman, 2000, fig. 10). $^{40}Ar/^{39}Ar$ age (hbl), 26.71±0.37 Ma at Los Pinos Pass; 26.26±0.31 Ma at Wheeler Geologic Monument

Tccd **Densely welded mafic dacite**—Dark-gray massive intracaldera tuff (63–64% SiO_2; 35% pl>>bi, hbl>>cpx, qz), exposed along the southern Cebolla Creek caldera wall at the head of East Willow Creek and across the Continental Divide to the north (SL). Strongly devitrified, except for black basal vitrophyre (2–3 m) along caldera-wall contact. Thickness, >250 m, with no base exposed

Tcc **Partly welded mafic dacite**—Gray to light-brown, glassy to weakly vapor-phase-devitrified tuff (62–66% SiO_2; 25–40% pl>>bi, hbl>>cpx), typical of proximal outflow sections. Contains orange-brown to black pumice fragments (2–5 cm across) and abundant small (1–3 cm across) andesitic lithics. Black vitrophyre near base of most welded sections. Thickness, 25–50 m

Tccn **Nonwelded mafic dacite**—Light-gray glassy tuff in thin and distal outflow sections (for example, ridge between West Willow and Rat Creeks; SL); in many places too thin to map separately from partly welded tuff (Tcc). Petrographically similar to partly welded tuff (Tcc). Thickness, 0–30 m

Rocks of the Rat Creek caldera cycle

The earliest ash-flow sheet of the San Luis sequence, the Rat Creek Tuff, is the smallest in volume, the most restricted in known areal extent, and the least understood. Evidence for the Rat Creek caldera (Lipman, 2000, p. 32–33) is also limited, because of cover by younger rocks

Mineral Creek Dacite—Postcaldera volcanism. Altered biotite-rich lavas and tuffs in upper Mineral Creek, interpreted as high-standing constructional fill within the Rat Creek caldera because these rocks are truncated along the Cebolla Creek caldera wall and unconformably onlapped by units of Mineral Mountain Rhyolite. Previously mapped variously as Nelson Mountain Tuff and intrusive dacite (Steven, 1967; Steven and Bieniewski, 1977). Thickness, >550 m

Tmix **Crystal-rich rhyolite lava flows**—Gray to tan thick flows (70–72% SiO_2; 15–20% pl>>bi), commonly containing black basal vitrophyres and underlying traction breccias

Tmid **Silicic dacite lava flows**—Variably altered flow-layered gray to light-brown flows (68–70% SiO_2; 20–25% pl>>bi>hbl, cpx)

Tmit **Silicic dacite tuff**—Yellow-ochre to tan zeolitic lithic-rich tuff (68–70% SiO_2; 15–20% pl>>bi>altered cpx?), interleaved with lavas (Tmid). Poorly exposed, mainly as float, but appears to be massive poorly bedded ash-flow deposits. Everywhere nonwelded, in places severely modified by hydrothermal alteration

Tmis **Tuffaceous sediments**—Yellow-tan zeolitic bedded tuff. Exposed entirely as float; may include ash-fall, surge, and water-reworked tuffs. Thickness, 0–50 m

Rat Creek Tuff—Caldera-forming eruption. Compositionally zoned ash-flow sheet (65–73% SiO_2) of relatively modest volume, generally poorly exposed beneath Nelson Mountain Tuff. Map subunits are primarily welding and compositional zones, rather than strictly sequential stratigraphic units. Remanent magnetic polarity, normal. Weakly welded deposits were widely eroded prior to eruption of Cebolla Creek Tuff, which directly overlies older units in many places within general distribution area of the Rat Creek Tuff. Mean of two $^{40}Ar/^{39}Ar$ ages (bi, in Rat Creek and on southeast slope of Nelson Mountain), 26.47±0.12 Ma. Thickness, typically 0–100 m; locally >250 m where ponded against La Garita caldera wall at Cathedral (MM)

Trdn **Nonwelded to partly welded dacite tuff**—Locally preserved upper part of the Rat Creek Tuff; yellow-tan to gray, porous, vapor-phase crystallized. Grades downward into welded silicic dacite and dacite (Trd). Phenocrysts same as in welded dacite (Trd)

Trd **Welded dacite tuff**—Light-brown devitrified upper part of proximal Rat Creek Tuff (65–70% SiO_2; 20–35% pl>>bi, sn>cpx). Sanidine compositions are similar to those in the outflow caprock of Nelson Mountain Tuff (Or_{65-67}). Commonly characterized by glassy black flattened pumices in brownish devitrified matrix where partly welded at base of zone, resulting in colorful halloween texture. Grades downward into rhyolitic tuff (Trr)

Trr **Nonwelded to partly welded rhyolite tuff**—Poorly exposed light-gray to yellow glassy pumiceous tuff (70–73% SiO_2; 5–20% pl, sn>bi>>cpx), commonly containing several percent centimeter-size fragments of andesitic to rhyolitic rocks. Glassy, ranging to zeolitic or argillically altered tuff. Grades upward into silicic dacite (Trd). High in some sections, sparse dark-gray crystal-rich scoria of andesitic to dacitic composition mark distal facies of the dacite tuff zone (Trd); especially well exposed at Wheeler Geologic Monument (HM) and along the southwest nose of Table Mountain (northern BH). Difficult to distinguish from rhyolitic Nelson Mountain Tuff (Tnn) in absence of intervening Cebolla Creek Tuff (Tcc)

Trrl **Lithic-rich zone in rhyolite tuff**—Nonwelded tuff containing abundant fragments of andesitic to rhyolitic lava, 5–20 cm in diameter; mainly exposed as float on south side of Nelson Mountain (SL). The abundant lithic fragments (lag breccia?) in this small local unit provide important evidence for deposition in proximity to the Rat Creek caldera source. Thickness, 0–10 m

Lava flows premonitory(?) to San Luis Caldera complex

Several petrologically diverse lava-flow assemblages, which overlie Wason Park Tuff adjacent to the southeast to southwest margins of the San Luis caldera complex, may represent initial eruptions of this “caldera cycle”, based on their ages, distributions, and compositions. Assignment to San Luis “cycle”, rather than to distal late stages of the earlier South River caldera cycle, is based in part on normal magnetic polarities of these flows

Dacite of Captive Inca—Tan to brown lava dome and associated volcaniclastic rocks (69–70% SiO_2; 15–25% pl>>bi, hbl>cpx). Named after the Captive Inca Mine, west of Nelson Mountain (SL). Previously mapped by Steven and Ratté (1973) as “Rat Creek volcano” along West Willow Creek. Overlies andesite lava flows of Bristol Head (Tba; relation known from mining exploration drill core); onlapped by Rat Creek Tuff. Magnetic polarity, normal. Thickness, 0–200 m

Tcds **Volcaniclastic sedimentary rocks**—Small outcrops of mainly conglomeratic mudflows, derived from the Captive Inca lava dome. Thickness, 0–20 m

Tcdf **Dacite flow**—Flow-layered to massive interior of lava dome that is largely devitrified

Tcdb **Flow breccia**—Basal and upper carapace breccia of lava dome, mostly originally glassy, but now variably altered to clays and zeolites. Thickness, 0–30 m

Tcdi **Vent intrusion**—Steeply flow-layered central zone, in which glassy and devitrified zones alternate on centimeter to meter scale

Ttd **Rhyolite of Table Mountain**—Large gray to tan porphyritic lava dome (73% SiO_2; 15% pl>sn>bi). Well-developed carapace breccia along crest of Table Mountain (BC) indicates near-total thickness of the lava dome is preserved. Overlies Wason Park Tuff; onlapped by Nelson Mountain Tuff. Magnetic polarity, unknown. Thickness, 0–200 m

Dacite of McKenzie Mountain—Tan to brown flow-layered lava dome (64–65% SiO_2; 20–30% pl>>bi, cpx). Formerly considered by Steven and Ratté (1973) to be a late lava flow of Fisher Quartz Latite on wall of Creede caldera but unconformably onlapped by Rat Creek and Nelson Mountain Tuffs. Differs from adjacent dacite of Captive Inca in absence of hornblende phenocrysts; no direct-contact age relation was found, but the dacite of McKenzie Mountain is inferred to be older, based on its reversed remanent magnetic polarity. $^{40}Ar/^{39}Ar$ age (bi), 26.40±0.13 Ma. Thickness, 0–200 m

Tmcd **Dacite flow**—Flow-layered to massive, largely devitrified interior of lava dome

Tmcb **Flow breccia**—Basal and upper carapace breccia of lava dome, mostly originally glassy but now partly altered to clays and zeolites

Tmci **Intrusions**—Dikes and vent neck occurring as steeply flow layered rocks, marked by structural discontinuity with main body of lava dome. On southeast flank of geographic McKenzie Mountain, a 400-m-wide slab of Wason Park Tuff has been tilted upward 30° and uplifted as much as 250 m by the endogenous interior of the dome

Dacite of Silver Park—Two thick compositionally similar flows of gray to tan mafic dacite (62% SiO_2; 25% pl>>cpx>>bi), capping the tableland of Wason Park Tuff southeast of La Garita Mountains (WW). Eruptive vent(s) not located. Despite considerable distance from the caldera cluster, this unit tenuously assigned to the San Luis caldera cycle (Lipman, 2000, p. 32) rather than South River, based on its normal magnetic polarity (D. Champion, written commun., 1999). Maximum thickness, >200 m

Tsf2 **Flow 2**—Areally restricted erosional remnants of upper flow, resting directly on steeply dipping ramp structures interpreted as marking the top of flow 1

Tsf1 **Flow 1**—Widespread lower flow, covering an area of about 50 km^2

Andesite of Bristol Head—Lava flows and associated breccias of aphyric to sparsely porphyritic gray andesite and capping flow of mafic dacite. No vent structures located, but geographically separate thick accumulations on Bristol Head and north of Bulldog Mountain (CR) indicate multiple eruptive centers. May constitute early peripheral eruptions of the San Luis caldera complex; alternatively, distal South River Volcanics erupted from outlying northern vents. Magnetic polarity, unknown. Thickness, 0–200 m

Tbd **Mafic dacitic flow and breccia**—Thick porphyritic biotite-bearing flow, capping Bristol Head (62–63% SiO_2; 20–30% pl>>bi>cpx)

Tba **Andesitic flows**—Aphanitic to finely porphyritic andesite forming many thin (2–10 m) lava flows (55–59% SiO_2; 5–10% pl>>hbl, cpx)

Tbav **Andesitic volcaniclastic rocks**—Crudely bedded conglomerates and breccias, interleaved with Bristol Head lava flows; largely deposited by mudflows derived from contemporaneous volcanic edifices. Obscure contact with lithologically similar volcaniclastic facies of the underlying Huerto Andesite (Thv) on steep southwest face of Bristol Head is marked by thin (0.5–1 m) ash-cloud veneer of Wason Park Tuff (Tw). Thickness, as much as 125 m on east slopes of Bristol Head

ROCKS OF THE SOUTH RIVER CALDERA CYCLE

The South River caldera, resulting from eruption of the Wason Park Tuff, is defined by a steep caldera-wall unconformity that juxtaposes the caldera-filling South River Volcanics against flat-lying regional ash-flow tuffs, now exhumed along the arcuate drainages of Red Mountain and Goose Creeks (fig. 5*B*, sheet 4). Erosion along Goose Creek, near Lake Humphreys (LH), has also exposed a thick section of densely welded tuff, interpreted as resurgently uplifted intracaldera Wason Park Tuff

South River Volcanics—Caldera fill. Andesitic-dacitic lavas and volcaniclastic sedimentary rocks are the dominant fill of the South River caldera (Yager and others, 1991). Constitute deeply eroded lower parts of large stratocones, as indicated by cross-cutting cogenetic intrusions at high present-day topographic levels. Lava-flow lithologies interfinger more complexly than mapped in many places. Contacts are shown between some prominent flows within subunits. Distinction from Fisher Dacite (Tfl) uncertain for some flows in northern areas. Thickness in southern parts of the caldera exceeds 900 m, with no base exposed

Tsri **Intrusions**—Andesitic dikes and arcuate-trending irregular bodies of dark-gray andesite to fine-grained diorite and granodiorite (54–65% SiO_2; pl>>hbl, cpx±bi) west and southwest of South River Peak and to the east near Goose Creek (SR), interpreted as discontinuous near-roof levels of a ring intrusion along the south margin of the South River caldera. Eastern body may be older, alternatively constituting an intrusive center for the thick hornblende-bearing lavas of Huerto Andesite exposed to the east at Table Mountain. The high-standing margin of the easternmost intrusion (south of the Continental Divide) is intensely brecciated. One body (Red Mountain, PM) contains a mappable upward-rafted inclusion (40 m diameter) of Precambrian quartzite (p€q). Pyritic and argillic hydrothermal alteration is locally intense along margins of intrusions and adjacent rocks. Dikes of porphyritic dacite and andesite radiate outward from several high-standing intrusive centers

Tsrx **Xenocrystic andesite lava flows**—Aphanitic to finely porphyritic dark-gray andesite at stratigraphically high levels near locally named "Red Mountain" (Point Ivy, northeast PM), containing xenocrystic quartz and sparse small phenocrystic hornblende (56–60% SiO_2; 5–20% small pl>hbl, cpx, qtz). Resembles xenocrystic flows of Hinsdale Formation in southeastern San Juan Mountains (Lipman and Mehnert, 1975), but more silicic and older. K-Ar whole-rock age, 27.25±0.20 Ma, close in time to Wason Park Tuff

Tsrb **Biotite dacite lava flows**—Light-gray coarsely porphyritic dacite, containing abundant phenocrystic biotite (64–66% SiO_2; 20–30% large pl>>bi, hbl>cpx±sn). Most abundant in valley bottoms, low in exposed sections, and in northern areas. Distinguished, in places only with considerable uncertainty, from lithologically similar flows of Fisher Dacite on basis of stratigraphic and topographic relations. Large ridge cap east of Ivy Creek (SC) may be an extension of Fisher Dacite, but diagnostic petrologic criteria are lacking

Tsrh **Mafic dacite lava flows**—Gray porphyritic dacite, containing abundant phenocrystic hornblende (62–64% SiO_2; 15–25% pl>hbl>bi, cpx). Dominant fill lithology in northeastern part of caldera, especially near Beautiful Mountain

Tsra **Hornblende andesite lava flows**—Gray finely porphyritic andesite, containing conspicuous hornblende phenocrysts (58–62% SiO_2; 15–30% pl>>hbl>cpx). Dominant fill lithology in southern part of caldera. $^{40}Ar/^{39}Ar$ age (hbl) for capping flow on South River Peak, 27.02±0.37 Ma

Tsrm **Andesite lava flows**—Dark gray aphanitic to finely porphyritic andesite, lacking conspicuous hornblende (59–60% SiO_2; 20% pl>cpx>>hbl?). Volumetrically minor unit

Tsrv **Volcaniclastic rocks**—Coarsely bedded polylithic breccia, conglomerate, and finer-grained volcanic sediments, mainly representing proximal deposition by synvolcanic mudflows. Accumulated as clastic aprons on flanks and between penecontemporaneous South River volcanoes

Tsrt **Caldera-wall talus**—Local lenses of coarse volcaniclastic breccia, underlying and irregularly interfingering with lava flows of South River Volcanics. Mapped only along South River caldera wall southeast of Beautiful Mountain (SR). Clasts are dominantly intermediate composition lavas probably derived from the thick Huerto Andesite on Table Mountain to the east, but sparse fragments of Wason Park and Blue Creek Tuffs indicate deposition during or after subsidence of South River caldera. Maximum thickness, 125 m

Wason Park Tuff—Distinctive regional ash-flow sheet of crystal-rich rhyolite (Ratté and Steven, 1967; Webber, 1988); dacitic intracaldera tuff is exposed locally near Lake Humphreys. More phenocryst rich and alkalic than other San Juan rhyolitic tuff sheets (Lipman and others, 1978); characterized by distinct tabular morpholology and sodic composition (Or_{55-60}) of sanidine phenocrysts. $^{40}Ar/^{39}Ar$ age (bi), 27.17±0.12 Ma. Remanent magnetic polarity, reverse. Cliff-forming outflow tuff sheet is as much as 200 m thick where ponded within moat of La Garita or Bachelor calderas

Twcd **Intracaldera dacitic tuff**—Dark-gray massive densely welded tuff (63–67% SiO_2; 30–40% pl>>sn, bi>cpx), variably propylitically altered. More mafic and phenocryst rich than outflow tuff sheet. Previously mapped as Mammoth Mountain Tuff (Steven and others, 1974); identification as part of the Wason Park based largely on distinctively sodic compositions (Or_{55-60}) and large tabular little-broken habit of sanidine phenocrysts (Lipman, 2000, p. 30). Obscure pumice textures and scarcity of lithic fragments permit confusion with lava flows of Fisher Dacite (Tfl) in some outcrops. Arcuate pattern of dips as steep as 50° to southeast appear to define flank of resurgently uplifted caldera floor, which was subsequently truncated along wall of Creede caldera. Basal contact not exposed; minimum thickness, >600 m

Twn **Nonwelded to partly welded tuff**—Upper light-gray vapor-phase crystallized tuff. Grades downward into welded tuff (Tw). Mapped locally where widely preserved and more than about 20 m thick, such as on tableland between Creede caldera and La Garita Mountains

Tw **Densely welded tuff**—Red-brown devitrified interior of cooling unit of compositionally and texturally distinctive rhyolite, locally grading upward into silicic dacite (68–74% SiO_2; 10–30% pl, sn>>bi>cpx). Phenocryst content increases (and silica decreases) upward to top of densely welded zone, then decreases in winnowed less welded upper part. Sanidine phenocrysts of main outflow sheet ($Or5_{58-52}Ab_{38-42}An_2Cs_{1-3}$; Webber, 1988) are the most sodic of any rhyolitic tuff erupted from the central caldera complex. Characterized by white collapsed pumice lenses as much as 0.3 m long, consisting of intergrown alkali feldspar and tridymite. In proximity to South River caldera, the pumice lenses are fluidal, with elongation ratios as much as 100:1. Commonly contains black basal vitrophyre as much as 5 m thick

ROCKS OF THE BLUE CREEK CYCLE (caldera concealed)

The Blue Creek Tuff was erupted from a source, almost certainly involving caldera subsidence (based on large eruptive volume), that is entirely concealed beneath the younger South River and (or) Creede calderas. The Blue Creek Tuff is both underlain and overlain by local lava flows, the volcanics of Beaver Creek, and the lava flows of McClelland Mountain that may constitute parts of the same eruptive cycle. Alternatively, these little-studied lavas may be related to older or younger caldera cycles or just to regional volcanic activity unrelated to any specific cycle of explosive volcanism

Lava flows of McClelland Mountain—Several flows of coarsely porphyritic dacite and local basal finely porphyritic silicic andesite that are widely distributed north and south of the Rio Grande near Wagon Wheel Gap. Possibly erupted from vents now marked by dikes and other small intrusions in Blue Creek

Tmd **Dacite, undivided**—Distal dacite, where correlations with more proximal flows are uncertain

Tmd2 **Dacite flow 2**—Gray to light-brown coarsely porphyritic upper flow (68% SiO_2; 25–30% large pl>>bi>cpx). Maximum thickness, 150 m

Tmd1 **Dacite flow 1**—Gray to light-brown coarsely porphyritic lower dacite flow, probably compositionally similar to upper flow. Maximum thickness, 100 m

Tma **Andesite flow**—Dark-gray lava flow of porphyritic andesite or mafic dacite (61–63% SiO_2; 15–30% small pl>cpx>bi) forms lowest flow north of East Bellows Creek. Maximum thickness, 50 m

Blue Creek Tuff—Crystal-rich dacite ash-flow sheet (64–66% SiO_2; 40% pl>>bi, cpx>>hbl). Previously included as part of the Mammoth Mountain Tuff by Ratté and Steven (1967), but lacks sanidine phenocrysts. Contact with underlying Mammoth Mountain Member of Carpenter Ridge Tuff is widely marked by a basal vitrophyre and, locally, by sparse float of tuffaceous sediments in West Bellows Creek and Shallow Creek (Lipman, 2000). At an exceptionally exposed contact at 11,500 ft, just east of forest-access road 523, along the ridge crest east of upper Middle Creek (PM), reworked tuffaceous sediments and surge beds fill meter-scale channels eroded into nonwelded upper Carpenter Ridge Tuff. Distribution largely controlled by ponding within the moat of the Bachelor caldera and the central segment of La Garita caldera. Wedge-out of flat-lying Blue Creek Tuff against tilted Mammoth Mountain Member (Tcm) on flank of Bachelor resurgent dome is especially clear in West Bellows Creek (WW). $^{40}Ar/^{39}Ar$ age (bi), 27.11±0.16 Ma. Remanent magnetic polarity, reverse. Maximum thickness, 250 m

Tbc **Densely welded tuff**—Dark-gray to greenish-gray massive tuff, characterized by well-developed flow-unit partings and a thick basal vitrophyre

Tbcn **Nonwelded to partly welded tuff**—Basal weakly welded tuff as much as 50 m thick, overlies sedimentary rocks within the Bachelor caldera (Tbs) on the south ridge of Bristol Head. Weakly welded upper part of the Blue Creek Tuff is typically poorly exposed and not mapped separately

Volcanics of Beaver Creek—Dominantly andesitic assemblage of lava flows and associated laharic breccias, along with a few dacitic flows, that caps ridge crests near the southeast margin of the South River caldera, representing deeply dissected remnants of a large stratocone. Previously included within the abandoned name "volcanics of Table Mountain" (Steven and Lipman, 1973; Yager and others, 1991), but the main eastern part of that unit, including the type area at Table Mountain, underlies the Carpenter Ridge Tuff and constitutes part of the Huerto Andesite (Lipman, 2000). The volcanics of Beaver Creek, as redefined, are entirely within La Garita caldera. The eruptive source has not been determined reliably; it may be concealed beneath the South River caldera. Alternatively, these lavas might have erupted from the large intrusion of andesite-granodiorite in upper Goose Creek that has been grouped with nearby intrusions associated with the South River Volcanics in the absence of definitive evidence to the contrary. Maximum thickness, >360 m

Tvbb **Silicic dacite lava flows**—Thick coarsely porphyritic light-colored flows (65–68% SiO_2; 5–30% pl>>hbl>bi), commonly characterized by conspicuous phenocrystic biotite. Locally flow layered lavas that are volumetrically minor parts of formation. Intercalated with volcaniclastic rocks (Tvbv) along Continental Divide and in upper Goose Creek (SR)

Tvbh **Dacitic lava flows**—Coarsely porphyritic flows of gray mafic dacite (62–65% SiO_2; 15–25% pl>hbl>>bi, cpx), characterized by abundant hornblende and sparse biotite; commonly flow layered

Tvba **Andesitic lava flows**—Dark-gray finely porphyritic flows (57–61% SiO_2; 10–25% pl>hbl>cpx), constituting the bulk of primary volcanic deposits in formation, especially in eastern areas

Tvbm **Andesitic cone breccia**—Finely shattered angular clasts of dark-gray hornblende andesite (60% SiO_2; 15% pl>hbl) forming a massive nonstratified local deposit within the volcaniclastic unit (Tvbv), probably emplaced as explosion breccia, that appears to represent remnants of a volcanic cone

Tvbv **Dacitic volcaniclastic rocks**—Coarsely bedded polylithic breccia and conglomerate, containing abundant clasts of light-gray dacitic lava, mainly representing proximal deposition by synvolcanic mudflows. Dominant volcaniclastic unit in western parts of preserved formation, although not mapped in detail

Tvbc **Andesitic volcaniclastic rocks**—Crudely bedded polylithic breccia and conglomerate, containing abundant clasts of hornblende andesite, mainly representing proximal deposition by synvolcanic mudflows. Dominant volcaniclastic unit in eastern parts of preserved formation

Tvbs **Volcanic sedimentary rocks**—Well-bedded fluviatile conglomerate and sandstone, representing distal alluvial deposits derived from the Beaver Creek volcano

ROCKS OF THE BACHELOR CALDERA CYCLE

The Bachelor caldera, entirely enclosed within central parts of La Garita caldera (fig. 5*B*, sheet 4), was the source of the Carpenter Ridge Tuff, the second largest eruptive unit (~1,000 km^3) from the central caldera cluster. Much of the topographic wall of this caldera is poorly exposed or concealed beneath younger deposits; it is well exposed on the southwest slope of Bristol Head. A small southwestern erosional outlier is inferred in the Seepage Creek area (WC), based on anomalously densely welded lithic rich character of the Carpenter Ridge Tuff in this area. Thick intracaldera Carpenter Ridge Tuff, which consists dominantly of phenocryst-poor rhyolite, forms the host rocks for the economically important vein mineralization of the Creede district (Steven and Ratté, 1965; Lipman and others, 1989)

Dacite of Shallow Creek—Distinctive phenocryst-rich silicic dacite (68% SiO_2; 35% sn, pl>bi) on the northwest side of the Bachelor caldera that may represent a late eruptive event of this caldera cycle

Tscf **Flow and flow breccia**—Massive to flow-layered white to light-gray lava and breccia. Maximum thickness, 175 m

Tsci **Intrusion**—North-trending broad dike in Shallow Creek, mostly bleached and argillically altered, that is exposed over a vertical range of about 400 m and grades into local lava flow at highest exposure levels

Tbs **Intracaldera sedimentary rocks**—Pale-yellow to tan fine-grained volcaniclastic rocks. Include finely laminated lacustrine sediments, tuffaceous sandy deltaic beds, and local tuffaceous breccias of probable mudflow origin. Poorly exposed, mostly as float, on southeast ridge of Bristol Head and south slopes of Nelson Mountain; widely present in exploration drill core in West Willow Creek area. Thickness, 0–50 m

Carpenter Ridge Tuff—Widespread caldera-forming ash-flow sheet, containing complex welding and compositional zonation (67–74% SiO_2), especially within Bachelor caldera. Volumetrically dominant rhyolite, containing 3–5% phenocrysts, grades locally upward to silicic dacite and dacite containing as much as 30% phenocrysts. Remanent magnetic polarity, reverse

Outflow tuff units

Tcm **Mammoth Mountain Member**—Phenocryst-rich tan to brown welded ash-flow tuff of silicic dacite (66–70% SiO_2; 25–35% pl>sn>bi, cpx). Dominant sanidine compositions (typically $Or_{60\text{-}63}Ab_{35\text{-}32}An_2Cs_{3\text{-}4}$; Webber, 1988; Riciputi, 1991) are slightly more sodic and barium-rich than in underlying rhyolite of the Bachelor Mountain Member. Previously interpreted as a separate ash-flow sheet, the Mammoth Mountain Tuff (Steven and Ratté, 1973), but gradationally overlies rhyolitic Campbell Mountain zone of Bachelor Mountain Member (Tcbc) within caldera except where landslide deposits of the Phoenix Park Breccia Member (Tcpl) intervenes (Lipman and others, 1989). On west slopes of Mammoth Mountain, locally grades upward into phenocryst-poor light-gray glassy and vapor-phase-crystallized nonwelded tuff at top of ash-flow sheet that is rhyolitic in composition and mapped as Windy Gulch zone (Tcbg). Largely intracaldera, but locally thinly present south of South Fork (BR). Large areas of welded tuff, which were previously included within the Mammoth Mountain Tuff, are now recognized as the Blue Creek Tuff (Lipman, 2000), separated from all subunits of the Carpenter Ridge Tuff by a complete cooling break and intervening sedimentary deposits. Maximum thickness, as much as 250 m

Tcrf **Mafic fiamme zone**—Locally deposited phenocryst-poor but lithic-rich upper part of outflow tuff sheet, containing sparse scoriaceous lenses of distinctive high-barium alkali andesite (56–63% SiO_2; 25–35% pl>>bi>cpx, sn) that are transitional into dacite (Lipman, 1975; Whitney and others, 1988; Dorais and others, 1991). Sparse sanidine phenocrysts ($Or_{54\text{-}61}Ab_{40\text{-}33}An_{3\text{-}2}Cs_{17\text{-}2}$; Whitney and others, 1988; Webber, 1988; Riciputi, 1991) are compositionally variable but even more sodic and barium rich than those of the intracaldera Mammoth Mountain Member. Presence of the andesitic scoria and lower matrix crystal content distinguishes this zone from the Mammoth Mountain Member. Such scoria are sparsely present widely where this zone is too thin or indistinct to map separately. Maximum thickness, 25 m on west slopes of Red Mountain Creek (PM boundary) and where associated with lithic concentrations within inferred caldera-fill scab west of Seepage Creek (WC). Also well developed, but not mapped separately, on west slope of Beaver Mountain south of South Fork

Tcr **Outflow rhyolite tuff**—Dominantly phenocryst poor tan rhyolite (Whitney and others, 1988), widely characterized by black basal vitrophyre and conspicuous central lithophysal zone. Exceptionally thick (as much as 300 m), where ponded in the southern segment of La Garita caldera. Where banked in steep depositional contact against fault scarps that postdate the Huerto Andesite (for example, saddle northwest of upper Cimarron Creek; PM), lower parts of the Carpenter Ridge locally have fluidal lineate welding textures, with variable steep dips, much like the Willow Creek facies within the Bachelor caldera. Outflow tuff is also thickly ponded along Los Pinos graben (SP and north of map area), which was downdropped during formation of La Garita caldera. In this area, the Carpenter Ridge was initially confused with Sapinero Mesa Tuff because of its low depositional level, topographically below most exposures of the Fish Canyon Tuff. Where Carpenter Ridge Tuff was deposited on wet intracaldera sediments or in shallow water in the northern moat of La Garita caldera, it contains striking ovoid welding zones defining elliptical masses 100–200 m across, with individual lithophysal gas cavities as much as 2 m in diameter, and bounded by steeply dipping foliations that appear to mark polygonal gas-escape zones (west of South Fork Saguache Creek, MM). Sanidine compositions of the Carpenter Ridge are somewhat variable from section to section, mostly $Or_{62\text{-}67}Ab_{35\text{-}31}An_{2\text{-}1}Cs_{1\text{-}4}$ (Whitney and others, 1988; Riciputi, 1991). Average $^{40}Ar/^{39}Ar$ age (3 samples; sn, bi), 27.35 Ma. Thickness, commonly 50–100 m; much thicker within southern La Garita caldera

Intracaldera units

Intracaldera Bachelor Mountain Member—Ash-flow accumulation of phenocryst-poor rhyolite (70–74% SiO_2; 25–35% pl, sn>>bi), more than 1 km thick with no base exposed, that is characterized by texturally diverse welding and crystallization zones. Sanidine phenocrysts ($Or_{67\text{-}62}Ab_{31\text{-}33}An_2Cs_{1\text{-}3}$; Webber, 1988; Riciputi, 1991) are compositionally similar to outflow tuff of the Carpenter Ridge. Interfingers complexly with landslide and talus breccia deposits derived by gravitational slumping from caldera walls during subsidence. Widely characterized by alkali-exchange alteration involving potassium metasomatism (shown by diagonal line pattern). In extreme cases, K_2O is >12% and Na_2O <0.5%; unaltered alkali contents are about 5% and 4%, respectively. Least-altered rhyolitic tuff previously mapped as rhyolitic part of Mammoth Mountain Tuff (Steven and Ratté, 1973)

Tcbi **Rheomorphic and intrusive tuff unit**—Small bodies of flow-layered rheomorphic rhyolitic tuff near Creede, typically characterized by steep dips and locally brecciated rock due to rapid deformation. Rheomorphism caused by plastic flowage of intensely welded and remobilized Willow Creek welding zone (Tcbw) while still hot. Commonly localized along early faults associated with resurgent doming of Bachelor caldera; exceptionally exposed in now-inaccessible mine workings. Locally gradational with fluidally welded rhyolite of the Willow Creek zone (Tcbw), but diapirs project into Campbell Mountain welding zone. Previously mapped entirely as flow-layered intrusions (Steven and Ratté, 1973); coarsely porphyritic massive rocks with seemingly euhedral phenocrysts east of lower Rat Creek, which are poorly exposed and widely altered, may be primary intrusions

Tcbg **Windy Gulch welding zone**—Gray porous slightly welded to nonwelded tuff; consists of pumiceous and locally lithic-rich rhyolitic tuff. Originally glass or vapor-phase crystallized; now variably zeolitized, argillized, and modified by potassium metasomatism. Grades into welded rhyolite of the Campbell Mountain welding zone (Tcbc). Mapped mainly near top of intracaldera tuff; also present adjacent to landslide-breccia deposits deep in unit, but mostly too thin to show on map. Also present locally above Mammoth Mountain Member, east of East Willow Creek, where compositional zonation becomes phenocryst poor and silicic upward. Thickness variable, 10–50 m at top of Bachelor Mountain Member

Campbell Mountain welding zone—Densely welded phenocryst-poor rhyolitic tuff, compositionally and texturally most similar to outflow Carpenter Ridge Tuff (Tcr). Black vitrophyre at base against caldera wall (Miners Creek) and against landslide sheets of Phoenix Park Breccia Member (Tcpl). Grades into fluidally welded rhyolite of the Willow Creek welding zone (Tcbw). $^{40}Ar/^{39}Ar$ age (sn, from vitrophyre), 27.46±0.21 Ma. Maximum thickness, 300 m

Tcbc **Least altered tuff**—Tan to gray-brown densely welded tuff, formerly included with rhyolitic Mammoth Mountain Tuff of Steven and Ratté (1973)

Tcbck **Potassium-metasomatized tuff**—Red-brown to purplish-gray tuff, variably affected by severe potassium metasomatism and loss of sodium (Ratté and Steven, 1967)

Tcbw **Willow Creek welding zone**—Light-gray zone of fluidally welded rhyolitic tuff, characterized by pumice-flattening ratios >10:1, and commonly 100:1. In places, lineate due to drawn-out pumices. Flow foliation locally swirly; locally grades into rheomorphic tuff unit (Tcbi). Base not exposed except at wedge-out against rhyolite of Miners Creek (Tmr) at west caldera wall (northwest CR). Maximum thickness, >600 m, but no base exposed

Tcsb **Shallow Creek Breccia Member**—Landslide breccia lenses, dominantly of porphyritic hornblende dacite, in western parts of caldera. Derived from precaldera volcanoes of the Conejos Formation exposed on west wall of caldera (for example, north of Bristol Head). Previously mapped as lava flows interfingering with the Bachelor Mountain Member (Steven and Ratté, 1965, 1973). Maximum thickness, as much as 350 m

Tcab **Andesite breccia member**—Locally mappable small blocks and masses of aphyric to sparsely porphyritic andesite and some dacite enclosed by intracaldera talus-breccia unit (Tcpt) of the Carpenter Ridge Tuff in northeastern parts of caldera (East Willow Creek, SL). Phenocrysts are smaller and sparser than in Shallow Creek Breccia Member, and hornblende is inconspicuous or absent. Probably derived from precaldera volcanoes on caldera walls

Tcwb **Wagon Wheel Gap Breccia Member**—Consists dominantly of large blocks, commonly 1–100 m in diameter, of sparsely porphyritic precaldera andesite-dacite, derived mainly from southeastern caldera wall. Blocks of Fish Canyon and Masonic Park Tuff are locally conspicuous. Matrix of nonwelded rhyolitic Carpenter Ridge Tuff (Tcbg), which was originally glassy but now argillized and zeolitized, is locally conspicuous but mostly weakly indurated and poorly exposed. Previously mapped as a primary volcanic accumulation of lava flows, tuffs, and breccias (Steven and Ratté, 1973). Thickness, >250 m

Phoenix Park Breccia Member—Breccia masses dominantly of La Garita Member of intracaldera Fish Canyon Tuff (Tfg), in matrix of finely comminuted Fish Canyon Tuff. Derived from La Garita Mountains along northeast caldera wall. Previously mapped as late ash-flow sheets of Fish Canyon type, which intertongued with Bachelor Mountain Member (Steven and Ratté, 1965, 1973)

Tcpl **Landslide-breccia unit**—Several sheets of landslide breccia, interfingering with upper parts of Bachelor Mountain Member of Carpenter Ridge Tuff (Tcbc, Tcbk, Tcbw) in East Willow Creek (SL); one sheet overlies Mammoth Mountain Member (Tcm). Enclosing tuffs become less welded and locally vitrophyric against slide breccias. Thickness of individual sheets, 0–50 m

Tcpt **Talus-breccia unit**—Monolithologic breccia consisting of fragments of Fish Canyon Tuff. Basal depositional contact, against northeast caldera wall, is obscure transition between transported talus blocks and undisturbed in-place welded Fish Canyon Tuff. Previously mapped as part of intracaldera Fish Canyon Tuff (La Garita Member) by Steven and Ratté (1973). Local vague bedding and aligned blocks define angle-of-repose depositional slopes. In places, net-veined by nonwelded rhyolitic ash of Carpenter Ridge Tuff. Thickness, 0–300 m

Tmr **Rhyolite of Miners Creek**—Local lava dome of sparsely porphyritic flow-layered rhyolite (74% SiO_2; 5% pl, sn>>bi). May constitute part of Bachelor caldera floor, representing eruption premonitory to petrologically similar Carpenter Ridge Tuff. Thickness, >300 m; base not exposed

ROCKS ERUPTED FROM THE SILVERTON CALDERA
(western San Juan Mountains)

Tclt **Crystal Lake Tuff**—Dominantly phenocryst-poor tan densely welded rhyolite tuff (72–74% SiO_2; 3–5% pl, sn>>bi), characterized by black basal vitrophyre and central lithophysal zone (Lipman and others, 1973; Steven and Lipman, 1976). Closely resembles overlying Carpenter Ridge Tuff. Interfingers with distal Huerto Andesite, along Clear Creek (BH) and west of Texas Creek (LS). Huerto volcanoes probably were major topographic barriers blocking spreading of these pyroclastic flows to the southeast. Magnetic polarity, reverse. Average $^{40}Ar/^{39}Ar$ age (2 samples; sn), 27.5 Ma (adjusted from Bove and others, 2001). Maximum thickness in map area, 50 m

ROCKS OF LA GARITA CALDERA CYCLE

The enormous La Garita caldera (35 x 75 km across in map area; 100 km if northern Cochetopa segment included) and its eruptive products define the overall geometry of the central San Juan caldera cluster (fig. 5*C*, sheet 4), all later calderas having formed within La Garita structure (Lipman, 1997b). Its associated ash-flow sheet, the Fish Canyon Tuff, which consists of monotonously uniform phenocryst-rich dacite, has long been recognized as among the world's largest ash-flow units (at least 5,000 km^3). Newly identified as parts of this caldera cycle are precursor pyroclastic deposits of the lava-like Pagosa Peak Dacite (Bachmann and others, 2000) and postcaldera lava eruptions of the Huerto Andesite. The structural segments of the caldera each have differing eruptive and postsubsidence histories, even though all formed during explosive eruption of the Fish Canyon Tuff as a single ash-flow cooling unit. Initial subsidence of the southern segment may have begun during eruption of the Pagosa Peak Dacite (Lipman, 2000); rectilinear margins along parts of this segment (especially in Williams and Beaver Creeks) reflect influence by older faults. Multiple nested caldera-wall unconformities locally provide evidence for recurrent subsidence within the southern segment: for example, east of

Williams Creek (CP), at Turkey Creek Lake (PP), and in lower Trout Creek (WC). Similarly, the linear depositional contacts of thickly ponded Blue Creek and Wason Park Tuffs along the caldera wall as mapped south of the Rio Grande (WC) may reflect precaldera initiation of faulting along the Clear Creek graben

Huerto Andesite—Andesitic lava flows and volcaniclastic rocks (Larsen and Cross, 1956; Lipman, 1975; Askren and others, 1991), forming remnants of large shield volcanoes and flanking erosional debris mainly within and adjacent to the southern segment of La Garita caldera. In this caldera segment, a mosaic of rectilinear faults cut Huerto rocks but are unconformably overlain by the next eruptive unit, Carpenter Ridge Tuff (Lipman, 2000, fig. 4). Huerto Andesite is at least 750 m thick under Bristol Head, within the central segment of La Garita caldera, but thins to zero thickness in a distance of 5 km against the northwest caldera wall at Boulder Creek (BH). Compositionally similar andesite in a small area of the northern segment (Nutras Creek, EP) is correlated with the Huerto on the basis of general stratigraphic position, directly overlying the dacite lava of Nutras Creek (Tfnd), and absence of andesitic lavas anywhere higher in the northern moat-filling tuff sequence. Maximum thickness, >800 m along the Continental Divide southwest of Creede

Thu **Andesitic lava flows and volcaniclastic rocks, undivided**—Along west-central margin of map area

Intrusions and vents—Dikes and more irregular small intrusions that likely represent vent feeders for Huerto eruptions

Thid **Dacite**—Light-gray north-northwest-trending dike on northeast side of Baldy Mountain (68% SiO_2; 5% pl>>bi), about 5 m thick. Possible feeder for distinctive compositionally similar lava flow at Ruby Lake (Thd)

Thi **Andesitic dikes and other intrusions**—Widely scattered, dark aphanitic to finely porphyritic intrusive rocks, petrographically similar to common andesite lava flows (Tha). Probably far more common than shown; only mappable in exceptionally exposed areas

Thip **Porphyritic andesitic dikes and other intrusions**—Distinctive platy-plagioclase intrusions, petrographically similar to the common porphyritic lava flows (Thap). In a relatively large intrusion in lower Trout Creek (WC) that is spatially associated with altered country rocks, porphyritic andesite grades into coarse gabbro (55% SiO_2), containing plagioclase crystals as much as 2 cm across

Thih **Intrusions of hornblende andesite and mafic dacite**—Dikes and irregular intrusive bodies, petrographically similar to hornblende-bearing andesite (Thah)

Lava flows—Thick-bedded sequence of flows and proximal breccias, constituting eroded remnants of large volcanic shields

Thd **Dacite**—A lava flow or dome of light-gray flow-layered dacite (68% SiO_2; 5% pl>>bi), near Ruby Lake (LS). Compositionally similar to thick dacite dike (Thid) to southeast at Baldy Mountain, which may represent intrusive feeder. $^{40}Ar/^{39}Ar$ age (bi), 27.65±0.20 Ma (F. Parrat and M. Dungan, written commun., 1998). Also, small area of hydrothermally altered porphyritic dacite (25% pl>>bi, cpx) poorly exposed beneath typical andesitic Huerto mudflow breccias at forks of Trout Creek (WC)

Tha **Finely porphyritic and undivided andesite**—Dark aphanitic to finely porphyritic lava flows (55–60% SiO_2; 0–10% pl>cpx), especially common beneath the platy-plagioclase lavas high in the unit

Thah **Hornblende-bearing andesite-dacite**—Light-gray porphyritic lavas and breccias characterized by phenocrystic hornblende (56–64% SiO_2; 10–30% pl>hbl, cpx), occurring mainly within and adjacent to the southeastern La Garita caldera. Thick flows of this type, preserved along the caldera margin at Table Mountain (MH), were previously assigned to the abandoned name ”volcanics of Table Mountain” (Steven and Lipman, 1973; Yager and others, 1991) where they were erroneously interpreted to overlie the Carpenter Ridge Tuff. Several massive knobs of steeply flow layered rock northwest of Turkey Creek Lake (PP) may be vent intrusions

Thap **Platy plagioclase andesite**—Distinctive lava flows (56–60% SiO_2; 15–30% pl>>cpx), characterized by large flow-aligned phenocrysts of tabular plagioclase. A recurrent andesitic rock type in the region, abundant in the Conejos Formation (Tcap) and also in the Sheep Mountain Andesite (Tsma). Especially common in upper parts of the Huerto, where mapped separately, but also occurs widely interfingering with other Huerto facies in relations too complex to map separately

Ths **Vent scoria**—Reddish cinders and scoria, occupying a broad basin 600 m across that is interpreted as an eroded vent crater at Red Lakes (LS)

Volcaniclastic rocks—Debris derived from primary Huerto volcanic edifices and oversteepened walls of La Garita caldera during continued emplacement of Huerto lavas

Thv **Bedded breccia and conglomerate**—Mostly reworked crudely bedded to well-bedded laharic conglomerates, sandstones, and mudflow breccias, containing clasts of dark andesite in light-gray sandy matrix. Commonly interfingers with Huerto lava flows. Angular breccia is more common, thickness is greater, and bedding is more irregular and crudely developed within La Garita caldera than in Huerto volcaniclastic accumulations beyond the caldera walls. In parts of the southern caldera segment, Huerto volcaniclastic rocks differ only slightly from the Conejos laharic breccias with which they are in contact along the caldera wall, especially the canyon walls of Porphyry Gulch (PM) and the Middle Fork Piedra River (CP). In these areas, the Huerto is darker in color, clasts are more angular, and clasts of porphyritic plagioclase andesite (Thap) are common in the Huerto breccias. Laharic breccias of hornblende andesite locally contain fragments of silicified wood as much as 1 m long on the north slopes of the West Fork San Juan River west of Beaver Creek (SR)

Thbf **Landslide breccia with clasts of Fish Canyon Tuff**—Lenses and thick masses of chaotic landslide debris of Fish Canyon Tuff, interleaved with lavas and volcaniclastic rocks of Huerto Andesite and banked against upper slopes of La Garita caldera wall. Especially thick along southeastern caldera wall in upper Beaver Creek (SR), where some shattered megablocks 100 m or more across are identified largely by discontinuities in flattened pumice foliations. More finely shattered breccia, superbly exposed along the cirque ridgecrest at the head of Omaha Creek (SM), contains subordinate andesite clasts, locally in a matrix of nonwelded Fish Canyon-like tuff

Thbp **Landslide breccia with clasts of Pagosa Peak Dacite**—Local lenses of chaotic landslide debris of Pagosa Peak Dacite, interleaved with lavas and volcaniclastic rocks of Huerto Andesite and banked against upper slopes of La Garita caldera wall northeast of Turkey Creek Lake (PP)

Thc **Conglomerate and sandstone with clasts of Fish Canyon Tuff**—Polylithic mudflow deposits in small discontinuous lenses, especially in canyon of Middle Fork Piedra River (CP), that provide critical evidence for location of caldera-wall unconformity between intracaldera Huerto deposits and underlying Conejos Formation volcaniclastic rocks that are otherwise lithologically similar

Tgs **Intracaldera sedimentary rocks**—Finely laminated shale and well-bedded tuffaceous sandstone, representing lake and deltaic deposits in the moat of La Garita caldera. Local calcareous beds, including minor travertine. Tan to brown where weathered; gray in creek bottoms where not oxidized. Exposed mainly in small outcrops along the Rio Grande (WW) and along Saguache and Miners Creeks west of Stone Cellar Campground (SP) where the sedimentary section is 300 m thick, with no base exposed. This great thickness may have resulted from local ponding behind a lava dam of dacite of Nutras Creek (Tfnd)

Tfnd **Dacite of Nutras Creek**—Massive to flow-layered gray to red-brown lava and associated breccia, forming a small erosional remnant on the northeast flank of La Garita resurgent dome (EP). Petrographically and chemically indistinguishable from the earlier-erupted Fish Canyon Tuff and Pagosa Peak Dacite. Magnetic polarity, normal (L. Brown, written commun., 1999). $^{40}Ar/^{39}Ar$ age (sn), 27.66±0.09 Ma (Bachmann and others, 2000). Maximum exposed thickness, 200 m

Fish Canyon Tuff—Nonwelded to densely welded gray to light-brown ash-flow tuff of compositionally uniform silicic dacite (66–68% SiO_2; 40–50% pl>>sn, bi>hbl). Sparse resorbed pinkish quartz, accessory sphene, and hornblende without augite are distinctive phenocrysts (Lipman, 1975; Whitney and Stormer, 1985). Sanidine phenocrysts (typically $Or_{72-74}Ab_{23-24}An_1Cs_{1.5}$) are relatively potassic and conspicuously zoned, with Cs varying 1–4 mol percent (Lipman and others, 1997; O. Bachmann and P. Lipman, unpub. data). Average $^{40}Ar/^{39}Ar$ age (4 samples; bi, sn), 27.6 Ma. Magnetic polarity, normal

Tgfc **Late intracaldera landslide breccia**—Massive monolithologic landslide breccia of Fish Canyon clasts, in Cochetopa caldera segment (SP; fig. 5*C*, sheet 4). Clasts are angular and ash matrix is minor, indicating emplacement late during caldera subsidence when the eruption was waning or over. Breccia is well lithified, even where deposited on weakly indurated caldera-wall units, perhaps because the Fish Canyon blocks were still hot. Maximum thickness, >150 m

Tfc, Tfc1, Tfc2, Tfc3, Tfc4, Tfc5, Tfc6 **Outflow tuff sheet**—A single large cooling unit of light-gray to tan regional tuff; preserved as much as 100 km beyond rims of La Garita caldera. Characterized by simple welding zonation except in thick proximal sections, especially in the South Fork area, where compound welding is well developed (as many as six cooling subunits mapped locally, arbitrarily numbered). Pumice fragments are obscure in many exposures of devitrified tuff, and lithic fragments typically are sparse. Small andesite fragments are atypically common in the proximal tuff west of Williams Creek (CP). Most densely welded tuff is massive, but upper parts commonly have slabby jointing parallel to obscure compaction foliation. Rare dark pumice lenses, which lack large phenocrysts and resemble crystal-poor rhyolite in the field, contain abundant finely milled crystal fragments and are compositionally identical to the more common pumice fragments of crystal-rich dacite. Maximum thickness, 300 m; widely 50–100 m thick

Tfg **La Garita Member**—Intracaldera tuff. Thick densely welded gray to red-brown tuff. Pumice lenses contain phenocrysts as much as 1 cm in diameter, some with granophyric overgrowths (Lipman and others, 1997). Partial cooling breaks present in some well-exposed sections. Differs from correlative outflow tuff in its greater thickness, denser welding, darker color, larger pumice fragments, and local presence of distinctive fragments of disaggregated granophyric granite (Lipman and others, 1997). Grades into outflow tuff sheet (Tfc) across buried caldera wall in Cebolla Creek (MM) and east of Williams Creek Reservoir (CP). Reddish densely welded tuff is typical in La Garita resurgent block; comparably dense tuff deep in thick sections of intracaldera tuff in the southern caldera segment is dark gray, due to propylitic alteration, and in places is similar in appearance to hornblende dacite lava flows. As much as 1.1 km thick on resurgent uplift in northern caldera segment, with top eroded and no base exposed

Tfgl **Lithic-rich partly welded zone**—Locally mappable partly welded zones between cliff-forming units of densely welded tuff on north slope of La Garita Mountains east of Benito Lake (HM). Angular fragments of andesitic lava 5–20 cm in diameter are common; may represent distal facies of caldera-collapse landslide deposit

Tgbf **Intracaldera landslide breccia with clasts of Fish Canyon Tuff**—Local lenses of chaotic landslide debris, banked against La Garita caldera wall in Deep Creek (ME)

Tgbp **Intracaldera landslide breccia with clasts of Pagosa Peak Dacite**—Local lenses of chaotic landslide debris, interleaved with intracaldera Fish Canyon Tuff (Tfg) in Rainbow Creek and banked against La Garita caldera wall along Beaver Creek (SR)

Tgbm **Intracaldera landslide breccia with clasts of Masonic Park Tuff**—Local small lenses of chaotic landslide debris, along inferred caldera-wall contact between Conejos and Huerto volcaniclastic rocks on west side of Middle Fork Piedra River (CP). Despite small size, these lenses provide critical evidence on location of the southern La Garita caldera wall

Tgbs **Intracaldera landslide breccia with clasts of Sheep Mountain Andesite**—Local lenses of chaotic landslide debris, interleaved with intracaldera Fish Canyon Tuff (Tfg) and banked against La Garita caldera wall, along Rainbow and Cimarron Creeks (SR). Small breccia lenses north of Saddle Mountain (SM) may include clasts of Summitville Andesite and Conejos Formation

Tgbw **Intracaldera landslide breccia with clasts of western San Juan tuff sheets**—Local lenses of chaotic landslide debris, interleaved with intracaldera Fish Canyon Tuff (Tfg) and banked against upper slopes of La Garita caldera wall in a lithologically complex erosional scab, west of Williams Creek (CP). Dominant clast lithologies are Sapinero Mesa and Blue Mesa Tuffs

Pagosa Peak Dacite—Lava-like crystal-rich pyroclastic deposit (66–68% SiO_2; 35–45% pl>>bi, sn>hbl, qz) that is petrographically and chemically indistinguishable from the later-erupted Fish Canyon Tuff (Tfc) and dacite of Nutras Creek (Tfnd) of La Garita caldera cycle (Lipman and others, 1997; Bachmann and others, 2000). Preserved as two thick lobes (800 – >1,000 m) along the southeast margin of the caldera. Contains large (as much as 2 m across) poorly vesiculated magma blobs in a fragmental matrix that together have undergone varied intense plastic deformation and rheomorphic flow. Large-volume eruption (200–300 km^3) was concurrent with local graben faulting and piecemeal subsidence, but seemingly without associated deep caldera collapse. Steep depositional contacts that locally truncated subhorizontal stratigraphy of older volcanic units on northwest slope of Saddle Mountain and farther west in Turkey Creek (SM) are interpreted to mark deposition against early subsidence scarps. Interpreted to have been emplaced from nonenergetic pyroclastic flows associated with low-energy fountaining eruptions. Truncated by topographic wall of La Garita caldera, and unconformably onlapped by Fish Canyon Tuff. In magma blobs, phenocrysts are large (1–15 mm), euhedral, and commonly unbroken. Sanidine phenocrysts (typically $Or_{72-74}Ab_{23-24}An_1Cs_{1.5}$) are relatively potassic and conspicuously zoned in Cs, similar to the more broken crystals in the Fish Canyon Tuff. Magnetic polarity, normal (L. Brown, written commun., 1999). $^{40}Ar/^{39}Ar$ age (sn), 27.52±0.09 Ma (Bachmann and others, 2000). Maximum thickness, >800 m at Mount Hope, where the top is eroded and the base not exposed

Tpl **Massive lava-like rocks**—Structureless to flow-layered devitrified light-gray dacite; from interior of unit where pyroclastic textures are obscure or completely obliterated. Lithic fragments are absent. Closely resembles primary lava where strongly flow layered and terminations of flattened blobs are obscure. Variably flow folded, especially high in thick sections; steep ramp structures at head of Camp Creek (SM) and west of Archuleta Lake (SR)

Tpc **Carapace breccia**—Blocks of flow-layered gray or brown dacite, forming breccia at tops of thick flow units, especially in the Cherry Cairn area (PP), that resulted from intense rheomorphic flow in interior of unit

Tpr **Rheomorphically brecciated zone**—Chaotically flow layered, flow-folded, and brecciated dacite adjacent to fault northwest of Eagle Mountain, where dacite was deforming concurrently with fault movement. Locally strongly oxidized

Tpbb **Pyroclastic breccia**—Crudely bedded monolithologic light-gray breccia, consisting of angular clasts of Pagosa Peak Dacite in an ashy matrix. Interlayered with massive and blobby Pagosa Peak rocks at Eagle Mountain (PP). Probably proximal deposits from low-energy late pyroclastic flows

Tpab **Lens of andesitic slide breccia**—Local small landslide lens of shattered porphyritic platy-plagioclase andesite, interlayered in pyroclastic breccia (Tpbb), on south ridge of Eagle Mountain (PP). Probably derived from Sheep Mountain Andesite (Tsma), exposed along faults that were active concurrently with eruption of the Pagosa Peak Dacite. Maximum thickness, 10 m

Tpb **Blob-and-ash deposits**—Interior devitrified zone of large poorly vesiculated magma blobs in a fragmental matrix; variably welded and indurated. Lithic fragments are absent. Grades upward into flow-layered or massive lava (Tpl), as blobs become flattened and homogenized by rheomorphic deformation and devitrification. Flattened blobs are elongate, lineate, and dip steeply along Continental Divide west of Wolf Creek Pass, apparently as ramp structures due to gravitational spreading of thick accumulation of lava-like unit (Tpl) to northwest (Bachmann and others, 2000, fig. 9)

Tpbl **Lithic-bearing blob-and-ash deposits**—Near-basal nonbedded zone of large poorly vesiculated dark-colored magma blobs in a fragmental matrix characterized by sparse centimeter-size andesitic lithic fragments. On southeast ridges of Pagosa Peak, this unit contains sparse clasts of Sheep Mountain Andesite as much as 0.5 m in diameter, presumably picked up from the local ground surface. Variably welded and indurated, in places, to black vitrophyre as much as 50 m thick

Tpp **Pyroclastic-flow deposits**—Nonwelded to weakly welded, light-gray deposits, containing sparse andesitic lithic fragments and well-vesiculated pumice, but lacking dense magma blobs. Present widely as a basal unit beneath lithic-bearing blob-and-ash deposits (Tpbl), commonly too thin to map separately (5–10 m). Southwest of Wolf Creek Pass occurs as three local ash-flow units (not separable at published map scale) between the lithic-bearing and overlying lithic-free blob-and-ash deposits. In Goose Creek, forms several horizons of surge-bedded tuff between blob-and-ash deposits (Tpb) and lava-like rocks (Tpl). Indistinguishable from main Fish Canyon Tuff (Tfc), except for presence of intervening blob-rich facies of the Pagosa Peak Dacite (Tpb). Maximum thickness, 25 m

ROCKS ERUPTED FROM THE PLATORO CALDERA COMPLEX

Multiple large ash-flow sheets of the Treasure Mountain Group, associated with recurrent subsidence at the Platoro caldera complex in the southeastern San Juan Mountains (Lipman, 1975; Dungan and others, 1989), reached southeastern parts of the map area. These units mostly underlie marginal facies of the lithologically similar Masonic Park Tuff (Tmp), but distal parts of the youngest major ash-flow sheet, the Chiquito Peak Tuff, overlie Masonic Park Tuff. The lithologic similarities and complementary areal extents of these two tuff sheets have, until recently, been cause for considerable stratigraphic confusion (Lipman and others, 1996)

Treasure Mountain Group—Multiple dacite to low-silica rhyolite ash-flow sheets that, within the map area, become increasingly distal westward

Ttc **Chiquito Peak Tuff**—Tan to light-brown phenocryst-rich tuff of compositionally uniform dacite (64–68% SiO_2; 20–30% pl>>bi, cpx>sn), distinguished from similar appearing Masonic Park Tuff (Tmp) by presence of sparse sanidine phenocrysts and slightly divergent biotite compositions. Characterized by more potassic sanidine compositions (Or_{64-67}) than other tuffs of the Treasure Mountain Group (Lipman and others, 1996), similar to later tuffs from central San Juan calderas. Andesite lithic fragments a few cm across are conspicuous. $^{40}Ar/^{39}Ar$ age (sn), 28.2 Ma (adjusted from Lipman and others, 1996). Magnetic polarity, reverse. Maximum thickness in map area, 75 m at Alberta Peak (near Wolf Creek Pass)

ROCKS OF THE MASONIC PARK CYCLE (caldera concealed)

The Masonic Park Tuff, the earliest ash-flow sheet erupted from a source in the central San Juan region, is transitional in age, petrology, and caldera location between the tuffs erupted earlier from the southeastern Platoro caldera complex and younger tuffs from the central cluster. The Mount Hope area was formerly interpreted as a caldera source for the Masonic Park Tuff (Steven and Lipman, 1976), but later studies cast doubt on this interpretation (Lipman and others, 1996). More likely, a caldera source for this tuff lies completely concealed within the southern segment of La Garita caldera

Sheep Mountain Andesite—Lava flows of distinctive porphyritic andesite and minor dacite (Larsen and Cross, 1956; Lipman, 1975), which directly overlie the Masonic Park Tuff, are exceptionally thick along the south margin of the volcanic field, suggesting proximity to a Masonic Park source concealed within the southern La Garita caldera. These lavas, lying below Chiquito Peak Tuff, are laterally stratigraphically equivalent to some flows of Summitville Andesite in the Platoro area, but they have been mapped separately because their contrasting porphyritic character, different areal distribution, and locus of maximum thickness indicates eruption from vents in the south-central San Juan region related to the Masonic Park cycle

Tsma **Porphyritic andesite**—Distinctive lava flows (56–58% SiO_2; 15–30% pl>>cpx), characterized by large (as much as 2 cm) flow-aligned phenocrysts of tabular plagioclase. A recurrent andesitic rock type in the region, common in the Conejos Formation (Tcap) and also in the Huerto Andesite (Thap). On southern slopes of Saddle Mountain, directly overlies similar platy-plagioclase flows of Summitville Andesite (Tsup), along an obscure contact where intervening Masonic Park Tuff has wedged to a discontinuous thin ash-cloud deposit. Maximum thickness, 200 m on western slopes of Sheep Mountain

Tsmd **Hornblende dacite**—Local flow of distinctive light-gray porphyritic dacite in Beaver Creek (SR) that underlies typical porphyritic andesite of Sheep Mountain. Thickness, 25–50 m

Tsmv **Volcaniclastic rocks**—Locally mappable tuffaceous carapace breccia and thin pyroclastic-flow deposits, mainly on the southeast flank of Pagosa Peak. Phenocrysts are similar to underlying lava flows of porphyritic andesite (Tsma). Maximum thickness, 15 m

Tmp Tmp1 Tmp2 Tmp3 Tmp4 **Masonic Park Tuff**—Greenish-gray to greenish-brown welded ash-flow sheet of compositionally uniform phenocryst-rich dacite (62–65% SiO_2; 35–45% pl>>bi, cpx). Characterized by exceptionally developed compound cooling zonations and numerous flow-unit partings, along which crystal-enriched surge beds are locally preserved, especially near the type area (along Rio Grande 5 km northwest of South Fork) where as many as four cooling subunits are mapped locally (arbitrarily numbered). Most densely welded and exceptionally thick along south mountain front, just outside southern segment of La Garita caldera. In lower Turkey Creek (SM), concentrations of flattened glassy pumices weather out to define subhorizontal layering that resembles bedding (Lipman, 1975, fig. 29). In steep landslide scar on east face of Saddle Mountain, Masonic Park Tuff wedges down to 1–2 m of crystal-poor white ash, probably a coignimbrite ash-cloud deposit, that separates two otherwise petrologically indistinguishable units of platy-plagioclase andesite (Summitville Andesite, Sheep Mountain Andesite). No overlap found with western San Juan tuff sheets across Williams Creek (CP); either spreading of Masonic Park ash flows to the west was blocked by local accumulations of Silverton Volcanics (Tsv), or lava flows of Sheep Mountain Andesite (Tsma) were a barrier to eastward spread of the western tuff sheets. In either case, Williams Creek appears to follow an Oligocene paleovalley defined by constructional volcanic features (also true for many other major drainages in the San Juan Mountains). $^{40}Ar/^{39}Ar$ age (bi), 28.30±0.23 Ma. Magnetic polarity, reverse. Maximum thickness, 300 m

Tmpl **Lower welding zone**—Weakly welded lower part of tuff sheet, locally sufficiently thick and well exposed to map separately along southern mountain front. Maximum thickness, 100 m

Tmpb **Brecciated tuff**—Monolithologic shatter breccia of Masonic Park clasts, along lower East Fork of Piedra River (south margin of PM). Gradational contact against normal Masonic Park Tuff; underlies and perhaps interfingers with Pagosa Peak Dacite. Appears to represent fossil landslide and talus deposits, probably along faults related to eruption of the Pagosa Peak Dacite

OLDER ROCKS RELATED TO WESTERN SAN JUAN CALDERAS

Regional ash-flow sheets erupted from several western San Juan sources (Lipman and others, 1973; Lipman, 1976; Bove and others, 2001) are exposed discontinuously along the west margin of the map area. These units locally overlie the Black Mountain Tuff (Ttb), from the Platoro caldera complex, and are overlain by Fish Canyon Tuff (Tfc). No direct stratigraphic age relation with the Masonic Park Tuff (Tmp) has been determined

Twbl **Tertiary landslide breccia**—Megabreccia, containing clasts as large as 10 m across of Ute Ridge and Sapinero Mesa Tuffs, that concordantly overlies in-place Sapinero Mesa Tuff and Silverton Volcanics along ridges west of Williams Creek (west CP). Matrix appears to be microbreccia of same tuff units. Origin uncertain and perplexing: possibly related to landsliding from structurally high block, peripheral to main La Garita caldera subsidence, and thereby correlative with lithologically similar breccias at lower topographic levels along the southwest caldera wall (Tgbw). Maximum thickness, 25 m

Silverton Volcanics(?)—Andesitic lavas and volcaniclastic rocks that overlie western San Juan tuff sheets and underlie Fish Canyon Tuff west of Williams Creek (CP) and in lower Trout Creek (WC). Stratigraphically equivalent to Silverton Volcanics, mostly ponded within the San Juan and Uncompahgre calderas, for which the nearest known erosional remnants are 35 km farther to the northwest. Similar to andesitic rocks of the underlying Conejos Formation and Summitville Andesite. Without the intervening western San Juan tuff sheets no contact could have been mapped, and upper parts of some andesite sections mapped as Conejos farther east could include correlative rocks. Massive andesite on ridge between Trout and Juniper Creeks (WC) overlies Ute Ridge Tuff and is covered by Fish Canyon Tuff along geometrically complex west margin of La Garita caldera. Maximum thickness, 200 m

Tsvl **Andesitic lavas and breccias**—Aphanitic to sparsely porphyritic dark flows and proximal breccias

Tsvv **Volcaniclastic rocks**—Mostly reworked crudely bedded to well-bedded conglomerates, sandstones, and mudflow breccias containing clasts of dark andesite in lighter-gray sandy matrix

Western San Juan tuff sheets—Distal facies of regional outflow tuff sheets from western San Juan caldera sources (Lipman and others, 1973; Lipman, 1976; Bove and others, 2001). Exposed discontinuously beyond northwest to southwest margins of central caldera cluster. Upper three sheets of phenocryst-poor rhyolite are lithologically similar and difficult to distinguish reliably in outcrop or thin section where the stratigraphic sequence is incomplete. Like tuffs of the Treasure Mountain Group to the east, sanidine phenocrysts in all the western ash-flow sheets tend to be relatively sodic, and some barium rich, in comparison to most units from central San Juan calderas

Tws **Sapinero Mesa Tuff**—Nonwelded to densely welded gray-brown and red-brown rhyolitic ash-flow sheet (72–74% SiO_2; 3–5% pl>sn>bi), containing conspicuous black basal vitrophyre, erupted from the composite Uncompahgre-San Juan caldera (Lipman and others, 1973). Where thick, contains a well-developed central lithophysal zone (as much as 10–20 m thick), similar to that in the Carpenter Ridge Tuff. Most widespread of the three phenocryst-poor western tuff sheets. Similar in general appearance and phenocryst mineralogy to tuff of Saguache Creek (Tsc) in northeastern map area, but is less densely welded and contains more potassic and barium-rich sanidine (average, $Or_{61}Ab_{33}An_2Cs_4$). $^{40}Ar/^{39}Ar$ age (sn), 28.0 Ma (adjusted from Bove and others, 2001). Magnetic polarity, reverse. Maximum thickness, 50 m

Twd **Dillon Mesa Tuff**—Nonwelded to densely welded gray-brown and red-brown rhyolite ash-flow sheet (72–74% SiO_2; 3–5% pl>sn>bi), erupted from the Uncompahgre caldera. A sample from the ridge north of Poison Park (CP) contains barium-rich sanidine (average, $Or_{61}Ab_{33}An_2Cs_4$), similar to the overlying Sapinero Mesa Tuff. $^{40}Ar/^{39}Ar$ age (sn), 28.1 Ma (adjusted from Bove and others, 2001). Magnetic polarity, reverse. A relatively small unit, absent in many sections. Maximum thickness, 15 m

Twb **Blue Mesa Tuff**—Nonwelded to densely welded gray-brown and red-brown rhyolitic ash-flow sheet (72–74% SiO_2; 3–10% pl>sn>bi), with conspicuous black basal vitrophyre, erupted from the Lost Lakes caldera (fig. 2, sheet 3). A sample from the ridge north of Poison Park (CP) contains low-barium sanidine (average, $Or_{60}Ab_{36}An_2Cs_2$), distinct from the megascopically similar overlying Dillon and Sapinero Mesa Tuffs. $^{40}Ar/^{39}Ar$ age (sn), 28.1 Ma (adjusted from Bove and others, 2001). Magnetic polarity, reverse. Maximum thickness, 75 m

Twu **Ute Ridge Tuff**—Nonwelded to densely welded gray-brown and red-brown dacitic ash-flow sheet (65–68% SiO_2; 20–30% pl>sn, bi, cpx), erupted from the Ute Creek caldera (fig. 2, sheet 3). No direct stratigraphic relation has been located with the Masonic Park Tuff (Tmp) of closely similar lithology and age, from which the Ute Ridge Tuff is distinguishable by presence of sparse phenocrystic sanidine. Overlies thin distal Black Mountain Tuff (Ttb) on ridge north of Poison Park west of Williams Creek (CP). Distribution and thickness variable, filling paleovalleys in rocks of the Conejos Formation. Contains sanidine (average, $Or_{63}Ab_{33}An_2Cs_2$), slightly more potassic than overlying rhyolitic Blue Mesa Tuff. Altered crystal-rich dacite tuff in lower Trout Creek (WC) identified as Ute Ridge, based on presence of sanidine phenocrysts. $^{40}Ar/^{39}Ar$ age (sn), 28.4 Ma (adjusted from Bove and others, 2001). Magnetic polarity, reverse. Maximum thickness, 50 m

Twa **Local andesitic lava flow**—Porphyritic dark lava flow (55% SiO_2; 15% pl>cpx), exposed only along nose of ridge west of Williams Creek, lying between Ute Ridge and Blue Mesa Tuffs. Thin discontinuous lava flows are present at this stratigraphic level on Pole Creek Mountain, south of Lake City caldera (fig. 1, sheet 3) in the western San Juan Mountains (Lipman, 1976). Thickness 15 m

ROCKS ERUPTED FROM THE PLATORO CALDERA COMPLEX

Multiple large ash-flow sheets of the Treasure Mountain Group and interleaved andesitic lavas and breccias of the Summitville Andesite, associated with recurrent subsidence at the Platoro caldera complex in the southeastern San Juan Mountains (Lipman, 1975; Dungan and others, 1989), reached southeastern parts of the map area. These units mostly underlie marginal facies of the lithologically similar Masonic Park Tuff (Tmp), but distal parts of the youngest major ash-flow sheet, the Chiquito Peak Tuff, overlie Masonic Park Tuff

Lower member of Summitville Andesite— Lava flows and volcaniclastic rocks, interleaved at several horizons with tuff sheets of the Treasure Mountain Group (upper-member lavas, overlying Chiquito Peak Tuff, are absent within the map area). Erupted from vents of uncertain location within or near the map area, in contrast to the main mass of Summitville Andesite that erupted from volcanoes within and along margins of the Platoro caldera. These lavas are mapped as Summitville Andesite because of their stratigraphic relations to tuffs of the Treasure Mountain Group. Alternatively, they could be considered petrogenetically as early eruptions of Sheep Mountain Andesite, constituting precursors to the Masonic Park eruptive cycle, an interpretation supported by the abundance of porphyritic andesite that is petrologically similar to the overlying Sheep Mountain, but unlike proximal Summitville Andesite

Tsua **Andesitic lava flows**—Aphanitic to sparsely porphyritic dark flows and proximal breccias, similar to the dominant lava type of proximal Summitville Andesite within the Platoro caldera

Tsup **Porphyritic andesite flows**—Distinctive coarsely porphyritic dark-gray lavas (15–30% pl>>cpx), characterized by flow-aligned tabular phenocrysts of plagioclase. A recurrent andesitic rock type in the region, dominant in Sheep Mountain Andesite (Tsma) and also common in the Conejos Formation (Tcap) and Huerto Andesite (Thap), but atypical of proximal Summitville Andesite within the Platoro caldera

Tsuv **Volcaniclastic rocks**—Mostly reworked poorly to well-bedded conglomerates, sandstones, and mudflow breccias, containing clasts of dark andesite in gray sandy matrix

Treasure Mountain Group—Multiple ash-flow sheets of dacite to low-silica rhyolite that, within the map area, become increasingly distal westward. Interleaved with Masonic Park Tuff (Tmp) and with lavas and breccias of Summitville Andesite. Characteristic phenocrysts throughout are pl>>bi>cpx; qz absent; sn sparsely present in upper units. Ages of entire tuff sequence, between about 29.5 and 28.2 Ma. Maximum total thickness in map area, 350 m at type locality (Treasure Mountain, WP)

Tt **Treasure Mountain Group, undivided**—Mapped as undivided in a few distal sections southeast of Pagosa Peak, where assignments to specific tuff sheets become uncertain due to thinning, decreased welding, and wedgeouts

Tts **South Fork Tuff**—Light-tan to gray variably welded tuff of uniform low-silica rhyolite (70–72% SiO_2; 10–20% pl>>sn, bi>cpx); in the map area is commonly difficult to map separately from winnowed nonwelded upper parts of the Ra Jadero Tuff. Characterized by sodic sanidine compositions (Or_{48-51}), in comparison to the younger tuff sheets. $^{40}Ar/^{39}Ar$ age (sn), 28.5 Ma (adjusted from Lipman and others, 1996). Magnetic polarity, reverse. Maximum thickness in map area, 30 m near South Fork

Ttr **Ra Jadero Tuff**—Gray to brown welded tuff of silicic dacite (65–68% SiO_2; 15–25% pl>> bi, cpx>sn); sparse hornblende phenocrysts and andesitic scoria locally present near top of unit. Characterized by basal and upper black vitrophyres, large (as much as 5 mm) blocky plagioclase phenocrysts, dark-gray to black pumice lenses, and abundant angular andesitic lithic fragments (typically a few centimeters in diameter). Contains more sodic sanidine compositions (average, Or_{54}) than younger tuff units from central San Juan calderas. $^{40}Ar/^{39}Ar$ age (sn), 28.5 Ma (adjusted from Lipman and others, 1996). Magnetic polarity, reverse. Maximum thickness in map area, 75 m near Treasure Mountain

Ttm **Middle tuff**—As many as 10 small-volume ash-flow sheets of mostly nonwelded light-colored dacite, containing pumice of widely varied compositions (60–70% SiO_2; 5–15% pl>>bi>cpx). Magnetic polarity, both normal and reverse. Maximum thickness in map area, 100 m on west slopes of Sheep Mountain

Ttj **La Jara Canyon Tuff**—Gray to brown welded tuff of phenocryst-rich dacite (64–68% SiO_2; 20–30% pl>>bi>cpx); hornblende phenocrysts and andesitic scoria sparsely present near top of unit. Black basal vitrophyre is conspicuous; plagioclase phenocrysts are smaller and more tabular than those in Ra Jadero Tuff. Difficult to distinguish from Black Mountain Tuff in some distal sections. $^{40}Ar/^{39}Ar$ age (bi), 29.0 Ma (adjusted from Lipman and others, 1996). Magnetic polarity, reverse. Maximum thickness in map area, 125 m near Treasure Mountain

Ttb **Black Mountain Tuff**—Gray to brown welded tuff of silicic dacite (68–70% SiO_2; 10–20% pl>>bi, cpx); hornblende phenocrysts and andesitic scoria sparsely present near top of unit in some sections. Characterized by basal black vitrophyre, dark-gray to black pumice lenses as much as 20 cm long, and common andesitic lithic fragments (typically a few centimeters in diameter). Most far-traveled tuff of Treasure Mountain Group, having filled paleovalleys. Most distal preserved exposures locally underlie Ute Ridge Tuff (Twu), erupted from a western San Juan source. $^{40}Ar/^{39}Ar$ age (bi), 29.1 Ma (adjusted from Balsley and others, 1988). Magnetic polarity, reverse. Maximum thickness in map area, 100 m near Treasure Mountain

Ttl **Lower rhyolite tuff**—Light-tan to gray variably welded tuff of uniform low-silica rhyolite (72–74% SiO_2; 3–6% pl>>bi>>cpx). Magnetic polarity, reverse. Fills erosional paleovalleys, causing large local variations in thickness and degree of welding. Along West Fork San Juan River and adjacent mountains (SM), unit is exceptionally thick and densely welded. Maximum thickness in map area, 75 m on east slopes of Saddle Mountain

ROCKS PREDATING CENTRAL CALDERA CLUSTER

Several ash-flow sheets, exposed locally in the northeast corner of the map and more widely to the north and east, were erupted from sources beyond the present map area, perhaps from Cochetopa Park. These predate any tuffs erupted from the central San Juan caldera cluster, having ages older than much of the precaldera Conejos Formation to the south (Lipman and Calvert, 2003). These tuff sheets overlie andesitic-dacitic lavas that are compositionally similar to the younger Conejos rocks farther south; lacking exposed interfingering relations, the Conejos cannot readily be subdivided based on field relations. The northeastern tuff units also represent an age and geographic progression toward caldera-related volcanism of lower Oligocene age in central Colorado (McIntosh and Chapin, 2004)

Tuff of Luders Creek—Compositionally zoned cooling unit, changing upward from weakly welded light-tan rhyolite tuff (5–10% pl, sn>>bi) to densely welded dark-gray dacite. Within map area exposed only as small areas in northeastern SP; more widespread and thicker to north and east. Similar in appearance and phenocryst mineralogy to outflow Nelson Mountain Tuff, with which the tuff of Luders Creek had been correlated previously (Steven and Lipman, 1976, fig. 24). Exposures northeast of map area show that laharic debris, derived from the tuff of Luders Creek, underlies Fish Canyon Tuff and overlies the tuff of Saguache Creek. Limited preserved distribution of this unit suggest probable eruption from the Cochetopa Park area. Maximum thickness within map area, 50 m

Tld **Welded dacite**—Upper dark-gray welded zone (66–68% SiO_2; 20–30% pl>sn, bi>cpx). Small slumped exposures of brownish-gray caprock, which closely resembles upper parts of outflow Nelson Mountain Tuff (Tnd). Contains pumice lenses of both crystal-poor rhyolite and crystal-rich dacite. Grades downward into rhyolite (Tln). Thickness, 10–20 m

Tln **Nonwelded to partly welded rhyolite**—Lower zone of weakly welded light tan tuff (72–73% SiO_2; 5–10% pl, sn>>bi), exposed within map area only as float on hill slopes beneath welded dacite (Tld). Thickness, 0–75 m

Tuff of Saguache Creek—Rhyolite tuff, exposed only in the northeastern map area (SP); correlative with more widely scattered erosional remnants of this unit in adjacent areas to north and east. Similar in appearance and phenocryst mineralogy to proximal Sapinero Mesa Tuff (Tws), to which this unit had been previously assigned in adjacent areas (Bruns and others, 1971; Steven and Lipman, 1976, fig. 10; Olson, 1988), but contains less biotite, has more sodic low-barium sanidine (Or_{50},$Ab_{46}An_3Cs_{0.5}$), and is more densely welded than the distal Sapinero Mesa in nearby areas. Also similar in appearance, but different in trace-element composition from underlying upper Bonanza Tuff (Bruns and others, 1971; Varga and Smith, 1984). $^{40}Ar/^{39}Ar$ age (sn) of tuff of Saguache Creek is 31.94±0.17 Ma (Lipman and Calvert, 2003), significantly younger than the upper Bonanza Tuff, 32.6 Ma (adjusted from McIntosh and Chapin, 2004). The preserved distribution of this unit, widespread to the north and east of Cochetopa Park where not hidden by younger rocks (to the south and west), suggests eruption from a largely buried caldera source, centered near North Pass, northeast of the map area (fig. 5*C*). Maximum thickness, 30 m

Tscc **Densely welded crystal-rich rhyolite**—Local upper zone of densely welded dark gray tuff (73.5% SiO_2; 15–20% pl, sn>>bi), exposed within map area only as small outcrops along Mexican Joe Canyon (northern SP). Thickness, 0–15 m

Tsc **Nonwelded to densely welded crystal-poor rhyolite**—Variably welded light-tan to red-brown tuff (74–76% SiO_2; 5–10% pl, sn>>bi). Locally grades upwards into more densely welded crystal-rich rhyolite (Tscc). Thickness, 0–75 m

Conejos Formation—Dominantly andesite and dacite as lava flows and proximal breccias erupted from central volcanoes, surrounded by voluminous aprons of volcaniclastic debris emplaced as mudflow and stream-fan deposits (Lipman, 1975; Colucci and others, 1991). These thick accumulations of intermediate-composition lavas and breccias, which underlie the caldera-related ash-flow sequence that dominates the central San Juan map area, constitute the volumetric bulk of the San Juan volcanic field. Subsequently deeply eroded, these early eruptive deposits are now discontinuously exposed as surviving topographic highs along margins of the ash-flow calderas. In distal areas, locally difficult to distinguish from younger suites of compositionally similar intermediate-composition lavas, which were emplaced concurrently with the ash-flow eruptions. Compositional subunits among Conejos lavas have been subdivided in varying detail, depending on degree of local diversity and quality of exposures. Proximal lavas tend to become more silicic upward, with biotite-bearing dacite and low-silica rhyolite especially abundant on northeast side of La Garita caldera. Northerly primary dips of lavas and other proximal deposits along the south mountain front suggest preservation of the north flank of a large stratovolcano centered farther south, with an intrusive core probably marked by the Jackson Mountain laccolith (Steven and others, 1974). Northern parts of this unit, which underlie the tuff of Saguache Creek (31.9 Ma) and the Bonanza Tuff (32.6 Ma) northeast of map area, are consistently older than the widespread Conejos rocks to the south, which are mainly 33–30 Ma (Lipman and Calvert, 2003). Maximum exposed thickness, 800 m along south margins of the caldera cluster; sections as much as 2.3 km thick have been penetrated by petroleum exploration drilling just east of the map area (Gries, 1985; Brister and Gries, 1994)

Tci **Intrusions**—Fine-grained equigranular to porphyritic monzonite and granodiorite (pl>>cpx>>bi), locally grading irregularly into porphyritic andesite. Occurs as small stocks, dikes, and rare sills representing the intrusive cores of Conejos volcanoes. The intrusive interior of one major Conejos volcano is well exposed at Sky City (ME) where truncated along the northeast wall of La Garita caldera; another, at Jackson Mountain, is immediately south of the map area

Lava flows and proximal breccias—Flows and flow breccias of aphanitic to porphyritic lavas from many volcanic centers, some of which probably lie within subsided areas of the central caldera cluster. Primary dips preserved on flanks of volcanoes are as steep as 30°

Tcf **Lava flows and breccias, undivided**—Andesitic to dacitic rocks, where not mapped in detail or in inaccessible cliff outcrop (CP)

Tca **Andesite**—Finely porphyritic to aphanitic dark-gray lava flows and breccia (55–61% SiO_2; 5–15% pl>cpx, hbl), constituting the most voluminous Conejos lithology. $^{40}Ar/^{39}Ar$ age (hbl) southeast of Bristol Head, 30.23±0.23 Ma

Tcap **Porphyritic andesite**—Distinctive coarsely porphyritic dark-gray lavas (56–60% SiO_2; 15–30% pl>>cpx), characterized by flow-aligned tabular phenocrysts of plagioclase. A recurrent andesitic rock type in the region, dominant in Sheep Mountain Andesite (Tsma), and also common in the Summitville Andesite (Tsup) and Huerto Andesite (Thap). A porphyritic andesite flow from near base of the Conejos section west of Snowball Park (SM) has a K-Ar (pl) age of 31.9±2.7 Ma

Tcd **Dacite**—Gray porphyritic flow-layered lava and breccia, characterized by light color and conspicuous biotite phenocrysts (62–68% SiO_2; 20–30% pl>>bi, cpx, hbl). Especially common along north margin of map area, where several large stratovolcanoes appear to have been truncated by collapse of La Garita caldera. $^{40}Ar/^{39}Ar$ age (hbl) in Cebolla Creek, 29.86±0.38 Ma

Tcfr **Rhyolite**—Light-gray flow-layered lava and breccia (70–74% SiO_2; 3–5%). Typically occurs high in Conejos sequence, close to central caldera cluster; may represent initial silicic magmatism precursor to explosive ash-flow eruptions

Tcv **Volcaniclastic rocks**—Mostly reworked crudely bedded to well-bedded conglomerates, sandstones, and mudflow breccias, containing clasts of dark andesite and dacite in lighter-gray sandy matrix. Primary dips are typically less than 5°

Tcs **Volcanic sandstone**—Poorly-bedded to well-bedded massive gray sandstone derived from andesitic volcanic rocks. Widely present as local thin units within the Conejos Formation. Mapped separately only along north slopes of the East Fork San Juan River (WP), where thickness locally exceeds 300 m, probably representing accumulation in basin between volcanic edifices. May include some primary deposits of andesitic ash-flow tuff

Tcas **Arkosic sandstone**—Local stream-fan deposits that locally interfinger as thin beds (1–5 m thick) with volcaniclastic deposits in the southwestern map area, for example, north of Poison Park (CP). Contains quartzo-feldspathic debris derived from Precambrian granitic sources in the Needle Mountains to the west. Lithologically broadly similar to prevolcanic sandstone of the underlying Blanco Basin Formation (Tbb)

Tcst **Tuff of Snowball Park**—Distinctive nonwelded ash-flow sheet of phenocryst-poor rhyolite (75–76% SiO_2; 1–3% pl>>bi), locally exposed near base of the Conejos Formation in south-central parts of the map area (SM). Small angular lithic fragments of andesite and sparse Precambrian rocks are conspicuous. Atypical component of the early intermediate-composition volcanic activity; may represent an early eruption from the deeply eroded large volcanic edifice centered on a granodioritic laccolithic body at Mount Jackson, just south of the map area. Maximum thickness, 75 m

Intrusions of uncertain affinity—Intrusive rocks, mostly dikes, lacking definitive features of areal distribution or petrology that permit confident correlation with a stratigraphically constrained volcanic sequence. Many of these are probably associated with Conejos-age volcanoes, but some are likely younger

Tia **Andesite**—Dark-gray intrusive rocks, typically containing small phenocrysts (pl>cpx, hbl)

Tid **Dacite**—Gray intrusive rocks, typically phenocryst rich, containing pl>bi>hbl, cpx

PREVOLCANIC ROCKS

Beneath the Oligocene volcanic rocks of the San Juan field, along the southwest margin of the map area, prevolcanic Cretaceous and Tertiary sedimentary deposits are mostly poorly exposed beneath widespread landslide deposits (Steven and others, 1974)

Tbb **Blanco Basin Formation (Eocene)**—Red-brown to light-tan arkosic sandstone, conglomerate, and red, yellow, and white claystone. Only locally exposed (WP, south SM, and Poison Park area in southwest CP), because of landslides and other surficial deposits at base of volcanic slopes. Conglomerates north of Poison Park contain cobbles of Precambrian rocks. Maximum thickness, about 40 m

Ku **Sedimentary rocks, undivided (Cretaceous)**—Dark-gray shale and tan sandstone, mainly assigned to the Mesa Verde Formation and Lewis Shale

p€q **Quartzite (Precambrian)**—A unique coherent block of light-gray faintly crossbedded quartzite, about 50 m across, forms a conspicuous rafted inclusion within the east flank of intrusion at Red Mountain (Tsri, east-central PM). It resembles quartzite in the Precambrian Uncompahgre Formation, exposed in the Needle Mountains, about 35 km west of Red Mountain

REFERENCES

Askren, D.R., Whitney, J.A., and Roden, M.F., 1991, Petrology and geochemistry of the Huerto Andesite, San Juan volcanic field, Colorado: Contributions to Mineralogy and Petrology, v. 107, p. 373–386.

Bachmann, Olivier, Dungan, M.A., and Lipman, P.W., 2000, Voluminous lava-like precursor to a major ash-flow tuff—Low-column pyroclastic eruption of the Pagosa Peak Dacite, San Juan volcanic field, Colorado: Journal of Volcanology and Geothermal Research, v. 98, p. 153–171.

————2002, The Fish Canyon magma body, San Juan volcanic field, Colorado—Rejuvenation and eruption of an upper crustal batholithic magma chamber: Journal of Petrology, v. 43, p. 1469–1503.

Balsley, S.D., Brown, L.L., Lux, D.R., Ferguson, K.F., Colucci, M.T., Dungan, M.A., and Lipman, P.W., 1988, Combined $^{40}Ar/^{39}Ar$, paleomagnetic, and stratigraphic constraints on the eruptive history of the Platoro-Summitville caldera complex, southeast San Juan volcanic field, Colorado [abs.]: Geological Society of America Abstracts with Programs, v. 20, p. A368–A369.

Barton, P.B., Rye, R.O., and Bethke, P.B., 2000, Evolution of the Creede caldera and its relation to mineralization in the Creede mining district, Colorado, *in* Bethke, P.M., and Hay, R.L., eds., Ancient Lake Creede—Its volcano-tectonic setting, history of sedimentation, and relation to mineralization in the Creede mining district: Geological Society of America Special Paper 346, p. 301–326.

Bethke, P.M., and Hay, R.L., eds., 2000, Ancient Lake Creede—Its volcano-tectonic setting, history of sedimentation, and relation to mineralization in the Creede mining district: Geological Society of America Special Paper 346, 332 p.

Bethke, P.M., and Lipman, P.W., 1987, Deep environment of volcanogenic epithermal mineralization—Proposed research drilling at Creede, Colorado: EOS, v. 68, p. 177, 187–189.

Bove, D.J., Hon, Ken, Budding, K.E., Slack, J.F., Snee, L.W., and Yeoman, R.A., 2001, Geochronology and geology of late Oligocene through Miocene volcanism and mineralization in the western San Juan Mountains, Colorado: U.S. Geological Survey Professional Paper 1642, 30 p.

Brister, B.S., and Gries, R.R., 1994, Depth and geometry of the northern Rio Grande rift in the San Luis Basin, south-central Colorado, *in* Keller, G.R., and Cather, S.M., eds., Basins of the Rio Grande Rift—Structure, stratigraphy, and tectonic setting: Geological Society of America Special Paper 291, p. 39–58.

Bruns, D.L., Epis, R.C., Weimer, R.G., and Steven, T.A., 1971, Stratigraphic relations between Bonanza center and adjacent parts of the San Juan volcanic field, south-central Colorado: New Mexico Geological Society Guidebook 22, p. 183–190.

Colucci, M.T., Dungan, M.T., Ferguson, K.M., Lipman, P.W., and Moorbath, Steven, 1991, Precaldera lavas of the southeast San Juan volcanic field—Parent magmas and crustal interactions: Journal of Geophysical Research, v. 96, p. 13,412–13,434.

Cross, Whitman, and Larsen, E.S., Jr., 1935, A brief review of the geology of the San Juan region of southwestern Colorado: U.S. Geological Survey Bulletin 843, 138 p.

Diehl, J.F., Beck, M.E., and Lipman, P.W., 1974, Palaeomagnetism and magnetic-polarity zonation in some Oligocene volcanic rocks of the San Juan Mountains, southwestern Colorado: Geophysical Journal of the Royal Astronomical Society, v. 37, p. 323–332.

Dorais, M.J., Whitney, J.A., and Stormer, J.C., Jr., 1991, Mineralogical constraints on the petrogenesis of trachytic inclusions, Carpenter Ridge Tuff, central San Juan volcanic field, Colorado: Contributions to Mineralogy and Petrology, v. 107, p. 219–230.

Dungan, M.A., Lipman, P.W., Colucci, M.T., Ferguson, K.M., and Balsley, S.D., 1989, Southeastern (Platoro) caldera complex, *in* Lipman, P.W., ed., IAVCEI fieldtrip guide—Oligocene-Miocene San Juan volcanic field, Colorado: New Mexico

Bureau of Mines and Mineral Resources Memoir 46, p. 305–329.

Elwood, B.B., 1982, Estimates of flow direction for calc-alkaline welded tuffs and paleomagnetic data reliability from anisotropy of magnetic susceptibility measurements, central San Juan Mountains, southwest Colorado: Earth and Planetary science Letters, v. 59, p. 303–314.

Emmons, W.H., and Larsen, E.S., 1913, A preliminary report on the geology and ore deposits of Creede, Colorado: U.S. Geological Survey Bulletin 530, p. 42–65.

Foley, N.K., Caddey, S.W., Byington, C.B., and Vardiman, D.M., 1993, Mineralogy, mineral chemistry, and paragenesis of gold, silver, and base-metal ores of the North Amethyst vein system, San Juan Mountains, Mineral County, Colorado: U.S. Geological Survey Professional Paper 1537, 39 p.

Gries, R.R., 1985, San Juan sag—Cretaceous rocks in a volcanic-covered basin, south-central Colorado: The Mountain Geologist, v. 22, p. 167–179.

Heiken, Grant, Krier, D., McCormick, T., and Snow, M.G., 2000, Intracaldera volcanism and sedimentation—Creede caldera, Colorado, *in* Bethke, P.M., and Hay, R.L., eds., Ancient Lake Creede—Its volcano-tectonic setting, history of sedimentation, and relation to mineralization in the Creede mining district: Geological Society of America Special Paper 346, p. 127–158.

Hon, Ken, and Mehnert, H.A., 1983, Compilation of revised ages of volcanic units in the San Juan Mountains, Colorado—Recalculated K/Ar age determinations using the IUGS constants: U.S. Geological Survey Open-File Report 83–668, 14 p.

Hulen, J.B., 1992, Field geologic summaries for core holes CCM–2 (Airport 1–6) and CCM–1 (Hosselkus 1–10): Creede Scientific Drilling Project Report ESL–920111–TR, 38 p.

Kunk, M.J., Sutter, J.F., and Naeser, C.W., 1985, High-precision $^{40}Ar/^{39}Ar$ ages of sanidine, biotite, hornblende, and plagioclase from the Fish Canyon Tuff, San Juan volcanic field, south-central Colorado: Geological Society of America Abstracts with Programs, v. 17, p. 636.

Lanphere, M.A., 1988, High resolution $^{40}Ar/^{39}Ar$ chronology of Oligocene volcanic rocks, San Juan Mountains, Colorado: Geochimica et Cosmochimica Acta, v. 52, p. 1425–1434.

————2000, Duration of sedimentation of the Creede Formation from $^{40}Ar/^{39}Ar$ ages, *in* Bethke, P.M., and Hay, R.L., eds., Ancient Lake Creede—Its volcano-tectonic setting, history of sedimentation, and relation to mineralization in the Creede mining district: Geological Society of America Special Paper 346, p. 71–76.

Larsen, Dan, and Crossey, L.J., 1996, Depositional environments and paleolimnology of an ancient caldera lake—Oligocene Creede Formation, Colorado: Geological Society of America Bulletin, v. 108, p. 526–544.

Larsen, E.S., and Cross, Whitman, 1956, Geology and petrology of the San Juan region, southwestern Colorado: U.S. Geological Survey Professional Paper 258, 303 p.

Le Bas, M.J., Le Maitre, R.W., Streckeisen, A., and Zanetin, B., 1986, A chemical classification of volcanic rocks based on the total alkali-silica diagram: Journal of Petrology, v. 27, p. 745–750.

Lipman, P.W., 1975, Evolution of the Platoro caldera complex and related volcanic rocks, southeastern San Juan Mountains, Colorado: U.S. Geological Survey Professional Paper 852, 128 p.

————1976, Geologic map of the Lake City caldera, western San Juan Mountains, Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I–962.

————1984, The roots of ash-flow calderas—Windows into the tops of granitic batholiths: Journal of Geophysical Research, v. 89, p. 8801–8841.

————1997a, Subsidence of ash-flow calderas—Relation to caldera size and magma-chamber geometry: Bulletin of Volcanology, v. 59, p. 198–218.

————1997b, Chasing the volcano: Earth, v. 6, no. 6, p. 32–39.

————2000, The central San Juan caldera cluster— Regional geologic framework, *in* Bethke, P.M., and Hay, R.L., eds., Ancient Lake Creede—Its volcano-tectonic setting, history of sedimentation, and relation to mineralization in the Creede mining district: Geological Society of America Special Paper 346, p. 9–70.

————2004, Chemical analyses of Tertiary volcanic rocks, central San Juan caldera complex, southwestern Colorado: U.S. Geological Survey Open-File Report 2004–1194.

Lipman, P.W., and Calvert, A., 2003, Southward migration of mid-Tertiary volcanism—Relations in the Cochetopa area, north-central San Juan Mountains, Colorado [abs.]: Geological Society of America Abstracts with Programs, v. 35, no. 5, p. 14.

Lipman, P.W., Doe, B.R., Hedge, C.E., and Steven, T.A., 1978, Petrologic evolution of the San Juan volcanic field, southwestern Colorado—Pb and Sr isotope evidence: Geological Society of America Bulletin, v. 89, p. 59–82.

Lipman, P.W., Dungan, M.A., and Bachmann, Olivier, 1997, Eruption of granophyric granite from a large ash-flow magma chamber—Implications for emplacement of the Fish Canyon Tuff and collapse of the La Garita caldera, San Juan Mountains, Colorado: Geology, v. 25, p. 915–918.

Lipman, P.W., Dungan, M.A., Brown, L.D., and Deino, Allen, 1996, Recurrent eruption and subsidence at the Platoro caldera complex, southeastern San Juan volcanic field, Colorado—New tales from old tuffs: Geological Society of America Bulletin, v. 108, p. 1039–1055.

Lipman, P.W., and Mehnert, H.H., 1975, Late Cenozoic basaltic volcanism and development of the Rio Grande depression in the southern Rocky Mountains: Geological Society of America Memoir 144, p. 119–153.

Lipman, P.W., Sawyer, D.A., and Hon, K., 1989, Central San Juan caldera cluster: New Mexico Bureau of Mines & Mineral Resources Memoir 46, p. 330–350.

Lipman, P.W., and Steven, T.A., 1976, Geologic map of the South Fork area, southeastern San Juan Mountains, Colorado: U.S.

Geological Survey Miscellaneous Investigations Series Map I–966.

Lipman, P.W., Steven, T.A., Luedke, R.G., and Burbank, W.S., 1973, Revised history of the San Juan Uncompahgre, Silverton, and Lake City calderas in the Western San Juan Mountains: U.S. Geological Survey Journal of Research, v. 1, no. 6, p. 627–642.

Lipman, P.W., Steven, T.A., and Mehnert, H.H., 1970, Volcanic history of the San Juan Mountains, Colorado, as indicated by potassium-argon dating: Geological Society of America Bulletin, v. 81, p. 2327–2352.

Lipman, P.W., and Weston, P.E., 2001, Phenocryst compositions of late ash-flow tuffs from the central San Juan caldera cluster—Results from Creede drill-hole samples and implications for regional stratigraphy, *in* Bethke, P.M., ed., Preliminary scientific results of the Creede caldera continental scientific drilling program, U.S. Geological Survey Open-File Report 94–260B, 43 p.

McIntosh, W.C., and Chapin, C.E., 2004, Geochronology of the central Colorado volcanic field: New Mexico Bureau of Mines and Mineral Resources Bulletin 160, p. 205–238.

Olson, J.C., 1988, Geology and ore deposits of the Cochetopa and Marshall Pass districts, Saguache and Gunnison Counties, Colorado: U.S. Geological Survey Professional Paper 1457, 44 p.

Parat, F., 2001, Contemporaneous magmatic differentiation of S-rich trachyandesitic and high-K calc-alkaline andesite in an intracontinental setting, San Juan volcanic field, Colorado, U.S.A.: University of Geneva, Switzerland, Ph.D dissertation, 121 p.

Ratté, J.C., and Steven, T.A., 1967, Ash flows and related volcanic rocks associated with the Creede caldera, San Juan Mountains, Colorado: U.S. Geological Survey Professional Paper 524–H, 58 p.

Riciputi, L.R., 1991, Petrology and Nd, Sr, and Pb isotopes of the central San Juan caldera cluster, Colorado: University of Wisconsin, Madison, Ph.D. thesis.

Riciputi, L.R., Johnson, C.M., Sawyer, D.A., and Lipman, P.W., 1995, Crustal and magmatic evolution in a large multicyclic caldera complex—Isotopic evidence from the central San Juan volcanic field: Journal of Volcanology and Geothermal Research, v. 67, p. 1–28.

Rosenbaum, J.G., Reynolds, R.L., Lipman, P.W., and Sawyer, D.A., 1987, Paleomagnetism of Oligocene ash-flow tuffs, central San Juan Mountains, Colorado: Geological Society of America Abstracts with Programs, v. 19, p. 330.

Schmitz, M.D., and Bowring, S.A., 2001, U-Pb zircon and titanite systematics of the Fish Canyon Tuff—An assessment of high-precision U-Pb geochronology and its application to young volcanic rocks: Geochimica et Cosmochimica Acta, v. 65, p. 2571–2587.

Smith, R.L., and Bailey, R.A., 1968, Resurgent cauldrons, *in* Coates, R.R., Hay, R.L., and Anderson, C.A., eds., Studies in volcanology: Geological Society of America Memoir 116, p. 613–662.

Steven, T.A., 1967, Geologic map of the Bristol Head quadrangle, Mineral and Hinsdale Counties, Colorado: U.S. Geological Survey Geologic Quadrangle Map GQ–631.

———1975, Middle Tertiary volcanic field in the southern Rocky Mountains, *in* Curtis, B.F., ed., Cenozoic history of the southern Rocky Mountains: Geological Society of America Memoir 144, p. 75–94.

Steven, T.A., and Bieniewski, C.L., 1977, Mineral resources of the La Garita Wilderness, San Juan Mountains, southwestern Colorado: U.S. Geological Survey Bulletin 1420, 65 p.

Steven, T.A., Hon, Ken, and Lanphere, M.A., 1995, Neogene geomorphic evolution of the central San Juan Mountains near Creede, Colorado: U.S. Geological Survey Miscellaneous Investigations Series Map I–2504.

Steven, T.A., and Lipman, P.W., 1973, Geologic map of the Spar City quadrangle, Mineral County, Colorado: U.S. Geological Survey Geologic Quadrangle Map GQ–1052.

Steven, T.A., and Lipman, P.W., 1976, Calderas of the San Juan volcanic field, southwestern Colorado: U.S. Geological Survey Professional Paper 958, 35 p.

Steven, T.A., Lipman P.W., Hail, W.J., Jr., Barker, Fred, and Luedke, R.G., 1974, Geologic map of the Durango quadrangle, southwestern Colorado: U.S. Geological Survey Miscellaneous Geologic Investigations Map I–764.

Steven, T.A., and Ratté, J.C., 1965, Geology and structural control of ore deposition in the Creede district, San Juan Mountains, Colorado: U.S. Geological Survey Professional Paper 487, 90 p.

———1973, Geologic map of the Creede quadrangle, Mineral and Saguache Counties, Colorado: U.S. Geological Survey Geologic Quadrangle Map GQ–1053.

Steven T.A., Schmitt, L.J., Jr., Sheridan, M.J., and Williams, F.E., 1969, Mineral resources of the San Juan Primitive Area, Colorado: U.S. Geological Survey Bulletin 1261–F, 187 p.

Tanaka, H., and Kono, M., 1973, Paleomagnetism of the San Juan volcanic field, Colorado: Rock Magnetism and Paleophysics, v. 1, p. 71–76.

Varga, R.J., and Smith, B.M., 1984, Evolution of the early Oligocene Bonanza caldera, northeast San Juan volcanic field, Colorado: Journal of Geophysical Research, v. 89, p. 8679–8694.

Webber, K.L., 1988, The Mammoth Mountain and Wason Park Tuffs—Magmatic evolution in the central San Juan volcanic field, southwestern Colorado: Houston, Texas, Rice University, Ph.D. thesis, 244 p.

Wentworth, C.M., and Fitzgibbon, T.T., 1991, ALACARTE user manual, version 1.0: U.S. Geological Survey Open-File Report OF 91–0587–C, 267 p.

Wetlaufer, P.H., Bethke, P.M, Barton, P.B., Jr., and Rye, R.O., 1979, The Creede Ag-Pb-Zn-Cu-Au district, central San Juan Mountains, Colorado—A fossil geothermal system: Fifth IAGOD Quadrennial Symposium, v. 2, Nevada Bureau of Mines and Geology Report 33, p. 159–164.

Whitney, J.A., Dorais, M.J., Stormer, J.C., Jr., Kline, S.W., and Matty, D.J., 1988, Magmatic conditions and development of chemical zonation in the Carpenter Ridge Tuff, central San Juan volcanic field, Colorado: American Journal of Science, v. 288–A, p. 16–44.

Whitney, J.A., and Stormer, J.C., Jr., 1985, Mineralogy, petrology, and magmatic conditions from the Fish Canyon Tuff, central San Juan volcanic field, Colorado: Journal of Petrology, v. 26, p. 726–762.

Yager, Douglas, Lipman, P.W., and Sawyer, D.A., 1991, Caldera-related lavas and intrusions of the south-central San Juan Mountains, Colorado—Analytical data: U.S. Geological Survey Open-File Report 91–313, 19 p.

Table 1. *Summary of major ash-flow tuffs, caldera sources, and* $^{40}Ar/^{39}Ar$ *ages, San Juan volcanic field, southwestern Colorado*

[Bold type, major tuff sheets of central caldera cluster. Age determinations from Lanphere, 1988, 2000, and unpub. data; Lipman and others, 1996; Bove and others, 2001]

Ash-Flow Sheets			Composition[1]	Caldera Source	Volume	Magnetic	Age[2]
SE Complex	*Central Cluster*	*West Cluster*			(m^3)	Polarity[2]	(Ma)
		Sunshine Peak	Si rhyolite - dacite	Lake City	200-500	R	23.1
	Snowshoe Mountain		**Mafic dacite**	**Creede**	**>500**	**N**	**26.7**
	Nelson Mountain		**Low-Si rhyolite⇒dacite**	**San Luis complex, Cochetopa Park**	**>500**	**N**	**~26.8?[4]**
	Cebolla Creek		**Mafic dacite**	**San Luis complex**	**250**	**N**	**~26.9?[4]**
	Rat Creek		**Low Si rhyolite⇒dacite**	**San Luis complex**	**150**	**N**	**~27.0?[4]**
	Wason Park		**Rhyolite**	**South River**	**>500**	**R**	**27.1**
	Blue Creek		**Dacite**	**(concealed)**	**250**	**R**	**27.2**
	Carpenter Ridge		**Low-Si rhyolite⇒dacite**	**Bachelor**	**>1,000**	**R**	**27.35**
		Crystal Lake	Low-Si rhyolite	Silverton	50-100	R	27.5[5]
	Fish Canyon		**Dacite**	**La Garita**	**>5,000**	**N**	**27.6**
Chiquito Peak			Dacite	Platoro	1,000	R	28.2[5]
	Masonic Park		**Dacite**	**(concealed)**	**500**	**R**	**28.3**
		Sapinero Mesa[3]	Low-Si rhyolite	San Juan	>1,000	R	28.0[5]
		Dillon Mesa[3]	Low-Si rhyolite	Uncompahgre?	25-100	R	28.1[5]
		Blue Mesa[3]	Low-Si rhyolite	Lost Lakes	100-500	R	28.1[5]
		Ute Ridge[3]	Dacite	Ute Creek	>500	R	28.4[5]
South Fork			Low-Si rhyolite	Platoro (Summitville?)	50	R	28.5[5]
Ra Jadero			Si dacite	Platoro (Summitville?)	150	R	28.5[5]
Ojito Creek			Si dacite	Platoro	100	N	~29
Middle tuff			Dacite	Platoro	100	N/R	~29
La Jara Canyon			Dacite	Platoro	1,000	R	29.0[5]
Black Mountain			Si dacite	Platoro	100	R	~29.5?
Lower rhyolite tuff			Low-Si rhyolite	Platoro	75	n.d.	~29.5?
Tuff of Rock Creek			Andesite	Platoro	25	n.d.	30-31?
	Tuff of Luders Creek		Low-Si rhyolite⇒dacite	Cochetopa?	50?	n.d.	n.d
	Tuff of Saguache Creek		Rhyolite	Cochetopa?	100?	N	31.9

[1]Si, silica; ⇒, compositionally zoned to

[2]N, normal polarity; R, reverse polarity; n.d., not determined

[3]Stratigraphic relation to southeast area is uncertain

[4]Age and stratigraphic relation to Snowshoe Mountain are uncertain

[5]Reported age reduced by 1% to provide consistency with the calibrations used by Lanphere (1988, 1994)

Table 2. *Characteristic features of ash-flow sheets in central San Juan region, southwestern Colorado*

[Bold type, major tuff sheets of central cluster; ⇒, zoned]

Ash-flow sheets	Composition	Textures and phenocrysts
Snowshoe Mountain Tuff	Mafic dacite	Phenocryst rich; densely welded within caldera, weakly welded outflow
Nelson Mountain Tuff	Low-Si rhyolite⇒dacite	Compositionally zoned; weakly welded crystal-poor to dense crystal-rich
Cebolla Creek Tuff	Mafic dacite	Typically weakly welded; abundant hornblende >> augite is distinctive
Rat Creek Tuff	Low Si rhyolite⇒dacite	Compositionally zoned; weakly welded rhyolite to dense dacite
Wason Park Tuff	Rhyolite	Phenocryst-rich rhyolite; tabular sanidine phenocrysts
Blue Creek Tuff	Dacite	Phenocryst rich; sanidine is absent (contrast with Mammoth Mountain Member)
Carpenter Ridge Tuff		
Mammoth Member (upper intracaldera)	Dacite	Phenocryst rich; sanidine is common (contrast with Blue Creek Tuff)
Outflow and lower intracaldera tuff	Low-Si rhyolite	Phenocryst-poor; common basal vitrophyre, central lithophysal zone
Crystal Lake Tuff	Low-Si rhyolite	Similar to rhyolitic Carpenter Ridge Tuff, but less welded within map area
Fish Canyon Tuff	Dacite	Distinctive light-gray, phenocryst-rich: resorbed quartz, hornblende, absence of augite
Sapinero Mesa Tuff	Low-Si rhyolite	Similar to rhyolitic Carpenter Ridge Tuff, but generally less welded within map area
Dillon Mesa Tuff	Low-Si rhyolite	Similar to rhyolitic Carpenter Ridge Tuff, but generally less welded within map area
Blue Mesa Tuff	Low-Si rhyolite	Similar to rhyolitic Carpenter Ridge Tuff, but generally less welded within map area
Ute Ridge Tuff	Dacite	Phenocryst-rich; contains sparse sanidine (in contrast to Masonic Park Tuff)
Chiquito Peak Tuff	Dacite	Phenocryst-rich; similar to Masonic Park, but contains sparse sanidine
Masonic Park Tuff	Dacite	Phenocrysts similar to Blue Creek Tuff; typically less welded
Tuff of Luders Creek	Low-Si rhyolite⇒dacite	Compositionally zoned; resembles Nelson Mountain Tuff
Tuff of Saguache Creek	Low-Si rhyolite	Resembles Carpenter Ridge and Sapinero Mesa Tuffs, but lacks phenocrystic biotite

Table 3. *Representative chemical analyses, central San Juan caldera cluster, southwestern Colorado*

[Major-element chemical analyses calculated to 100% volatile-free. Intrac, intracaldera; rhy, rhyolite; vitr, vitrophyre; xr, crystal rich; xp, crystal poor; plag, plagioclase. All chemical analyses determined at U.S. Geological Survey, Denver, Colorado. Samples and analyses (other than from P.W. Lipman): (1) sample from David Matty, 1985, (2) sample from David Sawyer, (3) sample from Dough Yager, 1989, (4) analysis from Riciputi, 1991]

Field Number	Sample Description	Major-element XRF												KEVEX XRF			
		SiO_2	TiO_2	Al_2O_3	$FeTO_3$	MgO	CaO	Na_2O	K_2O	P_2O_5	MnO	LOI	Total	Rb	Sr	Zr	Ba
	CREEDE CALDERA CYCLE																
85L-39	Fisher Dacite, Wagon Wheel Gap flow	65.4	0.66	15.4	5.01	1.66	4.07	3.46	3.85	0.27	0.07	1.93	99.84	94	587	174	1020
85S-129	Snowshoe Mtn Tuff, intrac, Point of Rocks	67.6	0.52	15.0	3.87	1.07	3.62	3.47	4.53	0.23	0.06	1.64	100.03	135	472	184	823
SJ-85-20	Snowshoe Mtn Tuff, outlfow, Cattle Mtn (1)	62.3	0.73	16.6	6.38	1.33	4.53	3.73	3.43	0.31	0.11	1.25	99.44	107	704	155	1010
	SAN LUIS CALDERA COMPLEX																
	Nelson Mountain cycle																
DS87-103	Resurgent intrusion (2)	57.0	1.06	17.31	8.14	0.11	2.19	5.77	3.64	3.04	0.45	0.73	98.66	84	759	187	1061
94L-19A	Volcanics of Baldy Cinco, dacite lava	64.4	0.64	15.90	4.51	1.11	3.41	3.78	4.31	0.37	0.09	0.70	98.52	144	580	210	1100
85S-121	Volcanics of Stewart Peak, andesite lava (2)	60.8	0.91	17.0	6.87	1.81	5.00	3.56	3.48	0.36	0.07	1.08	99.90	115	644	195	1040
85S-110	Nelson Mtn Tuff, intrac dacite, San Luis Pk (2)	62.8	0.69	16.4	5.76	1.94	4.52	3.80	3.61	0.31	0.10	1.77	99.96	107	671	183	
85L-10	Nelson Mtn Tuff, intrac dacite, E Willow Cr.	66.3	0.55	15.9	4.23	1.39	3.32	3.65	4.33	0.23	0.09	1.90	100.03	115	524	224	998
SD2-1064	Nelson Mtn Tuff, intrac rhy, SD-2 drillhole	70.7	0.33	14.8	2.25	0.57	1.84	3.72	4.77	0.08	0.08	4.80	99.21	118	313	226	1070
85L-29C	Nelson Mtn Tuff, xr rhy vitr, Nelson Mtn	70.2	0.37	15.3	2.40	0.68	1.89	3.63	5.44	0.10	0.09	2.61	100.17	144	310	280	
	Cebolla Creek cycle																
85S-139	Mineral Mountain Rhyolite, lava flow (2)	73.8	0.23	13.7	1.64	0.38	1.37	3.39	4.87	0.05	0.08	5.74	99.57	182	169	161	513
88L-50	Dacite of East Willow Creek	65.5	0.58	15.4	4.21	1.33	3.43	3.56	4.11	0.28	0.09	0.44	98.98	106	532	203	1003
85L-33D	Cebolla Creek Tuff	64.2	0.62	16.2	4.70	1.54	3.91	3.67	3.71	0.30	0.08	1.46	99.01	96	571	205	1020
	Rat Creek cycle																
89L-161-B	Mineral Creek Dacite, lava flow	68.6	0.44	15.58	3.06	0.64	2.55	2.51	5.48	0.22	0.04	5.14	99.17				
85L-29F	Rat Creek Tuff, dacite vitrophyre	65.8	0.57	16.6	3.87	1.37	3.22	3.89	4.17	0.21	0.09	2.03	99.82	97	622	337	1910
85L-30	Dacite of Captive Inca, vitrophyre	69.7	0.42	15.0	3.20	1.03	2.89	3.20	4.34	0.16	0.10	4.45	100.04	162	400	167	658
SJ85-3	Dacite of McKenzie Mtn flow, near vitrophyre (1)	63.7	0.68	15.9	5.79	1.93	4.43	3.49	3.65	0.30	0.09	2.29	99.93	116	628	170	870
	SOUTH RIVER CALDERA CYCLE																
88L-36	South River Volcanics, intrusion	58.3	0.82	17.37	7.77	2.36	5.80	4.11	2.35	0.52	0.15	1.55	99.56	43	843	179	959
88L-62E	South River Volcanics, dacite lava	64.5	0.75	16.72	3.58	1.12	4.22	3.64	4.51	0.23	0.04	1.92	99.37	72	721	180	1417
DS89-010	South River Volcanics, andesite flow (2)	59.8	0.85	16.49	7.07	2.36	5.63	3.98	2.93	0.46	0.10	0.52	99.68	55	891	204	1270
97L-5	Wason Park Tuff (intracaldera), Lake Humphreys	62.9	0.69	17.6	4.52	0.66	3.68	3.84	4.01	0.25	0.11	1.25	99.47	116	665	302	1200
TW-32	Wason Park Tuff, Antelope Park	71.2	0.38	14.6	2.19	0.53	1.40	3.65	5.57	0.08	0.09	3.08	99.71	160	231	256	896
	BLUE CREEK CYCLE																
88L-26	Volcanics of McClelland Mountain, dacite flow	66.8	0.44	15.1	2.62	0.78	2.28	3.16	5.25	0.15	0.09	0.44	97.11				
LR88-634	Blue Creek Tuff, Pallisades (4)	63.5	0.67	16.40	4.43	1.69	3.71	3.46	4.07	0.23	0.10	1.70	99.91	115	541	279	1175
89L-140	Volcanics of Beaver Creek	67.9	0.32	16.53	3.00	0.61	3.36	3.67	3.71	0.14	0.11	2.59	99.31	71	539	183	1043
	BACHELOR CALDERA CYCLE																
99L-11	Mafic fiamme, upper outflow tuff	51.1	1.06	20.8	8.45	2.78	6.91	3.81	2.34	0.68	0.11	1.37	99.4	69	1502	603	4800
87-132	Mammoth Mountain Member, dacite, Palisades	64.3	0.71	16.5	3.86	1.90	4.47	3.51	4.13	0.29	0.07	1.58	100.92	124	525	254	1187
85S-105	Bachelor Mtn Member, intrac rhy vitr, 1st Fork (2)	73.2	0.24	13.9	1.72	0.40	1.42	3.68	4.77	0.00	0.06	3.81	99.38	166	177	175	515
CR-24	Carpenter Ridge Tuff, outflow, Del Norte	72.1	0.27	14.7	1.76	0.39	1.51	3.75	5.17	0.00	0.07	3.25	99.68	164	250	75	1180
	LA GARITA CALDERA CYCLE																
97L-8	Huerto Andesite, dacite flow, Fern Creek	67.4	0.43	16.4	2.89	0.41	2.35	4.51	4.00	0.17	0.08	0.89	99.51	93	449	312	1290
LR88-589	Huerto Andesite, platy-plag flow, Ribbon Mesa (4)	58.8	1.03	17.1	7.44	0.08	1.72	6.14	3.46	3.66	0.43	1.32	99.90	94	552	278	827
DY89-25	Huerto Andesite, aphanitic flow	60.8	0.64	17.2	6.66	2.13	6.05	3.49	2.43	0.33	0.15	1.20	99.92	53	661	171	760
90L-21	Dacite of Nutras Creek	66.0	0.53	15.7	4.65	1.09	3.34	3.71	3.98	0.23	0.09	0.51	99.34	111	399	154	861
DS88-081	Intracaldera La Garita Member, Cochetopa Cr (2)	66.0	0.53	15.7	4.18	1.09	3.34	3.71	3.98	0.23	0.09	0.51	99.34	108	488	173	938
TFC-03	Fish Canyon Tuff, outflow, Goodrich Creek (2)	66.5	0.54	15.9	4.71	1.38	3.64	3.74	3.63	0.20	0.09	1.67	100.35				
94L-15	Pagosa Peak Dacite, Saddle Mountain	67.5	0.49	15.0	3.66	1.12	2.73	3.58	4.33	0.21	0.10	0.54	99.26	128	400	158	820
	MASONIC PARK CYCLE																
96L-5	Sheep Mountain Andesite, Scoria, Pagosa Peak	57.9	0.71	15.3	5.77	2.72	5.25	2.18	1.29	0.31	0.15	8.36	99.92	116	665	302	1200
93L-13-B	Masonic Park Tuff, Alder Creek	64.3	0.75	15.37	5.54	1.99	4.99	2.63	3.14	0.33	0.07	3.70	99.11	74	650	166	850

Table 3. *Representative chemical analyses, central San Juan caldera cluster, southwestern Colorado—continued*

Field Number	Sample Description	Major-element XRF												KEVEX XRF			
		SiO_2	TiO_2	Al_2O_3	$FeTO_3$	MgO	CaO	Na_2O	K_2O	P_2O_5	MnO	LOI	Total	Rb	Sr	Zr	Ba
	CREEDE CALDERA CYCLE																
85L-39	Fisher Dacite, Wagon Wheel Gap flow	65.4	0.66	15.4	5.01	1.66	4.07	3.46	3.85	0.27	0.07	1.93	99.84	94	587	174	1020
85S-129	Snowshoe Mtn Tuff, intrac, Point of Rocks	67.6	0.52	15.0	3.87	1.07	3.62	3.47	4.53	0.23	0.06	1.64	100.03	135	472	184	823
SJ-85-20	Snowshoe Mtn Tuff, outlfow, Cattle Mtn (1)	62.3	0.73	16.6	6.38	1.33	4.53	3.73	3.43	0.31	0.11	1.25	99.44	107	704	155	1010
	SAN LUIS CALDERA COMPLEX																
	Nelson Mountain cycle																
DS87-103	Resurgent intrusion (2)	57.0	1.06	17.31	8.14	0.11	2.19	5.77	3.64	3.04	0.45	0.73	98.66	84	759	187	1061
94L-19A	Volcanics of Baldy Cinco, dacite lava	64.4	0.64	15.90	4.51	1.11	3.41	3.78	4.31	0.37	0.09	0.70	98.52	144	580	210	1100
85S-121	Volcanics of Stewart Peak, andesite lava (2)	60.8	0.91	17.0	6.87	1.81	5.00	3.56	3.48	0.36	0.07	1.08	99.90	115	644	195	1040
85S-110	Nelson Mtn Tuff, intrac dacite, San Luis Pk (2)	62.8	0.69	16.4	5.76	1.94	4.52	3.80	3.61	0.31	0.10	1.77	99.96	107	671	183	
85L-10	Nelson Mtn Tuff, intrac dacite, E Willow Cr.	66.3	0.55	15.9	4.23	1.39	3.32	3.65	4.33	0.23	0.09	1.90	100.03	115	524	224	998
SD2-1064	Nelson Mtn Tuff, intrac rhy, SD-2 drillhole	70.7	0.33	14.8	2.25	0.57	1.84	3.72	4.77	0.08	0.08	4.80	99.21	118	313	226	1070
85L-29C	Nelson Mtn Tuff, xr rhy vitr, Nelson Mtn	70.2	0.37	15.3	2.40	0.68	1.89	3.63	5.44	0.10	0.09	2.61	100.17	144	310	280	
	Cebolla Creek cycle																
85S-139	Mineral Mountain Rhyolite, lava flow (2)	73.8	0.23	13.7	1.64	0.38	1.37	3.39	4.87	0.05	0.08	5.74	99.57	182	169	161	513
88L-50	Dacite of East Willow Creek	65.5	0.58	15.4	4.21	1.33	3.43	3.56	4.11	0.28	0.09	0.44	98.98	106	532	203	1003
85L-33D	Cebolla Creek Tuff	64.2	0.62	16.2	4.70	1.54	3.91	3.67	3.71	0.30	0.08	1.46	99.01	96	571	205	1020
	Rat Creek cycle																
89L-161-B	Mineral Creek Dacite, lava flow	68.6	0.44	15.58	3.06	0.64	2.55	2.51	5.48	0.22	0.04	5.14	99.17				
85L-29F	Rat Creek Tuff, dacite vitrophyre	65.8	0.57	16.6	3.87	1.37	3.22	3.89	4.17	0.21	0.09	2.03	99.82	97	622	337	1910
85L-30	Dacite of Captive Inca, vitrophyre	69.7	0.42	15.0	3.20	1.03	2.89	3.20	4.34	0.16	0.10	4.45	100.04	162	400	167	658
SJ85-3	Dacite of McKenzie Mtn flow, near vitrophyre (1)	63.7	0.68	15.9	5.79	1.93	4.43	3.49	3.65	0.30	0.09	2.29	99.93	116	628	170	870
	SOUTH RIVER CALDERA CYCLE																
88L-36	South River Volcanics, intrusion	58.3	0.82	17.37	7.77	2.36	5.80	4.11	2.35	0.52	0.15	1.55	99.56	43	843	179	959
88L-62E	South River Volcanics, dacite lava	64.5	0.75	16.72	3.58	1.12	4.22	3.64	4.51	0.23	0.04	1.92	99.37	72	721	180	1417
DS89-010	South River Volcanics, andesite flow (2)	59.8	0.85	16.49	7.07	2.36	5.63	3.98	2.93	0.46	0.10	0.52	99.68	55	891	204	1270
97L-5	Wason Park Tuff (intracaldera), Lake Humphreys	62.9	0.69	17.6	4.52	0.66	3.68	3.84	4.01	0.25	0.11	1.25	99.47	116	665	302	1200
TW-32	Wason Park Tuff, Antelope Park	71.2	0.38	14.6	2.19	0.53	1.40	3.65	5.57	0.08	0.09	3.08	99.71	160	231	256	896
	BLUE CREEK CYCLE																
88L-26	Volcanics of McClelland Mountain, dacite flow	66.8	0.44	15.1	2.62	0.78	2.28	3.16	5.25	0.15	0.09	0.44	97.11				
LR88-634	Blue Creek Tuff, Pallisades (4)	63.5	0.67	16.40	4.43	1.69	3.71	3.46	4.07	0.23	0.10	1.70	99.91	115	541	279	1175
89L-140	Volcanics of Beaver Creek	67.9	0.32	16.53	3.00	0.61	3.36	3.67	3.71	0.14	0.11	2.59	99.31	71	539	183	1043
	BACHELOR CALDERA CYCLE																
99L-11	Mafic fiamme, upper outflow tuff	51.1	1.06	20.8	8.45	2.78	6.91	3.81	2.34	0.68	0.11	1.37	99.4	69	1502	603	4800
87-132	Mammoth Mountain Member, dacite, Palisades	64.3	0.71	16.5	3.86	1.90	4.47	3.51	4.13	0.29	0.07	1.58	100.92	124	525	254	1187
85S-105	Bachelor Mtn Member, intrac rhy vit, 1st Fork (2)	73.2	0.24	13.9	1.72	0.40	1.42	3.68	4.77	0.00	0.06	3.81	99.38	166	177	175	515
CR-24	Carpenter Ridge Tuff, outflow, Del Norte	72.1	0.27	14.7	1.76	0.39	1.51	3.75	5.17	0.00	0.07	3.25	99.68	164	250	75	1180
	LA GARITA CALDERA CYCLE																
97L-8	Huerto Andesite, dacite flow, Fern Creek	67.4	0.43	16.4	2.89	0.41	2.35	4.51	4.00	0.17	0.08	0.89	99.51	93	449	312	1290
LR88-589	Huerto Andesite, platy-plag flow, Ribbon Mesa (4)	58.8	1.03	17.1	7.44	0.08	1.72	6.14	3.46	3.66	0.43	1.32	99.90	94	552	278	827
DY89-25	Huerto Andesite, aphanitic flow	60.8	0.64	17.2	6.66	2.13	6.05	3.49	2.43	0.33	0.15	1.20	99.92	53	661	171	760
90L-21	Dacite of Nutras Creek	66.0	0.53	15.7	4.65	1.09	3.34	3.71	3.98	0.23	0.09	0.51	99.34	111	399	154	861
DS88-081	Intracaldera La Garita Member, Cochetopa Cr (2)	66.0	0.53	15.7	4.18	1.09	3.34	3.71	3.98	0.23	0.09	0.51	99.34	108	488	173	938
TFC-03	Fish Canyon Tuff, outflow, Goodrich Creek (2)	66.5	0.54	15.9	4.71	1.38	3.64	3.74	3.63	0.20	0.09	1.67	100.35				
94L-15	Pagosa Peak Dacite, Saddle Mountain	67.5	0.49	15.0	3.66	1.12	2.73	3.58	4.33	0.21	0.10	0.54	99.26	128	400	158	820
	MASONIC PARK CYCLE																
96L-5	Sheep Mountain Andesite, Scoria, Pagosa Peak	57.9	0.71	15.3	5.77	2.72	5.25	2.18	1.29	0.31	0.15	8.36	99.92	116	665	302	1200
93L-13-B	Masonic Park Tuff, Alder Creek	64.3	0.75	15.37	5.54	1.99	4.99	2.63	3.14	0.33	0.07	3.70	99.11	74	650	166	850