Eruptive and noneruptive calderas, northeastern San Juan Mountains, Colorado: Where did the ignimbrites come from?

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ABSTRACT

The northeastern San Juan Mountains, the least studied portion of this well-known segment of the Southern Rocky Mountains Volcanic Field are the site of several newly identified and reinterpreted ignimbrite calderas. These calderas document some unique eruptive features not described before from large volcanic systems elsewhere, as based on recent mapping, petrologic data, and a large array of newly determined high-precision, laser-fusion ^{40}Ar/^{39}Ar ages (140 samples). Tightly grouped sanidine ages document exceptionally brief durations of 50–100 k.y. or less for individual Oligocene caldera cycles; biotite ages are more variable and commonly as much as several hundred k.y. older than sanidine from the same volcanic unit. A previously unknown ignimbrite caldera at North Pass, along the Continental Divide in the Cochetopa Hills, was the source of the newly distinguished 32.25-Ma Saguache Creek Tuff (~400–500 km^3). This regionally distinctive crystal-poor alkalic rhyolite helps fill an apparent gap in the southwestward migration from older explosive activity, from calderas along the N-S Sawatch locus in central Colorado (youngest, Bonanza Tuff at 33.2 Ma), to the culmination of Tertiary volcanism in the San Juan region, where large-volume ignimbrite eruptions started at ca. 29.5 Ma and peaked with the enormous Fish Canyon Tuff (5000 km^3) at 28.0 Ma. The entire North Pass cycle, including caldera-forming Saguache Creek Tuff, thick caldera-filling lavas, and a smaller volume late tuff sheet, is tightly bracketed at 32.25–32.17 Ma. No large ignimbrites were erupted in the interval 32–29 Ma, but a previously unmapped cluster of dacite-rhyolite lava flows and small tuffs, areally associated with a newly recognized intermediate-composition intrusion 5 × 10 km across (largest subvolcanic intrusion in San Juan region) centered 15 km north of the North Pass caldera, marks a near-caldera-size silicic system active at 29.8 Ma. In contrast to the completely filled North Pass caldera that has little surviving topographic expression, no voluminous tuffs vented directly from the adjacent Cochetopa Park caldera, which is morphologically beautifully preserved. Instead, Cochetopa Park subsided passively as the >500 km^3 Nelson Mountain Tuff vented at 26.9 Ma from an "underfit" caldera (youngest of the San Luis complex) 30 km to the SW. Three separate regional ignimbrites were erupted sequentially from San Luis calderas within an interval of less than 50–100 k.y., a more rapid recurrence rate for large explosive eruptions than previously documented elsewhere. In eruptive processes, volcanic compositions, areal extent, duration of activity, and magmatic production rates and volumes, the Southern Rocky Mountains Volcanic Field represents present-day erosional remnants of a composite volcanic field, comparable to younger ignimbrite terranes of the Central Andes.

Keywords: volcanism, ignimbrites, calderas, ^{40}Ar/^{39}Ar ages, San Juan Mountains, eruptive processes.

INTRODUCTION

The San Juan Mountains in southwestern Colorado have long been known as a site of exceptionally voluminous middle Tertiary volcanism, including enormous ignimbrite sheets and associated caldera structures (Cross and Larsen, 1935; Larsen and Cross, 1956; Steven and Ratté, 1965; Lipman et al., 1970). During the past 50 yr, volcanologic and petrologic studies of the San Juan region have concentrated mainly on ignimbrite-caldera magmatic foci in the central cluster (La Garita–Creede: Steven and Ratté, 1965; Lipman, 2000, 2006), southeastern area (Platoro complex: Lipman, 1975; Dungan et al., 1989; Lipman et al., 1996), and western calderas (Uncompahgre–Silverton–Lake City: Lipman et al., 1973; Hon and Lipman, 1989; Bove et al., 2001).

Much less studied has been the northeast San Juan region, which occupies a transition between earlier volcanism in the Sawatch Range and large-volume, younger, ignimbrite-caldera foci farther south and west (Fig. 1). Other than mineral-resource studies of small areas, much of this northeastern area has been mapped only in broad reconnaissance for the Colorado state geologic map (Tweto et al., 1976; Tweto, 1979). This report, based on new mapping of all volcanic rocks in 20 7.5′ quadrangles (Fig. 2) and detailed high-resolution geochronologic studies (140 new ages): (1) describes volcanic evolution of the previously unrecognized North Pass caldera and the morphologically beautifully preserved but enigmatic Cochetopa basin (Fig. 3), including unique features not previously described from ignimbrite calderas elsewhere; (2) quantifies a more rapid recurrence of large ignimbrite eruptions than previously known elsewhere; (3) documents the regional time-space-volume progression from the earlier Sawatch magmatic trend southward into the San Juan region; and (4) permits more rigorous comparisons between the broad Middle Tertiary magmatic belt in the western U.S. Cordillera and the type continental-margin arc volcanism in the central Andes.

METHODS

Studies initiated to characterize the geologic setting for the Creede Scientific Drilling Project (Bethke and Hay, 2000), were gradually

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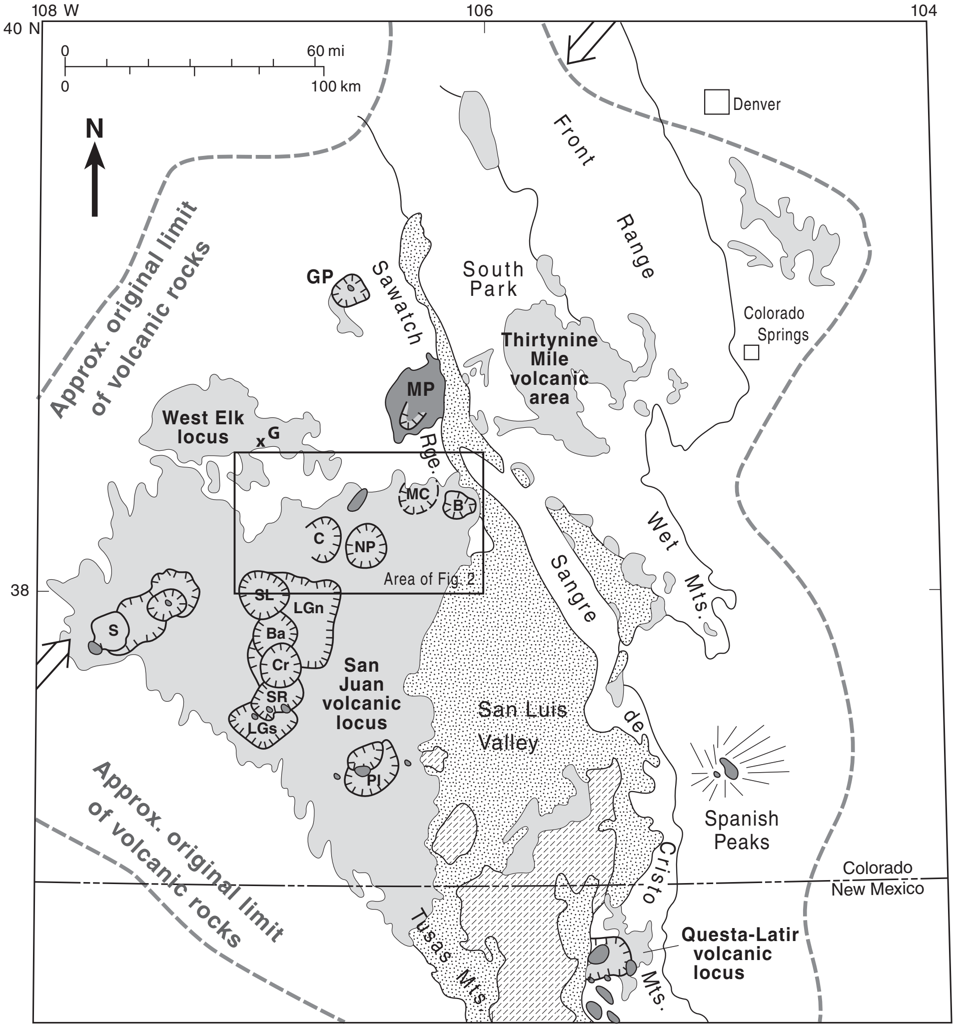

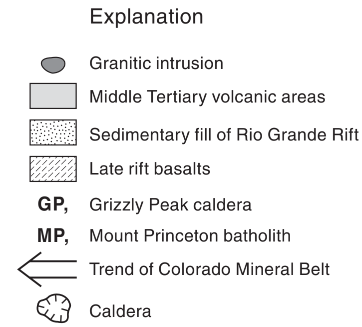

Figure 1. Map of Southern Rocky Mountain Volcanic Field, showing ignimbrite calderas, major erosional remnants and inferred original extent of mid-Tertiary volcanic cover, caldera-related granitic intrusions, and later sedimentary fill of the Rio Grande rift zone. Arrows indicate trend of late Cretaceous–early Tertiary (Laramide) intrusions of the Colorado Mineral Belt. Calderas: B—Bonanza; Ba—Bachelor; C—Cochetopa Park; Cr—Creede; LGn—La Garita north segment; LGs—La Garita, south segment; MC—Marshall Creek; Pl—Platoro; S—Silverton; SL—San Luis complex; SR—South River. Geographic locality: G—Gunnison. Modified from McIntosh and Chapin (2004); inferred original limit of volcanic rocks modified from Steven, 1975); intrusions from Tweto (1979) and Lipman (1988, 2000).

expanded to cover the entire central caldera cluster (Lipman, 2000, 2006) and adjacent areas to the northeast, as multiple stratigraphic, structural, geochronologic, and volcanologic problems emerged. Small parts of the present study area were recompiled from published quadrangle maps (Bruns et al., 1971; Olson et al., 1975; Olson, 1976a, 1976b; Olson, 1983; Olson and Steven, 1976a, 1976b), but many stratigraphic-correlation and other problems were encountered. All Tertiary volcanic rocks and other areas that required significant reinterpretation were remapped during 2001–2006 (Fig. 2). Fieldwork compilation at 1:24,000 scale (Fig. 2) is being prepared for publication as a 1:50,000-scale U.S. Geological Survey I-Series map.

Critical to the interpretations presented here is the large array (140 samples) of new high-resolution ^{40}Ar/^{39}Ar ages for the northeast San Juan study area. Especially useful have been single-crystal laser-fusion ages on sanidine phenocrysts, obtained wherever this phase was present; additional determinations are incremental-heating plateau ages for biotite and hornblende phenocrysts and for groundmass concentrates from lavas lacking datable phenocryst phases. The ages were determined at the New Mexico Geochronology Research Laboratory by methods similar to those described in McIntosh and Chapin (2004). Multiple samples were dated for most major volcanic units, to evaluate correlations and to improve precision of pooled ages. For most single-crystal laser-fusion ages, 10–15 feldspar grains were analyzed for each site; as many as 36 grains were dated for a few stratigraphically critical sites. Analytical uncertainties for individual samples are reported to two standard deviations (95% confidence level); pooled sanidine ages for multiple sites from a single unit are listed as weighted means, with uncertainties as the standard error (S_e).

Recovery of sufficiently large grains for single-crystal analysis was a problem for some dacites that contain only sparse small sanidine fragments. In some separates, plagioclase grains were unintentionally included, and the number of sanidine analyses is accordingly lower. For some samples with small and/or sparse sanidine fragments, several grains were combined for fusion; such samples are noted separately in the tables. During early stages of this study, Andrew Calvert generated two key ^{40}Ar/^{39}Ar ages for the northeastern ignimbrites (Lipman and Calvert, 2003). A few additional ages for the area are from Lanphere (1988, 2000, and M. Lanphere, 1999, personal commun.). Prior K-Ar and ^{40}Ar/^{39}Ar dates are adjusted to an age of 28.02 Ma for the Fish Canyon Tuff (Renne et al., 1998).

Age results are summarized in Table 2; analytical determinations for each sample are tabulated in GSA Data Repository Appendix 1[1]. Laser-fusion sanidine data (89 samples) for individual feldspar grains are listed in Appendix 2

[1]GSA Data Repository Item 2008085, six tables of analytical data (^{40}Ar/^{39}Ar ages and whole-rock chemical analyses), is available at www.geosociety.org/pubs/ft2008.htm. Requests may also be sent to editing@geosociety.org.

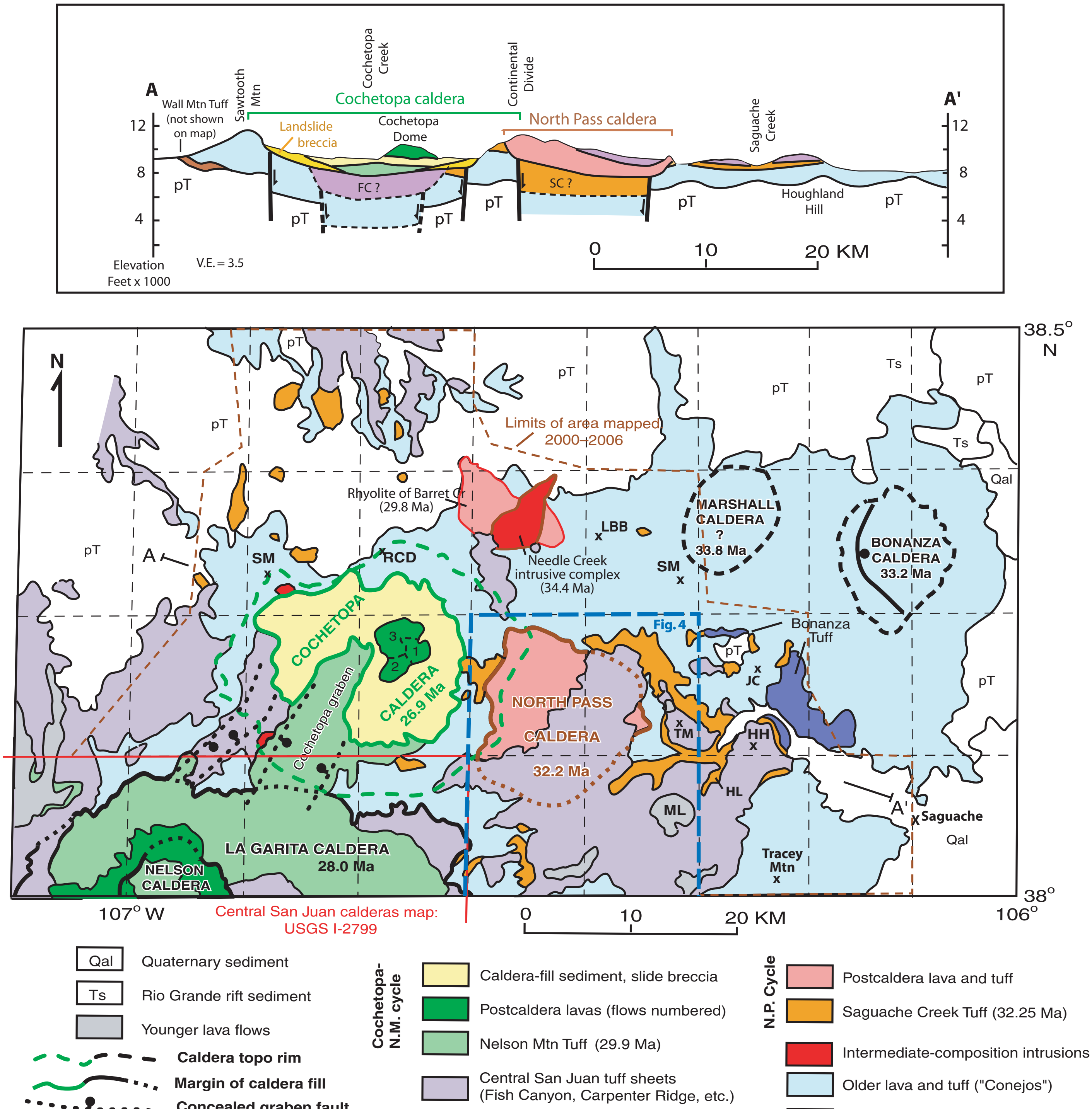

Figure 2. Generalized geologic map and cross section, northeast San Juan region, based on recent geologic mapping (2000–2006). Geographic localities: HH—Houghland Hill; HL—Houselog Creek; JC—Jacks Creek volcano; LBB—Long Branch Baldy; ML—Mount Lion; RCD—Razorback Dome; SM—Sawtooth Mountain; TM—Trickle Mountain. The Nelson caldera is youngest subsidence of the San Luis caldera complex. Dashed rectangular grid—boundaries of 7.5′ quadrangle maps.

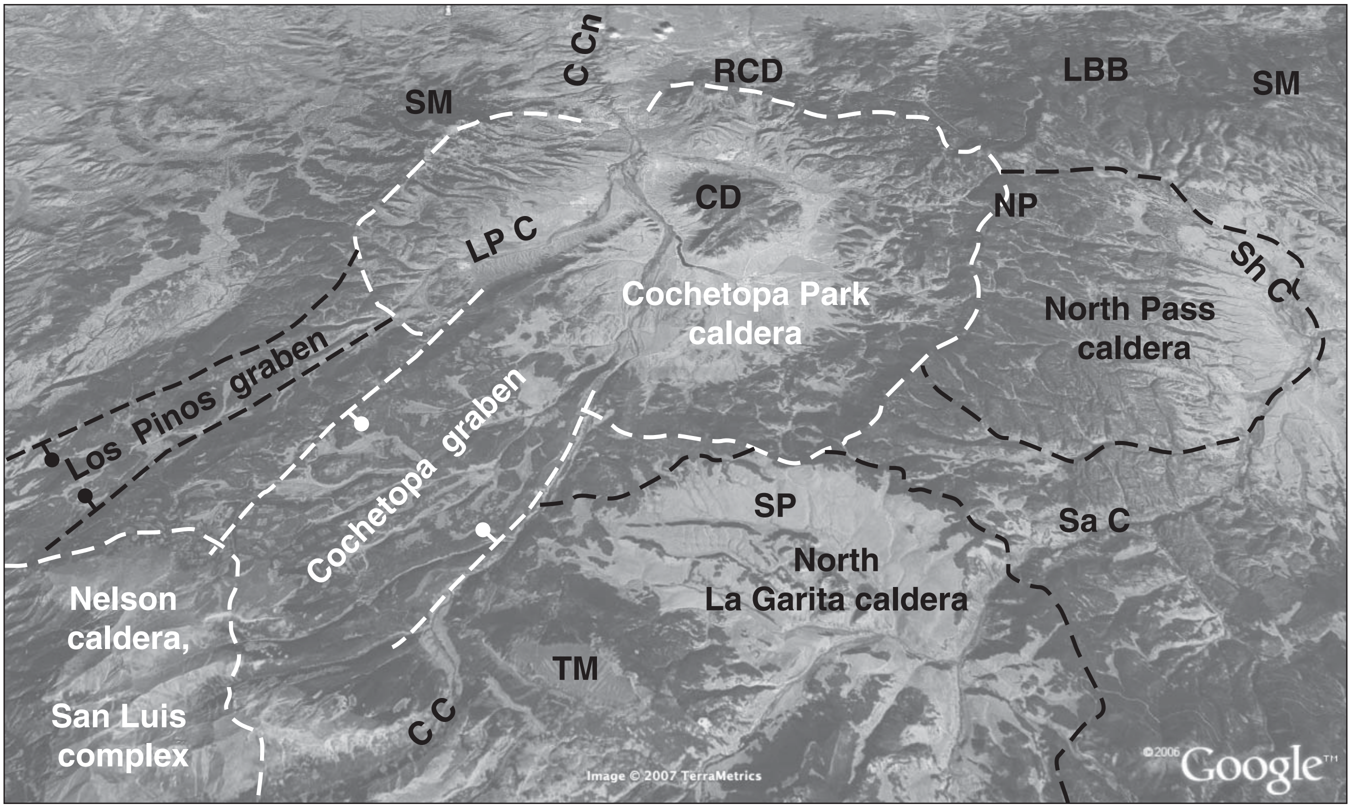

Figure 3. Oblique view (*Google Earth*), looking north at Cochetopa and North Pass calderas. The topographic rim of Cochetopa Park caldera (~30 km across) is morphologically well preserved (dashed white lines): along its northwest and north sides, high points on the rim are marked by Sawtooth Mountain (STM) and Razor Creek Dome (RCD); the east rim is along the Continental Divide, which defines the boundary with the older North Pass caldera farther to the east; and the south boundary also follows the Continental Divide where the Cochetopa Park caldera merges with the northern segment of the La Garita caldera. The northeast-trending Los Pinos graben formed at the time of collapse at La Garita, and the parallel Cochetopa graben, which breaches the north wall of La Garita caldera and forms a low segment of Cochetopa rim, is filled by thick tongue of Nelson Mountain Tuff. This lobe of densely welded tuff was channeled northeast from its eruptive source within the San Luis caldera complex at lower left of image, and flowed into the Cochetopa Park caldera where it thins to only a few meters of nonwelded tuff in the southeastern parts of the caldera basin. Other geographic localities: CC—upper Cochetopa Creek; CCn—Cochetopa Canyon (outlet from Cochetopa Park caldera, carved in Precambrian granitic rocks); CD—Cochetopa Dome (sequence of crystal-poor lava flows of petrologically evolved rhyolite that accumulated within Cochetopa caldera shortly after its collapse); LBB—Long Branch Baldy (high point along Continental Divide, where 33-Ma Bonanza Tuff banks against high-standing erosional remnants of a large andesitic stratocone); NP—North Pass (followed by Colorado Hwy 114); LPC—Los Pinos Creek; SaC—Saguache Canyon (outlet from La Garita caldera, carved in >32-Ma intermediate-composition lavas, and inherited from Oligocene topography); SM—Sargents Mesa (high flat along the Continental Divide, locally capped by Bonanza Tuff); SP—Saguache Park (Carpenter Ridge and Wason Park Tuffs, banked against the northern La Garita caldera wall); TM—Table Mountain (high-standing erosional remnant of Nelson Mountain Tuff that ponded within the La Garita caldera).

(see footnote 1), and age-probability distribution plots (Deino and Potts, 1992) for the feldspar analyses are compiled in Appendix 3 (see footnote 1). Data for step-heating analyses (51 samples) on biotite (20), hornblende (11), and groundmass (20) are listed in Appendix 4 (see footnote 1), and age-spectra plots for these samples are presented in Appendix 5 (see footnote 1). Paleomagnetic pole directions were determined for a few sites, to complement prior observations (Tanaka and Kono, 1973; Diehl et al., 1974; Rosenbaum et al., 1987), as tests of age and stratigraphic correlations (Table 3).

Rock names are used in general accordance with the International Union of the Geological Sciences (IUGS) classification (Le Bas et al., 1986). The San Juan 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. Although the intermediate-composition rocks tend to straddle IUGS field boundaries, some plotting in lower parts of the trachyandesite and trachydacite fields, such rocks are here referred to as andesite and dacite for simplicity and consistency with prior stratigraphic nomenclature in the region. Phenocryst assemblages serve to distinguish many of the major tuff sheets (Table 1). Cited chemical and petrographic data include 130 new major-oxide and trace-element analyses for samples from the study area (Appendix 6), supplemented by data for regional units from Lipman (2004).

REGIONAL FRAMEWORK

Mid-Tertiary volcanic deposits once formed continuous cover across much of the Colorado Rocky Mountains and into northern New

Mexico (Fig. 1), constituting a composite Southern Rocky Mountain Volcanic Field, for which the San Juan region is the largest erosional remnant (Steven, 1975; Lipman, 1989, 2007). Subareas of the Southern Rocky Mountains Volcanic Field, now separated by later erosion, have previously been described as multiple separate volcanic fields (San Juan, Sawatch, Thirtynine Mile, Latir, West Elk, Central Colorado, etc.), rather than as time-space transgressive magmatic foci within a large composite field.

Activity in the Southern Rocky Mountains Volcanic Field peaked between 38 and 26 Ma (McIntosh and Chapin, 2004; Lipman, 2007). Dominantly intermediate-composition lavas and breccias (andesite-dacite) were erupted from widely scattered central volcanoes, and major volcanic foci, initially established by clustered stratocones, became eruption sites for approximately 30 caldera-associated ignimbrites of more silicic compositions (see Table 1 for those germane to this study), in response to increased magmatic input focused at these sites. Composite volumes of the early-intermediate volcanoes are large; in the San Juan region stratigraphic sequences commonly are more than a kilometer thick, and total volume, estimated at 25,000 km^3 (Lipman et al., 1970), exceeds that of the later erupted ignimbrites by ~50%.

Original areal extent of the overall Southern Rocky Mountains Volcanic Field appears to have exceeded 100,000 km^2, with a total volume of volcanic deposits greater than 50,000 km^3 (Lipman, 2007). Peak magmatic volumes in the Southern Rocky Mountains Volcanic Field, associated with ignimbrite eruptions, define a general (if imperfect) progression (Fig. 1) from early eruptions along the Sawatch Range in central Colorado (37–33 Ma: McIntosh and Chapin, 2004), southward into the San Juan region (32–27 Ma: Lipman et al., 1970), and later to the 25-Ma Latir-Questa magmatic center in northern New Mexico (Lipman, 1988; Johnson et al., 1989).

Mid-Tertiary volcanic rocks of the northeastern San Juan Mountains lie along the broad boundary between Precambrian-cored uplifts of the Southern Rocky Mountains, which formed by contraction during low-angle plate subduction in late Cretaceous to early Tertiary time, and less deformed Paleozoic and Mesozoic sedimentary rocks along the northeastern flank of the Colorado Plateau (Fig. 1). These differences in geologic setting strongly influenced structural and morphologic evolution during volcanism. To the south and west in the San Juan region, ignimbrite volcanism generated a well-stratified plateau, interrupted locally by complexities associated with calderas. The original mid-Tertiary volcanic terrain was much like the Altiplano of the central Andes, because voluminous eruptions buried and subdued most of the preexisting paleotopography. In contrast, northeastern parts of the San Juan volcanic accumulation lap onto the more rugged paleotopography associated with earlier Tertiary uplifts of the Southern Rockies.

Valleys developed during erosion of the early Tertiary uplifts, as well as those developed during the growth of central volcanoes prior to large ignimbrite eruptions, strongly influenced the distribution of subsequently emplaced volcanic deposits (e.g., Chapin and Lowell, 1979). Some major paleovalleys survived the entire period of volcanism, and many present-day San Juan drainages are inherited from the mid-Tertiary landscape, leading to our fieldwork expression: "once a valley, always a valley." Most conspicuous within the present study area (Figs. 2 and 4) is the course of lower Saguache Creek (Figs. 2 and 4), which coincides with a broad paleovalley between Oligocene stratocones to the north and south. All the major Oligocene ignimbrites of the region were deposited preferentially along this paleovalley.

Exposed pre-Tertiary rocks also provide useful information on paleotopography at the inception of volcanism and subsequent events. Notably, small windows of Precambrian granite, but no Mesozoic sedimentary rocks, are exposed around margins of the North Pass caldera (Fig. 4), showing that this caldera formed within a prevolcanic highland, probably a southern continuation of the Sawatch Range uplift of late Cretaceous age. In eastern parts of the map area, considerable paleorelief existed on the Precambrian rocks prior to burial by Tertiary volcanism. Farther west and north, gently dipping Mesozoic sedimentary rocks are widely present beneath the volcanic cover, reflecting proximity to the Colorado Plateau.

Due to the greater paleorelief, the stratigraphic record of sequential eruptions is less complete in the northeastern San Juan Mountains than in central parts of this volcanic region. Many volcanic deposits in this sector accumulated in deep valleys, which were incompletely filled and then re-excavated by erosion between successive eruptions. The regional ignimbrites, rather than forming a stratified plateau, commonly are preserved in inverted topographic order, with earlier tuff sheets capping ridges, and younger units exposed at lower levels within paleovalleys. In many places, welded tuffs are exposed as isolated scabs, unconformably against slopes of paleovalleys, without stratigraphic continuity between sequential deposits. Frequent miscorrelations of ignimbrite units in previously mapped local areas of the northeastern San Juan region have resulted from such complexities, along with limited exposures due to forest cover,

TABLE 1. MAJOR IGNIMBRITES AND CALDERAS OF THE NORTHEASTERN SAN JUAN MOUNTAINS*

	Ignimbrite					Caldera		Postcaldera magmatism	
Caldera site	Tuff name	% SiO_2	Rock, phenocrysts	Vol. (km^3)	Age (Ma)	Name	Area (km)	Lavas/events	Age (Ma)
Central SJ	Snowshoe Mountain	62–66	Xr dacite	>500	26.87	Creede	20 × 25	Fisher Dacite	26.2–26.8
San Luis	Nelson Mountain	Zoned 74–63	Xp rhy; Xr dacite	>500	26.90	Nelson-Cochetopa	10 × 14, 20 × 25	Andesite flows	25.9–26.9
complex	Cebolla Creek	61–64	Xr dacite, hbl, no san	250	26.9	Cebolla Creek	14 × 16	Mineral Mountain Rhy.	26.9
	Rat Creek	Zoned 74–65	Xp rhy–Xr dacite	150	26.91	Rat Creek	9 × 12	Andesite-dacite	26.9
Central SJ	Wason Park	Zoned 72–63	Xr rhyolite–dacite	>500	27.38	South River	20 × 20	Andesite-dacite	27.4–?
cluster	Carpenter Ridge	Zoned 74–66	Xp rhy–Xr dacite	>1000	27.55	Bachelor	25 × 30	Dacite flows	27.5–27.4
	Fish Canyon	66–68	Xr dacite, hbl, qtz	>5000	28.02	La Garita	35 × 75	Huerto Andesite	28.0–27.6
W San Juan	Sapinero Mesa	72–75	Xp rhyolite	>1000	28.27	Uncompahgre–San Juan	20 × 45	Andesite-rhyolite	28–27
NE San Juan	(Barret Creek)	65–73	(Xr dacite–rhy lavas)	50?	29.8	[failed?]	--	Andesite flows	n.d.
	Luders Creek	66–73	Xp rhy–Xr dacite	50?	32.17	North Pass?	?	--	--
	Saguache Creek	73–75	Alkali rhyolite, no bio	250-500	32.25	North Pass	15 × 17	Andesite-dacite	32.2
Sawatch	Bonanza	74–63	Zoned: dac-rhy-dac	250?	33.2	Bonanza	10 × 15	Andesite	33–32
Trend	Wall Mountain	70–73	Xr rhyolite	1000±	36.9	Mount Princeton	15 × 30?	Mount Aetna caldera	36.6–30

Note: rhy—rhyolite; dac—dacite; san—sanidine; qtz—quartz; bio—biotite; hbl—hornblende; xr—crystal-rich; xp—crystal-poor; g.d.—granodiorite; monz—monzonite; n.d.—not determined.

*Compiled from diverse sources, cited in text.

TABLE 2. SUMMARY OF NEW $^{40}Ar/^{39}Ar$ AGE DETERMINATIONS, NORTHEAST SAN JUAN REGION

Unit	Mineral	Analysis	N	Age (Ma) ± S_e/2s*	Comments
HINSDALE FORMATION					
Basalt flow	Groundmass	Plateau	1	21.81 ± 0.21	Overlies Carpenter Ridge Tuff
CREEDE CALDERA					
Fisher Dacite	Sanidine	SCLF	2	26.77 ± 0.04	Post-resurgence, Fisher Mountain
Fisher Dacite	Sanidine	SCLF	2	26.82 ± 0.05	Pre-resurgence, W flank Snowshoe Mountain
Snowshoe Mountain Tuff	Sanidine	SCLF	4	26.87 ± 0.02	Both intracaldera and outflow locations
SAN LUIS–COCHETOPA CALDERA CYCLE					
Dacite of Baldy Cinco	Sanidine	SCLF	4	25.89–26.16	Section at Baldy Cinco
Rhyolite of Cochetopa Dome	Sanidine	SCLF	8	26.86 ± 0.03	Four lava flows and moat-tuff samples
Intrusions of high-Si rhyolite	Sanidine	SCLF	3	27.10 ± 0.04	Intrusions north of Cochetopa caldera
Nelson Mountain Tuff, intracaldera	Sanidine	SCLF	2	26.91 ± 0.04	Small crystals
Nelson Mountain Tuff, outflow	Sanidine	SCLF	8	26.90 ± 0.02	
Cebolla Creek Tuff	Bio & hbl	Plateau	4	27.10 ± 0.07	Biotite and hornblende ages slightly too old
Rat Creek Tuff (dacite)	Sanidine	SCLF	8	26.91 ± 0.02	
Dacite flow of McKenzie Mountain	Biotite	Plateau	1	27.08 ± 0.08	Probable precursor lava
Wason Park Tuff	Sanidine	SCLF	5	27.38 ± 0.05	
Andesite of Mount Lion Creek	Groundmass	Plateau	3	27.46–27.51	Overlies distal Carpenter Ridge Tuff
Carpenter Ridge Tuff	Sanidine	SCLF	4	27.55 ± 0.05	
Crystal Lake Tuff	Sanidine	SCLF	1	27.41 ± 0.11	Bove et al. (2001): 27.62 ± 0.07
Huerto Andesite (lava flows)	Hbl and gm	Plateau	5	27.64–28.32	
Fish Canyon Tuff	Sanidine	SCLF		28.02	Standard age
Masonic Park Tuff	Biotite	Plateau	1	28.89 ± 0.08	From Lanphere (1998)
Sapinero Mesa Tuff	Sanidine	SCLF	4	28.27 ± 0.06	Bove et al. (2001): 28.38 ± 0.03 Ma
Dillon Mesa Tuff	Sanidine	SCLF	3	28.42 ± 0.08	Bove et al. (2001): 28.58 ± 0.04 Ma
Blue Mesa Tuff	Sanidine	SCLF	2	28.46 ± 0.04	Bove et al. (2001): 28.58 ± 0.07 Ma
Ute Ridge Tuff	Sanidine	SCLF	1	29.12 ± 0.05	Bove et al. (2001): 28.81 ± 0.05 Ma
BARRET CREEK RHYOLITE-DACITE DOME COMPLEX					
Rhyolite and dacite lava flows	Sanidine	SCLF	4	29.63–29.85	"Failed caldera" suite?
LAVAS AND TUFF, EAST SIDE OF NORTH PASS CALDERA					
Basalt of Point Benny	Groundmass concentrate	Plateau	5	30.22 ± 0.10	Most mafic early lava in San Juan region
Andesite of Lone Tree Gulch	Groundmass concentrate	Plateau	1	30.21 ± 0.17	
Tuff of Big Dry Gulch	Biotite	Plateau	1	30.47 ± 0.08	No sanidine, excess Ar biotite spectrum
Aphanitic andesite, Hill 9519'	Groundmass concentrate	Plateau	1	29.98 ± 0.31	
Hbl andesite flow, Hill 9519'	Hornblende	Plateau	1	30.41 ± 0.79	Poor plateau
NORTH PASS CALDERA CYCLE					
Luders Creek Tuff	Sanidine	SCLF	4	32.17 ± 0.04	
Volcanics of Cochetopa Hills					
Dacite of East Pass Creek	Biotite	Plateau	3	32.07–32.31	Main area of caldera-fill flows
Dacite of East Pass Creek (?)	Bio & Hbl	Plateau	1	32.82 ± 0.08	At south caldera wall(?)
Rhyolite of Taylor Canyon	Sanidine	SCLF	1	32.15 ± 0.10	
Rhyolite breccia, Taylor Canyon	Sanidine	SCLF	1	32.44 ± 0.08	Possibly landslide breccia from a precursor flow?
Saguache Creek Tuff	Sanidine	SCLF	6	32.25 ± 0.05	
Precursor? tuff, Spanish Creek	Sanidine	SCLF	4	32.50 ± 0.03	
EARLY LAVAS, TUFFS, AND INTRUSIONS					
Rhyolite flow, Cebolla Creek	Biotite	Plateau	1	31.49 ± 0.14	Below Blue Creek Tuff
Dacite, Sawtooth Mountain	Biotite	Plateau	1	32.00 ± 0.09	Summit lava flow
Porphryitic dacite, Carneros Pass	Sanidine	SCLF	1	32.72 ± 0.09	Highest flow (below Fish Canyon Tuff)
Bonanza Tuff	Sanidine	SCLF	1	33.17 ± 0.06	Mean age, 33.2 Ma (McIntosh and Chapin, 2004)
Needle Creek Intrusions	Hornblende	Plateau	3	34.28–34.42	
"Conejos" hbl-rich dike	Hornblende	Plateau	1	34.61 ± 0.16	Intrudes Cochetopa caldera-floor andesite
Conejos crystal dacite (sanidine-bearing)	Sanidine	SCLF	2	34.04 ± 0.06	Beneath sequence of andesites
Wall Mountain Tuff	Sanidine	SCLF	1	36.85 ± 0.08	Mean age, 36.9 Ma (McIntosh and Chapin, 2004)

Note: Individual samples and full analytical data, in Appendix 1. Ages for multiple samples are weighted means or ranges.
Bold—regional ignimbrite sheets; N—number of sample sites; SCLF—single-crystal laser fusion; Plateau—incremental-heating analysis.
*S_e/2s, Standard error of the weighted mean for SCLF; 2 s.d. (95% confidence level) for plateau ages.
Mineral abbreviations: Bio—biotite; gm—groundmass separate; Hbl—hornblende.

TABLE 3. NEW PALEOMAGNETIC DETERMINATIONS, NORTHEAST SAN JUAN MOUNTAINS

Pmag no.	Ar/Ar no.*	Unit	Location*	Declination	Inclination	$Alpha_{95}$	N	Comment
NM3035	--	Landslide breccia, FCT clasts	Mexican Joe Canyon	Random-cold				Monolithologic; no CRT clasts
NM3036	03L-32	Landslide breccia, FCT clasts	Los Pinos narrows	Random-cold				Sparse CRT clasts (03L-32)
NM3037	99L-20A	Saguache Creek Tuff	Saguache Creek	170.1	–55.1	16.1	6	East of North Pass caldera
NM3038	02L-26	Luders Creek Tuff	Luders Creek	98.5	50.2	4.1	7	Rotated block: slumped
NM3039	01L-11	Saguache Creek Tuff	Salaya Creek	166.4	–55.2	6.3	8	West of North Pass caldera
NM3040	03L-45	Sapinero Mesa Tuff?	House Log Creek	116.1	–65.4	3.7	8	Similar to Sapinero Mesa Tuff
NM3041	03L-46	Tuff of Big Dry Gulch	Big Dry Gulch	175.8	–37.6	6.2	6	Crystal-poor dacite, lacks sanidine
NM3043	02L-50	Wason Park Tuff	Sheep Creek	174.7	–16.0	10.2	3	Most distal site for this unit
NM3048	NM3048	Sapinero Mesa Tuff	Gateview	124.9	–55.4	6.0	8	More proximal site

*Latitude and longitudes of dated samples listed in Appendix 1. Location for NM3035: 38°07.05', 106°41.64'.
FCT—Fish Canyon Tuff; CRT—Carpenter Ridge Tuff

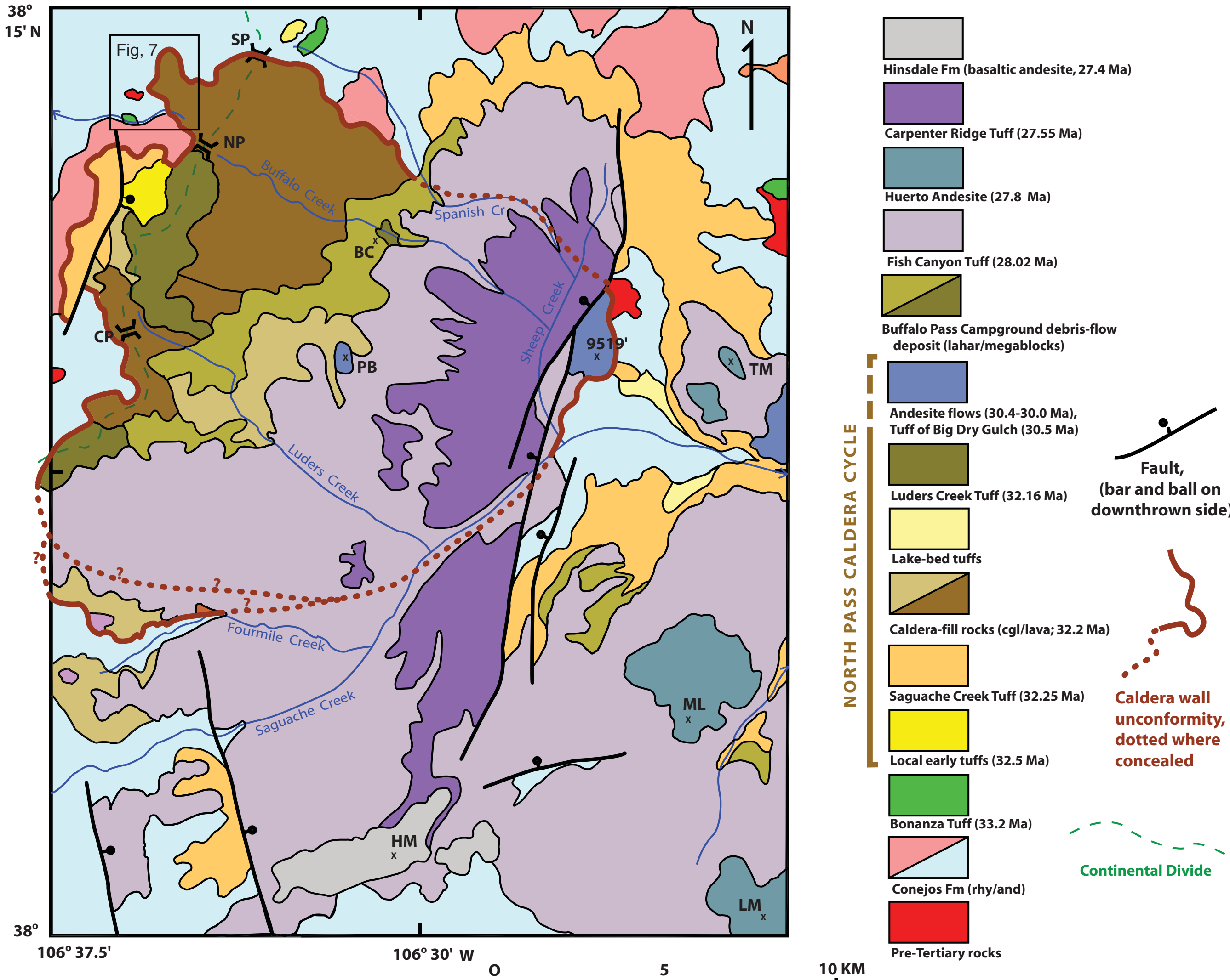

Figure 4. Generalized geologic map of the North Pass caldera (unpublished mapping, 2001–2006). The caldera was filled to overflow by younger rocks, and subsequently tilted gently eastward toward a Rio-Grande rift-related fault zone along Sheep Creek. Geographic localities: BC—Buffalo Pass Campground; CP—Cochetopa Pass; HM—Hat Mountain; LM—Lake Mountain; ML—Mount Lion; NP—North Pass; PB—Point Benny; SP—Spanish Pass; TM—Trickle Mountain; 9519′—Hill 9,519′ elevation. Insert, area of Figure 7.

incomplete knowledge of the regional eruptive sequence, and inadequate recognition of petrographic distinctions among tuff sheets.

Early Northern Volcanism along the Sawatch Trend

Volcanism in northern parts of the Southern Rocky Mountains Volcanic Field began at least as early as 38 Ma, as recorded andesitic lavas and breccias in the Thirtynine Mile volcanic area (McIntosh and Chapin, 2004). The first regional ignimbrite was the far-traveled (>100 km from source) Wall Mountain Tuff (Chapin and Lowell, 1979) at 36.9 Ma, erupted from vents above the 25 × 35-km Mount Princeton batholith (Johnson et al., 1989; Lipman and Calvert, 2003), the largest Tertiary intrusion in the Rocky Mountains (Fig. 1 and Table 1). North of the Mount Princeton batholith is the Grizzly Peak caldera, active at 34.3 Ma (McIntosh and Chapin, 2004). Nested within the southern margin of the Princeton batholith is the slightly younger Mount Aetna caldera (Fig. 1), source of the 34.0-Ma Badger Creek Tuff and associated intrusions (34.1–29.6 Ma; McIntosh and Chapin, 2004). Farther south are small exposures of a probable caldera fragment along Marshall Creek, likely the source of the Thorn Ranch Tuff at 33.8 Ma (Gregory and McIntosh, 1996). The less eroded and better exposed Bonanza center, source of the Bonanza Tuff at 33.2 Ma, lies within the San Juan erosional remnant, but is more appropriately considered the youngest and southernmost caldera along the Sawatch trend (Varga and Smith, 1984; McIntosh and Chapin, 2004). The Bonanza center contains voluminous andesite erupted before and after ignimbrite eruptions, as well as postcaldera intrusions.

San Juan Volcanic Region

Farther south, the San Juan region contains the largest erosional remnant of the composite mid-Tertiary volcanic field. The San Juans are notable for the numerous large-volume, compositionally diverse, ignimbrite eruptions and associated caldera collapses (Steven and Lipman, 1976), at least

18 having been active within the 2.5-m.y. interval 29.4–26.9 Ma. As mid-Tertiary volcanism migrated southward from the Sawatch Range trend, widely scattered intermediate-composition centers (dominantly andesite, lesser dacite, and minor rhyolite) erupted lava flows and flanking volcaniclastic breccias in the San Juan region starting at 35–34 Ma (Lipman et al., 1970).

After several million years of such precursory volcanism, large ignimbrite eruptions of crystal-rich dacite began in the northeast San Juans with eruption of the newly recognized Saguache Creek Tuff from the North Pass caldera at 32.2 Ma, as detailed in this report. Tuff eruptions gradually became widespread: in the southeast San Juans at ca. 29.4 Ma (Platoro caldera complex), followed shortly by eruptions mainly of crystal-poor rhyolite from western San Juan calderas (Steven and Lipman, 1976; Bove et al., 2001). Ignimbrite activity progressively focused in the central San Juan region, leading to eruption of the enormous Fish Canyon Tuff (5000 km^3 of monotonously uniform, crystal-rich dacite) and collapse of the 35 × 75-km La Garita caldera at 28.0 Ma (Lipman, 2000, 2006; Bachmann et al., 2002). In the central San Juans, seven major eruptions of compositionally diverse ignimbrite, with volumes of 100–1000 km^3, erupted during a 1.1-m.y. interval from calderas nested within the enormous La Garita caldera (Fig. 1). At each caldera, initial post-ignimbrite volcanism consisted of intermediate-composition to silicic lavas and breccias (Table 1) that variably filled the caldera depressions, some to overflowing.

The eruptive and subsidence history of the most northerly of the central San Juan systems, the San Luis complex from which three regional ignimbrite sheets were erupted in rapid succession at 26.9 Ma, is closely related to development of the Cochetopa Park caldera (Figs. 1–2). In particular, the final large eruption, which produced the Nelson Mountain Tuff, appears to have triggered subsidence, both at the eruption site in the San Luis complex, and also at Cochetopa Park as discussed below. The primary Oligocene morphology of the Cochetopa caldera (Fig. 3) has been exceptionally preserved because of rapid infilling by weakly indurated moat sediments, which were preferentially eroded during the past few million years. In contrast, the North Pass caldera is concealed beneath erosion-resistant, caldera-filling lavas that form an inverted present-day topography along the present-day Continental Divide.

EARLY LAVAS AND INTRUSIONS: SAGUACHE-COCHETOPA REGION (35–32 Ma)

As elsewhere in the San Juan region, ignimbrite sheets and other rocks associated with calderas in the Saguache-Cochetopa region overlie thick lava sequences that erupted from large central volcanoes (Fig. 2). In comparison with the early-intermediate assemblage farther south and west in the San Juan Mountains, the northeastern area contains higher proportions of proximal lavas and breccias relative to more distal laharic conglomerates and other volcaniclastic rocks, and dacite and rhyolite are more voluminous components of the dominantly andesitic lava assemblage. The early flows are broadly correlative with the Conejos Formation elsewhere in the San Juans (Lipman et al., 1970; Dungan et al., 1989), but interstratified ignimbrite sheets, including several from caldera centers along the Sawatch trend, and datable sanidine phenocrysts in some silicic lavas help define the eruptive history of early lavas in more detail than has been possible thus far elsewhere in the region. These lavas are locally exposed over a vertical range of more than 1000 m from along Saguache Creek to the Continental Divide (Fig. 4), although thicknesses decrease northward toward the Gunnison valley. Total thickness and volume is far greater for the early lavas than for interstratified and overlying ignimbrite sheets. At least six eruptive centers for these rocks lie within the area of Figure 2; they probably include the earliest eruptions in the San Juan region, with activity becoming younger to the west and south.

A large composite stratocone or cluster of volcanoes, within which the Bonanza caldera is centered, is overlain by the 33.2-Ma Bonanza Tuff on its flanks and must be among the oldest of these centers, although detailed mapping and $^{40}Ar/^{39}Ar$ dating are lacking for much of the area. These lavas, locally designated the Rawley Andesite (Varga and Smith, 1984), include local dacite and rhyolite flows low in the section, resting directly on Precambrian basement. An upper lava sequence of the Bonanza center, including caldera-filling flows, is also andesitic; its age is bracketed as 33–32 Ma by the Bonanza Tuff and overlying 32.2-Ma Saguache Creek Tuff.

South of the Saguache valley, a thick lava pile marks the north flanks of large central volcano, separate from the Bonanza center. The Bonanza Tuff wedges out within these southern lavas, above a sequence of dark andesite flows, but below capping lavas of porphyritic dacite on Tracey Mountain (Fig. 2). A petrographically unusual flow high in this assemblage, containing sanidine phenocrysts as large as 2 cm across, yielded a $^{40}Ar/^{39}Ar$ age of 32.72 ± 0.09 Ma, consistent with its inferred position beneath the Saguache Creek Tuff.

Well-exposed radial dikes and outward-dipping andesitic lavas just east of the North Pass caldera define the core of another volcano centered in the Jacks Creek drainage (Bruns et al., 1971) that is about the same age as Rawley Andesite at Bonanza. The Jacks Creek volcano predates eruption of the Bonanza Tuff, which laps out low on its flanks, but no direct ages have yet been determined for this center. Andesitic to rhyolitic lavas that are capped by scattered erosional remnants of Bonanza Tuff as far east as the Continental Divide just north of North Pass (Fig. 4) also must be roughly correlative to the Rawley Andesite. Just northwest of the Continental Divide in Needle Creek, several phases of a large intrusion (Fig. 2) that varies texturally from granodiorite to andesite has yielded hornblende $^{40}Ar/^{39}Ar$ ages of 34.3–34.4 Ma (Table 2). This intrusion likely marks the core of another large volcano. A nearby dacite flow, low in the lava assemblage, has sanidine $^{40}Ar/^{39}Ar$ ages of 34.0–34.1 Ma.

The core of yet another large central volcano that consists dominantly of andesite is marked by an intrusion of fine-grained hornblende granodiorite exposed on the northwest inner slope of the Cochetopa Park caldera (Fig. 2). Lavas on the northwest flank of the edifice form Sawtooth Mountain, and the northeast flank is preserved as Razor Creek Dome (Fig. 3). The age of this volcano is bracketed only by the underlying Wall Mountain Tuff (36.9 Ma) and overlying Saguache Creek Tuff (33.2 Ma). A dike low in the edifice has a hornblende $^{40}Ar/^{39}Ar$ age of 34.61 ± 0.16 Ma, and the capping flow on Sawtooth Mountain yielded a hornblende age of 32.00 ± 0.09 Ma.

A highly altered intrusion of porphyritic dacite along a structural ridge between two northeast-trending graben, exposed along the southwest margin of Cochetopa Park caldera, is a probable center for thick andesitic lavas that underlie the 32.2-Ma Saguache Creek Tuff along the Continental Divide where it separates Cochetopa Park from La Garita caldera to the south (Fig. 2). Farther southwest, along the north margin of La Garita caldera, some dacite lavas are as young as 29.2 Ma (Lipman, 2006), but direct stratigraphic relations to Saguache Creek or Bonanza Tuffs are absent.

SAGUACHE CREEK TUFF AND NORTH PASS CALDERA CYCLE (32.2 Ma)

A recurrent problem in studies of San Juan volcanism has been establishing reliable regional correlations of multiple widespread but discontinuously exposed ignimbrite units of similar petrologic characteristics. Among such puzzles has been the inferred extreme northeast extent of the Sapinero Mesa Tuff, a large-volume ignimbrite erupted from the western San Juan caldera cluster (Steven and Lipman, 1976, Fig. 10). Since the late 1960s, the Sapinero Mesa has been inferred to include densely welded, crystal-poor rhyolite tuff that crops out widely in the valley of Saguache Creek, as much as 90 km from the western San Juan caldera cluster (Bruns et al., 1971; Simon and Wendlandt, 1999). This distribution of the Sapinero Mesa is highly asymmetric to the source caldera, and the tuff in the Saguache valley is atypically thick and densely welded, in comparison to similarly distal portions of this unit elsewhere.

Such concerns, along with recognition of problems with published interpretations of the Cochetopa Park caldera (Lipman, 2000, p. 37), led to tentative inference that the rhyolitic tuff in Saguache Creek might be a separate ignimbrite erupted from this more proximal caldera. Initial study in the Cochetopa area demonstrated (1) that the tuff in Saguache Creek was indeed a different ignimbrite, distinguishable from the Sapinero Mesa Tuff by hand-lens petrography (absence of biotite), more alkalic rock and mineral compositions, and isotopic ages (Lipman and Calvert, 2003), but (2) that at least the last major subsidence at Cochetopa Park was too young to be associated with eruption of this tuff (postdating emplacement of the Fish Canyon Tuff, which overlies the welded tuff in Saguache Creek). Detailed mapping in Cochetopa Park and farther east has now documented that the previously unrecognized North Pass caldera (Fig. 3) was the source of the tuff in Saguache Creek.

As interpreted here, the North Pass caldera is an equant basin, ~15 km across, which straddles the present-day Continental Divide in the Cochetopa Hills (Fig. 4). This caldera cycle includes precursor ignimbrites of probable small volume and limited areal extent, the regional caldera-related Saguache Creek Tuff, a thick sequence of lava flows and volcaniclastic rocks that filled the caldera, and the late-erupted Luders Creek Tuff that may have erupted from within central parts of the caldera now covered by younger ignimbrites from the central caldera complex. Small preserved areas of younger andesite flows (ca. 30 Ma) may be late parts of the North Pass cycle, or just continued background flux of intermediate-composition magmatism. An alternative proposed caldera source for the Saguache Creek Tuff, 30 km farther northeast along the Continental Divide (Turner et al., 2003), is instead the site of a large andesitic stratovolcano that predated the 33-Ma Bonanza Tuff; no mapped geologic features support presence of a major ignimbrite caldera in this area.

Precursor(?) Tuff (32.5 Ma)

Two small areas of distinctive rhyolitic ignimbrite, exposed within short distances east and north of the North Pass caldera, have ages only a few hundred thousand years older than the main ignimbrite eruption from this caldera. Although exposures are too small to depict on Figure 4, these tuffs overlie the assemblage of early lavas, are younger than the Bonanza Tuff, and seem plausibly interpreted as initial eruptions broadly associated with the North Pass cycle. Both were initially considered potential candidates for distal deposits from Sawatch Range centers, but their younger age precludes such correlations.

Nonwelded, light-gray, crystal-rich tuff (20%–25% phenocrysts, including abundant quartz) is as much as 25 m thick on both sides of Saguache Creek, just east of Sheep Creek (Fig. 4), where it is overlain by tuffaceous sediments and Saguache Creek Tuff. Two sanidine ages from this tuff are 32.49 ± 0.07 and 32.54 ± 0.05 Ma. A small erosional remnant of densely welded, dark-gray to brown rhyolitic tuff crops out above Bonanza Tuff, low along a ridge just north of Spanish Creek (Fig. 4). It has sanidine ages of 32.48 ± 0.05 and 32.55 ± 0.05 Ma (Appendix 1), similar to the nonwelded tuff farther southeast, and may be a more welded correlative.

Saguache Creek Tuff (32.25 Ma)

As here defined, the Saguache Creek Tuff is a distinctively alkalic, crystal-poor, rhyolitic ignimbrite (72.3%–75.4% SiO_2) that is widely preserved in the Saguache basin, as well as in scattered erosional remnants farther northwest (Fig. 2). Its newly mapped distribution is roughly symmetric around the North Pass caldera, allowing for more Oligocene erosion in the northwest sector and widespread cover by younger rocks to the southwest. On published quadrangle maps, many of the scattered northwestern outcrop areas, which are now reliably identified as Saguache Creek Tuff by composition and isotopic age, were previously miscorrelated with diverse regional ignimbrites from the central caldera cluster.

Maximum exposed thickness of the tuff, 50–75 m, is along the axial Saguache paleovalley. Although widely eroded elsewhere, the areal extent and thickness of preserved densely welded exposures yield an estimated 250 km^3 magmatic volume for the outflow sheet. If thickly ponded within its source caldera as typical of other large San Juan ignimbrites, total volume of this tuff (neglecting downwind ash) could be ~500 km^3. Where thickness of the Saguache Creek Tuff exceeds a few tens of meters, the interior of the sheet is densely welded, commonly with gray pumice lenses (to 10 cm) in a purple-brown matrix. A central zone of spherical to lenticular gas cavities 5–10 cm in longest dimension is common where densely welded, as is typical of other crystal-poor ignimbrites in the region. In places, the Saguache Creek is densely welded nearly to its base, but the lower 5–10 m commonly is nonwelded white to tan tuff. Where not eroded, 10–20 m of upper nonwelded vapor-phase to glassy tuff is widely present, though typically largely covered by talus and slope wash from overlying units.

The Saguache Creek Tuff widely rests on the early (35–33 Ma) andesitic lavas, but as much as 10–20 m of water- and wind-reworked tuffaceous sediments are present locally between andesite and overlying ignimbrite along the axial Saguache paleovalley. In the paleovalley, this ignimbrite is widely overlain conformably by Fish Canyon Tuff that is 4 m.y. younger, with only thin intervening tuffaceous sediments. Weakly welded biotitic rhyolitic tuff that appears to be distal Sapinero Mesa Tuff and discontinuous 30-Ma andesite lavas are also present locally between the two regional ignimbrites along Saguache Creek. To the northeast, the Saguache Creek laps out against Bonanza Tuff and overlying "upper andesite" on the flank of the Bonanza caldera center. In contrast to the conformable sequence in the Saguache paleovalley, to the northwest the discontinuous erosional remnants of Saguache Creek Tuff typically cap ridges and mesas, while Fish Canyon Tuff was deposited lower within re-excavated paleovalleys. In places, paleolandside and talus of Saguache Creek clasts are overlain by Fish Canyon Tuff along walls of such paleovalleys, documenting times of valley erosion.

No in-place Saguache Creek Tuff or older rocks are exposed anywhere centrally within the area mapped as the North Pass caldera; caldera-filling dacite and rhyolite lavas have yielded ages similar to or younger than the Saguache Creek (Table 2). Along the east margin of the North Pass caldera, small remnants of outflow Saguache Creek Tuff are truncated abruptly and covered by the lava sequence that is interpreted to have filled the caldera (Fig. 5A). Along the west margin, a high ridge of east-dipping Saguache Creek Tuff is interpreted as intracaldera tuff, wedging out against the topographic wall and truncated by minor faulting, perhaps of Rio Grande rift age, that downdrops younger caldera-fill rocks to the east (Fig. 4). This elliptical exposure is exceptionally thick, dips 15°–25° into the caldera, and is overlain by caldera-fill units. In contrast, proximal outflow tuff sheets are typical absent or thin on high-standing caldera rims elsewhere in the San Juan region.

Major phenocrysts (3%–10% total) of the Saguache Creek Tuff are sodic low-barium sanidine ($Or_{50}Ab_{46}An_{3}Cs_{0.5}$), and plagioclase; biotite is absent or extremely sparse. Otherwise similar-appearing, crystal-poor rhyolitic ignimbrites of the San Juan region, such as the Sapinero

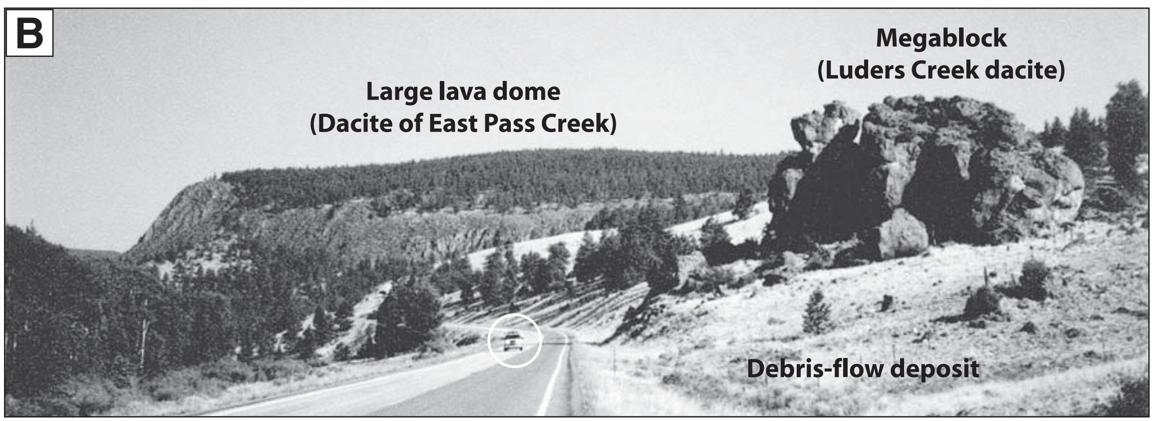

Figure 5. Photographs: (A) East wall of North Pass caldera, as viewed obliquely from the south across Saguache Valley (along Colorado Highway 114). Outflow Saguache Creek Tuff and underlying Conejos lavas and tuffs are abruptly truncated along caldera wall; then onlapped by ponded caldera-filling dacite and andesite lavas (ca. 30 Ma) and overlying Fish Canyon Tuff. (B) Megablock of shattered Luders Creek Tuff, forming large clast (20 m across) within the Buffalo Pass debris-flow deposit, makes bold outcrops along Colorado Highway 114 at the Buffalo Pass campground, looking west. Note vehicle on highway, for scale. On skyline is near-original profile of a thick caldera-filling lava dome (dacite of East Pass Creek, volcanics of Cochetopa Hills); sample from base of southern (left) cliff yielded a $^{40}Ar/^{39}Ar$ age (biotite) of 32.20 ± 0.09 Ma (Table 2, Appendix 1).

Mesa and Carpenter Ridge Tuffs, contain biotite phenocrysts, have more potassic sanidine compositions (typically Or_{60-65}), and have less alkalic major- and trace-element compositions (lower Na, Zr, and light rare-earth elements [REE] such as La and Ce; higher Sr and Ba). Despite broad similarities to other crystal-poor rhyolite tuffs of the area, such compositional details show that the Saguache Creek Tuff is regionally unique (Fig. 6). The eruption age is tightly constrained at 32.25 ± 0.05 Ma, from the weighted mean of six new laser-fusion sanidine $^{40}Ar/^{39}Ar$ determinations from geographically diverse sites (Table 2). The Saguache Creek Tuff has a reversed paleomagnetic direction, based on sites along Saguache Creek and west of the North Pass caldera (Table 3).

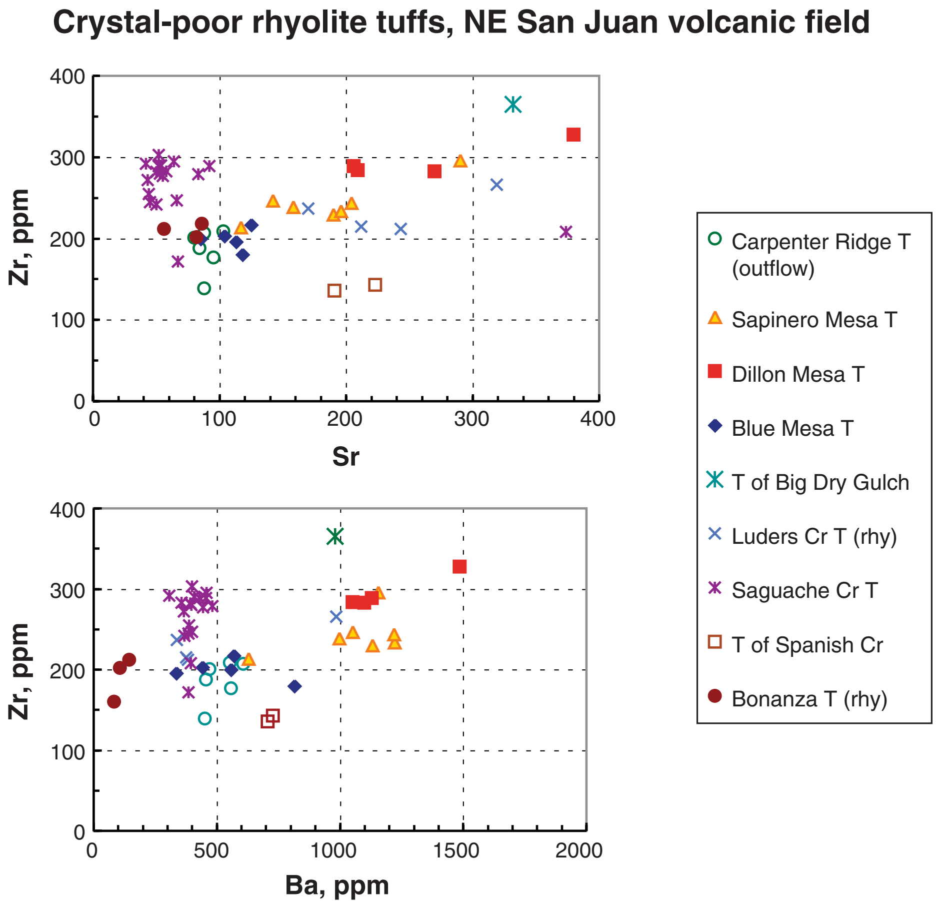

Figure 6. Sr-Zr and Ba-Zr variation diagrams, documenting compositional distinctions among megascopically similar crystal-poor rhyolitic ignimbrites of San Juan region. Most tuff sheets plot along a broadly similar variation trend, becoming more Sr and Ba rich with increasing Zr, but the Saguache Creek Tuff is compositionally unique in having low Sr and Ba at high Zr contents. The Saguache Creek is notably different from the Sapinero Mesa Tuff, in which it was previously included. For compositionally stratified ignimbrites, such as Luders Creek and Bonanza, only rhyolite compositions are plotted. T—Tuff.

Formation of the North Pass Caldera

Eruption of the Saguache Creek Tuff from a nonresurgent caldera in the North Pass area, which was then filled by younger lavas, is documented unambiguously by the distribution of this ignimbrite, abrupt truncations of regional units and local hydrothermal alteration along caldera margins, and the ages and compositions of caldera-filling rocks. The regional distribution of the erosional remnants of Saguache Creek Tuff is broadly symmetric around flanks of the caldera, with distal erosional remnants preserved as much as 15 km east, 10 km south, and 30 km northwest (Fig. 2). Absence of distal exposures to the southwest is due to widespread cover by young volcanic units of the central caldera cluster. Small isolated paleohills of Precambrian granitic rocks exposed around the margins of the caldera-filling assemblage, but nowhere within the depression, also help define limits of the North Pass caldera.

Caldera subsidence at North Pass postdates emplacement of the Saguache Creek Tuff, which is truncated along exposed sectors of the eastern and western caldera margins, and predates the Fish Canyon Tuff. The caldera-slope unconformity that defines surface expression of the North Pass caldera, although unimpressive around much of its perimeter because precaldera Conejos (Rawley) andesite and dacite are lithologically similar to the caldera-filling lavas and volcaniclastic rocks, is especially clearly displayed on the east side, just east of Sheep Creek, a tributary of Saguache Creek (Fig. 4). Here bleached and otherwise hydrothermally altered Conejos lavas and overlying Saguache Creek Tuff are abruptly truncated along a steep, westward-facing contact, against which are banked thick ponded flows of andesite, and overlain by anomalously thick and densely welded Fish Canyon Tuff (Fig. 5A).

A similar truncation of regional units, including Saguache Creek Tuff, is associated with local hydrothermal alteration along the west caldera margin, although relations are less clear on this flank because of fault complexities and more limited exposures. On this side of the caldera, in roadcuts along Colorado Highway 114, highly disrupted Conejos rocks and small masses of welded Bonanza Tuff are intermixed with nonwelded Saguache Creek Tuff on scales too complex to depict even on a detailed geologic map (Fig. 7); the assemblage is interpreted as caldera-margin megabreccia. The caldera-fill assemblage is also notably less altered than adjacent Conejos lavas and volcaniclastic rocks that define the caldera margins.

The caldera was filled by thick dacite lava flow and local rhyolite domes (volcanics of Cochetopa Hills), which have isotopic ages similar to the 32-Ma Saguache Creek Tuff. Otherwise lithologically similar precaldera lavas of the Conejos Formation and Rawley Andesite are largely or entirely older (33–35 Ma) in areas adjacent to the North Pass caldera. In addition, laharic volcaniclastic rocks within the caldera area, which mainly have clasts of intermediate-composition lavas, locally contain sparse fragments of Saguache Creek Tuff, requiring that these deposits are also younger than otherwise similar clastic rocks of the Conejos Formation and Rawley Andesite that underlie this ignimbrite adjacent to the caldera.

The caldera-filling lavas are resistant to erosion, holding up a segment of the present-day Continental Divide; as a result, the caldera remains largely buried. The thickness of exposed caldera fill exceeds 500 m, but erosion has been insufficient to expose underlying rocks.

As a result, the total subsidence cannot be documented from exposures, nor can the likely presence of thick intracaldera Saguache Creek Tuff.

Caldera-Filling Lavas (Volcanics of Cochetopa Hills, 32.2 Ma)

The volcanics of Cochetopa Hills are a diverse assemblage of lava flows and volcaniclastic deposits that accumulated rapidly within the North Pass caldera after subsidence during eruption of the Saguache Creek Tuff. The bulk of the lavas at exposed levels are flows of porphyritic dacite; these overlie diverse volcaniclastic rocks and scattered lava domes of crystal-poor rhyolite with compositions similar to the Saguache Creek Tuff (Fig. 8).

Massive flows of gray to tan crystal-rich dacite (dacite of East Pass Creek) are the dominant exposed fill in the caldera. The thickest and most widespread accumulations are north of North Pass, where multiple flows are locally mappable, based on zones of basal vitrophyre and upper carapace breccia. Individual flows are as thick as 200 m; total exposed thickness is greater than 500 m. These flows are petrographically fairly uniform, containing 20%–30% phenocrysts of blocky plagioclase (to 1 cm), biotite, and clinopyroxene ± hornblende; sanidine is absent. Compositionally, this unit is typical dacite of the region (SiO_2, 61.4%–66.0%). Biotite plateau $^{40}Ar/^{39}Ar$ ages for three samples from the main area of exposure are 32.07–32.31 Ma, consistent with eruption soon after the Saguache Creek Tuff at 32.25 ± 0.05 Ma (Table 2). A small outlier of similar dacite that is banked unconformably against a slope along the inferred south margin of the North Pass caldera yielded slightly older ages of 32.82 ± 0.08 Ma (bio) and 32.75 ± 0.15 Ma (hbl); interpretation of this flow as part of the caldera fill remains ambiguous.

Scattered lava domes of phenocryst-poor, gray to light-tan rhyolite (rhyolite of Taylor Canyon), exposed locally beneath the dacite of East Pass Creek, are also interpreted as fill of the North Pass caldera. Flow layering, glassy carapace breccia, and ramp structures near upper surfaces are typical. Several analyzed flows, exposed along the west caldera wall and farther to the east (74%–76% SiO_2; 1%–5% sanidine, plagioclase), are similar to the Saguache Creek Tuff in lacking biotite phenocrysts and containing elevated levels of incompatible trace elements. One of these yielded a sanidine age of 32.15 ± 0.10 Ma. Exposed thickness is as much as 150 m.

At lowest exposed levels, laharic conglomerate, sandstone, and water-reworked tuff are interlayered with and underlie the lava flows within the North Pass caldera. Most widespread are crudely bedded laharic breccias, along with better bedded conglomerate, that mainly contain clasts of dark andesite and dacite in weakly indurated lighter gray sandy matrix. Outcrops are rare; the unit typically forms loose cobbles on subdued slopes. These rocks, likely recording rapid postcollapse erosion of Conejos (Rawley) lavas along the inner caldera slopes, closely resemble volcaniclastic sediments of the older Conejos Formation. A key to identification as a younger volcaniclastic deposit is presence of rare clasts of Saguache Creek Tuff.

Thin deposits of white to light-tan bedded rhyolitic tuff deposited in shallow-lake or low-energy stream environments are preserved discontinuously along the west caldera margin, where they interfinger with and overlie older caldera-fill units. These deposits resemble younger tuffaceous sedimentary fill of the Cochetopa Park caldera to the west, but their higher topographic level and location along margins of the North Pass caldera suggest that they are late sedimentation in this caldera, probably in conjunction with eruption of rhyolitic lava flows or the Luders Creek Tuff. Obscure gully exposures along the west side of the Continental Divide demonstrate that at least some lake beds underlie the Luders Creek Tuff. The preserved thickness is less than 30 m, consistent with rapid filling of the North Pass caldera by the volcanics of Cochetopa Hills without any long-persistent lake- or other sediment-filled basin.

Luders Creek Tuff (32.17 Ma)

A distinctive compositionally zoned ignimbrite, which crops out on the Continental Divide along the west side of the North Pass caldera (Fig. 4), appears to be a late eruptive unit of the North Pass cycle, based on its age and location. As defined here, the Luders Creek Tuff grades from weakly welded tan rhyolite (72%–73% SiO_2; 5%–10% plagioclase and sanidine phenocrysts, and sparse biotite) upward into densely welded dark dacite (66%–68% SiO_2; 20%–30% plagioclase, sanidine, biotite, and sparse clinopyroxene).

The Luders Creek Tuff is broadly similar in appearance and phenocryst mineralogy to the much younger Nelson Mountain Tuff (26.9 Ma), with which this tuff had been correlated previously (Steven and Lipman, 1976, Fig. 24). The small remaining areas of in-place Luders Creek Tuff overlie dacite and rhyolite flows (volcanics of Cochetopa Hills); widespread laharic debris-flow deposits of Buffalo Pass, derived from Luders Creek Tuff, overlie the Saguache Creek Tuff and underlie Fish Canyon Tuff across much of the Saguache paleovalley. Some shattered blocks in the debris-flow deposit are as much as 25 m across (Fig. 5B), and the volume of Luders Creek Tuff in this deposit exceeds that of preserved in-place exposures. The origin of this large debris flow is unknown, but it is locally interleaved with ca. 30-Ma andesitic lava flows and therefore ~2 m.y. younger than eruption of the Luders Creek Tuff.

Four sanidine $^{40}Ar/^{39}Ar$ ages for the Luders Creek (weighted mean: 32.17 ± 0.04 Ma) are only slightly younger than the Saguache Creek Tuff (32.25 ± 0.02 Ma), providing a tight age bracket for the entire sequence of lavas and volcaniclastic deposits within the North Pass caldera (Table 2). Limited preserved distribution of the Luders Creek Tuff suggests probable eruption either from within the North Pass caldera beneath subsequent cover by Fish Canyon and Carpenter Ridge Tuffs or from within the adjacent Cochetopa Park area. Maximum preserved thickness is 75 m.

Late Andesite Flows and Associated Rocks (30.0–30.5 Ma)

Several small areas of andesitic lava and a thin, partly welded dacite tuff of similar age, deposited at ca. 30 Ma along the east side of the North Pass caldera (Fig. 8), may be late phases broadly associated with this caldera cycle, or local phases of the regional flux of dominantly intermediate-composition lava eruptions.

Oldest are a porphyritic hornblende andesite on Hill 9519′ (58.1% SiO_2) and an overlying aphyric andesite flow that bank thickly against the sloping east wall of the caldera at Sheep Creek (Fig. 5A). The thick hornblende andesite and its inclined columnar-jointed contact against the caldera wall somewhat resemble an intrusive body, but emplacement as a ponded lava flow is indicated by presence of elliptical vesicles, even within the most massive parts of the unit, and by continuity with subhorizontal eastern parts of the flow that directly overlie Saguache Creek Tuff where the lava overflowed the caldera margin. These flows, which are overlain by the widespread laharic breccia derived from the Luders Creek Tuff, have yielded $^{40}Ar/^{39}Ar$ ages of 30.41 ± 0.79 Ma (hornblende) and 29.98 ± 0.31 Ma (groundmass concentrate), respectively (Table 2). The ponding of these lavas, as well as the anomalously thick and densely welded character of overlying Fish Canyon Tuff, demonstrate that the east side of the North Pass caldera remained incompletely filled at the time of their eruption, 2 m.y. after initial caldera collapse.

A thin, weakly welded ignimbrite of crystal-poor dacite (tuff of Big Dry Gulch), of restricted areal extent and small volume, is a distinctive local marker unit, above the Saguache Creek Tuff and laharic debris-flow deposit with Lud-

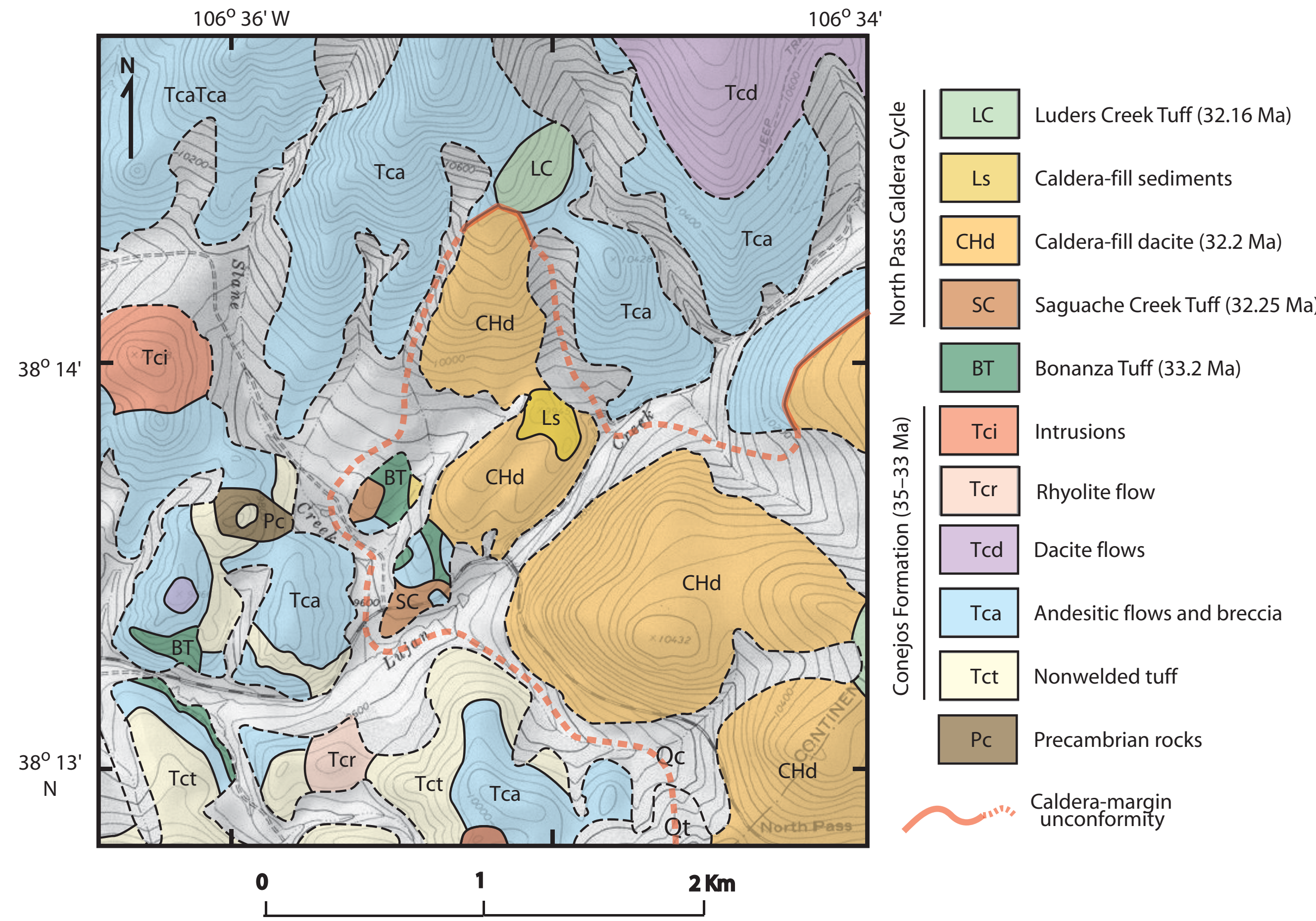

Figure 7. Geologic map of the northwest margin, North Pass caldera, showing complexly intermixed lithologies along Colorado Highway 114, near the junction of Lujan and Slane Creeks. These features are interpreted as intracaldera landslide megabreccia, in a matrix of nonwelded to weakly welded Saguache Creek Tuff that erupted from this caldera. The megabreccia and tuff matrix are overlain by thick caldera-filling lavas (dacite of East Pass Creek). Location shown on Figure 4.

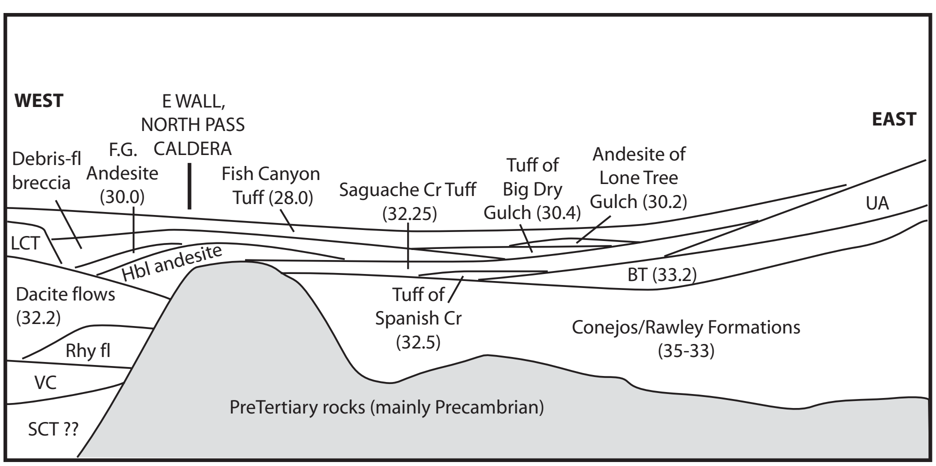

Figure 8. Schematic east-west stratigraphic cross section, along Saguache valley. Ages of units, in Ma (parentheses). BT—Bonanza Tuff; F.G.—Fine-grain andesite; LCT—Luders Creek Tuff (32.17 Ma); SCT—Saguache Creek Tuff (intracaldera); Rhy fl—intracaldera flows (32.2 Ma); UA—Upper andesite of Bonanza center; VC—volcaniclastic conglomerates (intracaldera).

ers Creek clasts, and below andesitic lavas along the upper Saguache valley (Fig. 8). This gray tuff sheet (67.1% SiO_2) contains 3%–5% phenocrysts of plagioclase and abundant biotite; sanidine is absent, in contrast to otherwise similar-appearing distal portions of crystal-poor regional ignimbrites such as Sapinero Mesa or Carpenter Ridge Tuffs. Its $^{40}Ar/^{39}Ar$ plateau age of 30.47 ± 0.08 Ma (biotite) links it in time to the late andesite that may represent final stages of the North Pass cycle.

Several well-stratified andesitic lava flows (59% SiO_2) and associated volcaniclastic rocks (andesite of Lone Tree Gulch) intervene between the tuff of Big Dry Gulch and overlying Fish Canyon Tuffs along the paleo-Saguache valley, on the southeast flank of Trickle Mountain and adjacent areas. Individual flows are 5–10 m thick; maximum total thickness is ~50 m. A groundmass-concentrate $^{40}Ar/^{39}Ar$ age of 30.21 ± 0.17 Ma links this andesite assemblage closely to the andesite flows ponded against the east wall of the North Pass caldera, but the location of these flows well to the east suggests that they represent continued regional flux of intermediate-composition volcanism unrelated to any caldera cycle.

Chaotic breccia and some possibly intact lava flows of dark-gray, crystal-poor andesite (andesite of Big Dry Gulch) form rugged massive outcrops in upper reaches of Big Dry Gulch, a southern tributary of Saguache Creek. Much of this unit appears to have been emplaced by chaotic landslides; some parts may be primary eruptive deposits, perhaps on a proximal flank of the source eruptive edifice. These masses of andesite breccia remained topographic highs at time of eruption of the Fish Canyon Tuff. Age and emplacement relations are unknown relative to the andesite of Lone Tree Gulch; they may represent proximal and more distal portions of one eruptive sequence.

A flow of silicic alkalic basalt (52.0% SiO_2), erupted from a vent ("Point Benny") centrally located within the North Pass caldera (Fig. 4), also overlies the laharic breccia deposit containing Luders Creek clasts. This finely olivine-phyric basalt contains widely distributed sparse xenocrysts of quartz and feldspar, derived from disaggregated fragments of Precambrian granite. This flow and vent are the only known Oligocene basalt in the San Juan region. The weighted mean $^{40}Ar/^{39}Ar$ age of 30.22 ± 0.10 Ma for groundmass-concentrate determinations on five samples, sampled to bracket diverse amounts of Precambrian xenocrystic detritus, is consistent with stratigraphic position beneath Fish Canyon Tuff, and also with eruption about concurrent with the late andesite ponded against the east wall of the North Pass caldera.

NORTHERN RHYOLITE-DACITE DOME FIELD (29.8 Ma)

Spatially unrelated to the North Pass caldera system, but broadly concurrent with the late-erupted andesitic lavas just described, is a cluster of silicic domes and flows centered on upper Barret Creek, in the north-central part of the study area (Fig. 2). These rocks range from nearly aphyric rhyolite (1%–5% sanidine and plagioclase, sparse biotite; 73%–76% SiO_2) to crystal-rich silicic dacite and low-Si rhyolite (15%–35% plagioclase-sanidine-quartz-biotite; 67%–74% SiO_2). Individual flows are 50–150 m thick; preserved exposures of the composite flow field cover an area of ~150 km^2. The range of laser-fusion $^{40}Ar/^{39}Ar$ ages for sanidine phenocrysts from four separate lava flows is 29.63 ± 0.06–29.85 ± 0.09 Ma; biotite from a fifth flow yielded a slightly older age of 30.08 ± 0.09 Ma (Table 2; Appendix 1). These silicic flows lap onto the eroded core of an older Conejos (Rawley) andesitic volcano, including a central intrusion of fine-grained granodiorite (pooled $^{40}Ar/^{39}Ar$ plateau age of 34.36 ± 0.07 Ma on hornblende from three sites) that, with dimensions of 5 × 10 km in area, is the largest early intrusion in the San Juan region.

The rhyolite-dacite dome field at Barret Creek constitutes the only sizable area of silicic volcanism, anywhere in the San Juan region, in the time interval between peak activity of the North Pass cycle at 32 Ma and inception of ignimbrite eruptions from the Platoro caldera complex in southeastern mountains at 29.4 Ma. The most dacitic lavas are compositionally and petrographically similar to the voluminous Fish Canyon Tuff, documenting that generation of this regionally distinctive magma type began relatively early in the San Juan region, well north of the area that would become the La Garita caldera. Possibly representing an aborted or failed caldera system, the Barret Creek lavas provide a further bridge in the transition between earlier ignimbrite activity along the Sawatch trend and the younger centers in the San Juan region.

YOUNGER ERUPTIONS FROM OTHER SAN JUAN CALDERAS (28.3–26.9 Ma)

The northeastern San Juan Mountains were formerly blanketed by regional Oligocene ignimbrites erupted from farther to the south and west, and widespread remnants of this cover have survived erosion. Locally erupted intermediate-composition lava flows and volcaniclastic rocks interfinger with these ignimbrites within the study area. The following sections summarize new age data and aspects of these tuffs that bear on development of the North Pass and Cochetopa Park calderas.

Sapinero Mesa Tuff

The Sapinero Mesa Tuff, a crystal-poor rhyolite erupted from the western San Juan caldera cluster at 28.27 ± 0. 06 Ma (Table 2), is among the largest ignimbrites in the San Juan region, with an estimated volume of 1000 km^3 or more (Lipman et al., 1973; Bove et al., 2001). With the unit now recognized as Saguache Creek Tuff excluded from this ignimbrite, the preserved distribution of Sapinero Mesa Tuff is mainly confined to scattered erosional remnants in the western half of the study area. In these distal areas, the Sapinero Mesa Tuff is rarely more than 20 m thick, only partly welded, light gray in color due to vapor-phase crystallization, and phenocrysts are sparse, small, and more broken than in more proximal sites.

Small areas of lithologically similar tuff are also discontinuously present farther east along the Saguache paleovalley, especially in the tributary of Houselog Creek, where the tuff has a similar sanidine $^{40}Ar/^{39}Ar$ age (28.20 ± 0.06 Ma) and reverse paleomagnetic pole position as the Sapinero Mesa farther west (Tables 2–3). This apparently distal eastern area of thin Sapinero Mesa Tuff probably was channeled down the Saguache paleovalley, thus resulting in an overall distribution much like that depicted previously (e.g., Steven and Lipman, 1976, Fig. 10), even though the thick densely welded tuff sheet formerly identified as Sapinero Mesa in this area is now recognized to be the older Saguache Creek Tuff.

Fish Canyon Tuff

The crystal-rich dacitic Fish Canyon Tuff, erupted from the 75 × 35-km La Garita caldera at 28.02 Ma, is the most voluminous ignimbrite anywhere in the Southern Rocky Mountains Volcanic Field, with a volume greater than 5000 km^3 (Lipman, 2000; Bachmann et al., 2002). Seven additional large ignimbrite sheets erupted from caldera sources within the La Garita caldera during the next 1.1 m.y. (Table 1), forming the central caldera cluster (Lipman, 2000, 2006). The north margin of the La Garita caldera is within the present study area (Fig. 2), and proximal Fish Canyon Tuff originally blanketed most or all of the northeastern San Juan region, banking out locally against paleotopographic highs such the early central volcanoes. Within the North Pass caldera, the Fish Canyon is up to 300 m thick, densely welded, and widely preserved, indicating that the subsidence basin had been incompletely filled. Eruption of the Fish Canyon Tuff also appears to be closely intertwined with early development of the unusual caldera structure at Cochetopa Park, as discussed in a later section.

Carpenter Ridge and Wason Park Tuffs

The Carpenter Ridge Tuff, another >1000-km^3 ignimbrite erupted at 27.55 ± 0.05 Ma from the Bachelor caldera centrally within the La Garita caldera (Fig. 1), also once covered much of the northeast San Juan region as a widespread thin sheet of densely welded crystal-poor rhyolite. This crystal-poor rhyolitic ignimbrite commonly contains a near-basal black vitrophyre and a central lithophysal zone, even where only a few tens of meters thick. In addition to its stratigraphic position above the Fish Canyon Tuff, the Carpenter Ridge can be distinguished in outcrop from the otherwise similar-appearing Saguache Creek Tuff by the presence of biotite phenocrysts. Proximal Sapinero Mesa Tuff closely resembles the Carpenter Ridge, but the distal Sapinero Mesa within the present study area is only partly welded and lacks lithophysae. The Carpenter Ridge Tuff provides an important stratigraphic marker, helping define faults and structures associated with eruption of the Fish Canyon Tuff from younger features formed during later subsidence at Cochetopa Park.

The Wason Park Tuff, a crystal-rich rhyolite erupted at 27.38 ± 0.05 Ma from the South River caldera of the central San Juan cluster (Fig. 1), mainly ponded within the La Garita caldera, but locally escaped to the northeast following paleovalleys that breached the La Garita wall. The most northeastern preserved outcrops of the Wason Park are at Sheep Creek (Fig. 4), against the east margin of the North Pass caldera, demonstrating that this side of the caldera remained a topographic low 5 m.y. after initial subsidence.

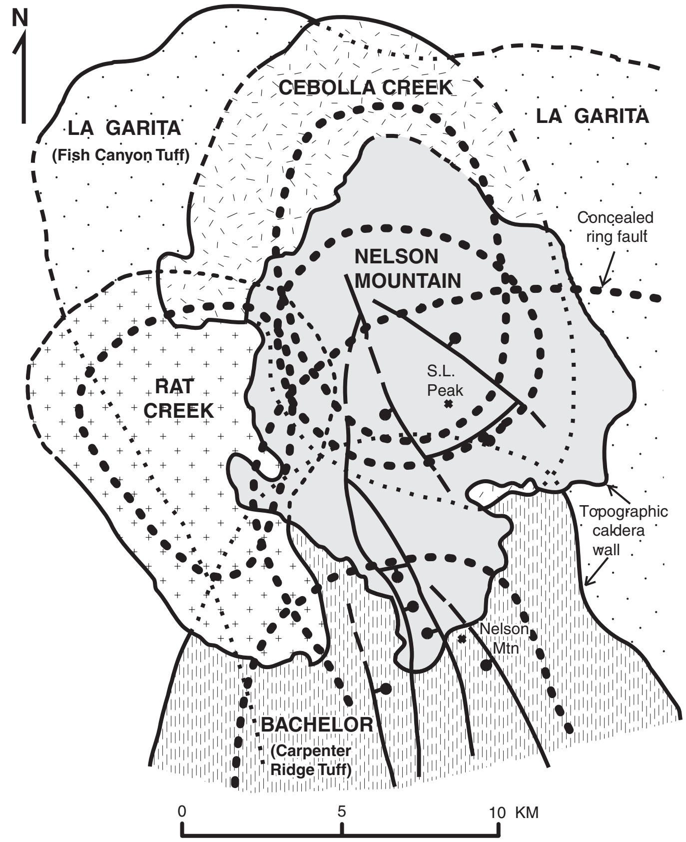

Figure 9. Generalized map of the San Luis caldera complex, showing caldera topographic margins (unconformities between precaldera and caldera-fill rocks) and inferred structural boundaries (concealed ring faults).

Younger Intermediate-Composition Lava Flows

Several mesa-capping erosional remnants of aphanitic to sparely porphyritic andesitic to dacitic lava southeast of the North Pass caldera (“younger lava flows,” Fig. 2) were erupted concurrently with ignimbrites from the central caldera cluster. Older flows that overlie the Fish Canyon Tuff in the vicinity of Mount Lion have yielded ages of 28.0–27.6 Ma (seven samples) on groundmass separates (Appendix 1); flows on one mesa west of Tracey Mountain are overlain by a thin remnant of Carpenter Ridge Tuff (27.55 Ma), stratigraphically consistent with the isotopic results. These flows are thus equivalent to the Huerto Andesite, a major unit within and adjacent to the La Garita caldera to the southwest. Other mesa-capping flows that overlie the Carpenter Ridge Tuff directly south of the North Pass caldera (Fig. 2) have ages of 27.51–27.46 Ma, consistent with eruption before the Wason Park Tuff at 27.38 Ma. These flows, which have no stratigraphic counterparts nearby in the central caldera cluster, are accordingly informally designated the andesite of Lion Mountain Creek (Appendix 1). Most of these localities were previously interpreted as Miocene Hinsdale Formation (Tweto, 1979), but only one small mesa cap of Hinsdale lava has been confirmed, a flow on Houghland Hill (Fig. 2) dated at 21.81 ± 0.21 Ma.

Rocks of the San Luis Caldera Complex

Three compositionally diverse ignimbrites and associated lavas of the San Luis complex, nested along the northwestern side of the La Garita caldera (Figs. 9 and 10), are the youngest major eruptions from the central San Juan cluster, other than the Snowshoe Mountain Tuff from the Creede caldera farther south (Lipman, 2000, 2006). Our new age results show that all four of these ignimbrites were erupted geologically rapidly between 26.91 ± 0.02 and 26.87 ± 0.02 Ma (Table 2, weighted means), a time span too brief to resolve reliably by $^{40}Ar/^{39}Ar$ dating. The eruptive history of the San Luis complex (Lipman, 2000) is summarized briefly, because the last-erupted Nelson Mountain Tuff is interpreted as closely intertwined with subsidence at Cochetopa Park.

Rat Creek Tuff

The initial ignimbrite erupted from the San Luis complex, the Rat Creek Tuff, is compositionally zoned from weakly indurated, light-tan crystal-poor rhyolite upward into densely welded, crystal-rich dark dacite (73%–65% SiO_2). The Rat Creek Tuff is the smallest of the San Luis ignimbrites in estimated volume (~150 km^3), the most restricted in known extent, and its source is the least understood (Lipman, 2000, p. 32–33). Within the present study area, preserved exposures of the Rat Creek Tuff are limited to ponded fill within the northern La Garita caldera and to weakly welded distal tuff along the northeast-trending Los Pinos graben (Figs. 2–3). Exposed fill of the Rat Creek

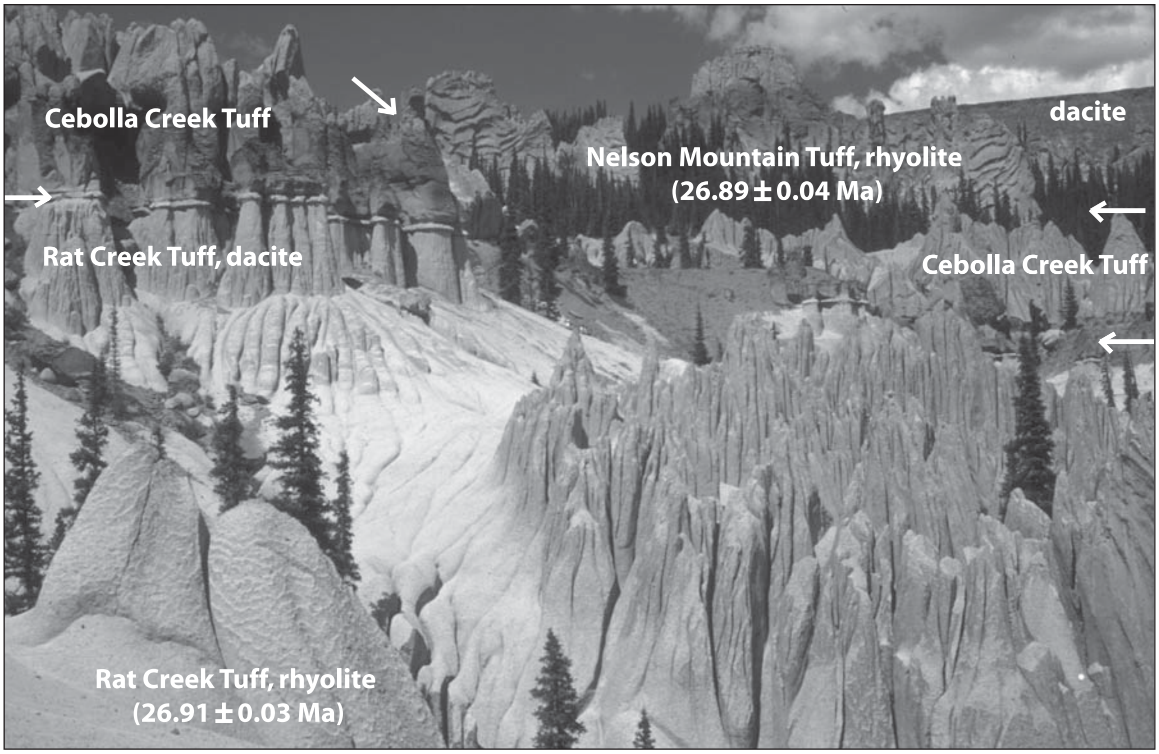

Figure 10. The three outflow ignimbrites erupted from the San Luis caldera complex, exceptionally exposed at Wheeler Geologic Monument. Arrows indicate contacts between units. Lowest sheet is weakly welded Rat Creek Tuff, separated from densely welded basal Cebolla Creek Tuff by 0.5 m of surge-bedded ash. The Cebolla Creek is distinctively hornblende rich; it becomes less welded upward. Surge beds and accretionary lapilli also are present in basal nonwelded crystal-poor (~5%) rhyolitic ash of the Nelson Mountain Tuff. The densely welded caprock of the Nelson Mountain is more crystal rich (~25%) and transitional to dacite that is more phenocryst rich than the basal rhyolite. Plotted ages are single-crystal sanidine laser-fusion analyses for rhyolite samples at Wheeler Monument (samples 06L-45 and 06L-47: Appendices 1–3; see footnote 1); the pooled weighted means for all samples from these two ignimbrites are indistinguishable (26.91 ± 0.02 for Rat Creek Tuff; 26.90 ± 0.03 for Nelson Mountain Tuff).

caldera consists of lavas and interleaved tuffs (Mineral Creek Dacite), and erosional levels are insufficient to expose probable intracaldera Rat Creek Tuff (Fig. 9). Eight Rat Creek samples from geographically widespread sites have a weighted-mean laser-fusion sanidine age of 26.91 ± 0.02 Ma; biotite from one of these sites yielded an older step-heating age of 27.08 ± 0.09 Ma.

Cebolla Creek Tuff

The Cebolla Creek is a distinctive, compositionally uniform ignimbrite of gray to light-brown, weakly vapor-phase–devitrified mafic dacite (62%–66% SiO_2; 25%–40% phenocrysts of plagioclase, biotite, hornblende, and sparse clinopyroxene). In contrast to other dacitic tuffs of the San Luis complex, the Cebolla Creek lacks sanidine, and hornblende is abundant. Hornblende and biotite plateau ages for this unit (27.07–27.13 Ma) are ~0.2 m.y. older than sanidine ages for the underlying Rat Creek Tuff (Table 2). Such slightly older ages for these mafic minerals relative to sanidine are fairly common among dated volcanic rocks in the San Juan region (see Appendix 1).

Like the underlying Rat Creek Tuff, exposures of outflow Cebolla Creek deposits are weakly welded and are limited to ponded fill within the northern La Garita caldera and along the Los Pinos graben. These lower tuff sheets were widely eroded prior to eruption of the overlying Nelson Mountain Tuff, which rests directly on older units in many places within the general distribution area of the Cebolla Creek Tuff. The source caldera for the Cebolla Creek Tuff, although now largely concealed beneath the Nelson Mountain caldera source and flanking postcollapse volcanoes, appears to be the largest among the three of the San Luis complex, with dimensions of 12 × 17 km at present erosional levels (Fig. 9). The Cebolla Creek caldera was filled, first by thick densely welded intracaldera tuff of similar composition to the outflow sheet, then by bulbous flows of crystal-poor rhyolite lava (Mineral Mountain Rhyolite).

Nelson Mountain Tuff

This unit includes a regional ignimbrite sheet and thick intracaldera fill; like the Rat Creek, it grades upward in composition from weakly welded, crystal-poor rhyolite to densely welded, dark crystal-rich dacite (73%–63% SiO_2). The Nelson Mountain is the most densely welded and voluminous outflow deposit erupted from the San Luis complex (estimated >500 km^3), and its eruption was followed by growth of large volcanoes on the eastern and western caldera flanks (Stewart Peak Volcanics and Baldy Cinco Dacite), roughly concurrent with resurgent uplift of the caldera interior (Lipman, 2000).

Exposed intracaldera Nelson Mountain Tuff is more than 800 m thick on San Luis Peak, and erosional remnants of the outflow sheet are preserved widely around southwest and southeast sides of the San Luis complex, where this tuff

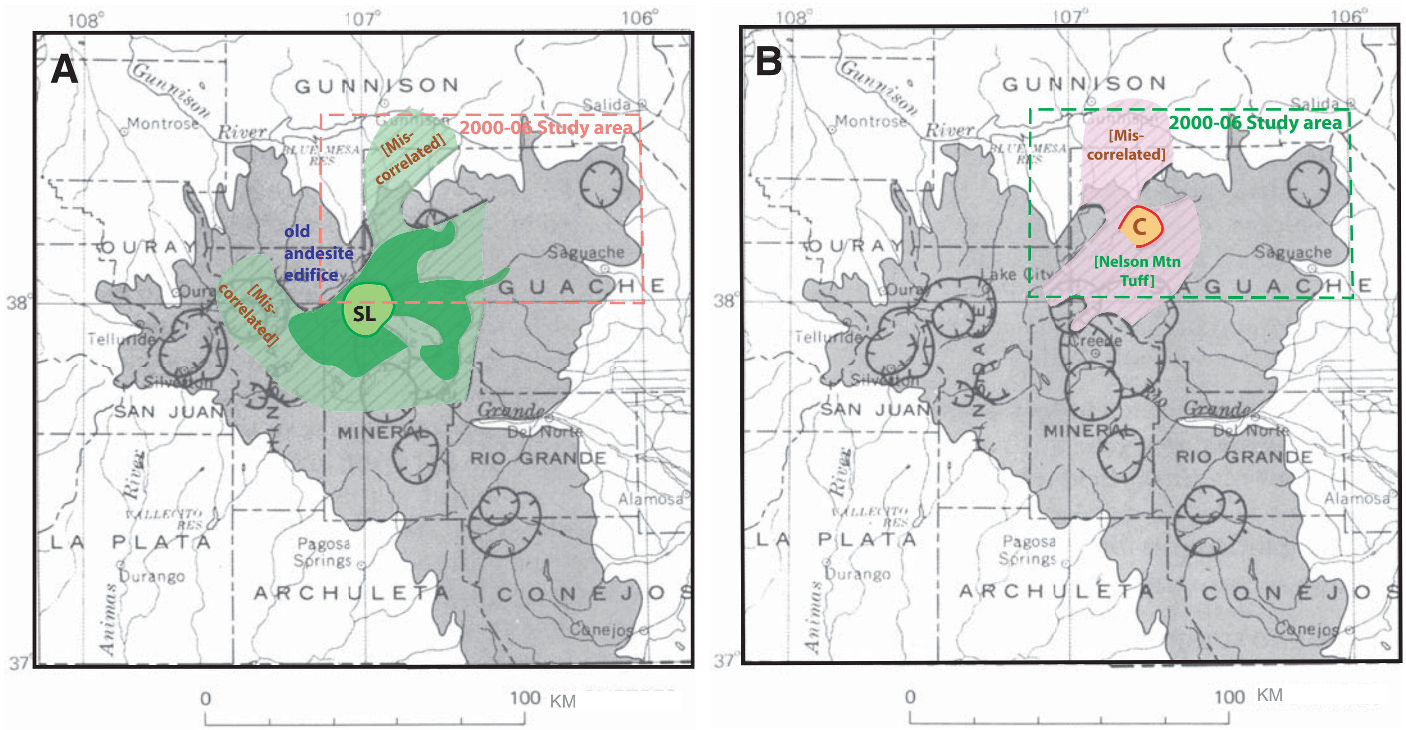

Figure 11. Distribution of Nelson Mountain Tuff. (A) Preserved distribution as currently understood (dark green), in relation to its eruptive source from the San Luis caldera complex (SL), and comparison to previous interpretation for this unit (light green: Steven and Lipman, 1976, Fig. 23). (B) Comparison to previous misinterpretation of "Cochetopa Creek Tuff" and its inferred source from Cochetopa caldera (Steven and Lipman, 1976, Fig. 24): southern areal extent attributed to this unit is Nelson Mountain Tuff; inferred northern extent involves miscorrelations with diverse older tuff sheets (see text for further discussion).

spread across northern parts of the La Garita caldera (Lipman, 2006). A northeastern outflow lobe of the Nelson Mountain was able to cross the La Garita wall, following paleovalleys of the Los Pinos and Cochetopa Creek grabens into Cochetopa Park, and a weakly welded distal facies of this unit reached the southeastern side of the Cochetopa Park caldera (Fig. 11). The northeastern lobe was once considered to be a separate younger ignimbrite sheet ("Cochetopa Creek Tuff") interpreted to have erupted from the Cochetopa Park caldera (Steven and Bieniewski, 1977; Olson and Steven, 1976a), but more detailed mapping, paleomagnetic pole positions, and age determinations have documented its correlation as outflow Nelson Mountain Tuff (Lipman, 2000, p. 37).

New single-crystal sanidine age determinations for the Nelson Mountain Tuff, both outflow and intracaldera (Table 2), have resolved some enigmatic problems concerning this unit. Previously determined $^{40}Ar/^{39}Ar$ incremental-heating plateau ages on multiple-grain sanidine concentrates, although analytically reproducible, differed by as much as 1 m.y. between samples from differing geographic localities and for intracaldera versus outflow parts of this ignimbrite unit (Lipman, 2000, Fig. 11, and discussion therein). The new single-crystal laser-fusion results document the presence of sanidine xenocrysts and also grains with degassed melt inclusions, yielding a scattering of ages substantially older or younger than the average for closely grouped grains in individual samples (Fig. 12; Appendices 1–3). When statistically anomalous crystals are excluded, sanidine from eight outflow samples yield a weighted mean age of 26.90 ± 0.02 Ma, and two samples of intracaldera Nelson Mountain have a mean of 26.91 ± 0.04 Ma (Table 2). In contrast, four biotite ages have a weighted mean of 27.25 ± 0.06 Ma (Appendix 1), again documenting slightly older apparent ages for this mineral, in comparison to sanidine.

Mapping for the present study has also shown that many areas of ridge-capping ignimbrite north of the Los Pinos graben and extending nearly to the Gunnison Valley, which were depicted as Nelson Mountain Tuff and/or Cochetopa Creek Tuff on previously published quadrangle maps (Olson, 1976a, 1976b; Olson and Steven, 1976a, 1976b; Olson, 1988), instead consist entirely of diverse pre-Nelson Mountain regional units, including at various sites the Wall Mountain, Saguache Creek, Fish Canyon, and Carpenter Ridge Tuffs. The Nelson Mountain and earlier tuffs from the San Luis complex may well have originally been deposited over sizable areas to the north, but as the youngest and topographically highest deposits, they have been entirely eroded. No "Cochetopa Creek Tuff" or Nelson Mountain Tuff remains preserved anywhere north of the Cochetopa Park caldera (Fig. 11).

Despite the widespread outflow and thick intracaldera accumulation of the Nelson Mountain Tuff, constituting the largest of the three San Luis ignimbrites in eruptive volume (Table 1), the source caldera within the San Luis complex is anomalously small relative to the estimated eruptive volume of tuff (500 km^3). The basin defined by the unconformity between wall rocks and caldera fill is 10 × 15 km, but the southern third of the basin is a truncated paleovalley, as documented by mapping and mine data (Lipman, 2000). The paleovalley is well outside of the structurally subsided block, which has estimated maximum dimensions of only ~8 × 10 km and an area of ~65 km^2 (Fig. 9). To accommodate the 500-km^3 erupted volume of the Nelson Mountain Tuff would thus require on the order of 8 km average caldera subsidence, but the asymmetric trap-door subsidence geometry at this caldera (Lipman, 2000) permits only ~500 m of subsidence on the northern side of the caldera and no more than 1.5–2 km at the more deeply subsided southern side. In the present study, we ascribe this inconsistency between eruptive and subsidence volumes associated with eruption of the Nelson Mountain Tuff to complex interrelations with subsidence at the much larger Cochetopa Park caldera centered 30 km to the northeast.

COCHETOPA PARK CALDERA: RELATION TO NELSON MOUNTAIN TUFF (26.9 Ma)

Cochetopa Park (Figs. 3 and 13), just north of the La Garita caldera (Fig. 2), is among the larger and most morphologically obvious caldera basins (~30 km in diameter) in the region, but its depth of subsidence appears to be less than for other San Juan calderas. Subsidence was only ~300 m along the southern margin, as constrained by downdropped Saguache Creek Tuff and underlying rocks on the caldera floor. Subsidence was as much as 700–800 m on the northern side where precollapse lavas on the caldera floor are structurally coherent, as shown by the continuity of andesite dikes and lava flows. In contrast, geometric modeling of other large San Juan calderas suggests structural subsidence of 3–5 km (Lipman, 1997), similar to caldera-fill sections exposed in tilted calderas elsewhere in the western USA (Seager and McCurry, 1988; Lipman 1993; John, 1995; John et al., 2008).

The earliest caldera-fill deposits at Cochetopa Park are thick massive aprons of coarse landslide breccia, banked against the inner caldera slopes (Fig. 14). This distribution is in contrast to slide breccias at other more deeply subsided calderas in the San Juan region, where the landslide deposits spread widely across the subsided basin and interfinger with thick intracaldera tuff. The location of slide breccias at Cochetopa Park, hanging on slopes of the inner caldera wall, is thus in accord with the relatively limited subsidence interpreted from offsets of the caldera floor. The landslide deposits reflect lithologies on the adjacent caldera rims: around the north side, breccia consisting of andesitic clasts is dominant, along with areally restricted lenses of monolithologic breccia derived from Saguache Creek Tuff; around south and east sides are monolithologic slide breccias of shattered Fish Canyon Tuff (Fig. 14A), in places with sparse clasts derived from Carpenter Ridge Tuff (Fig. 14B). Confident identification of the crystal-poor, biotite-bearing rhyolite clasts as derived from

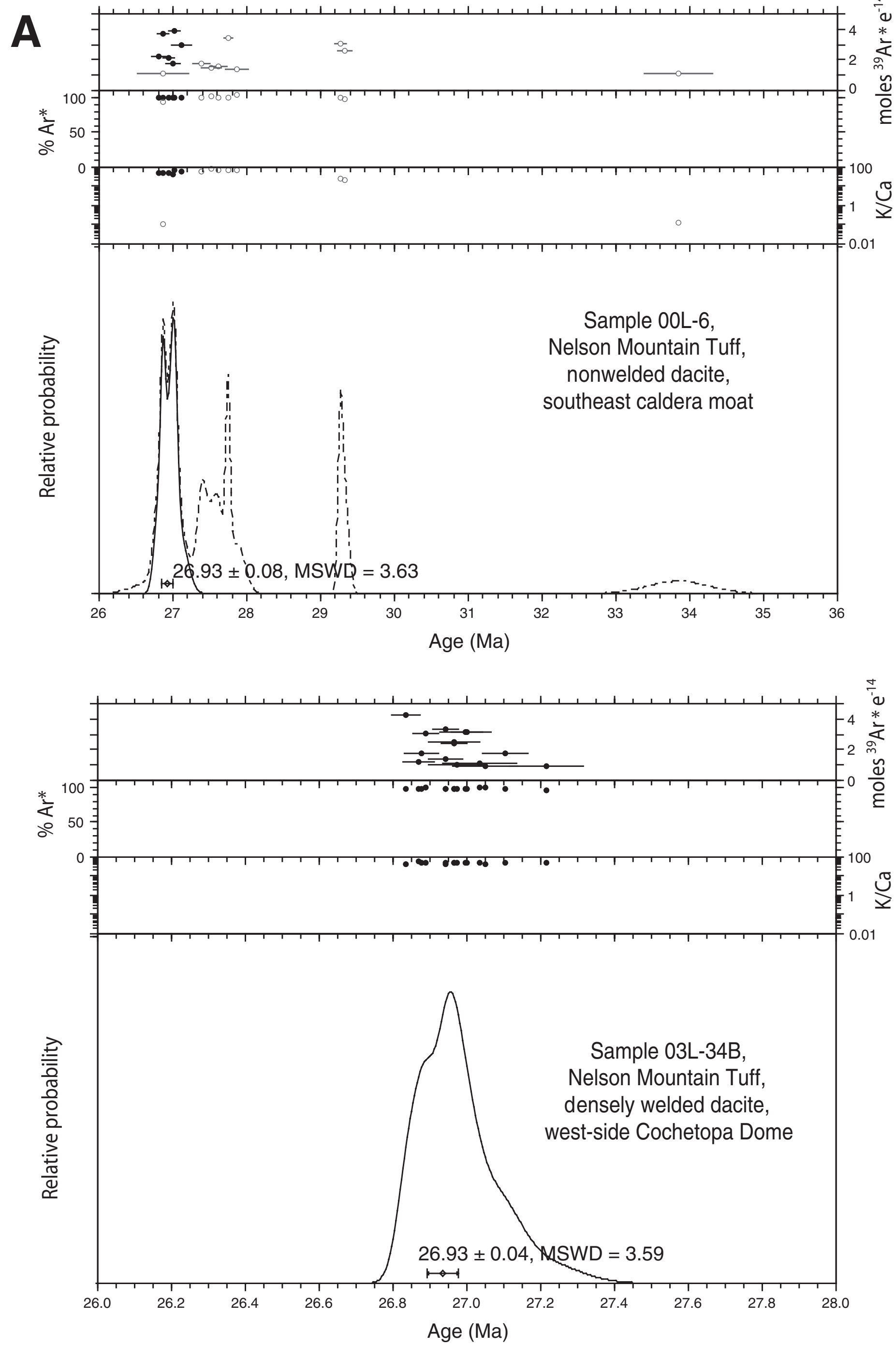

Figure 12. Examples of new age results. (A) Relative-probability diagrams for single-crystal–sanidine $^{40}Ar/^{39}Ar$ age determinations on two representative samples of Nelson Mountain Tuff; both samples are dacite from within the Cochetopa caldera (note nonuniform age scales on the *x* axis). Sample 00L-6, from the most distal nonwelded area of this unit (southeast moat of the caldera), contains abundant xenocrystic sanidine grains with variable ages. Some of these crystals have ages appropriate for the Fish Canyon and Carpenter Ridge Tuffs, both of which crop out on the caldera rims and are present as landslide breccia blocks directly beneath the Nelson Mountain sample site. Two analyzed xenocrystic grains are plagioclase, as indicated by their low K/Ca ratios. In contrast, sample 03L-34B, from densely welded dacitic tuff in a quarry on the west side of Cochetopa Dome, lacks obvious xenocrysts but yields a nearly identical age 26.93 ± 0.04 Ma. MSWD—Mean square weighted deviate. (*Continued on following page*.)

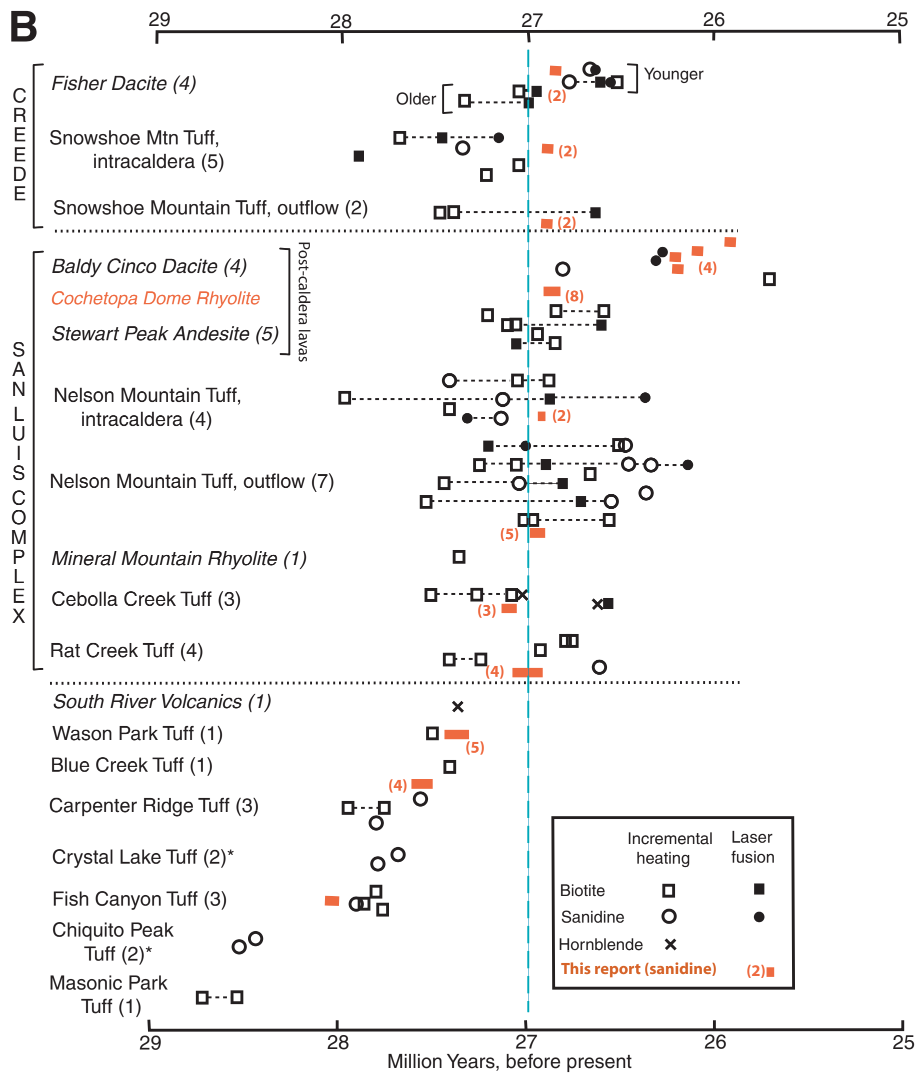

Figure 12 (*continued*). (B) Summary of $^{40}Ar/^{39}Ar$ age determinations for tuff sheets and lavas of the central San Juan region, illustrating the narrow range in ages obtained for multiple samples of individual eruptive units, in comparison to previously published results. Diagram modified from Lipman (2000, Fig. 11). Units are listed in stratigraphic order, but sequence of samples plotted for each unit is not significant. Caldera-fill lavas listed in italic type. New determinations by sanidine single-crystal laser fusion are in red; bar indicates range in age for multiple samples; number of samples in brackets; samples calibrated to Fish Canyon Tuff at 28.02 Ma. Prior ages (in black, mostly from Lanphere [1988, 2000], and M. Lanphere, 1999, personal commun.) are recalibrated to Fish Canyon Tuff at 28.02 Ma. Ages marked by asterisks are from Lipman et al. (1996) and Bove et al. (2001). Dashed horizontal lines connect phenocryst phases from single samples; numbers of separately sampled localities analyzed for each unit are listed in parentheses. Dashed vertical line (blue), at 27 Ma, provides visual guide for rapid sequence of eruptive events during San Luis and Creede caldera cycles, as documented by the new sanidine age determinations (red).

the Carpenter Ridge, rather than lithologically similar Sapinero Mesa Tuff, is critical evidence in interpreting the time of major caldera subsidence. Sanidine $^{40}Ar/^{39}Ar$ ages on two clasts from west and northeast caldera sectors are 27.59 ± 0.05 and 27.48 ± 0.05 Ma (Table 2), confirming identity as Carpenter Ridge Tuff. Some massive slide breccias of monolithologic Fish Canyon debris, characterized by closely packed clasts with little or no interstitial matrix fines, were initially considered candidates for a hot emplacement mechanism, but random paleomagnetic pole orientations of clasts for sites both on west and southeast sides of the caldera (Table 3) are inconsistent with this hypothesis. In places, distal Nelson Mountain Tuff directly overlies the landslide deposits, documenting subsidence at Cochetopa Park and rapid slump failures of the oversteepened inner walls to generate the slide breccias during eruption of this ignimbrite, before it reached distal areas of deposition.

The caldera was further filled by a thick central pile of crystal-poor high-silica lava flows (Cochetopa Park Rhyolite), surrounded by thin nonwelded pyroclastic flow deposits, airfall ash, and tuffaceous sediments (Fig. 13). These lavas, the most petrologically evolved Oligocene rhyolites in the San Juan region (Appendix 6), have $^{40}Ar/^{39}Ar$ ages (weighted mean of eight samples: 26.86 ± 0.03) that are only slightly younger than the Nelson Mountain Tuff (26.90 ± 0.02). Although subsidence is relatively modest in outer parts of the caldera, based on the floor geometry, exposures are inadequate to excluded deeper subsidence centrally within this little eroded caldera. Cochetopa Park is also the site of a large Bouguer gravity low (25–30 mgal; Plouff and Pakiser, 1972; Drenth and Keller, 2004), suggesting presence of thick low-density fill in central parts of the caldera and/or a shallow subcaldera silicic pluton.

The morphologic preservation of the Cochetopa caldera is especially striking (Figs. 3 and 13). It is among the few calderas in the Southern Rocky Mountains Volcanic Field for which the original topographic rims can still be reconstructed with confidence. Survival of the constructional geometry at Cochetopa caldera is due to a combination of: (1) late development, thereby less obscured by subsequent volcanism; (2) relatively shallow subsidence and only modest volume of postcaldera volcanism, thus never filled by dense rocks that would resist erosional excavation; (3) partial fill by weakly indurated tuffaceous sediments that have been exhumed geologically recently; and (4) presence of erosion-resistant rocks (Precambrian) at the present-day (and probable Tertiary) drainage outlet (Cochetopa Canyon) that has limited

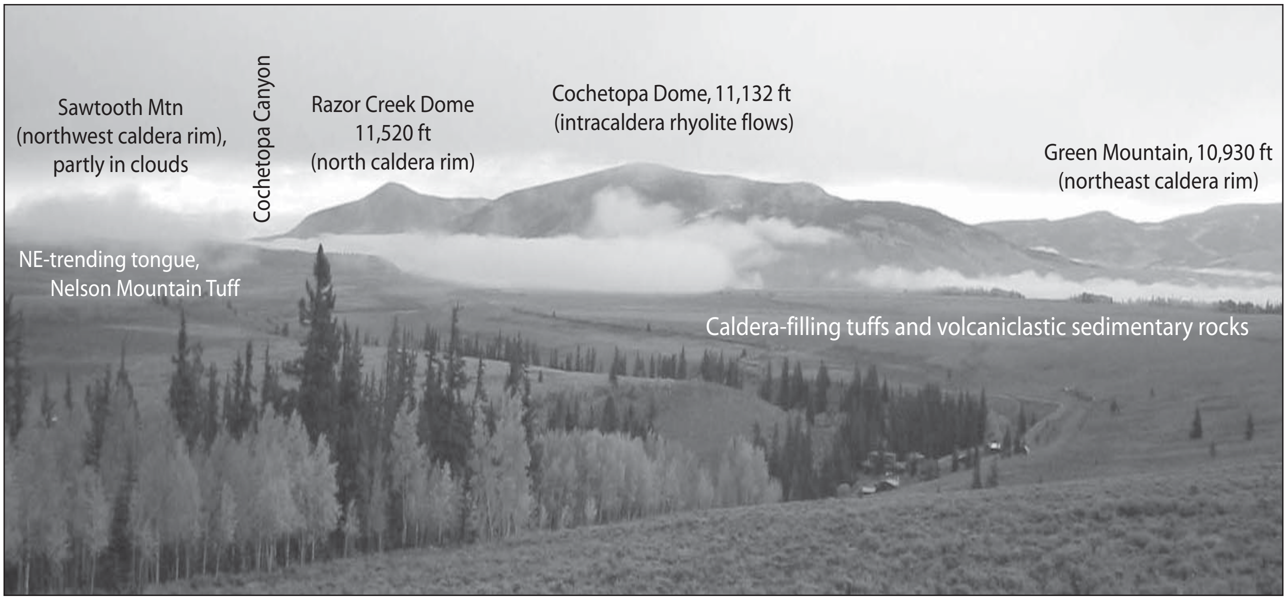

Figure 13. Panoramic view of Cochetopa Dome (sequence of rhyolitic lava flows within caldera) and north caldera walls as viewed from south. Snow-covered northwest caldera rim, at left of image, is Sawtooth Mountain (12,009 ft); northeast caldera rim is marked by Razor Creek Dome and Green Mountain on right side. Light-colored eroding outcrops in foreground are weakly indurated tuff and volcaniclastic sedimentary fill of the caldera basin.

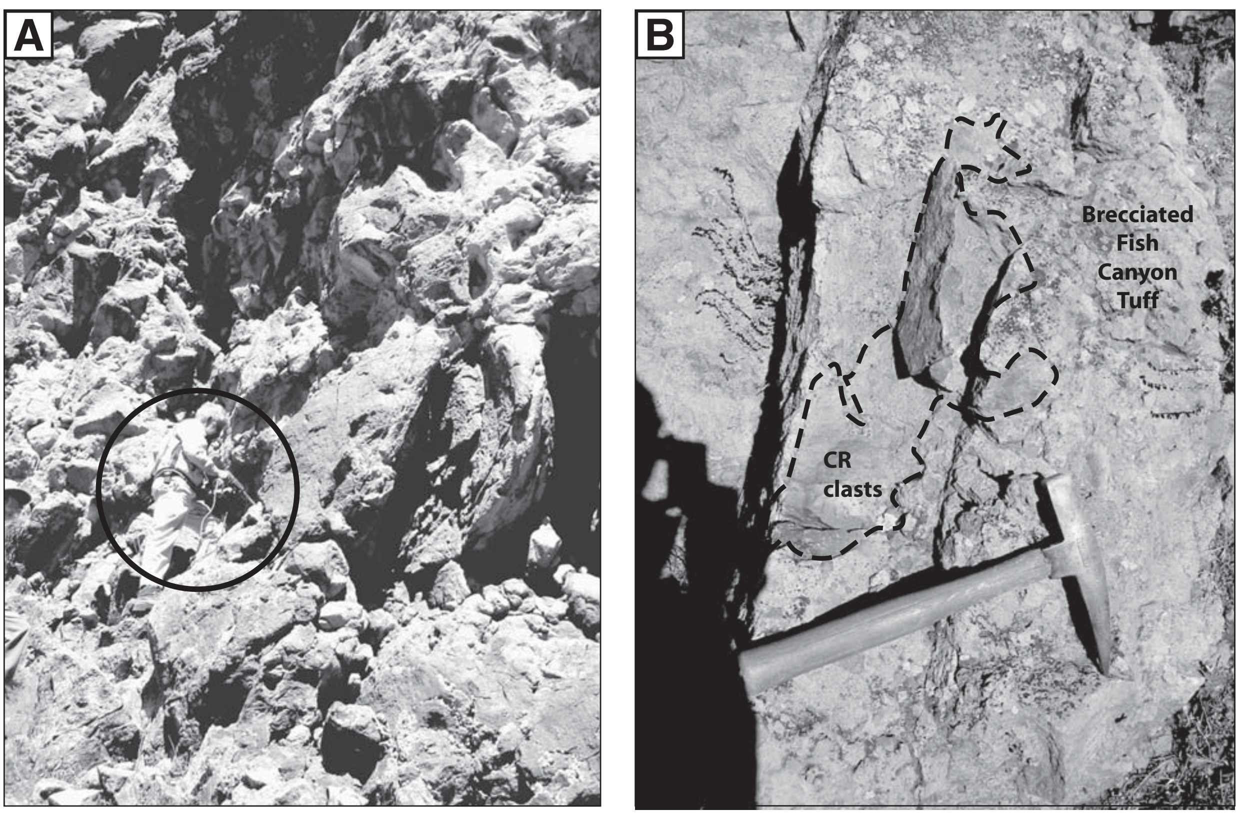

Figure 14. Photographs, landslide breccia of Fish Canyon Tuff at west margin of Cochetopa Park caldera. (A) Typical exposure of monolithologic angular to rounded clasts, framework supported, with little or no interstitial matrix. Paleomagnetic measurements at this site (NM3036, Table 3) show that the clasts were emplaced at low temperature. (B) Rare clasts of phenocryst-poor rhyolitic Carpenter Ridge Tuff (CR), intermixed with dominant Fish Canyon fragments (same site as 14A), document that landsliding was unrelated to eruption of the Fish Canyon.

downcutting and dissection of the caldera basin. The contrasting lack of morphologic expression at the North Pass caldera reflects the absence of all the factors just listed.

The time of collapse at Cochetopa Park caldera and identity of an associated regional ignimbrite has been a long-standing problem (Steven and Lipman, 1976, p. 22–25; Lipman, 2000, p. 37). Cochetopa caldera was previously interpreted as associated with eruption of the "Cochetopa Creek Tuff" (Steven and Bieniewki, 1977), but all rocks south of Cochetopa caldera formerly interpreted as "Cochetopa Creek Tuff" are now known to be Nelson Mountain Tuff (Lipman, 2000). The timing of last major subsidence is now firmly established as postdating eruption of the Fish Canyon and Carpenter Ridge Tuffs, based on clasts in the slide breccias deposited along the caldera wall, and all younger large-volume ignimbrite sheets were demonstrably erupted from vents to the south, within the central San Juan caldera cluster. As a result of these reinterpretations, no "Cochetopa Creek Tuff" or other obvious late ignimbrite sheet remains that could have had an eruptive source from the Cochetopa caldera, even though this large morphologic and structural basin clearly formed by subsidence.

As reinterpreted here, the Cochetopa Park area has been a site of recurrent structural events associated with several large eruptions, perhaps including the Luders Creek Tuff at 32.2 Ma, followed by graben formation and possible modest subsidence during Fish Canyon eruptions of the La Garita cycle at 28.0 Ma. Indicators for events associated with eruption of the Fish Canyon Tuff include: (1) formation of the NE-trending Los Pinos and parallel Cochetopa Creek grabens (Figs. 2–3) during or after eruption of the Fish Canyon Tuff, but prior to eruption of the Carpenter Ridge Tuff at 27.55 Ma (Lipman, 2000); (2) development of fault-scarp breccias in Fish Canyon Tuff where downdropped along the west margin of Cochetopa caldera, prior to emplacement of the Carpenter Ridge Tuff; (3) exceptionally thick densely welded Fish Canyon Tuff (<300 m) that is locally preserved where deposited against steep slopes along southwest and north margins of Cochetopa caldera, and in places characterized by unusual rheomorphic textures; and (4) post-Fish Canyon andesite flows northeast of Cochetopa Park, which predate the Carpenter Ridge Tuff and are analogous in stratigraphic position to the caldera-related Huerto Andesite to the south, suggesting that the Fish Canyon magmatic system extended into the northeast San Juan region. As such, the Cochetopa Park area may have been the site of a northerly fourth segment of caldera subsidence during eruption of the Fish Canyon Tuff, directly on line with the composite La Garita structure, which then would have a north-south extent of ~100 km. No deep subsidence in the Cochetopa Park area seems likely at that time, however, as indicated by the apparent absence of thick ponded Carpenter Ridge Tuff that would have been expected to accumulate within the resulting basin.

Much of the record of structural development at Cochetopa during the Fish Canyon eruptions is concealed by the sizable later subsidence event that formed most presently exposed features of the caldera basin. As interpreted here, this beautifully preserved structure owes its modern appearance largely to passive collapse during discharge of the 26.9-Ma Nelson Mountain Tuff (~500 km^3), from the "underfit" depression within the San Luis caldera complex 30 km to the southwest. Evidence is strong that the Nelson Mountain Tuff erupted from the San Luis complex (Lipman, 2000), but completely lacking for any venting from the Cochetopa area. The preserved distribution of outflow Nelson Mountain Tuff is symmetrical around the San Luis complex, while Cochetopa Park is at the northeastern distal limit of the distribution of this tuff. Intracaldera Nelson Mountain Tuff is >800 m thick, densely welded, and propylitically altered within the San Luis caldera system (Lipman, 2000), while preserved exposures of the Nelson Mountain become nonwelded and wedge out within eastern parts of Cochetopa caldera. Neither Nelson Mountain nor the earlier Fish Canyon accumulated to a multi-kilometer thickness at Cochetopa Park, nor acquired the welding and alteration features typical of intracaldera deposits within other San Juan calderas. Relatively shallow caldera collapse is also indicated by the widespread accumulation of landslide and talus breccias high along the inner caldera walls, rather than having moved farther downslope and spreading across the caldera floor as observed at more deeply subsided San Juan calderas (Lipman, 1997, 2000).

During the Nelson Mountain eruption, magma is interpreted to have moved from the Cochetopa to San Luis areas along a SW-trending dike system, expressed at the surface by the large Cochetopa graben (Fig. 15). Cochetopa Park caldera must have begun to subside before or early during eruption of the compositionally zoned Nelson Mountain Tuff (crystal-poor rhyolite to crystal-rich dacite), as evidenced by deposition of welded Nelson rhyolite within western parts of the caldera, after landslides had already been generated from oversteepened caldera walls. Such passive (noneruptive) subsidence at a site distant from associated ignimbrite vent is uncommon. Previously, such a configuration appears to have been thoroughly documented only for the much smaller 1912 eruption (~13 km^3 magma volume) from Novarupta crater in the Aleutians, where main caldera collapse was 10 km distant at Katmai volcano (Hildreth and Fierstein, 2000). Another geometrically somewhat similar analog involving linked subsidences may be the paired ignimbrites that erupted concurrently from the Rotorua and Ohakuri calderas in the Taupo zone of New Zealand (Gravley et al., 2007).

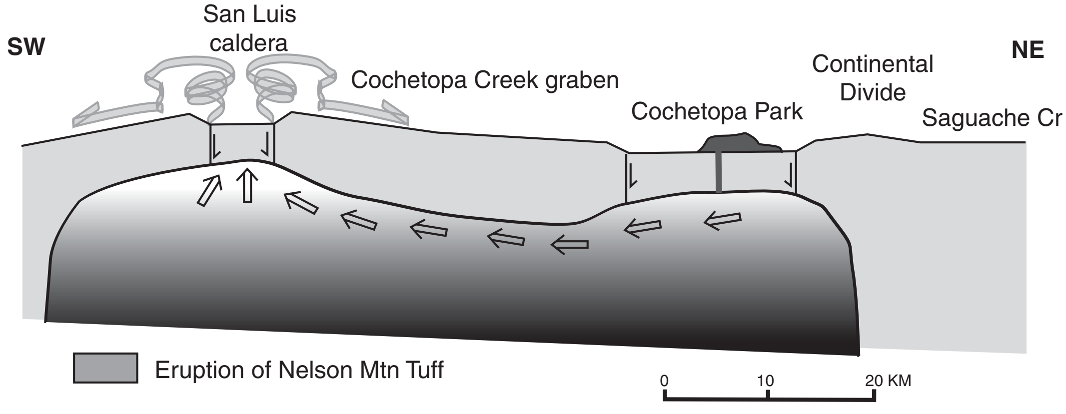

Figure 15. Interpretive model, relation between Cochetopa and Nelson Mountain subsidences, illustrating inferred southwest flow of magma from Cochetopa Park to erupt as Nelson Mountain Tuff from vents within the San Luis complex.

OVERVIEW: CALDERA STRUCTURE AND ERUPTIVE HISTORY

The interpretations developed here for the North Pass, Cochetopa Park, and San Luis caldera systems provide new insights for complexities of caldera structure in relation to eruptive history, durations, and recurrence intervals for multiple ignimbrite cycles, overall development of the composite Southern Rocky Mountains Volcanic Field, and broad comparisons with continental-margin Cordilleran volcanism elsewhere.

Caldera Structure

The three caldera systems that are the focus of this paper are strikingly different despite their spatial, age, and compositional affinities. North Pass is a relatively simple, nonresurgent ignimbrite caldera, almost completely filled by later products of the same cycle (Fig. 2, cross section). North Pass is notable in part for its history of having been overlooked during previous studies of San Juan ignimbrite volcanism, despite its location along the Continental Divide, transected by a paved state highway (Colorado Highway 114). In addition, North Pass is important as the source of the distinctively alkalic Saguache Creek Tuff, compositionally distinct from other crystal-poor rhyolite ignimbrites of the San Juan region. This caldera also provides a transition in space and time between earlier ignimbrite sources along the Sawatch trend to the north and younger calderas farther south and west in the San Juan Mountains.

In contrast, Cochetopa Park is perhaps the morphologically best preserved and among the largest caldera basins in the region, yet no sizable ignimbrite vented directly from this depression, and it appears to have subsided less deeply than other calderas of the region. Recognition that Cochetopa Park caldera subsided in response to eruption of the Nelson Mountain Tuff from a vent area 30 km to the southwest, as magma moved laterally along a fault-controlled dike system (Fig. 15), provides an example of caldera-geometry and ignimbrite-plumbing complexity on a scale previously undocumented.

Linking events at Cochetopa Park to the San Luis complex further clarifies the complex eruptive history of this polycyclic caldera system. The combined subsidence at Cochetopa Park and San Luis calderas during eruption of the Nelson Mountain Tuff accounts for the previously puzzling "underfit" subsidence in the San Luis area during this eruption. Postcollapse emplacement of the Cochetopa Rhyolite, the most highly fractionated Oligocene rocks known in the San Juan region, further expands the broad compositional diversity associated with the San Luis system, and supports interpretations from isotopic data (Riciputi et al., 1995) that these northern centers are magmatically distinct from other parts of the central caldera complex.

Overall, these new field and geochronologic results illustrate how obscure some volcanic geology can remain, even after many years of work. Prior to this study, the tuff in Saguache Creek was a large regional ignimbrite without a plausible eruptive source, and the morphologically obvious Cochetopa Park caldera had no apparent associated ignimbrite. Yet the interpretations developed here involve no link between these two prior regional "orphans"—ignimbrite and caldera. More broadly, important problems of volcanic stratigraphy and eruptive history remain undeciphered elsewhere in the San Juan region, which will only be resolved by detailed mapping and laboratory studies. As a resulting caution, detailed petrologic interpretations may go seriously astray, if eruptive units are miscorrelated and analyzed samples inadequately characterized.

Durations, Compositions, and Recurrence Intervals for Ignimbrite Caldera Cycles

The $^{40}Ar/^{39}Ar$ age determinations reported here have resolved serious inconsistencies in prior geochronologic results for ignimbrite volcanism in the San Juan region, as well as providing greatly improved constraints on remarkably brief durations for some individual caldera cycles (Fig. 12B).

The single-crystal sanidine ^{40}Ar-^{39}Ar dates show that all phases of the North Pass cycle, including the Saguache Creek Tuff, postcaldera lavas, and the late Luders Creek Tuff, erupted between 32.25 ± 0.05 and 32.17 ± 0.04 Ma, an interval too brief to resolve, but probably less than 100 k.y. In contrast, during the subsequent 4 m.y., volcanism was relatively quiescent within the North Pass area, limited to small andesite lavas at ca. 30 Ma, and erosion was subdued. In many places the 28-Ma Fish Canyon Tuff rests directly on Saguache Creek Tuff, with only a few meters of intervening fluvial deposits.

In addition, the new age results provide tight constraints on late eruptions from calderas in the central San Juan cluster: four multi-hundred, cubic-kilometer ignimbrites and associated lavas flows of diverse compositions erupted from the San Luis and Creede caldera areas at 26.9 Ma. The tight recurrence interval was not evident from previous incremental-heating $^{40}Ar/^{39}Ar$ plateau ages, which were stratigraphically inconsistent on time scales beyond analytical precision (Fig. 12B; also Lipman, 2000, Fig. 11, and discussion therein). The new single-crystal sanidine results show that three of these tuff sheets, Rat Creek (>150 km^3), Cebolla Creek (>250 km^3), and Nelson Mountain Tuffs Creek (>500 km^3) erupted from spatially overlapping sources in the San Luis caldera complex, between 26.91 ± 0.02 (weighted mean of eight Rat Creek samples; 195 sanidine fusions) and 26.90 ± 0.03 Ma (ten Nelson Mountain samples; 129 sanidine fusions). These three large-volume ignimbrites, along with diverse interlayered lava sequences, thus appear to have erupted and associated calderas subsided within an interval of 50–100 k.y. or less. A sequence of four early-postcollapse rhyolitic lavas and associated tuffs at Cochetopa Park erupted within ~50 k.y., at 26.86 ± 0.03 Ma (eight samples), while an andesitic stratocone grew within the San Luis caldera complex. Soon after the ignimbrites from San Luis sources, Snowshoe Mountain Tuff (>500 km^3) erupted from the Creede caldera, 20 km to the south, at 26.87 ± 0.02 Ma (5 samples), and caldera-filling lavas accumulated within 100 k.y. Within these limited time intervals, eruptive compositions fluctuated widely. Rat Creek and Nelson Mountain Tuffs are compositionally zoned from crystal-poor low-Si rhyolite to clinopyroxene-bearing dacite, while the intervening Cebolla Creek Tuff is uniform mafic hornblende-rich dacite. Lavas ponded within calderas of the San Luis complex vary from andesite to low-Si rhyolite, while Cochetopa Dome lavas are nearly aphyric high-Si rhyolite.

Comparably brief recurrence intervals seemingly have been documented elsewhere only for less voluminous ignimbrite sequences. Smaller volume younger examples include four ignimbrites with a cumulative volume of 300 km^3 from Aso caldera in southern Japan, erupted at 270, 140, 120, and 90 ka (Nakada et al., 2003). Four overlapping caldera collapses at Santorini in the Aegean were each associated with silicic tuff with volumes of several tens of kilometers, at 203, ~100, 21, and 3.6 ka (Druitt, 1999). In contrast, larger "super-eruption" systems in the western USA, such as Yellowstone, had repose periods of 0.5–1 m.y., even when erupted compositions were uniform rhyolite. The more rapid sequential eruptions of large-volume compositionally diverse tuffs and lavas in the San Juan region document that repose periods between "super eruptions" can be shorter than previously recognized and that compositions of voluminous subcaldera magma systems can evolve remarkably rapidly.

Magma Compositions

Overall, the San Juan region is a high-K province of broadly calc-alkaline character (Appendix 6), similar to Tertiary volcanic rocks in adjacent segments of the eastern Cordillera of North America and interior portions of continental-margin arcs elsewhere (Lipman et al., 1978; Dungan et al., 1989; Riciputi et al., 1995; Chapin et al., 2004; de Silva and Gosnold, 2007). Major-element compositions of successive ignimbrites and associated caldera-related lava flows in the San Juan region are relatively constant at any specified fractionation level (proxied by SiO_2 content), but trace elements vary more widely among eruption cycles in northern areas (Fig. 6). In comparison to most ignimbrites and lavas from the central caldera cluster (Lipman, 2004), volcanic rocks of the northeast San Juan region (Bonanza and North Pass cycles) are modestly more alkalic (higher total alkalis and incompatible elements such as Ba, Zr, and light REE; lower in Sr). The more alkalic character of these northeastern San Juan caldera systems is shared by regional lavas unrelated to any local caldera cycle, such as the flows of Huerto Andesite; these are also relatively alkalic, distinct from lavas at the same stratigraphic level in southern parts of the La Garita caldera (Parat et al., 2005). At the San Luis complex, rocks of the Rat Creek cycle contain higher Ba and Zr than the subsequent Cebolla Creek and Nelson Mountain cycles, seemingly recording presence of both northeastern and central magma compositions during early magma evolution at this rapidly erupting polycyclic caldera complex.

COMPARISONS WITH CORDILLERAN IGNIMBRITE VOLCANISM ELSEWHERE

The calderas of the northeastern San Juan Mountains provide a critical link between earlier ignimbrite eruptions from sources along the Sawatch Range to the north and younger loci of silicic volcanism farther south and west within the San Juan region and into northern New Mexico (Fig. 16). Together these large ignimbrite calderas define a magmatic progression of large-scale explosive volcanism southward through the Southern Rocky Mountains Volcanic Field from 38 to 26 Ma, on a scale comparable in size to other Cenozoic volcanic segments in the Tertiary Cordilleran magmatic belt of the Americas.

Although located along the eastern margin of the broad U.S. Cordillera, the Southern Rocky Mountains Volcanic Field is similar in composition and eruptive history to mid-Tertiary volcanism farther west in the Basin-Range province (Stewart and Carlson, 1976; Lipman, 1992). The Southern Rocky Mountains Volcanic Field was one locus of discontinuous middle Tertiary magmatism, continuing southward through the Mogollon-Datil region, west-central New Mexico (Chapin and others., 2004), into Trans-Pecos, Texas (Henry and Price, 1984), and the vast Sierra Madre Occidental of northern Mexico (McDowell and Clabaugh, 1979). Both the Southern Rocky Mountains Volcanic Field and Basin-Range volcanic centers (Stewart and Carlson, 1976) define concurrent southward progressions of eruptive centers during mid-Tertiary time, requiring a common large-scale tectonic control, most likely evolving plate-boundary conditions along the west margin of the American plate (Lipman, 1992). Throughout the western USA, the mid-Tertiary magmatic flare-up appears triggered by a time-transgressive regional transition from low-angle plate convergence to an increasingly extensional stress regime, with peak volcanism largely preceding the bulk of extension (Lipman et al., 1970; Coney and Reynolds, 1977; Chapin et al., 2004),

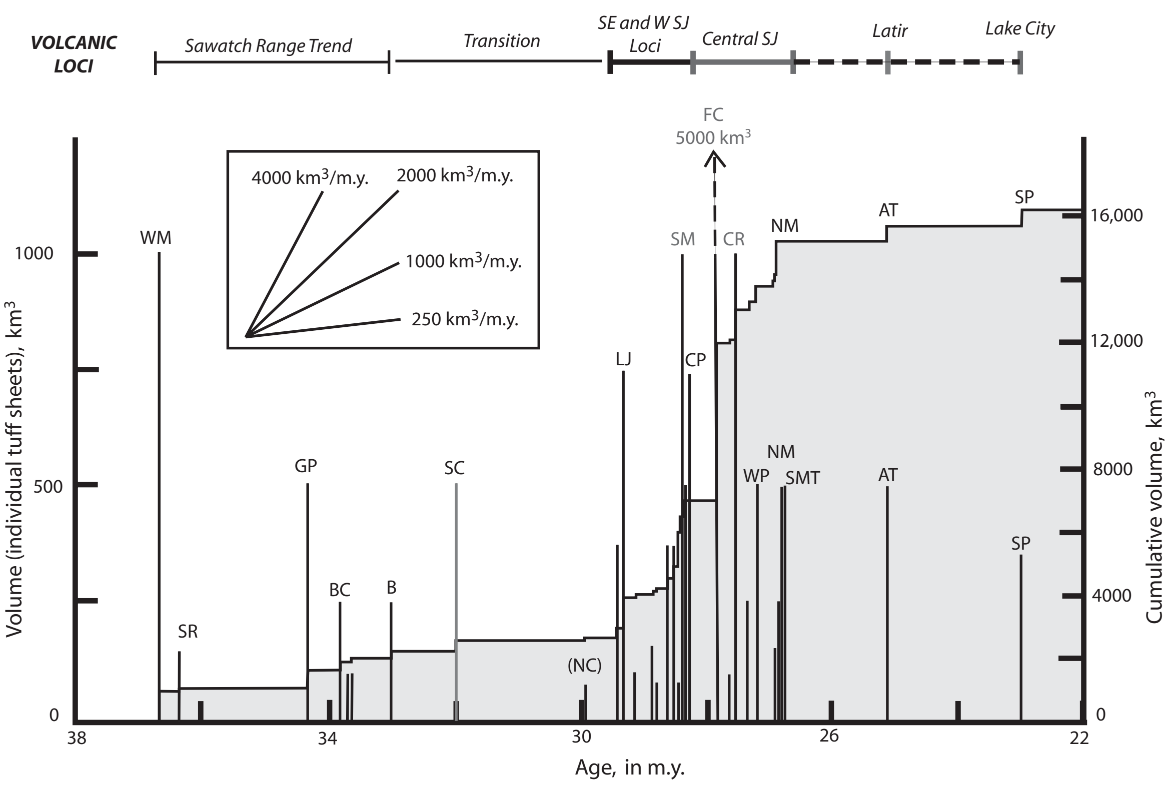

Figure 16. Age-distance-volume plot, southward progression of Tertiary ignimbrite-caldera volcanism, Southern Rocky Mountains Volcanic Field (SRMVF). Abbreviations: AT—Amalia Tuff; B—Bonanza Tuff; BC—Badger Creek Tuff; CP—Chiquito Peak Tuff; CR—Carpenter Ridge Tuff; FC—Fish Canyon Tuff; GP—Grizzly Peak Tuff; LJ—La Jara Canyon Tuff; NC—Needle Creek flow field; NM—Nelson Mountain Tuff; SC—Saguache Creek Tuff; SJ—San Juan; SM—Sapinero Mesa Tuff; SMT—Snowshoe Mountain Tuff; SP—Sunshine Peak Tuff; SR—Tuff of Stirrup Ranch; WM—Wall Mountain Tuff; WP—Wason Park Tuff.

Additionally, in eruptive processes, volcanic compositions, areal extent, duration of activity, and magmatic production rates and volumes, the Southern Rocky Mountains Volcanic Field represents present-day erosional remnants of a composite silicic volcanic field, originally comparable to younger ignimbrite terranes of the central Andes (Table 4), such as the well-documented Altiplano-Puna Volcanic Complex (de Silva, 1989; Lindsay et al., 2001; Schmitt et al., 2003; Zandt et al., 2003; de Silva et al., 2006; de Silva and Gosnold, 2007). Both areas involved eruption of numerous dacite to rhyolite ignimbrites with volumes of >100 km^3 (~30 in the Southern Rocky Mountains Volcanic Field, at least 15 in Altiplano-Puna Volcanic Complex). In both terranes, volumes of individual ignimbrite sheets are as much as several thousand cubic kilometers, and some are compositionally zoned. Some calderas in both regions were polycyclic, with the largest caldera sources 50 km or more across. Area covered in both regions is on the order of 70,000–100,000 km^2, during eruptive activity of ~10 m.y. duration (37–26 Ma in the Southern Rocky Mountains Volcanic Field and 10–1 Ma in the Altiplano-Puna Volcanic Complex). Cumulative magmatic volume of ignimbrites is ~15,000 km^3 for the Southern Rocky Mountains Volcanic Field, ~12,000 km^3 for the Altiplano-Puna Volcanic Complex, and estimated peak magma-production rates are as high as 8000 km^3/m.y. for both regions. Calderas in both areas are associated with precaldera and postcaldera andesitic to dacitic lava eruptions, although the pre-ignimbrite volcanism in the Altiplano-Puna Volcanic Complex is less well known because of smaller amounts of postvolcanic erosion in this younger region. The calderas and other magmatic centers of both areas lie within regional gravity lows that suggest the subvolcanic growth of upper crustal composite batholiths is associated with the silicic volcanism. Both the Altiplano-Puna Volcanic Complex and the Southern Rocky Mountains Volcanic Field lie along the east margins of broad, long-lived Cordilleran magmatotectonic zones, associated with plate convergence and low-angle subduction. The Altiplano-Puna Volcanic Complex is associated with a regional seismic anomaly interpreted as indicating the presence of partial melt in the middle crust; any comparable feature(s) are no longer present beneath the Southern Rocky Mountains Volcanic Field, plausibly because of its greater age.

TABLE 4. SUMMARY FEATURES OF SOUTHERN ROCKY MOUNTAIN VOLCANIC FIELD (SRMVF) IN COMPARISON WITH ALTIPLANO-PUNA VOLCANIC COMPLEX (APVC)*

	SRMVF	APVC
Original area, volcanic rocks	~100,000 km^2	~70,000 km^2
Ignimbrites (>100 km^3)	30 eruptions	15 eruptions
Duration, ignimbrite eruptions	37.6–26.9 Ma	10.2–ca. 1 Ma
Magmatic volume (DRE), ignimbrites	~15,000 km^3	~12,000 km^3
Maximum volume (DRE), individual ignimbrite	>5000 km^3	2200 km^3
Peak ignimbrite extrusion rate	8000 km^3/m.y.	12,000 km^3/m.y.
Maximum dimension, source caldera	75 km	60 km
Ignimbrite compositions	Dacite-rhyolite	Mainly dacite
Precaldera volcanism	Mainly andesite	Andesite
Ratio, precaldera and ignimbrite volcanism	~2:1, by volume	Unknown in detail; <<1:1
Postcaldera volcanism	Andesite-rhyolite	Mainly dacite
Subvolcanic intrusions	Mainly granodiorite	(None exposed)
Geophysical expression		
Negative gravity anomaly	-60 mgal, shallow	-60 mgal, no depth estimate
Seismic attenuation (melt)	(Nonpreserved)	Partial melt, mid-crust

*Data from Lipman (2007) and de Silva and Gosnold (2007) and references therein.
DRE—dense rock equivalent.

In comparison with the Altiplano-Puna Volcanic Complex and similar areas elsewhere in the American Cordillera, the Southern Rocky Mountains have certain advantages for studies of continental-arc volcanism. Structural complexity is substantially less than that associated with severe late Cenozoic extension farther west in the Basin-Range, because much of the Southern Rocky Mountains Volcanic Field, especially the San Juan region, overlies little deformed strata of the Colorado Plateau. In addition, the rugged topographic and erosional relief of the most elevated region in the USA, coupled with structural exposure of diverse upper crustal levels along Rio Grande rift faults, provide outcrop exposures ranging from morphologically virtually intact volcanic edifices in parts of the San Juan region to deep within upper crustal plutons along the fault-bounded Sawatch and Latir range fronts. The areal extent, eruptive volume, and compositional diversity of preserved volcanic deposits formed with a limited time span in the Southern Rocky Mountains Volcanic Field, including at least 30 ignimbrite calderas characterized by varied geometries and eruption histories, provide exceptional opportunities to compare and contrast diverse volcanic processes associated with upper crustal Cordilleran magmatism. The new results reported here for the northeastern San Juans illustrate how much remains to be learned from this much-studied volcanic region.

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