Incremental assembly and prolonged consolidation of Cordilleran magma chambers: Evidence from the Southern Rocky Mountain volcanic field

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ABSTRACT

Recent inference that Mesozoic Cordilleran plutons grew incrementally during $>10^6$ yr intervals, without the presence of voluminous eruptible magma at any stage, minimizes close associations with large ignimbrite calderas. Alternatively, Tertiary ignimbrites in the Rocky Mountains and elsewhere, with volumes of $1–5 \times 10^3$ km³, record multistage histories of magma accumulation, fractionation, and solidification in upper parts of large subvolcanic plutons that were sufficiently liquid to erupt. Individual calderas, up to 75 km across with 2–5 km subsidence, are direct evidence for shallow magma bodies comparable to the largest granitic plutons. As exemplified by the composite Southern Rocky Mountain volcanic field (here summarized comprehensively for the first time), which is comparable in areal extent, magma composition, eruptive volume, and duration to continental-margin volcanism of the central Andes, nested calderas that erupted compositionally diverse tuffs document deep composite subsidence and rapid evolution in subvolcanic magma bodies. Spacing of Tertiary calderas at distances of tens to hundreds of kilometers is comparable to Mesozoic Cordilleran pluton spacing. Downwind ash in eastern Cordilleran sediments records large-scale explosive volcanism concurrent with Mesozoic batholith growth. Mineral fabrics and gradients indicate unified flowage of many pluton interiors before complete solidification, and some plutons contain ring dikes or other textural evidence for roof subsidence. Geophysical data show that low-density upper-crustal rocks, inferred to be plutons, are 10 km or more thick beneath many calderas. Most ignimbrites are more evolved than associated plutons; evidence that the subcaldera chambers retained voluminous residua from fractionation. Initial incre-

mental pluton growth in the upper crust was likely recorded by modest eruptions from central volcanes; preparation for caldera-scale ignimbrite eruption involved recurrent magma input and homogenization high in the chamber. Some eroded calderas expose shallow granites of similar age and composition to tuffs, recording sustained postcaldera magmatism.

Plutons thus provide an integrated record of prolonged magmatic evolution, while volcanism offers snapshots of conditions at early stages. Growth of subvolcanic batholiths involved sustained multistage open-system processes. These commonly involved ignimbrite eruptions at times of peak power input, but assembly and consolidation processes continued at diminishing rates long after peak volcanism. Some evidence cited for early incremental pluton assembly more likely records late events during or after volcanism. Contrasts between relatively primitive arc systems dominated by andesitic compositions and small upper-crustal plutons versus more silicic volcanic fields and associated batholiths probably reflect intertwined contrasts in crustal thickness and magmatic power input. Lower power input would lead to a Cascade- or Aleutian-type arc system, where intermediate-composition magma erupts directly from middle- and lower-crustal storage without development of large shallow plutons. Andean and southern Rocky Mountain–type systems begin similarly with intermediate-composition volcanism, but increasing magma production, perhaps triggered by abrupt changes in plate boundaries, leads to development of larger upper-crustal reservoirs, more silicic compositions, large ignimbrites, and batholiths. Lack of geophysical evidence for voluminous eruptible magma beneath young calderas suggests that near-solidus plutons can be rejuvenated rapidly by high-temperature mafic recharge, potentially causing large explosive eruptions with only brief precursors.

INTRODUCTION

Surface volcanoes and upper-crustal plutons in diverse geologic settings tend to share common features of mineral and chemical composition, emplacement age, and magmatic volume. Especially since the mid-twentieth century recognition of voluminous silicic ignimbrites associated with caldera sources as widespread components of U.S. Cordilleran volcanic fields (e.g., Ross and Smith, 1961; Steven and Ratté, 1965; Elston, 1984), such volcanism has been broadly interpreted as the surface manifestation of large-scale magmatism concurrent with growth of composite subvolcanic batholiths (Buddington, 1959; Smith, 1960; Hamilton and Myers, 1967; Lipman et al., 1978; Hildreth, 1981; Lipman, 1984, 1992; Macdonald and Smith, 1988; Miller and Miller, 2002; Metcalf, 2005; Bachmann et al., 2007a).

Alternatively, some recent field and geochronologic studies have suggested that individual Mesozoic Cordilleran plutons grew and solidified incrementally in small batches during $>10^6$ yr intervals, without the presence of voluminous eruptible magma ("large tank") at any stage during pluton growth and batholith assembly (Glazner et al., 2004; Coleman et al., 2004; Bartley et al., 2005; Glazner et al., 2006). Such growth of plutons in small increments would minimize any close associations with large ignimbrite calderas and suggest that batholith growth is largely unrelated to surface volcanism. Linked to these interpretations are inferences that ignimbrite eruptions record ephemeral magma chambers that (1) grow rapidly due to exceptionally high magmatic power input to the upper crust, (2) evacuate nearly completely during ignimbrite eruption, and (3) leave little geologic record in the form of crystallized crustal plutons. Such relations between ignimbrite volcanism and short-lived source chambers are presented as alternative processes, unrelated

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to sustained incremental pluton emplacement as the dominant process in assembly of Cordilleran batholiths (Glazner et al., 2004, their Fig. 6; Bartley et al., 2005). As such, these interpretations represent something of a return to inferences that volcanism and plutonism involve fundamentally different evolutionary processes (e.g., Read, 1957; Marsh, 1988, 1990).

How to reconcile such alternatives? Large continental Cenozoic volcanic fields, such as those in the Southern Rocky Mountains where high topography and deep erosion expose internal structures of volcanic centers and subvolcanic plutons (Steven and Lipman, 1976; Lipman et al., 1978; Johnson et al., 1989), provide time-space-composition evidence for broadly unified evolution of upper-crustal magma systems in a Cordilleran setting. Such perspectives help merge clear evidence for incremental pluton assembly with that for the presence of large eruptible chambers during peak magmatic input. The emphasis here is on mapped eruptive sequences, compositional progressions, structural and geometric relations between calderas and plutons, and geochronologic controls on magmatic longevity and repose intervals at large ignimbrite centers presented in the broad context of petrogenetic, thermal, and geophysical modeling by others.

This report summarizes growth histories of Cenozoic volcanic fields (with primary reference to the mid-Tertiary of the Southern Rocky Mountains), compares them with Mesozoic Cordilleran batholiths, and proposes an integrated volcano-plutonic model for incremental assembly and prolonged consolidation of large silicic magma chambers. The overall Southern Rocky Mountain volcanic field (SRMVF), described synoptically for the first time early in this report as a prime example of batholith-related volcanism, has previously been generally studied as separate erosionally dismembered volcanic areas, rather than as a unified Cordilleran magmatic feature comparable in scale to younger Andean continental-margin volcanism. Readers interested primarily in magma-chamber evolution and batholith development may prefer, however, to go directly to the section "An Integrated Volcano-Plutonic Model," which attempts to reconcile evidence for incremental pluton assembly with that for associated large-volume volcanism.

PROLONGED GROWTH OF VOLCANIC FIELDS: RECORD OF INCREMENTAL MAGMA-CHAMBER ASSEMBLY?

Large calc-alkaline volcanic fields in the western United States, especially those containing ignimbrite-caldera episodes, commonly contain compositionally diverse products erupted over multimillion-year intervals. A typical pattern involves initial eruption of intermediate-composition lavas from central volcanoes, followed by one or more large ignimbrites of more silicic composition; concurrent caldera subsidence is central within the area of prior lava vents (e.g., Lipman et al., 1970; Elston, 1984; Steven et al., 1984). Mineralogical, chemical, and isotopic diversity in the erupted deposits records recurrent complex processes of crystal fractionation, crustal assimilation, recurrent open-system recharge by mantle-derived mafic magmas, and magma mixing. Postignimbrite magmatism, including lavas erupted within or adjacent to the caldera, and in some instances as resurgent uplift of the caldera floor, provides a surface record of continued evolution in the subvolcanic chamber. Such progressions of surface volcanism have been widely interpreted as providing instantaneous sequential snapshots of changing magma-chamber process through time. In contrast, subvolcanic plutons exposed in deeply eroded volcanic fields or older igneous terranes represent the time-integrated and partly homogenized end products of sequential eruptive events as successive magmatic pulses accumulated, fractionated, and consolidated in the upper crust (Hamilton and Myers, 1967; Lipman, 1984, 1992; Metcalf, 2005).

Relatively small young ignimbrite systems, such as Crater Lake in Oregon and the Jemez field in New Mexico, provide high-resolution age and petrologic records for growth of such upper-crustal systems. Crater Lake (Bacon, 1983, 1992; Bacon and Druitt, 1988) has been active since at least 420 ka (Bacon and Lanphere, 2006), and pluton growth in the subvolcanic magma chamber is recorded by granitoids with zircon ages of 30–200 ka, erupted as xenolithic clasts during the 7.7 ka ignimbrite eruption (Bacon et al., 2000; Bacon and Lowenstern, 2005).

Larger in scale but similar in evolution is the late Cenozoic Jemez field, where eruption of basalt to rhyolite lavas commencing ca. 13 Ma constructed a composite volcanic field with an area of ~3000 km^2 and volume on the order of 750 km^3 (Smith and Bailey, 1968; Goff et al., 1989; Self et al., 1996). Eruptive activity peaked with emplacement of crystal-poor ignimbrites (Bandelier Tuff) and collapse of the Valles caldera at 1.6 and again at 1.3 Ma; each ignimbrite has a magmatic volume of ~300 km^3. Despite low crystal contents of the tuffs, mass-balance calculations for trace-element fractionation suggest that 40%–50% of the total magma volume remained in the source reservoir as crystal-rich residue (Stix et al., 1988; Hervig and Dunbar, 1992). Caldera collapse during emplacement of the 1.3 Ma ignimbrite was followed by resurgent uplift of the caldera floor and eruption of nearly aphyric rhyolite domes and tuffs as recently as 50–60 ka. The duration of precursor volcanism (an order of magnitude longer than at Crater Lake), the compositionally diverse products, and the intermittent eruption of relatively primitive mantle-derived basalt interspersed with evolved rhyolite all point to repeated open-system evolution of a growing upper-crustal magma reservoir over a multimillion-year period, preparatory to ignimbrite eruptions during peak magma input. A –35 mgal Bouguer gravity low centered on the caldera (Goff et al., 1989) and seismic-wave delays (Steck et al., 1998) are consistent with the presence of an upper-crustal silicic intrusion of low-density hot material beneath the caldera but little or no remaining melt. Nevertheless, the resurgent uplift, prolonged postcollapse intracaldera volcanism, and geothermal activity indicate late magmatic evolution in the subvolcanic chamber continuing to the present, 1.3 m.y. after the last caldera subsidence.

Older larger ignimbrite centers in the Southern Rocky Mountains, where subvolcanic intrusions are accessible in surface exposure, are here considered to offer particularly informative geometric and temporal analogs for pluton evolution in composite batholiths such as the Mesozoic Sierra Nevada of California and elsewhere along the western Cordillera. Although relatively distant from the plate margin, such eastern Cordilleran volcanism is closely similar in rock composition, areal extent and volume, and eruptive duration to the type continental-margin volcanism of the central Andes (Lipman et al., 1978; Johnson et al., 1990; Chapin et al., 2004). Accordingly, the previously incompletely documented age-composition-volume progression of Tertiary volcanism in the Southern Rocky Mountains is summarized here, augmented by new data, to provide a factual framework for interpreting connections between large-scale silicic volcanism, magma-chamber evolution, and pluton consolidation.

LARGE-VOLUME IGNIMBRITE VOLCANISM: COMPOSITE SOUTHERN ROCKY MOUNTAIN VOLCANIC FIELD

Exemplifying ignimbrite volcanism on a much larger scale, comparable in size to other Cenozoic volcanic segments of the Cordilleran magmatic belt, is the composite mid-Tertiary volcanic field of the SRMVF in Colorado and northern New Mexico (Fig. 1). From 38 to 23 Ma, this region of ~100,000 km^2, which had been the site of Precambrian-cored uplifts that formed the Southern Rocky Mountains in Late Cretaceous to early Tertiary time, was blanketed by thick volcanic sequences erupted
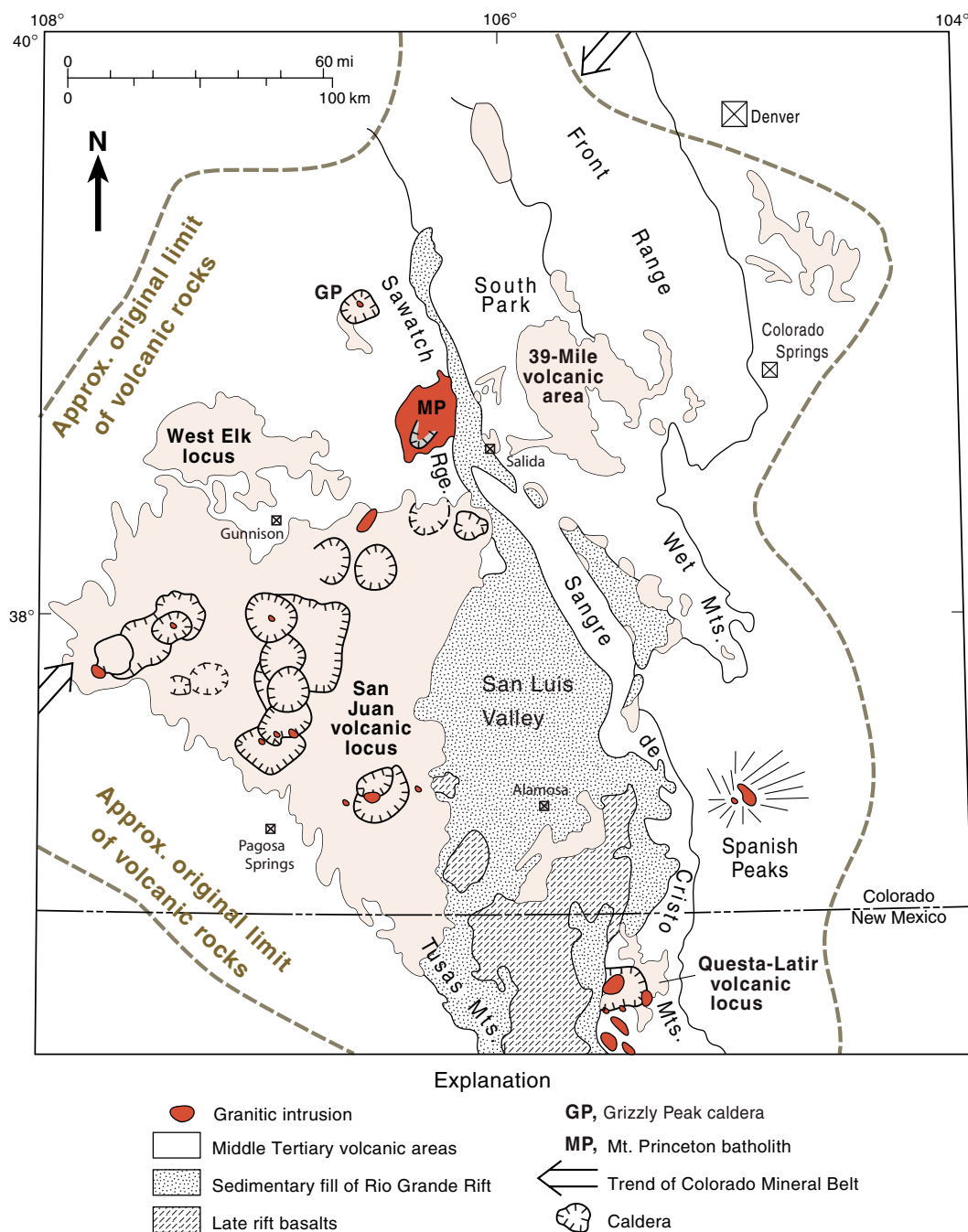
Figure 1. Map of Southern Rocky Mountain volcanic field, showing ignimbrite calderas, major erosional remnants, and inferred original extent of once nearly continuous mid-Tertiary volcanic cover, caldera-related granitic intrusions, and later Tertiary sedimentary fill of the Rio Grande rift zone. Arrows indicate trend of Late Cretaceous–early Tertiary (Laramide) intrusions of the Colorado Mineral Belt. Map was modified from McIntosh and Chapin (2004); inferred original limit of volcanic rocks from Steven (1975); and intrusions from Tweto (1979) and Lipman (1988, 2000).

from multiple centers (Steven, 1975; McIntosh and Chapin, 2004), including 30 large-volume regional ignimbrites and associated calderas (Table 1). The SRMVF was one locus of discontinuous middle Tertiary Cordilleran magmatism that continued southward through the Mogollon-Datil region, west-central New Mexico (Elston, 1984; Ratté et al., 1984), into Trans-Pecos, Texas (Henry and Price, 1984) and the vast Sierra Madre Occidental of northern Mexico (McDowell and Clabaugh, 1979). Subareas of the SRMVF, now separated by later Cenozoic erosion, have thus far commonly been described as multiple separate volcanic fields (San Juan, Sawatch, Thirtynine Mile, Latir, West Elk, Central Colorado, etc.). Alternatively, as previously suggested by Steven (1975), these volcanic loci can be more appropriately viewed as present-day erosional remnants of a much larger composite silicic volcanic field, originally comparable in size, composition, and magmatic duration to younger ignimbrite terranes such as the well-documented Altiplano-Puna volcanic complex of the central Andes (de Silva, 1989; Lindsay et al., 2001; Schmitt et al., 2003; de Silva et al., 2007; de Silva and Gosnold, 2007).

Although located along the eastern margin of the broad U.S. Cordillera, the SRMVF is similar in composition and eruptive history to mid-Tertiary volcanism farther west in the Basin and Range and elsewhere along the Pacific margin of the Western Hemisphere. Throughout the western United States, the mid-Tertiary magmatic flare-up appears to have been triggered by regional transition from low-angle plate convergence to an increasingly extensional regime,

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TABLE 1. REGIONAL IGNIMBRITES AND CALDERAS OF THE SOUTHERN ROCKY MOUNTAIN VOLCANIC FIELD

Site / Name	Ignimbrite SiO₂ (%)	Rock, phenocrysts	Vol. (km³)	Age (Ma)	Caldera Name	Area (km)	Precursor volcanism Composition	Age (Ma)	Postcaldera magmatism Volcanics	Intrusions	Age (Ma)	Vol. best estimate	Cumul. vol.
West San Juan (SJ) Mountains													
Sunshine Peak	Zoned, 76–68	Qtz, sodic san	200–500	23.0	Lake City	15 x 18	(Uncompahgre caldera)	28	Dacite lava flows	syenite-granodiorite	23–18	350	15,950
Latir Mountains, NM													
Amalia	76–77	Peralk: qtz, sodic san	500	25.1	Questa	14 x >15	Andesite-dacite	30–25	(eroded)	Granite-q.m.	25–18	500	15,600
Central San Juan San Luis complex													
Snowshoe Mtn	62–66	Xl-rich dacite	>500	26.9	Creede	20 x 25	(older calderas)	27.3–27.5	Fisher Dacite	(resurg., no exposure)	26.2–26.7	500	15,100
Nelson Mountain	Zoned 74–63	Xp rhy; xl dacite	>500	26.9	San Luis–Cochetopa	9 x 9, 20 x 25	Mineral Mtn Rhyolite	26.9	Andesite lava flows	Granodiorite	25–26.8	500	14,600
Cebolla Creek	61–64	Xl dacite, hbl, no san	250	26.9	San Luis complex	14 x 16	Andesite-dacite	26.9	Mineral Mtn Rhy.	(none exposed)	26.9	250	14,100
Rat Creek	Zoned 74–65	Xp rhy-xl dacite	150	26.9	San Luis complex	9 x 12	Andesite-dacite	27	Andesite-dacite	(none exposed)	26.9	150	13,850
Central San Juan cluster													
Wason Park	Zoned 72–63	Xl rhyolite-xl dacite	>500	27.2	South River	20 x 20	(La Garita caldera)	27.8	Andesite-dacite	Granodiorite	27.8–?	500	13,700
Blue Creek	64–66	Xl dacite, no san	250	27.3	[concealed]	—	(Bachelor caldera)	27.5	Andesite-dacite	(none exposed)	27.3	250	13,200
Carpenter Ridge	Zoned, 74–66	Xp rhy-xl dacite	>1000	27.5	Bachelor	25 x 30	Huerto Andesite	27.5–27.8	Dacite flow	(none exposed)	~27.3	1000	12,950
W San Juan													
Crystal Lake	72–74	Xp rhyolite	50–100	27.6	Silverton	20 x 20	Andesite-dacite	27.6–28.3	(eroded)	Granodiorite	27	75	11,950
Central San Juan													
Fish Canyon	66–68	Xl dacite, san, hbl, qtz	5000	28.0	La Garita	35 x 75	Andesite, dacite	27.8–28.3	Huerto Andesite	(none exposed)	27.8–27.6	5000	11,875
SE San Juan													
Chiquito Peak	64–67	Xl dacite, sanidine	500–1000	28.35	Platoro	18 x22	Andesite flows	28–28.5	Andesite-dacite	Granodiorite	28–23	500	6875
Western San Juan													
Sapinero Mesa	72–75	Xp rhyolite	>1000	28.35	Uncompahgre–San Juan	20 x 45	Andesite flows	29–35	Andesite-rhyolite	Granodiorite	28–27	1000	5875
Dillon Mesa	72–75	Xp rhyolite	50–100	28.4	Uncompahgre?	20 x 20	Andesite flows	29–36	??	(none exposed)		75	4875
Blue Mesa	72–74	Xp rhyolite	200–500	28.5	Lost Lakes (buried)	10 x 10	Andesite flows	29–35	Andesite flows	(none exposed)	28.5	350	4800
Ute Ridge	66–68	Xl dacite, sanidine	250–500	28.6	Ute Creek	8 x 8	Andesite flows	29–35	??	Qtz monzonite	28.6	350	4450
Central San Juan													
Masonic Park	62–66	Xl dacite, no san	500	28.8	[concealed]	—	Andesite flows	30–35	Andesite	(none exposed)	28.8–28.4	500	6375
Southeast San Juan													
South Fork	68–70	Xl dacite, san	50–100	28.8	Platoro/ Summitville?	8 x 12?	??		Andesite-dacite	(none exposed?)	28.7–28.4	75	4100
Ra Jadero	64–66	Xl dacite, san	150	28.8	Summitville?	8 x 12	Andesite flows	29	Andesite flows	(none exposed?)	28.8	150	4025
Ojito Creek	67–70	Xl dacite, no san	100	29.1	Summitville?	8 x 12	Andesite flows	29.2	Andesite flows	(none exposed?)	29	100	3875
La Jara Canyon	66–68	Xl dacite, no san	500–1000	29.3	Platoro	20 x 24	Andesite flows	30–35	Andesite flows	(none exposed?)	29.2	1000	3775
Black Mountain	67–69	Xl dacite, no san	200–500	29.4	Platoro	—	Andesite flows	30–35	Andesite flows	(none exposed?)	29.4	350	2775
NE San Juan													
(Barret Creek)	65–73	(Xl dacite-rhy lavas)	50?	29.8	[failed?]	—	Andesite flows	30–35	Andesite flows	G.d.-andesite	n.d.		
Saguache Creek	73–75	Alkali rhyolite, no bio	250–500	32.2	North Pass	15 x 17	Andesite flows	32–33	Andesite-dacite	(none exposed)	32–30	350	2425

(continued)

TABLE 1. REGIONAL IGNIMBRITES AND CALDERAS OF THE SOUTHERN ROCKY MOUNTAIN VOLCANIC FIELD (continued)

North-south Sawatch Range trend

Name	Composition		Volume	Age (Ma)	Caldera dims	Source caldera	Precursor lavas		Caldera fill	Intrusion age	Associated intrusion		
Bonanza	Zoned: dac-rhy-dac	74–63	250?	33.0	10 x 15	Bonanza–Gribbles	Andesite flows	33–36?	Andesite	33–32	G.d.-granite	250	2075
Thorn Ranch	Xl rhyolite	77	50–100?	33.7	10 x 10?	Marshall Creek	Andesite flows	34–36?	(eroded)		(none exposed?)	75	1825
East Gulch	Xl rhyolite	75–76	50–100?	33.7	10 x 15	Marshall Cr, or Aetna?	Andesite flows	34–36?	Andesite flows		(none exposed?)		
Badger Creek	Xl dacite	69–70	250?	33.8	10 x 15	Mount Aetna	Andesite flows	34–36?	(eroded)	33.8–30	G.d.-qtz monz, dikes	250	1750
Grizzly Peak	Xl rhy-dacite-andesite	Zoned: 77–57	500?	34.3	17 x 23	Grizzly Peak	Rhyolite (sparse)	35–36?	(eroded)	34–30	G.d.-qtz monz, dikes	500	1500
Stirrup Ranch	Xl rhyolite	73	100–200?	36.5		Mount Princeton?	??		(eroded)	36.4–30	G.d.-qtz monz, dikes		
Wall Mountain	Xl rhyolite	70–73	1000+/–	36.7	15 x 30?	Mount Princeton	Andesite (most eroded)	38	Badger Cr Tuff	36.6–30	Mt Princeton, Antero	1000	1000

Note: Sites are color-coded as in Figure 7; compiled from diverse sources, cited in text. Abbreviations: rhy—rhyolite; dac—dacite; san—sanidine; qtz—quartz; hbl—hornblende; xl—crystal-rich; xp—crystal-poor; g.d.—granodiorite; monz—monzonite; bio—biotite; n.d.—not determined; q.m.—quartz monzonite.

and peak volcanism largely preceded the bulk of extension (Lipman et al., 1970; Coney and Reynolds, 1977; Lipman, 1992; Chapin et al., 2004). The Southern Rocky Mountains have the interpretive advantages of substantially less structural complexity than that associated with severe late Cenozoic extension farther west in the Basin and Range; much of the SRMVF, 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 United States coupled with structural exposure of diverse upper-crustal levels along bounding faults of the Rio Grande rift provide outcrop levels 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 within a limited time span, including at least 30 ignimbrite calderas characterized by varied geometries and eruption histories, provide favorable opportunities to compare and contrast diverse volcanic processes associated with upper-crustal Cordilleran magmatism.

Intermediate-composition lavas and associated breccias (andesite, mafic dacite) were precursors to most ignimbrite eruptions as well as large components of caldera-fill sequences. Major volcanic loci tended to migrate north to south in the SRMVF, including both intermediate-composition lavas and ignimbrite eruptive centers (Table 1). Small scattered erosional remnants of volcanic rocks in northern Colorado (e.g., Corbett, 1968) may include an ignimbrite caldera in Rocky Mountain National Park (e.g., Izett, 1966; Corbett, 1968), but these are too fragmentary and inadequately studied to interpret in detail. The earliest well-documented regional ignimbrite erupted from a caldera source was the far-traveled Wall Mountain Tuff at 36.7 Ma (Chapin and Lowell, 1979; McIntosh and Chapin, 2004); the southernmost, and among the youngest ignimbrite events, was eruption of the Amalia Tuff from the Questa caldera at 25 Ma (Lipman, 1988). Structural unroofing associated with younger extension along the Rio Grande rift and deep erosion of this high-standing region has exposed broadly synvolcanic batholithic intrusions associated with both of these ignimbrite centers. Geographically and temporally between these early and late centers, the San Juan region contains the largest preserved erosional remnant of the composite middle Tertiary volcanic field. The San Juan Mountains are notable for the large number of high-volume compositionally diverse ignimbrite eruptions and associated caldera collapses;

at least 18 were active within the 2.5 m.y. interval 29.4–26.9 Ma (Table 1).

The SRMVF, because of widely preserved exposures of both volcanic and plutonic components, provides especially broad perspectives on overall magmatic evolution within the North American Cordilleran margin. The general southward progression of ignimbrite volcanism in the SRMVF is paralleled by a concurrent progression in the Basin and Range of Nevada and Utah (Stewart and Carlson, 1976; Christiansen and Yeats, 1992), and peak times of eruptive activity are concurrent with a third locus of mid-Tertiary ignimbrites and calderas in the Mogollon-Datil field of New Mexico (Elston, 1984; McIntosh et al., 1991; Chapin et al., 2004).

Sawatch Range Ignimbrite Centers

At least five relatively old ignimbrites of the SRMVF were erupted from caldera sources aligned along the north-trending Sawatch Range uplift in central Colorado (Fig. 1). The first of these is the Wall Mountain Tuff, a distinctive phenocryst-rich rhyolite (74% SiO_2) erupted at 36.7 Ma. The widespread areal distribution of this tuff, large inferred volume, and age relations strongly suggest that its source was a now-eroded caldera above the 25 × 35 km Mount Princeton batholith (Fig. 2), the largest Tertiary intrusion in the Southern Rocky Mountains (Tweto, 1979; Shannon, 1988; McIntosh and Chapin, 2004). Present-day exposures of the tuff, all distal paleovalley fills, extend onto the High Plains, 150 km east of Mount Princeton (Chapin and Lowell, 1979), and to the north flank of the San Juan Mountains 85 km to the southwest (Lipman and Calvert, 2003). Although impossible to quantify rigorously because of severe subsequent erosion, this great areal extent indicates an initial eruptive volume among the largest ignimbrite sheets in the region—probably >1000 km^3. Preserved distal outflow deposits typically rest directly on prevolcanic rocks, but sparse andesite xenoliths in the tuff document at least some precursory volcanism in proximal areas.

The Princeton batholith (Table 2) consists of texturally variable medium-grained equigranular to porphyritic granodiorite (65%–69% SiO_2) that is exposed over vertical relief of more than 1.5 km. This intrusion has yielded a U-Pb zircon age of 36.6 ± 0.4 Ma (Fridrich et al., 1998) and variable K-Ar and $^{40}Ar/^{39}Ar$ cooling ages of 35–36 Ma—dates similar to, or only slightly younger than, the Wall Mountain Tuff (McIntosh and Chapin, 2004). The more mafic composition and slightly younger age of the Mount Princeton intrusion, in comparison with associated tuff, are typical of other caldera-related intrusions, as detailed below; both features are
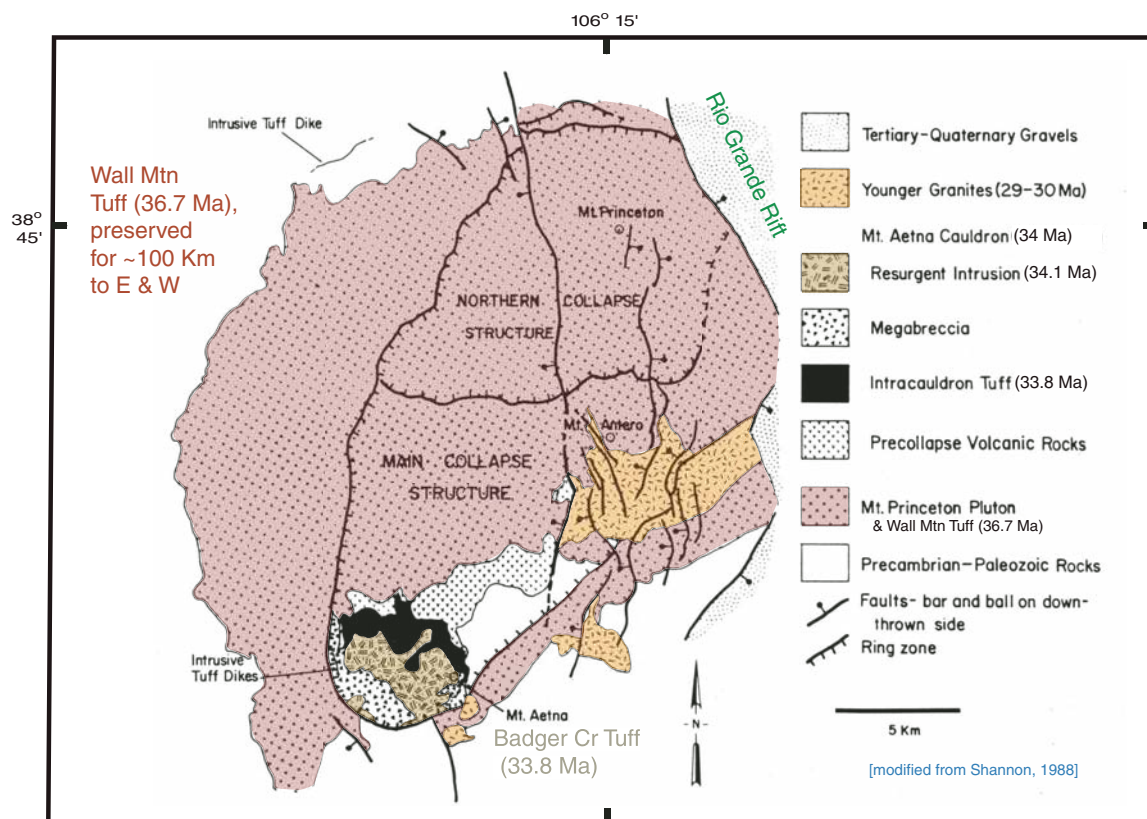
Figure 2. Generalized map of Mount Princeton batholith and Mount Aetna caldera (from Shannon, 1988). This batholith, the largest Phanerozoic intrusion in the Southern Rocky Mountains, is inferred to have underlain a caldera source for large-volume eruption (>1000 km³?) of the Wall Mountain Tuff at 36.7 Ma, but no subsidence structures related to this eruption have been recognized at present erosional levels. Exposed collapse structures all appear related to eruption of the Badger Creek Tuff (33.9 Ma) and perhaps other relatively late units such as the East Gulch Tuff (33.7 Ma). Intrusive activity continued for ~7 m.y. after initial cooling of the Princeton batholith and became increasingly silicic and petrologically evolved with time.

compatible with slow solidification of deeper, less-evolved portions of a magma chamber that had previously erupted explosively from more-evolved upper levels.

Nested within the southern margin of the Princeton batholith is the slightly younger Mount Aetna caldera (Fig. 2), source of the 33.8 Ma Badger Creek Tuff (Shannon, 1988; Johnson et al., 1989), a phenocryst-rich dacite compositionally distinct from the Wall Mountain Tuff, and associated postcaldera intrusions (34.1–29.6 Ma; McIntosh and Chapin, 2004). Thus, the Wall Mountain–Badger Creek eruptive cycles record activity of a sustained magmatic system active intermittently for at least 6 m.y. A third center, the Grizzly Peak caldera, centered 50 km north of Mount Aetna (Fig. 1), erupted the strongly compositionally zoned Grizzly Peak Tuff at 34.3 Ma (Fridrich and Mahood, 1987; Fridrich et al., 1991). Two additional ignimbrite-caldera centers (Marshall Creek, Bonanza) that are 2–4 m.y. younger than the Wall Mountain and Badger Creek Tuffs and

lie along the north-south Sawatch Range uplift (Fig. 1) also have associated andesitic volcanism before and after ignimbrite eruptions, as well as postcaldera intrusions (Table 1; McIntosh and Chapin, 2004). The Bonanza caldera lies within the San Juan erosional remnant but is closely aligned in structural trend and age with the Sawatch Range volcanic centers.

Questa Caldera and Latir Volcanic Locus

The southernmost Questa caldera, in northern New Mexico, formed at 25 Ma, in response to eruption of the ~500 km³ Amalia Tuff, a crystal-poor rhyolite of regionally unique peralkaline composition (Lipman, 1988). The Amalia Tuff is the sole ignimbrite erupted from the Latir volcanic locus, for which preserved erosional remnants record eruption of compositionally diverse calc-alkaline andesite-dacite lavas over a 3–5 m.y. interval leading to the caldera eruptions. Just before the Amalia Tuff, small volumes of compositionally similar peralkaline lava

erupted at near-caldera sites, marking a transition to more-evolved compositions inferred to reflect increased magma input and degree of crystal fractionation (Lipman, 1988; Johnson et al., 1990). The peralkaline magmas are severely depleted in compatible elements such as Ba and Sr and have large negative Eu anomalies; the apparent removal of large amounts of feldspar would require a sizable reservoir of nonerupted magma to retain the crystal residue.

Particularly informative for the Latir-Questa system, several kilometers of late Cenozoic structural relief along the master bounding fault of the Rio Grande rift zone provide a cross section from the volcanic sequence down into upper parts of a compositionally diverse array of eight subvolcanic granitic to granodiorite plutons (Table 2). The plutons crop out for nearly 40 km north-south, both within the Questa caldera and to the south (Fig. 3). Some intrusive rocks within the caldera are similar in age to the Amalia Tuff at 25 Ma, and margins of one are peralkaline granite indistinguishable in composition

from the ignimbrite. As outcrop levels deepen to the south, K-Ar and $^{40}Ar/^{39}Ar$ ages decrease, to as young as 18 Ma for the southernmost Lucero pluton (Lipman, 1988; Czamanske et al., 1990). An elongate Bouguer gravity low (~−20 mgal) encloses the Questa caldera and associated plutons along the west flank of the Latir Range to the south (Cordell et al., 1986), but the gravity low does not reflect the southern margin of the caldera relative to the southern plutons. Because erosion has completely removed any original low-density caldera fill or other proximal postcaldera deposits, the gravity anomaly can only reflect the shape of coalesced low-density upper-crustal intrusions, for which the exposed plutons represent high-standing cupolas (Lipman, 1988). Thus, the Questa-Latir area is interpreted to record early growth of a subcaldera composite batholith during ignimbrite eruption, with pluton assembly and evolution continuing for ~7 m.y. after peak volcanism.

San Juan Volcanic Region

As mid-Tertiary volcanism migrated southward along the Sawatch Range trend, widely scattered intermediate-composition centers (dominantly andesite, lesser volumes of dacite, and minor rhyolite) erupted lava flows and flanking volcaniclastic breccias in the San Juan region starting at ca. 35 Ma (Lipman et al., 1970; McIntosh and Lipman, unpublished data). After several million years of such precursory volcanism, large ignimbrite eruptions of crystal-rich dacite began in the southeast San Juan region at ca. 29 Ma (Platoro caldera complex: Lipman, 1975; Steven and Lipman, 1976), followed soon after by eruptions mainly of crystal-poor rhyolite from western San Juan calderas (Lipman et al., 1973; Bove et al., 2001). Ignimbrite activity progressively focused in the central San Juan region (Fig. 4), 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 27.8 Ma (Lipman, 2000; Bachmann et al., 2002). Each of these caldera loci formed within clusters of intermediate-composition central volcanoes that had grown over 3–5 m.y. intervals (Steven and Lipman, 1976). At each locus, initial postignimbrite volcanism consisted of intermediate-composition lavas and breccias that variably filled the caldera depressions—some to overflowing; earlier caldera structures also became loci for further nested ignimbrite eruptions and subsidence. At the Platoro complex, five ignimbrites, with volumes of ~100–500 km^3 each, were erupted sequentially within ~1.0 m.y (Table 1). In the western San Juan Mountains, the younger Silverton and Lake City calderas were each nested

TABLE 2. INTRUSIONS ASSOCIATED WITH CALDERAS AND SILICIC VOLCANIC CENTERS, SOUTHERN ROCKY MOUNTAIN VOLCANIC FIELD

Caldera, silicic center	Intrusion name, structural setting	Size (km)	Dominant composition	Texture	SiO$_2$ (wt%)	Cooling Age (Ma)	Postcaldera duration (m.y.)	Data sources
Lake City	Nellie Creek - arcuate plugs	Small	Evolved rhyolite	Porphyro-aphanitic	76	19	5	Hon and Lipman (1989)
	Resurgent	1 × 3	Syenite-granodiorite	Fine- to med.-grain equigranular	64–66	23	Small	Hon and Lipman (1989)
	Ring dikes	Small	Rhyolite-dacite	Fine-grain porphyritic	66–73	23	Small	Hon and Lipman (1989)
Questa	Lucero - S batholith	5 × 5	Granite	Coarse grain	76	18.5	~6	Czamanske et al. (1990)
	Rio Hondo - S batholith	8 × 8	Quartz monzonite	Med.-grain porphyritic	62–76	20–23	2–5?	Czamanske et al. (1990)
	Moly Mine - S caldera ring	2 × 12	Evolved granite	Fine to medium grain	68–77	24.5	~1?	Czamanske et al. (1990)
	Cabresto Lake	3 × 3	Granodiorite	Medium-grain equigranular	70–76	24.5	~1?	Czamanske et al. (1990)
	Pinabete Pk - resurgent	1 × 2	Quartz monzonite–granite	Med.-grain equigranular to porphyritic	73–77	25	Small	Czamanske et al. (1990)
	Rito del Medio - resurgent	2 × 4	Granite	Med.-grain miarolitic	77	25	Small	Czamanske et al. (1990)
San Luis	Rough Creek - volcano core	2 × 3	Dacite	Fine-grain porphyritic	61–65	25.9*	~1?	Lipman (2000, 2006)
	Mineral Creek - volcano core	2 × 4	Dacite	Fine-grain porphyritic			~1?	Lipman (2000, 2006)
	Spring Creek - resurgent	4 × 8	Granodiorite		60–66		Small	Lipman (2000, 2006)
South River	Piedra–Goose Cr - ring intrusions	2 × 11	Granodiorite	Fine- to med.-grain equigranular	58–63	26.7*	Small?	Lipman (2000, 2006)
Silverton	Sultan Mtn - bulbous ring intrusion	3 × 8	Granodiorite	Medium-grain equigranular	64–66	27*	~1?	Bove et al. (2001)
Platoro	Alamosa River - bulbous ring intr.	3 × 8	Granodiorite–quartz monzonite	Fine- to med.-grain equigranular to porphyritic	56–65	29.1 ± 1.2	Small	Lipman (1975)
	Cataract Cr - sector graben	2 × 3	Granodiorite	Fine- to med.-grain equigranular	59	undated	Undated	Lipman (1975)
	Cat Creek - proximal	3 × 3	Granodiorite	Fine- to med.-grain equigranular	60–66	undated	Undated	Lipman (1975)
North Pass	Cochetopa Pass - ring intrusion	1 ×2	Dacite porphyry	Fine-grain porphyritic	64–66	32*	Small?	Lipman and McIntosh (2006a)
Needle Creek	Early core, silicic dome field	5 × 10	Granodiorite to andesite	Fine-grain equigranular to aphanitic	58–60	34.35	Small?	Lipman and McIntosh (2006a)
Aetna	Resurgent	3 × 6	Quartz monzonite	Medium-grain porphyritic	66	34.07	Small	Shannon (1988)
	Ring dikes	Small	Quartz monzonite	Fine- to med.-grain equigranular	67	34.13	Small	Shannon (1988)
Grizzly Peak	Lincoln Gulch - piston resurgent	4 × 6	Granodiorite	Porphyro-aphanitic	60–70	34.8 ± 1.1	Small?	Fridrich et al. (1998)
"Wall Mtn"	Antero - late intrusion	5 × 8	Biotite leucogranite	Coarse grain to aplitic	74	29.6	~7	Shannon (1988)
Mt. Princeton	Mt. Princeton - subcaldera pluton	25 × 35	Quartz monzonite	Med.-grain equigranular to porphyritic	65–69	36.6–~36	Small	Fridrich et al. (1998)

*Intrusion age estimated from associated lava flows.

within earlier collapse depressions (Fig. 4; Steven and Lipman, 1976). In the central San Juan Mountains, seven major eruptions of compositionally diverse ignimbrite, with volumes of 100–1000 km³, erupted from calderas nested within the La Garita caldera (Fig. 5), essentially representing continued postcollapse volcanism of the Fish Canyon magmatic cycle at a remarkably large scale and brief time interval. Six of these tuffs erupted between 27.5 and 26.9 Ma (Lipman and McIntosh, 2006b), and ages for the last four are within uncertainties of the $^{40}Ar/^{39}Ar$ method (26.9 ± 0.05 Ma). Two of the tuff sheets are crystal-rich augite-bearing dacite; one is a mafic hornblende dacite; four are compositionally zoned from initially erupted crystal-poor rhyolite upward into dacite (Table 1). Collectively, these eruptions appear to record repeated replenishment and varied crystal fractionation in rapidly evolving batholith-scale subvolcanic magma reservoirs.

Subvolcanic intrusions are relatively sparse and small in the San Juan region compared to those along the Swatch trend or the Questa-Latir system, but sizable intrusions are present within several calderas (Table 2) and typically consist of fine-grained granodiorite. While surface exposures thus provide only limited perspectives on the scale of the subvolcanic magmatic system active during growth of the San Juan field, regional Bouguer gravity data define a steep-sided flat-floored negative anomaly that extends over an elliptical area of ~75 × 100 km and has an amplitude of about −50 mgal (Fig. 6). Along with a similar gravity low of comparable areal extent to the north, which links Mount Princeton batholith and Grizzly Peak caldera areas (Behrendt and Bajwa, 1974), these are the most negative gravity lows (>–355 mgal) anywhere in the United States. The San Juan anomaly has long been modeled as recording the presence of an upper-crustal granitic batholith, with much of its upper contact within a few kilometers of the present surface (Plouff and Pakiser, 1972; Drenth and Keller, 2004). The negative anomaly encloses most of the calderas in the San Juan region, but individual calderas have little or no gravity expression, and sizable central portions of the gravity low are outside any caldera (Fig. 6), indicating that caldera fills contribute little to the anomaly. Such a relation is consistent with the character of caldera-filling rocks, which are typically dominated by densely welded intra-caldera tuff at least several kilometers thick, overlain by intermediate-composition lavas. Because cumulative subsidence on multiple nested calderas, especially in the central San Juan cluster, in places is interpreted to exceed 10–15 km (Fig. 16 in Lipman, 2000), growth of the subvolcanic batholith to its present shallow-crustal level must have continued after caldera subsidence.

Consistent with this timing for sustained batholith assembly and consolidation is the resurgent uplift at many of the San Juan calderas and sustained intervals of postcaldera lava eruptions. Thus, the general pattern of mid-Tertiary ignimbrite volcanism in the San Juan region, and elsewhere in the Southern Rocky Mountains, is a several-million year period of multistage open-system magmatism: premonitory eruptions of dominantly intermediate-composition lavas from central volcanoes, ignimbrite eruptions at times of peak magma input, and waning surface magmatism as subvolcanic plutons of a composite batholith consolidate beneath the volcanic locus.
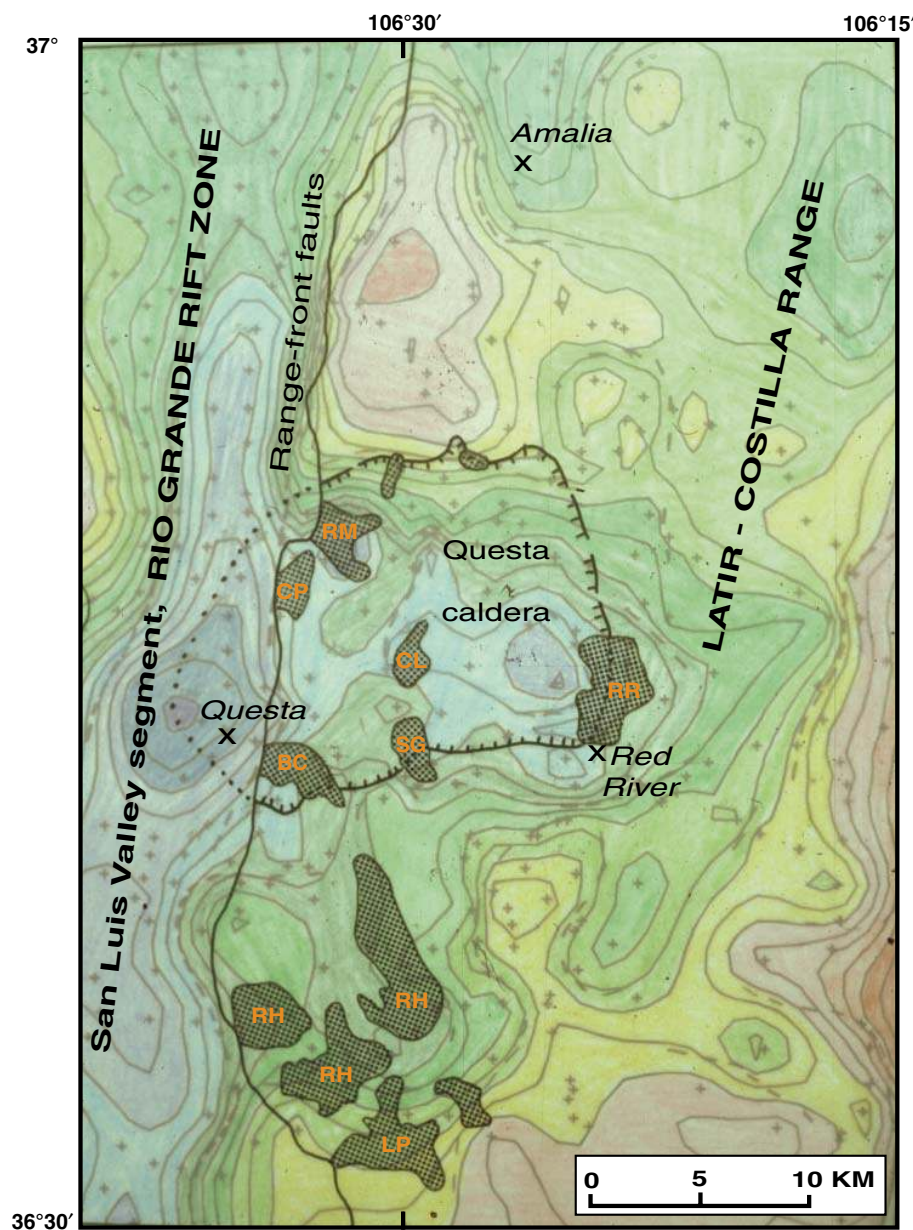

Figure 3. Map showing distribution of exposed granitic plutons (cross-hatched) of the Questa-Latir area and margins of the Questa caldera (Lipman, 1988) in relation to Bouguer gravity anomalies (Cordell et al., 1986). Green-blue—gravity lows; red-yellow—gravity highs. Contour interval = 2 mgal. Plutons: BC—Bear Creek; CL—Cabresto Lake; CP—Canada Pinabete; LP—Lucero Peak; RH—Rio Hondo; RM—Rito del Medio; RR—Red River; SG—Sulfur Gulch.
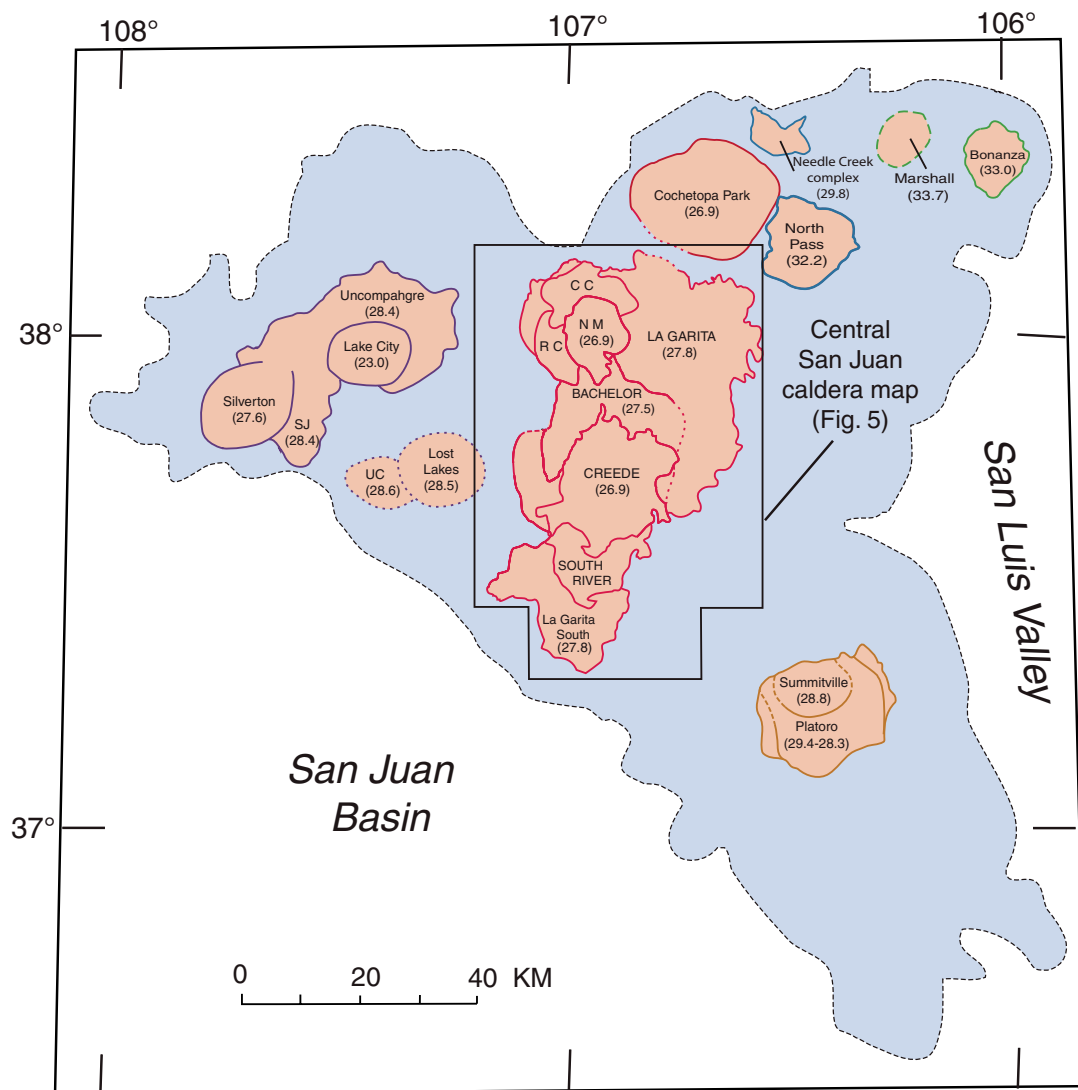
Figure 4. Calderas and present-day extent of mid-Tertiary volcanic rocks in the San Juan region, calderas, and ages. Caldera margins are color-coded by geographic loci (see Figs. 7–8). Data are from Lipman (2000), Bove et al. (2001), and Lipman and McIntosh (2006).

INCEPTION OF UPPER-CRUSTAL MAGMATISM IN THE SRMVF: PRECURSORS TO IGNIMBRITES

Construction of large stratocones that dominantly consist of intermediate-composition lavas and breccias marked the inception of volcanism in the SRMVF, which generally commenced several million years prior to initial ignimbrite eruptions in the same area. 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), is roughly double that of the later-erupted ignimbrites. High-K calc-alkaline andesite and dacite are dominant compositions; true basalt is absent, indicating that even at early stages in the mid-Tertiary magmatic episode, mantle-derived magmas were efficiently modified by lower-crustal assimilation, magma

mixing, and other fractionation processes (Lipman et al., 1978; Johnson et al., 1990; Johnson, 1991; Riciputi et al., 1995).

Small hypabyssal stocks, commonly exposed in cores of these volcanoes and loci for outward radiating dikes, are similar in composition to the dominant eruptive products; large silicic plutons are absent. Along with flanking lavas, these widely scattered high-level intrusive centers have been inferred to record initial phases of assembly of upper-crustal magma chambers that subsequently coalesced and enlarged to become sites for ignimbrite eruptions (Lipman et al., 1978). Phenocryst-poor rhyolitic lavas, though regionally rare, occur as late eruptive products from some central volcanoes, especially those clustered close to sites of subsequent ignimbrite eruptions; these may mark increasing efficiency of fractionation processes as magmatic power input enlarged the size and energetics of the initial subvolcanic magma chambers.

IGNIMBRITES IN THE SRMVF: PEAK POWER INPUT TO THE MAGMATIC SYSTEM

Major volcanic foci, initially established by growth of clustered stratocones, became sites of ignimbrite eruptions and caldera collapse (Table 1), presumably in response to increased magmatic power input focused at these sites. For at least the brief times of ignimbrite eruptions, large upper-crustal chambers must have contained 10^2–10^3 km^3 of eruptible magma associated with caldera subsidence tens of kilometers across.

Ignimbrites in the SRMVF tend to vary between phenocryst-poor rhyolite (<5%–10% crystals) and phenocryst-rich dacite (as much as 45% crystals), either as discrete compositionally uniform sheets (dominantly crystal-rich dacites) or as compositional zonations from rhyolite to dacite (Table 1). The overall petrologic features
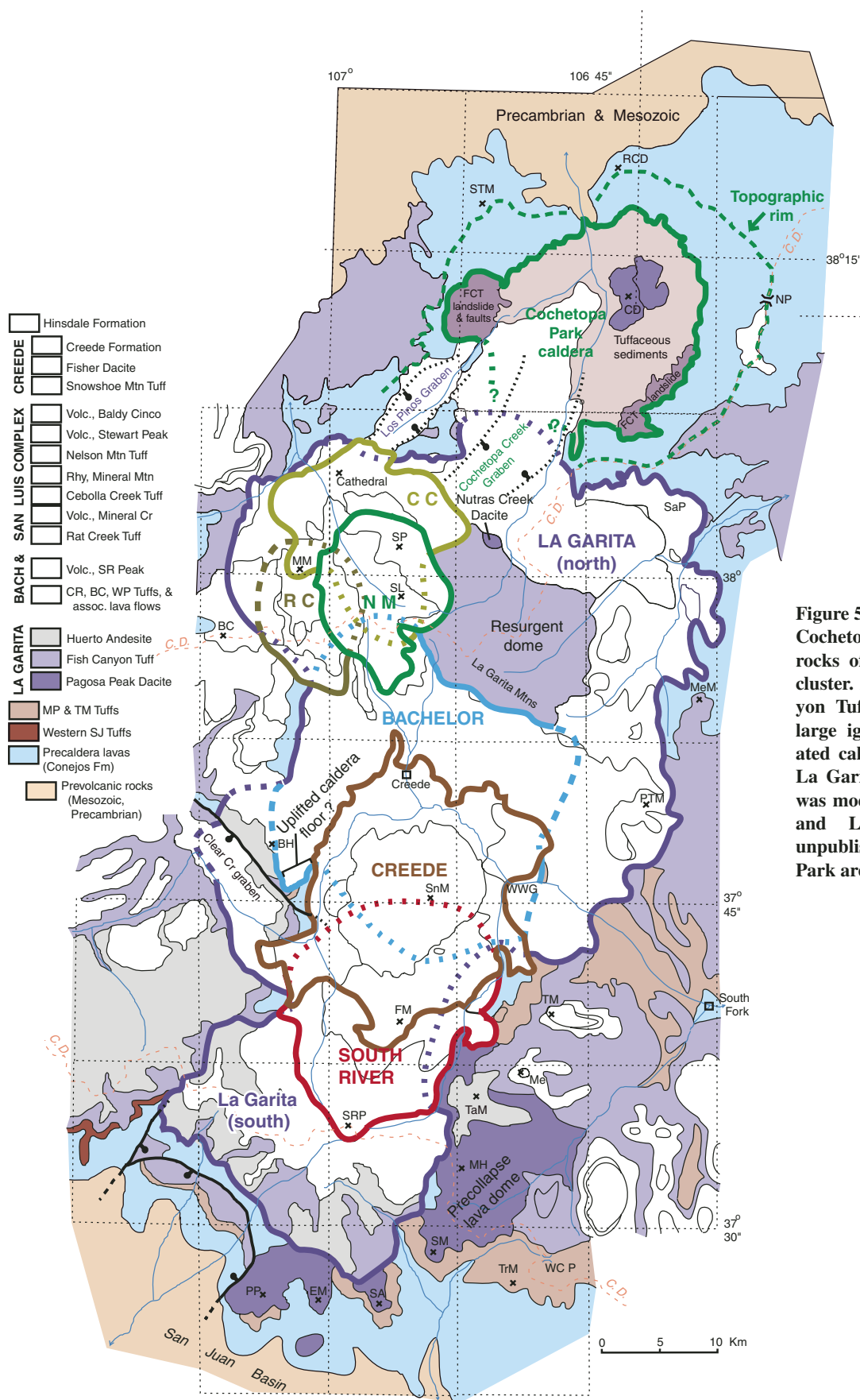
Figure 5. Geometry of the La Garita and Cochetopa Park calderas and associated rocks of the central San Juan caldera cluster. After eruption of the Fish Canyon Tuff at 27.8 Ma, seven additional large ignimbrite eruptions and associated calderas were localized within the La Garita caldera within 0.9 m.y. Map was modified from Lipman et al. (1997) and Lipman (2006), incorporating unpublished mapping in the Cochetopa Park area (2001–2005).
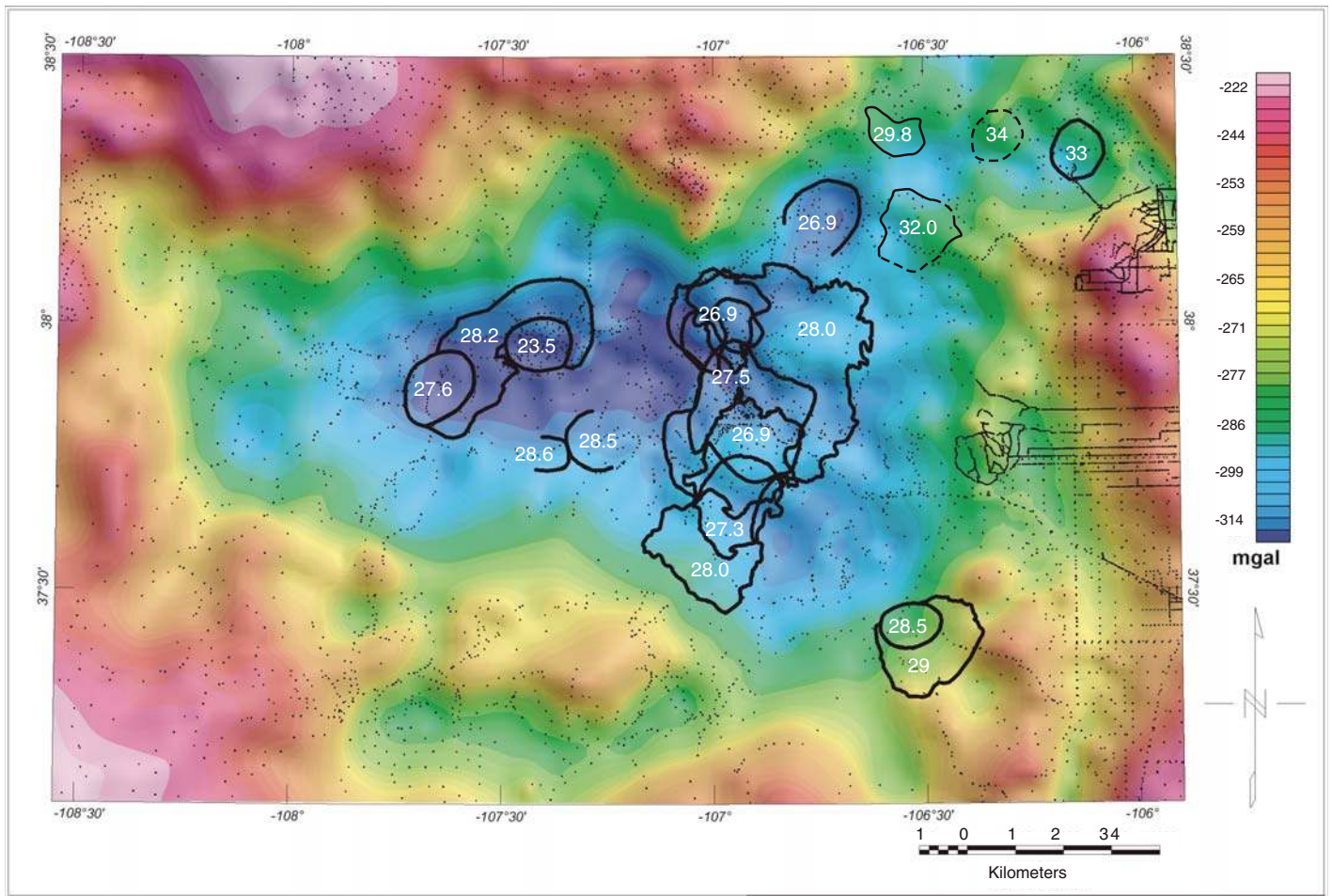
Figure 6. Bouguer gravity map of the San Juan region (modified from Plouff and Pakiser, 1972; Drenth and Keller, 2004). A steep-sided flat-floored 50 mgal gravity low, which encloses most calderas (especially younger ones), is interpreted as the site of an upper-crustal subvolcanic batholith. Most individual calderas have little or no gravity expression, probably because any shallow low-density fill has been largely removed by erosion. Caldera outlines—black lines, red numbers—ages in Ma, gravity stations—black dots.

of the ignimbrites and associated lavas of the caldera cycle document diverse recurrent processes of magma generation and evolution, including continued input of mafic mantle-derived magma, addition of lower-crustal components by melting and assimilation, high-level crystal fractionation and separation of evolved melts by crystallization and volatile-driven separation of evolved melts, mixing between more evolved and relatively primitive portions of compositionally stratified or otherwise compositionally complex chambers, and interplay between chamber cooling and resultant crystallization versus reheating ("defrosting") accompanying mafic-magma recharge (Lipman et al., 1978; Johnson et al., 1990; Riciputi et al., 1995; Bachmann et al., 2002)

So much evidence has been presented for such diverse processes in subvolcanic chambers that it can only be briefly summarized here in relation to the SRMVF. At the central San Juan caldera

cluster, the rapid sequential eruption of multiple ignimbrite sheets of large volume and diverse compositions from overlapping caldera sources (Fig. 5; Table 1) requires recurrent regeneration of "large tanks" of eruptible magma. Rhyolitic tuffs, even though mostly crystal poor, have petrologic signatures of strong feldspar fraction (e.g., depletion of compatible elements such as Sr, Ba, and Eu), despite the low phenocryst contents of the erupted tuffs. Similarity of the crystal-poor rhyolites, some having volumes on the order of 1000 km^3 (e.g., Sapinero Mesa and Carpenter Ridge Tuffs), to matrix (melt) compositions in crystal-rich dacites documents efficient separation of rhyolitic liquids from crystal residues in upper-crustal magma chambers (Halliday et al., 1991; Bachmann and Bergantz, 2004). Generation of crystal-poor rhyolitic tuffs of large volume is not just confined to high-temperature volatile-poor magmas (cf. Christiansen, 2005). Dacite tuffs are close in composition

to evolved lavas erupted from the earlier central volcanoes; they also have affinities with the typical granodiorite-granite assemblage of large Cordilleran batholiths (Lipman, 1984; Bachmann et al., 2002). Recurrent outpourings of intermediate-composition lavas (andesite, mafic dacite) during inception and waning of ignimbrite caldera cycles in the San Juan region show that open-system mantle inputs in the roots of the systems continued in large volume during and after peak explosive volcanism.

Other features also support interpretation of the ignimbrite magmas as having resulted from complex multistage processes over extended time intervals. These include diverse disequilibrium mineral assemblages as first described 70 yr ago (Larsen et al., 1938), which indicate that some of the crystal cargo in porphyritic volcanic rocks consists of "antecrysts," recycled from earlier magmatic events, rather than true phenocrysts that grew in the matrix melt that

surrounded them (e.g., Nakada et al., 1994; Gardner et al., 2002; Bachmann et al., 2002). For example, dating of diverse crystal phases from the Fish Canyon Tuff, the only unit in the SRMVF thus far subjected to sufficiently detailed geochronologic study, records a prolonged crystallization history, with U-Pb zircon ages as much as 0.5 m.y older than Ar-Ar ages for sanidine (Schmitz and Bowring, 2001; Bachmann et al., 2007b). Hornblende and plagioclase zoning, feldspar and quartz resorption textures, and mineral isotopic variability also have led to the interpretation that the enormous volume of compositionally homogeneous dacite magma erupted to form the Fish Canyon Tuff was generated by remobilization of an existing solidified but near-solidus granodiorite pluton (Bachmann et al., 2002; Charlier et al. 2004). Similar processes are likely for other SRMVF ignimbrites that have thus far been less studied.

Volumes of SRMVF tuffs (Fig. 7) and dimensions of calderas (Table 1) provide further insights into the geometry of the associated magma chambers. Where exposures are most favorable, minimum subsidence was commonly greater than 2 km, as documented by the depth of unfilled caldera basin plus thick intracaldera tuff, without reaching the caldera floor (Lipman, 2000). Total subsidence at many SRMVF calderas was thus likely 3 km or more, but well within the range of up to 5 km subsidence documented for some calderas elsewhere (John, 1995; Lipman, 1997). The eruption of as much as 5000 km^3 of homogeneous magma (Fish Canyon Tuff) from a chamber below a caldera subsidence as much as 75 km across (La Garita caldera) requires the presence of an enormous low-aspect-ratio body of mushy eruptible magma in the upper crust. Such a lenticular or tabular volume of eruptible magma must have been assembled incrementally over a sustained time interval, at least several hundred thousand years as indicated by zircon U-Pb ages (Schmitz and Bowring, 2001; Bachmann et al., 2007b). During this prolonged assembly process, successive pulses of magma, which were unlikely to have been identical, were blended effectively to achieve the striking whole-rock homogeneity of the Fish Canyon Tuff along with associated precursor and successor lavas. What was the power input necessary to keep such a volume alive for several hundred thousand years or more? How much of the total chamber volume is represented by the regional-scale sill-like dimensions of the erupted magma? What intrusive record of analogous ignimbrite eruptions might be discernible in the exposed upper crust? Some answers are possible from large granitic plutons, as discussed next.

SUBVOLCANIC INTRUSIONS DURING WANING OF IGNIMBRITE MAGMATISM: BRIDGE TO THE BATHOLITHIC ENVIRONMENT

Shallow granitic intrusions associated with ignimbrite calderas in the SRMVF vary substantially in composition, texture, structure, and age relative to host calderas (Table 2). Such variability is inferred to provide perspectives on multistage processes involved in pluton assembly and subsequent evolution during and after prolonged surface volcanism.
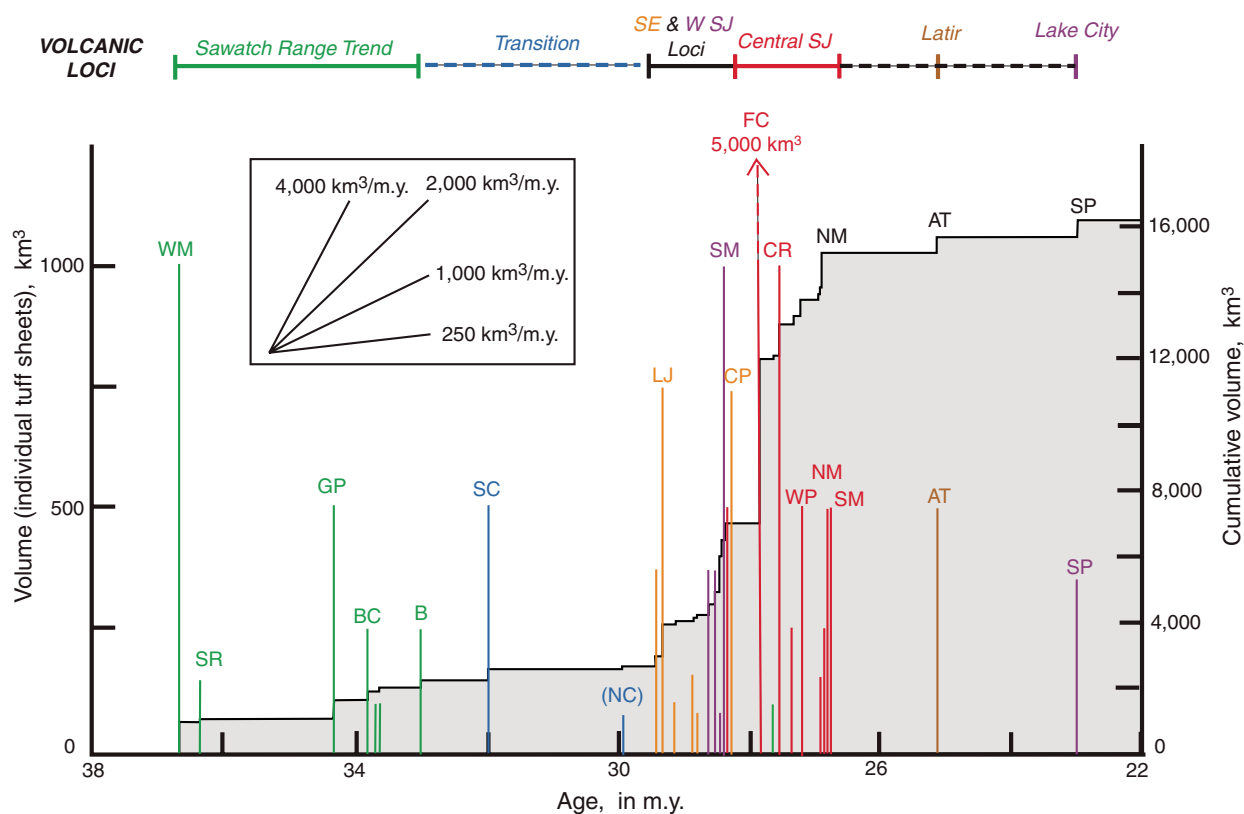

Figure 7. Age-volume plot for large Southern Rocky Mountain volcanic field ignimbrites. Locations of ignimbrite sources are color-coded as on Figure 4. Overall magma production for ignimbrite eruptions was ~1000 km^3/m.y. from 37 to 22 Ma; peak production during eruptions from the central San Juan caldera complex exceeded 4000 km^3/m.y. (Lipman et al., 1996). Peak production, dominated by eruption of the Fish Canyon Tuff at 27.8 Ma, was near mid-stage in evolution of the volcanic field, as is documented for several other volcanic regions dominated by ignimbrite eruptions (e.g., west-central New Mexico, McIntosh et al., 1991; SW Nevada, Sawyer et al., 1994; central Andes, de Silva et al., 2007).

Composition

The most common compositions in the SRMVF are granodiorite and mafic granite, chemically equivalent to andesite and dacite (Table 2); silicic granites are rare and typically small in volume. Most intrusive compositions are more mafic than those of the associated ignimbrites (Fig. 8), especially where the tuff is silicic. For example, eruption of the Crystal Lake Tuff (72%–74% SiO$_2$) from the Silverton caldera at 27.6 Ma was followed by solidification of the Sultan Mountain stock (64%–66% SiO$_2$) along the southern ring-fault zone at 26.6 Ma (Lipman et al., 1976; Bove et al., 2001). Where an ignimbrite is compositionally zoned, associated intrusions tend to have compositions close to the more mafic last-erupted tuff at the top of the ignimbrite sheet. For example, intracaldera resurgent granodiorite (60%–66% SiO$_2$) of the San Luis caldera complex intrudes the thick intracaldera accumulation of Nelson Mountain Tuff (74%–66% SiO$_2$).

A few plutons become more silicic upward, and others progress toward more evolved compositions with time. In the Questa area, the Rio Hondo pluton consists dominantly of uniform megacrystic granodiorite (64%–66% SiO$_2$), except within 100–200 m of its gently dipping roof, where it grades into equigranular granite (72%–74% SiO$_2$) that is widely invaded by aplitic sheets (Lipman, 1988; Johnson et al., 1990). The Mount Princeton batholith (ca. 36 Ma), which consists of equigranular and porphyritic granodiorite, is the locus for subsequent intrusion of smaller bodies of highly evolved Mount Antero Granite at ca. 30 Ma (Shannon, 1988).

No subvolcanic plutons associated with the SRMVF display major compositional layering or large-scale evidence for mingling of silicic and mafic magma, such as that well preserved deep in some plutons elsewhere (Wiebe, 1994; Wiebe and Collins, 1998). Shallow levels of large silicic chambers may be too dynamic to preserve clear records of the recharge and mingling by mafic magma that seem essential to overall evolution of plutonic systems.

Age

Intrusions geographically associated with calderas have ages that vary from indistinguishable from the associated ignimbrite to millions of years younger, age ranges which document prolonged magma-chamber evolution during waning of a volcanic cycle culminating with ignimbrite eruption. Intrusion compositions are most similar to erupted tuffs if they are closely linked in time; intrusions that are substantially younger than a spatially associated ignimbrite tend to be more

compositionally diverse. For example, at Questa, the peralkaline granite of Virgin Canyon, which forms selvages along margins of the intracaldera resurgent intrusion (granite of Rito del Medio), is indistinguishable in isotopic age (at 25 Ma) and chemically identical to the Amalia Tuff from this caldera (Lipman, 1988; Czamanske et al., 1990). In contrast, slightly younger Mo-mineralized intrusions (24.5 Ma) along the south caldera margin are highly evolved calc-alkaline granites, and the even younger Rio Hondo pluton south of the caldera is granodiorite.

Resurgent intrusions of fine-grained syenite within the Lake City caldera are compositionally similar and indistinguishable in K-Ar age at 23 Ma from late-erupted trachyte of the compositionally zoned Sunshine Peak Tuff (Hon and Lipman, 1989), but rhyolite intrusions emplaced 4 m.y. later along the north margin of this caldera are calc-alkaline, quartz rich, and highly evolved (Lipman et al., 1976; Bove et al., 2001). As a distant young example for which age resolution is exceptionally precise, at the Chegem caldera in southern Russia, fine-grained granodiorite
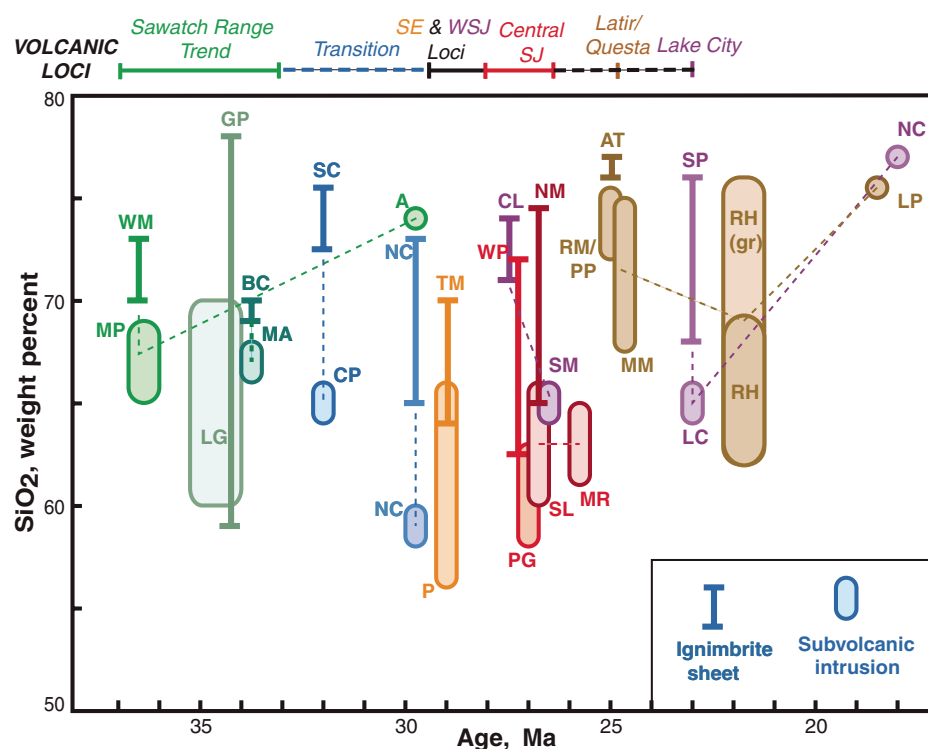

Figure 8. Age-compositional comparison of ignimbrite sheets and associated subcaldera intrusions. Intrusions tend to be more mafic than associated tuff, especially when close in age. Ignimbrite sheets that contain large ranges of SiO$_2$ are compositionally zoned, reflecting gradients in source magma chambers. Some late intrusions are highly differentiated granite and rhyolite. Related tuffs and intrusions are connected by dashed lines. Areas of ellipses plotted for intrusions reflect age uncertainties and compositional range, without conveying information on pluton size or dominant composition. Locations of ignimbrite sources are color-coded as on Figure 4. Ignimbrites and related volcanic rocks: AT—Amalia Tuff; BC—Badger Creek Tuff; CL—Crystal Lake Tuff; GP—Gribbles Park Tuff; NC—Needle Creek flow-dome complex; NM—Nelson Mountain Tuff (San Luis caldera complex); SC—Saguache Creek Tuff; SP—Sunshine Peak Tuff; TM—tuff sheets of Treasure Mountain Group (Platoro caldera complex); WM—Wall Mountain Tuff; WP—Wason Park Tuff. Intrusions: A—Antero Granite; CP—Cochetopa Pass dacite porphyry; LG—Lincoln Gulch laccolith; LP—Lucero pluton; MA—Mount Aetna pluton; MM—Moly Mine and associated plutons along south margin of Questa caldera; MP—Mount Princeton granodiorite; MR—Mineral–Rough Creek intrusions of San Luis caldera complex; NCI—Needle Creek intrusive complex; NC—Nellie Creek rhyolite plugs; P—Platoro caldera intrusions; PG—Piedra–Goose Creek intrusions; RH—dominant granodiorite phase of Rio Hondo pluton; RH(gr)—granitic roof rocks of Rio Hondo pluton; RM/PP—Rito del Medio and Pinabete Peak resurgent intrusions of Questa caldera; SL—resurgent intrusions of San Luis caldera complex.

within a piston-block intracaldera uplift and the associated ignimbrite sheet are indistinguishable in age at 2.84 ± 0.03 Ma (Gazis et al., 1995); the intrusion is similar in composition to late phases of the compositionally zoned tuff.

Texture

Textures of caldera-related plutons vary greatly within short distances, from medium-grained holocrystalline to dense aphanitic rock that can be difficult to distinguish from lava. Most common are fine-grained variably porphyritic holocrystalline plutons that are texturally similar to central intrusions in cores of the intermediate-composition central volcanoes that erupted widely as precursors to the caldera-forming ignimbrites. Many caldera-related plutons probably represent the cores of postcollapse volcanic edifices, the lavas of which are preserved as thick fill sequences within calderas such as Bonanza, Platoro, Uncompahgre–San Juan, La Garita (southern segment), South River, and San Luis in the San Juan region (Table 1).

Not surprisingly, the shallowest intrusions tend to be the finest grained, the most texturally variable, and in places difficult to distinguish reliably from volcanic country rocks. For example, the 10 × 20 km Needle Creek intrusion of andesite to fine-grained granodiorite, at the core of a 34 Ma silicic center of rhyolite lavas and small ignimbrite eruptions (Fig. 4), is the areally largest intrusion in the San Juan region, but it has been included with the lava sequence (Tweto, 1979) until recent field work (2003–2004) in the northeastern part of this long-studied volcanic area (Lipman, unpublished data).

Other intrusions, especially the largest and deepest, have more uniform medium to coarse granitic textures and merge in appearance with Mesozoic plutons of the western Cordillera. For example, the lowest exposed parts of the Rio Hondo pluton, in canyons south of the Questa caldera, are medium-grained granodiorite containing Rapakivi-type K-feldspar megacrysts to 5 cm in length, sparse lenticular mafic inclusions, and a weak mineral foliation; these rocks texturally resemble those of the Half Dome or Mount Whitney plutons in the Sierra Nevada. The Rio Hondo pluton is also similar in bulk composition, mineral components, and phenocryst texture to some porphyritic volcanic rocks in the SRMVF, such as the South Mountain dacite dome along the margin of the Platoro caldera (Steven and Ratté, 1960) or late-erupted megacrystic Fish Canyon Tuff (Lipman et al., 1997). The large Mount Princeton batholith (25 × 35 km) also consists mainly of medium-grained equigranular to porphyritic granodiorite, similar to many Mesozoic granitoids of

the western Cordilleran region. In light of the presence of K-feldspar megacrysts in dacitic volcanic rocks of the SRMVF and elsewhere (e.g., Zellmer and Clavero, 2006), interpretation of megacrystic fabrics in Sierran plutons as products of late-magmatic or subsolvus textural coarsening, unrelated to flowage during early pluton growth (Johnson et al., 2006), appears to be an unnecessary dichotomy. Sizable megacrysts that initially grew as early crystallizing phases during volcanic stages may preserve shape orientations that record magma-flowage fabrics in subvolcanic intrusions, even if further enlarged and unmixed during late-stage crystallization and prolonged subsolidus cooling.

Even the largest Tertiary subvolcanic plutons mostly lack conspicuous mineral fabrics, in contrast to the coherent flow foliations that characterize many deeper-level plutons in the western Cordillera. Such differences may reflect smaller proportions of crystals present in magmas at times of last flowage when they were emplaced as shallow subvolcanic plutons. In contrast to the subvolcanic plutons, associated dikes and sills that contain tabular phenocrysts commonly preserve contact-parallel foliations near their margins.

Structure

As exposed in rugged terrain of the Southern Rocky Mountains, the best-exposed large caldera-related plutons appear to be plug-shaped at present outcrop levels, and they have equant to weakly elongate shapes and steep contacts. Outer contacts are typically sharp, without migmatitic or other mixed zones or conspicuous contact metamorphism, consistent with shallow emplacement into cool country rocks. Gently dipping roof contacts are exposed locally, particularly for the Rito del Medio and Rio Hondo plutons associated with the Questa caldera, but floors that would be indicative of relatively thin sill or laccolithic geometry are absent. Nevertheless, the largest intrusions, such as Mount Princeton (25 × 35 km) and the clustered plutons (20 × 40 km) in the Questa area have batholithic dimensions that require a broadly laccolithic overall geometry to limit their vertical extent within the upper crust.

Smaller intrusions near the calderas tend to be more irregular in shape and boundary contacts. In addition to subequant plugs, elongate "megadikes" hundreds of meters or more wide and tabular sill-laccolith shapes are present. Some intrusions contain multiple compositional-textural subunits, with complex crosscutting relations between dike-like and sill-shaped bodies. Even though they are less common in larger intrusions, such structural complexities are inferred to record multistage sequences of

incremental pluton growth that became homogenized and obscured by prolonged crystallization and solidification in large plutons.

Discrete laccolithic intrusions with arched roof rocks and subhorizontal sills are present locally around the flanks of the San Juan region (Steven et al., 1974) and at scattered igneous centers farther west on the Colorado Plateau (Tweto, 1979). Only a few of these isolated intrusions can be shown to have associated surface volcanic deposits (dominantly intermediate-composition lavas), and none has any apparent relation to caldera or ignimbrite centers. Such lenticular or tabular intrusions appear to be satellitic to the major magmatic foci. They are confined to shallow structural levels, within near-horizontal Mesozoic sedimentary rocks, or along the contact between Mesozoic strata and overlying Tertiary volcanic sequences. These outlying intrusions are in distinct geometric contrast to the major caldera-related plutons, which display steeply dipping margins and multi-kilometer-scale vertical extent where exposures are favorable.

As constrained by the widely preserved near-horizontal volcanic cover, no major uplift or other regional upper-crustal deformation resulted from emplacement of the composite batholith inferred from gravity data to underlie much of the central San Juan region. In addition to resurgence localized within some calderas, the crest of the gravity low appears to have localized weak buoyant uplift and extension (Steven and Lipman, 1976). Modest broad uplift and extension is suggested by locally increased outward dips (only a few degrees at most) of ignimbrite sheets and by graben faults, beyond limits of individual calderas, which record distension over the eastern parts of the inferred batholith. Total buoyant uplift indicated by such structures is a few hundred meters at most, an amount inadequate to accommodate any substantial volume of inferred SRMVF batholiths (Lipman, 1988). Although the Southern Rocky Mountains contain the highest terrain in the regionally elevated western U.S. Cordillera, deep parts of the Bouguer gravity low in Figure 6 coincide more with the topographically subdued headwater basin of the Rio Grande than with peaks along the Continental Divide that bound this basin.

Volcanic and underlying strata exposed adjacent to margins of larger plutons in the SRMVF typically are abruptly truncated, without deflection or other structural evidence of deformation involved in generating space for intrusion. In the absence of major buoyant uplift, much of the space for pluton emplacement at upper-crustal levels must have come from large-scale stoping, for which caldera subsidence is perhaps one manifestation. At somewhat lower intrusive levels (>2–3 km?), buoyant rise of sequential

magma batches, likely accompanied by modest ballooning of the dominant mass of crystal mush during late pluton consolidation, may have contributed to emplacement, as inferred widely for plutons exposed in the Sierra Nevada batholith (Paterson and Vernon, 1995; Žák and Paterson, 2005). Additionally, gravitational loading of the upper crust by volcanic eruptions and associated pluton emplacement seems necessarily to have generated substantial crustal subsidence beneath the evolving volcanic-plutonic system (Lipman, 1988; Glazner and Miller, 1997), in a mode comparable to the processes that have caused many kilometers of seafloor crustal subsidence beneath large basaltic volcanoes such as those of the Hawaiian Islands (Moore, 1987). Such subsidence of crust beneath a batholith in effect represents simple material exchange, as magma from the mantle and lower crust is transferred to solidify at shallower levels. Mafic residua, remaining from lower-crustal fractionation to produce granitic compositions at shallow levels, are likely to have become sufficiently dense to lose their crustal identity, either to sink into the mantle as the gravitational anchors (Shaw and Jackson, 1973; Arndt and Goldstein, 1987), through wholesale delamination of the lower crust (Arndt and Goldstein, 1989; Kay and Kay, 1993), or simply by becoming so dense that such residua are geophysically indistinguishable from underlying mantle.

RAPID MAGMATIC EVOLUTION IN SUBCALDERA CHAMBERS OF THE SRMVF

In addition to evidence for assembly of caldera-related magma bodies over multimillion-year intervals from precursor volcanism during waxing of an ignimbrite magmatic cycle to postcaldera intrusions during waning stages, recent field and geochronologic studies have documented rapid short-term variations in erupted compositions of caldera-related magmas.

One type of variation is due to concurrent open-system involvement of multiple compositional inputs to a high-level caldera-related chamber. For example, the culminating 7.7 ka ignimbrite eruption at Crater Lake involved two distinct magmas: high Sr and low Sr (Bacon and Druitt, 1988). Similarly the 27.5 Ma eruption of the Carpenter Ridge Tuff in the central San Juan Mountains, in addition to a compositional gradient from early crystal-poor rhyolite to later crystal-rich dacite, contains late-erupted scoria of alkalic andesite that plot on divergent variation trends (Dorais et al., 1991). The magma chamber for the 34.3 Ma Grizzly Peak Tuff in the Sawatch Range is interpreted to have contained at least seven distinct compositional

units, as recorded by grouped pumice compositions (Fridrich and Mahood, 1987).

In contrast, rapid sequential alternations in magma-chamber composition are recorded by successive ignimbrite eruptions from the central San Juan caldera complex (Table 1). Following upon the enormous eruption of Fish Canyon Tuff (uniform hornblende-bearing crystal-rich dacite) at 28.0 Ma, three successive ignimbrites of large volume (100–1000 km^3), that are each petrologically distinct, erupted from overlapping caldera sources nested within the La Garita caldera area during an interval of less than 0.2 m.y. The compositionally zoned Carpenter Ridge Tuff at 27.55 ± 0.05 Ma was followed by eruption of the Blue Creek Tuff, a contrasting crystal-rich dacite that lacks sanidine and accordingly cannot be dated with precision. Overlying the Blue Creek Tuff and bracketing its age is the distinctive Wason Park Tuff, an alkalic crystal-rich rhyolite that is unique among San Juan tuff sheets. It erupted at 27.44 ± 0.03 Ma, after which its source South River caldera filled to overflowing with a >1-km-thick sequence of andesite-dacite lavas.

Even more tightly constrained (Lipman and McIntosh, 2006b) are time-compositional variations among the youngest ignimbrites and associated lavas erupted from the central San Juan cluster (Table 3). Three ignimbrites, which erupted sequentially from the San Luis complex, are bracketed between 26.92 ± 0.05 Ma (Rat Creek Tuff) and 26.91 ± 0.03 Ma (Nelson Mountain Tuff). The lower and upper tuffs are each compositionally zoned from crystal-poor rhyolite upward into clinopyroxene-bearing dacite, but the intervening Cebolla Creek Tuff is a contrastingly uniform mafic dacite (62%–64% SiO_2) that contains abundant hornblende and lacks sanidine. Despite the relatively mafic composition of the Cebolla Creek Tuff, its source caldera was filled by thick flows of crystal-poor sanidine rhyolite prior to eruption of the Nelson Mountain Tuff. In contrast, the subsided vent area for the Nelson Mountain Tuff was

filled to overflowing by andesite lavas erupted from a central volcano concurrently with caldera resurgence. As a further complexity during this event, magma drained laterally from beneath the Cochetopa caldera (from which no ignimbrite erupted directly) to participate in the Nelson Mountain eruption 30 km to the southwest (Lipman and McIntosh, 2006a). After subsiding, the Cochetopa Park caldera was partly filled by several thick flows of crystal-poor to aphyric rhyolite with analytically indistinguishable ages averaging 26.86 ± 0.04 Ma, only slightly younger than the Nelson Mountain Tuff. Finally, centered 25 km farther south in the central caldera cluster, the morphologically beautifully preserved Creede caldera erupted the Snowshoe Mountain Tuff, which is another mafic dacite dated at 26.87 ± 0.03 Ma. These repeated eruptions of petrologically diverse rhyolites and dacites within a time span of no more than 0.05–0.1 m.y., from overlapping source areas within the La Garita caldera, document continuing high-power recharge of a composite magmatic system a million years after peak ignimbrite eruptions (Fish Canyon Tuff) in the central San Juan region. Analogously, at the Platoro caldera complex in the southeast San Juan Mountains, four large ignimbrite sheets (and numerous smaller ones) erupted from a single magmatic locus within ~0.5 m.y. (Table 4), after which a final large-volume tuff sheet (Chiquito Peak) erupted after a 0.4 m.y. repose interval (Lipman et al., 1996).

Such rapid sequential ignimbrite eruptions from multicyclic caldera systems, though on smaller volumetric scale, are especially well documented at Aso in Japan and Santorini in the Aegean. At Aso, four ignimbrite sheets with a cumulative volume of ~300 km^3 erupted at 270, 140, 120, and 90 ka (Nakada et al., 2003). At Santorini, at least four overlapping caldera collapses were each associated with explosive eruptions of silicic tuff with volumes of several tens of kilometers, at 203, ca. 100, 21, and

TABLE 3. RAPID SEQUENTIAL ERUPTION OF LATE TUFF SHEETS, CENTRAL SAN JUAN REGION (SAN LUIS–COCHETOPA CALDERA COMPLEX, CREEDE CALDERA)

Unit	Composition	Caldera	Vol. (km^3)	Age (Ma)	No. samples
Snowshoe Mtn Tuff	dacite	Creede	>500	26.87 ± 0.03	5
Cochetopa lavas	high-Si rhy	Cochetopa	2–3	26.86 ± 0.04	6
Nelson Mtn Tuff	rhy - cpx dacite	San Luis 3	>500	26.91 ± 0.03	7
Cebolla Creek Tuff	hbl dacite	San Luis 2	>250	[no sanidine]	–
Rat Creek Tuff	rhy - cpx dacite	San Luis 1	>150	26.92 ± 0.05	3

Note: Ar-Ar single-crystal laser fusion ages are from W. McIntosh (2006, written commun.). Four large-volume tuff sheets and interlayered lavas document rapid petrologic evolution in a subvolcanic batholith: tuffs are diverse in composition, but erupted within ~50 k.y. Batholithic-scale subcaldera magma chambers can evolve petrologically and change from dormant to active more rapidly than previously documented. Abbreviations: rhy—rhyolite, cpx—clinopyroxene, hbl—hornblende.

3.6 ka (Druitt et al., 1999). At both these caldera centers, as in the San Juan Mountains, explosive eruptions of silicic tuff alternated with more quiescent emplacement of intermediate-composition lavas. At the Taupo center in New Zealand, ignimbrites erupted even more frequently during the late Pleistocene and Holocene (Wilson, 1993), although most eruptions were much smaller in volume than the mid-Tertiary tuffs in the SRMVF. Such polycyclic sequences document both the rapidity with which caldera cycles wax and wane, reflecting the short life spans of upper-crustal chambers, and also their propensity for sustained activity as repeated open-system recharge reinvigorates a dormant upper-crustal system.

COMPARISONS WITH MESOZOIC CORDILLERAN BATHOLITHS

The Mesozoic Sierra Nevada, the largest batholith within the U.S. Cordillera, has long been recognized to contain a mosaic of plutons distinguishable by composition, texture, and discontinuities in mineral foliation (Cloos, 1935; Hamilton, 1956; Bateman, 1992). Compositions vary from gabbro to granite; granodiorite and granite are by far the most voluminous. Groups of plutons were emplaced in several pulses, mainly from 160 to 85 Ma (Chen and Moore, 1982). Individual plutons in the central Sierra Nevada vary in shape from subequant to highly elongate, as much as 60 km across. Marginal contacts are commonly steep where exposed in rugged terrain, but original shapes of many older plutons have been obscured and otherwise complicated by later intrusions. This is in contrast to other parts of the Mesozoic Cordilleran batholith belt (western Sierra foothills, Klamath Mountains, and farther north in Oregon and Washington), where metamorphic country rocks surround discrete plutons with concentric internal structures (e.g., Compton, 1955; Davis et al., 1965; Taubeneck, 1957).

Textures and structures within plutons can be particularly informative about emplacement history. Many young or isolated Cordilleran plutons that have not been disrupted by later intrusions or overprinted by regional strain have relatively simple concentric foliation trends defined by multiple mineral phases and elliptical mafic inclusions. Such textures, which are parallel to and most strongly developed near contacts, suggest late pluton-wide flowage of magma that contained abundant crystals (Paterson et al., 1998). Lack of conspicuous mineral foliations in some Sierran plutons, similar to shallower subvolcanic intrusions, suggests limited crystallization prior to final emplacement and solidification. In places, foliations trend across abrupt compositional boundaries, mapped as contacts between separately emplaced plutons; such features may indicate joint flowage of successively emplaced separate magma batches. Within some plutons, sharp contacts become gradational along strike. Others contain irregular or crosscutting foliation trends suggestive of multistage flowage and complex emplacement histories (e.g., Cloos, 1935; Hamilton, 1956; Paterson and Vernon, 1995).

Particularly revealing of coherent pluton-wide flowage are isolated plutons that are concentrically zoned in composition, with more pronounced mineral foliations near margins and weaker interior foliations in which fewer mineral phases participate. For example, at the 15 × 20 km Jurassic Canyon Creek pluton in northwestern California (Davis et al., 1965), biotite, hornblende, and plagioclase all define the foliation of marginal quartz diorite, but biotite is randomly oriented in the trondhjemitic interior (Fig. 9). Similar structures and textures have been described for the El Pinal Tonalite, Baja California (Duffield, 1968). Such patterns are plausibly interpreted as the result of the late flowage at a time when the more leucocratic interior contained fewer crystal phases than the margins, and biotite had not yet crystallized. However incrementally magma accumulated to form these plutons, the mineral fabric indicates coherent pluton-wide flowage of a body that contained increasing proportions of melt toward its interior.

Size and Spacing of Plutons and Calderas

In addition to composition, texture, and structure, the size and spacing of plutons in composite batholiths provide evidence for possible relations to ignimbrite eruptions. Contrary to some recent statements (e.g., Christiansen, 2005; esp. Fig. 2), the largest mapped plutons within composite Cordilleran batholiths, such as Half Dome Granodiorite (20 × 60 km) or Mount Givens Granodiorite (15–30 × 80 km) in the Sierra Nevada, or the Butte Granodiorite of the Boulder Batholith (30 × 70 km), are areally comparable to the largest well-documented calderas (e.g., La Garita, 35 × 75 km; Yellowstone, 40 × 60 km; La Pacana, 35 × 60 km; Toba, 30 × 90 km). Smaller plutons are more common, as are smaller calderas. While caldera dimensions (typically measured rim to rim for young calderas and by extent

TABLE 4. DURATIONS AND REPOSE PERIODS, CALDERA-RELATED MAGMATISM, SOUTHERN ROCKY MOUNTAINS (IN Ma)

Area	Precaldera volcanism	Caldera events (no. ignimbrites)	Postcaldera lavas/intrusions
A. Durations			
Lake City	28–23	23.0 (1)	23.0–18
Questa	ca. 32–26	26.5 (1)	26.5–23, 18
Central San Juan	ca. 35–29	28.8–26.9 (9)	26.9–25
West San Juan	ca. 35–29	28.8–27.6.0 (5)	28–23
SE San Juan	ca. 35–29	ca. 29.4–28.4 (5)	28.4–23
Wall Mtn./Mt. Princeton	†	36.7–33.8 (3)	36.6–29.6

Young caldera/tuff	Age (Ma)	Older caldera host	Age (Ma)	Repose period (m.y.)
B. Repose intervals				
Valles, upper tuff	1.23	Valles, lower tuff	1.61	0.48
Lake City	23.3	Uncompahgre	28.2	4.9
Creede	26.87	Bachelor	27.55	0.7
San Luis complex:				
Nelson Mtn.	26.86	Cebolla Creek	26.9	<0.1
Cebolla Creek	26.9	Rat Creek	26.91	<0.1
Rat Creek	26.91	La Garita	28.02	1.1
South River	27.4	La Garita	28.02	0.6
Bachelor	27.55	La Garita	28.02	0.5
Silverton	27.6	San Juan	28.3	0.7
La Garita	28.02	(Masonic Park)	28.8	0.8
Platoro complex:				
Chiquito Peak	28.41	Ra Jadero/South Fork	28.77	0.4
Ra Jadero	28.77	Ojito Creek	29.1	0.3
Ojito Creek	ca. 29.1	La Jara Canyon	29.3	0.2
La Jara Canyon	29.3	Black Mountain	29.4	0.1
Mt. Aetna/Badger Cr	33.8	Princeton/Wall Mtn.	36.7	2.9

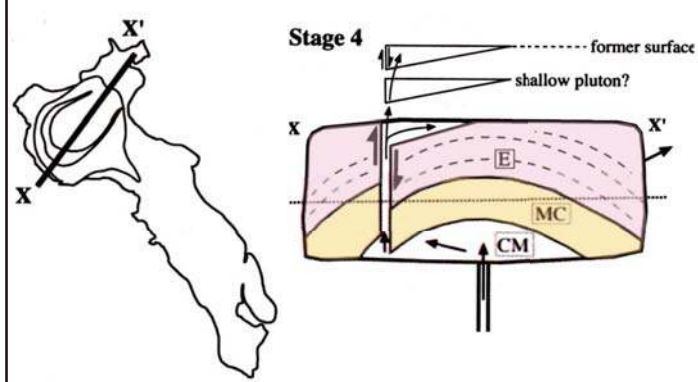†Proximal volcanic rocks entirely eroded.

A Minarets caldera, Sierra Nevada
(Fiske and Tobisch, 1994)
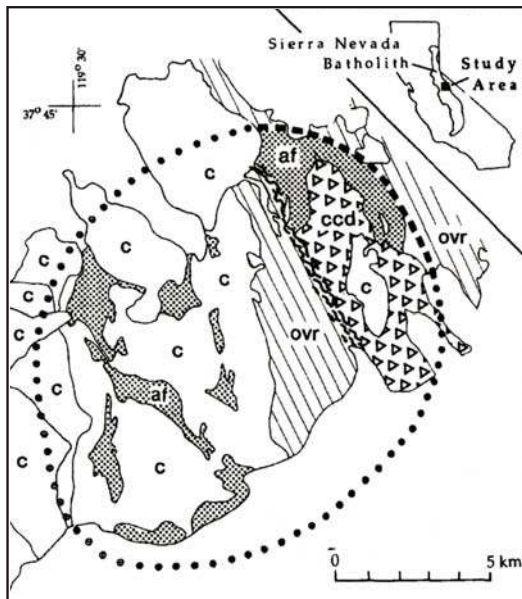
E **Canyon Creek pluton:** Mafic margin; trondjemitic interior;
Gradational; no internal contacts; Foliate biotite in margin, but not in interior

MARGIN: 61.5% SiO$_2$ INTERIOR: 73.2% SiO$_2$

□ Plagioclase   ⬡ Biotite   ▬ Hornblende
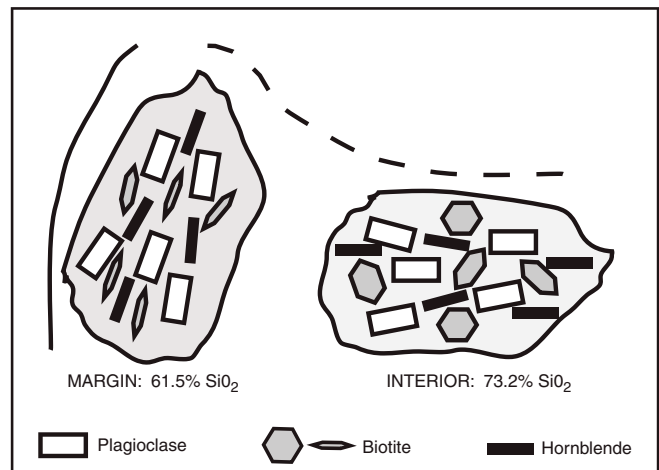
B Mount Givens pluton, Sierra Nevada (McNulty et al., 2000)

D
Canyon Creek
pluton

C Cross section, El Pinal pluton (Duffield, 1968)
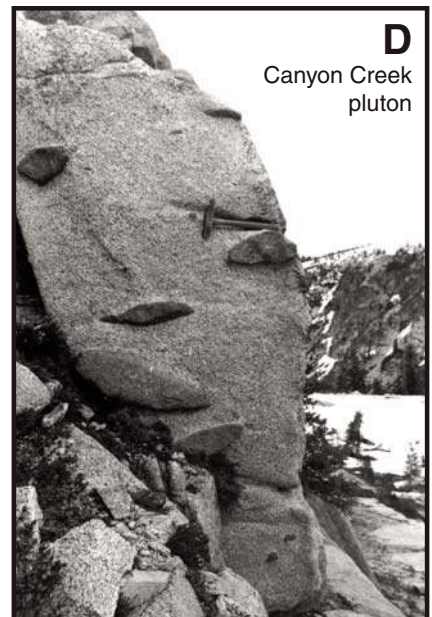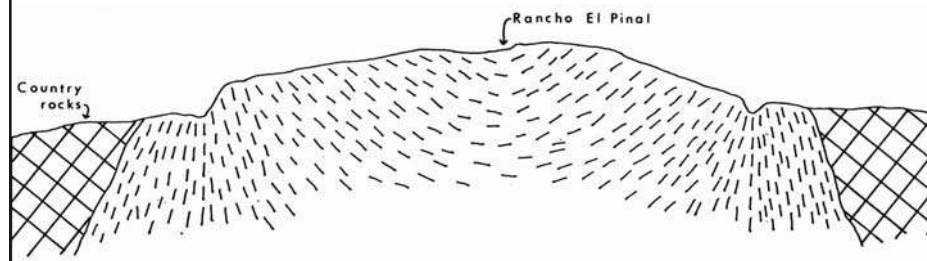
Figure 9. Cordilleran caldera-related plutons. **(A)** Late Cretaceous Minarets Range caldera, Sierra Nevada (Fiske and Tobisch, 1994). af—ash-flow tuff; ccd—caldera collapse deposit; c—coeval granitoids; ovr—older volcaniclastic rocks. **(B)** Mount Givens pluton, with horseshoe-shaped ring dike in northwestern portions, interpreted as possible trap-door caldera subsidence (McNulty et al., 2000). E—equigranular facies; MC—megacrystic facies; CM—Cow Meadow granodiorite.**(C)** Schematic cross section of foliation trends through Cretaceous El Pinal pluton, Baja California, interpreted as the result of caldera subsidence of roof rocks (Duffield, 1968). **(D)** Subhorizontal foliation in Jurassic Canyon Creek pluton (Davis et al., 1965), as recorded by flattened mafic inclusions. **(E)** Diagram illustrating contrasting fabrics in margin and interior of Canyon Creek pluton; plagioclase and hornblende define foliation throughout, but randomly oriented large biotites in pluton interior are interpreted as indicating postflowage crystallization. This pluton has a similar overall cross-section geometry as the El Pinal intrusion (C).

of caldera-fill rocks for older structures) do not directly record the size of the related sub-surface magma chamber, margins of negative gravity anomalies at isolated calderas correspond closely to caldera shape, suggesting that they provide a good measure of an associated shallow subsurface magma cupola.

Spacing between calderas in large composite volcanic fields can also be compared to pluton spacing in batholiths. Some nested confocal caldera complexes of the SRMVF (e.g., Platoro, San Luis) were sites of multiple eruptions and associated subsidences centered around a common point; such recurrent caldera events could

be analogous to emplacement of nested intrusions such as those of the Tuolumne Intrusive Suite. Other calderas in the SRMVF are spaced 40–50 km apart (e.g., Grizzly Peak to Mount Princeton, or Mount Aetna to Bonanza: Fig. 1), comparable to separations between some Sierran plutons of similar age.

The clustering of calderas in the Southern Rocky Mountains is hardly unique, though perhaps especially quantifiable because the deep erosion and absence of subsequent structural complexity expose a relatively complete record of volcanism. Similar Tertiary caldera clusters are present farther south in the less-dissected Mogollon-Datil region (Chapin et al., 2004) and in Nevada-Utah (Best et al., 1989), although they are somewhat obscured by severe Basin and Range extension. Similar size and spacing also characterize the Japanese arc, where numerous Miocene calderas have been recognized despite limited erosional relief and heavy vegetative cover (Fig. 10).

Youngest Sierran Plutons

Older plutons in the Sierra Nevada commonly have been disrupted by younger intrusions, but the youngest intrusions, emplaced at 95–85 Ma (Coleman and Glazner, 1997), preserve intact shapes. Perhaps best studied is the Tuolumne Intrusive Suite, a concentrically nested sequence of mapped plutons, becoming more silicic inward, that have long been thought to have crystallized from large batches of sequentially emplaced magma (Bateman and Chappell, 1979). This interpretation of unified fractionation of cogenetic magma batches was initially brought into question by recognition of isotopic discontinuities between successive intrusive units (Kistler et al., 1986). Recent zircon Pb-U age determinations now indicate that successive units of the Tuolumne Suite were emplaced over an interval spanning 5–10 m.y.; even large individual component plutons such as the 60-km-long Half Dome Granodiorite may have grown and solidified incrementally over several million years (Coleman et al., 2004).

Another structural style of intrusion has produced composite plutons that consist of steeply dipping sheets separated by screens of country rocks (e.g., McNulty et al., 2000; Wiebe et al., 2002; Mahan et al., 2003). These have been variously interpreted as coalescence of multiple dikes or as tilted sequences of magma layers that were initially emplaced subhorizontally. One of these, the McDoogle pluton, also yielded analytically distinguishable ages from component units, perhaps 94–98 Ma (Mahan et al., 2003).

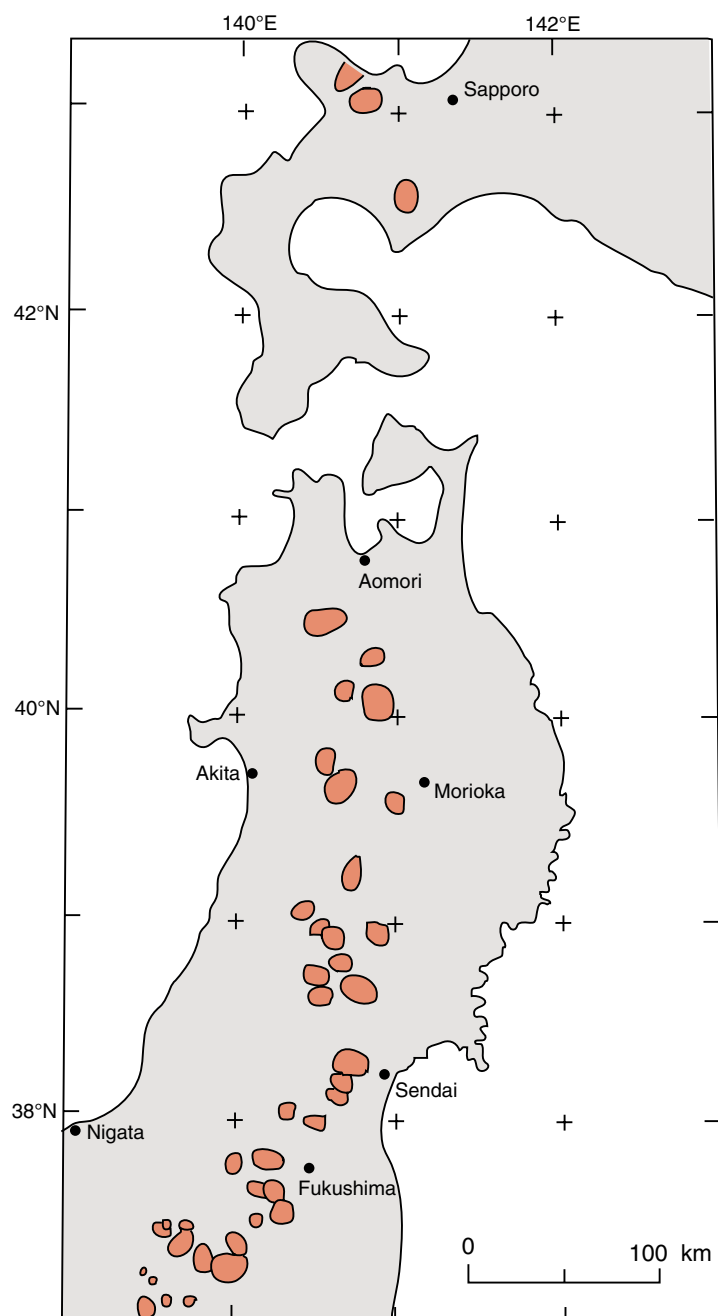Such long time spans for pluton consolidation, which are inconsistent with some thermal

Figure 10. Spacing of known Tertiary calderas in northern Honshu, Japan. The distribution and size of these numerous calderas, along axis of an active arc, are comparable to those of individual granitic plutons in composite Cordilleran batholiths such as the Sierra Nevada in California or the Coastal batholith of the Peruvian Andes. Data were compiled from Ito et al. (1989), Otake et al. (1997), and Yamamoto (1992, 1994).

models for solidification rates of rapidly emplaced upper-crustal magma bodies, have been major lines of evidence for proposals that even large granitic plutons that are broadly homogeneous accumulated incrementally over millions of years, without ever existing as "large tanks" of crystals in magmatic liquid (Glazner et al., 2004; Bartley et al., 2005). Can such interpretations of incremental assembly be reconciled with direct evidence for large-volume explosive volcanism and caldera formation associated with emplacement of Cordilleran plutons? Incremental emplacement need not be an issue; the volcanic fields discussed here all involve successive emplacement of compositionally diverse magmas over comparably long time intervals. But what evidence exists within individual Sierran-type intrusions for episodes of pluton-scale magma bodies that could erupt volcanically?

Associated Volcanism?

For the youngest Sierran plutons, any direct proximal records of associated volcanism have been lost to erosion; present exposure levels appear to represent depths of several kilometers or more below the original surface, as deduced from geologic structure and mineral geobarometry (Ague and Brimhall, 1988). One indication of associated volcanic activity, however, is the widespread presence of large downwind deposits of airborne volcanic ash falls, now exposed as widespread bentonite beds and clay-rich shale in Nevada and Utah. Some of these have been correlated over large areas and dated at 88.3–90.9 Ma by K-Ar, contemporaneous with the youngest Sierran granitic rocks (Elder, 1988). The distribution and thickness of the bentonite beds are comparable with ash-fall deposits that accompanied large-volume late Cenozoic ignimbrite eruptions; these ash beds thus provide direct evidence for voluminous explosive activity during emplacement of Sierran plutons. Farther east and downwind from the western U.S. batholith terrain, Cretaceous shales contain voluminous volcanigenic clay derived from windborne volcanic ash (Schultz, 1965; Hamilton and Myers, 1967; Schultz et al., 1981), offering additional documentation for large-scale explosive volcanism during Cordilleran magmatism.

Less direct evidence indicating that large-scale volcanic deposits existed directly over shallow granitic plutons in the Sierran region comes from volcaniclastic sedimentary rocks contemporaneous with, to slightly younger than, pluton emplacement. Volcanic fragments in Cretaceous sandstones, from lower parts of the Great Valley sequence west of the Sierra Nevada, grade upward to a quartzo-feldspathic assemblage derived from batholithic rocks, with only minor accompanying metamorphic detritus (Dickinson, 1970).

Ignimbrite Calderas Associated with Sierran-Type Plutons

The youngest volcanic deposits in continental settings are stratigraphically highest and likely to erode most rapidly; products of earlier volcanic stages are more likely to survive in the geologic record. In contrast to the Sierra Crest pulse, proximal volcanic deposits associated with older plutons are locally preserved in the Cordilleran region, especially thick accumulations of tuff that were dropped down during associated caldera collapse. Particularly well documented is a 2.3-km-thick section of 98–101 Ma tuff and associated collapse breccias in the Ritter Range caldera (Fig. 9A), which are intruded by the Jackass Lakes pluton, interpreted to be related to caldera resurgence (Fiske and Tobisch, 1994; McNulty et al.,2000). Several thick tuff sequences in older Mesozoic roof pendants have also been interpreted as intracaldera assemblages associated with earlier Sierran plutonism (Busby-Spera, 1984; Saleeby et al., 1990; Schweikert and Lahren, 1999). At the Late Cretaceous Boulder Batholith in Montana, thick welded tuffs of the Elkhorn Mountain volcanics, locally preserved as roof rocks of the large Butte Granodiorite, are contemporaneous with the intrusions in space and time, and they likely are remnants of caldera-fill accumulations (Hamilton and Myers, 1967; Robinson et al., 1968; Fig. 2G in Lipman, 1984).

Ring intrusions, exposed at levels below any preserved volcanic rocks and long interpreted as deep records of caldera formation (e.g., Smith and Bailey, 1968), are additional evidence for calderas associated with Cordilleran plutons. Although associated volcanic rocks are not preserved, a horseshoe ring structure, 15 × 20 km across at the northwest end of the elongate Mount Givens pluton (ca. 90 Ma), has been suggested as the root zone of a caldera structure (McNulty et al., 2000), and several ring intrusions of similar age in the Peninsular Ranges batholith to the south have also been interpreted as subvolcanic caldera structures (Johnson et al., 2002). In a few Mesozoic Cordilleran plutons, mapped synformal foliation basins within large equant intrusions may record subsidence of an overlying roof block during caldera formation (Fig. 9), for example, the Cretaceous El Pinal Tonalite in Baja California (Duffield, 1968) or the Jurassic Canyon Creek pluton in the Klamath Mountains (Davis et al., 1965).

Such fragmentary records of ignimbrite eruption and caldera formation associated with Sierran and other Cordilleran plutons suggest the need for a model of multistage magma assembly and consolidation that can reconcile evidence for incremental pluton assembly with that for associated large-volume volcanism.

AN INTEGRATED VOLCANO-PLUTONIC MODEL

Any large upper-crustal magma chamber must grow incrementally over extended time intervals, whether at fairly steady rates or more episodically, but how does magma-chamber growth relate to surface volcanism, especially for large-volume ignimbrite eruptions? Do ignimbrite chambers develop rapidly in response to brief periods of magma input at high rates without sustained precursor magmatism ("immaculate conception" of ignimbrites), with eruption largely evacuating the source chamber, thus representing processes unrelated to growth of large crustal plutons and composite batholiths (Glazner et al., 2004, 2006; Bartley et al., 2005)? In such interpretations, subvolcanic magma-chamber processes are contrasted to pluton emplacement and batholith development by incremental assembly in small magma batches, without any "big tank" stage, when a large volume of substantially liquid magma was present in the growing pluton. Structural discontinuities, textural and compositional variations, and prolonged age spans interpreted isotopically within mapped plutons are proposed as records of such initial assembly, only partly overprinted by later consolidation processes.

Alternatively, features of continental-margin arcs, as well as the SRMVF, have long been inferred to record lengthy and complex growth histories for volcanic centers and subvolcanic intrusions, some of batholithic scale (e.g., Buddington, 1959; Smith, 1960, 1979; Hamilton and Myers, 1967; Lipman et al., 1978). By such perspectives, volcanoes and plutons provide complementary evidence of prolonged magmatic processes. Volcanic products record sequential snapshots of earlier stages in magma-chamber assembly and multistage evolution. In contrast, solidified plutons are inferred to acquire much of their compositional, textural, and structural character during later-stage consolidation, some even postvolcanic, rather than preserving clear evidence of early magma-chamber assembly (Lipman, 1984, 1992).

Evidence for such large intermittently active upper-crustal magma chambers at Cordilleran ignimbrite centers includes: (1) nested multi-cyclic calderas, with repose intervals of $<10^5$ to 10^6 yr; (2) prolonged intermediate-composition precursor volcanism, with only minor evolved compositions; (3) common culminating eruption

of highly evolved phenocryst-poor rhyolite and compositionally zoned ignimbrites that require complementary crystal residues; (4) compositional trends and mineral assemblages indicative of low-pressure fractionation of ignimbrite magmas in the upper crust; (5) continued eruption of intermediate-composition lavas, similar to the precursor volcanism, during and after generation of sequential ignimbrite sheets; (6) areal association of caldera complexes with upper-crustal batholiths, both directly exposed beneath volcanic rocks and inferred from geophysical data; (7) dominant intrusive compositions that are similar to least-evolved tuffs; (8) geometry of associated granitic plutons with steep bounding contacts and thickness of 10 km or more in the upper crust, rather than thinner floored bodies of laccolith or sill geometry, even though large plutons and composite batholiths must be broadly laccolithic to remain in upper crust; (9) rarity of voluminous basalt, in either volcanic deposits or associated intrusions, indicating effective mixing, at least at exposed levels; (10) coherent late mineral fabrics and concentric compositional zoning in many plutons, indicating pluton-wide flowage processes late in consolidation history; and (11) long-lived geothermal systems at calderas indicative of sustained magmatic recharge.

Whether or not a "big-tank" stage is involved, incremental magma generation and assembly of large silicic igneous bodies, either volcanic or plutonic, generally must be a prolonged process (Jellinek and DePaolo, 2003). Individual arc volcanoes are commonly active for hundreds of thousands of years. Large granitic plutons, like the Half Dome or Butte Granodiorite, with areal dimensions on the order of 2000 km^2 and geophysically estimated thicknesses of 10 km or more for the silicic component alone (Fliedner and Ruppert, 1996), must have upper-crustal granitic volumes on the order of 20,000 km^3, and likely overall volumes several times larger, including more mafic mid- and lower-crustal roots (Ducea, 2001). Growth of such plutons, even if fed continuously by mafic input at rates comparable to the most active volcanoes on earth (0.1 km^3/yr, at hotspot systems such as Kilauea or Mauna Loa in Hawaii), would require on the order of 0.5–1 m.y. at peak magma input. In contrast to the frequent eruptions from such high-power-input basaltic volcanoes, large silicic continental volcanoes erupt episodically (commonly with repose periods of 10^3–10^4 yr or longer), and magma input may be similarly non–steady state. Recent U-Pb and U-Th zircon geochronologic evidence for long magmatic residence times in well-studied volcanic systems (Halliday et al., 1989; Reid et al., 1997; Vasquez and Reid, 2002; Bachmann et

al., 2007b) is consistent with inference of incremental magma assembly and prolonged crystallization histories in subvolcanic chambers. A high-resolution geochronologic study of at least one Cordilleran pluton (Cretaceous Mount Stuart pluton, North Cascades) has documented incremental assembly over a 5 m.y. interval, and a large (>500 km^3) melt-rich magma reservoir present at one stage (Matzel et al., 2006) could be a plausible candidate for association with voluminous volcanism.

How Completely Do Ignimbrite Eruptions Drain Source Chambers?

In light of the diverse magmas erupted to form the SRMVF ignimbrites, a corollary issue is the degree to which ignimbrite eruptions drain their source magma chambers, and what posteruption record of ignimbrite-caldera formation might be preserved at deeper crustal levels. The subsidence geometry of SRMVF calderas indicates that a low-aspect sill-like or lenticular volume of magma tens of kilometers across and at least several kilometers thick erupted to form individual ignimbrite sheets. For the largest calderas, such as La Garita, the geometry of its magma body would have been 30–40 km × 75–100 km in plan view but only a few kilometers thick, if it were to erupt nearly completely without large deeper remnants being preserved in the upper crust. In contrast, petrologic data, such as the more silicic compositions of ignimbrites compared to associated intrusions and lavas (Fig. 7), large compositional zonations within some tuff sheets, and evidence for extreme crystal fractionation to generate rhyolite tuffs (Fig. 11), all require voluminous complementary crystal residues. Such features point to association between evolved ignimbrite compositions and more mafic residual magma that did not erupt. For sequential large-volume ignimbrite eruptions from nested caldera complexes such as Platoro and San Luis in the San Juan Mountains, recurrent cumulative subsidence is interpreted to have been greater than 10–15 km (Lipman et al., 1996; Lipman, 2000). At such sites, the complementary crystal residua would also have been many kilometers thick, plausibly available to constitute the compositions observed in subvolcanic plutons at sites such as Mount Princeton and Questa.

If ignimbrite magma chambers typically erupted and drained nearly completely, where are the predicted residua preserved in the upper crust, in the form of thin laccoliths or sills of cumulate texture granite? Instead, where exposures are sufficient, subcaldera plutons in the SRMVF are steep-sided in their upper parts, without exposed floors, even where cropping

out over vertical distances of a kilometer or more (Mount Princeton, Questa). As an extreme example in southern Russia, upper parts of the Eldjurta pluton, adjacent to the 2.8 Ma Chegem caldera, are exposed for nearly a kilometer vertically in canyon walls, and an exploration drill hole has penetrated an additional 4 km into this intrusion without encountering significant compositional variation or reaching an intrusion floor or other compositional contacts (Gazis et al., 1995). Rather than near-complete eruption of ephemeral tabular magma chambers to form large-volume ignimbrites, such exposures suggest eruption of volatile-rich upper parts of a vertically extensive magmatic system. Below the eruptible cap of evolved magma would lie a dominant mass of crystal mush bounded by a viscosity barrier (Smith, 1979). Residua of mafic magma from the mantle would be yet deeper, along with thermally elevated and compositionally modified crust (Hildreth and Moorbath, 1988; Lipman, 1988; Hildreth, 2004). The presence of such "stacked" magmatic systems is supported by available seismic-tomographic images for young calderas such as Yellowstone and Toba, which show lowered velocities in the upper and middle crust, some of which extend into the mantle (Miller and Smith, 1999; Masturyono et al., 2001).

The ratio of dominant mass to eruptible magma in silicic systems has been estimated to be as high as 10:1 (Smith, 1979; Crisp, 1984), but where an ignimbrite eruption has drained the upper several kilometers of a chamber, as appears likely at many SRMVF calderas, this ratio may be lower (see discussion by White et al., 2006), especially at the time of peak volcanism, even if the vertical extent for solidified granitic plutons in the upper crust is on the order of 10 km or more. A typical vertical zonation in such an active (high-power) upper-crustal magmatic system would include:

1. A buoyant volatile-rich cap of crystal-poor rhyolite as much as several kilometers thick, where repose intervals between eruptions are sufficient for prolonged crystal fractionation and efficient separation of interstitial melt. Such gas-rich, largely liquid magma may drain nearly completely during an ignimbrite eruption; remnants may be preserved as postcaldera lavas or small evolved granites that solidify during waning of the magmatic cycle.

2. A dominant magmatic volume of crystal-rich mush in a rhyolitic matrix liquid; some magma with crystal contents as high as 40%–50% can reach the surface as late-erupted dacite in compositionally zoned tuff sheets, but a large amount remains in the chamber to solidify as granodiorite or granite. When an ignimbrite eruption is triggered before repose is sufficient

to fractionate a rhyolitic cap, probably because high-magmatic-power input rapidly heats and fluidizes the upper parts of a chamber, large volumes of "monotonous-intermediate" dacite can erupt. In caldera complexes that contain multiple nested structures involving cumulative subsidence of 10–15 km, as in the central San Juan region (Fig. 16 Lipman, 2000), repeated fractionation events to generate successive ignimbrite magmas must have been accompanied by thick crystal residues that remained in the subvolcanic magma system and solidified to form subvolcanic granitic plutons.

3. More mafic roots of the system, containing ponded mantle-generated melts that have variably differentiated, reacted with crust, and mixed with earlier-generated silicic magma. Such lower zones are augmented by crystal-fractionation residue, solidified granitoids foundered from sidewall and roof-zone margins, and recrystallized stoped blocks from the chamber roof.

4. A variably reconstructed lower-crustal section below the active magmatic column, which has been thermally elevated and chemically modified by assimilation and melting as mafic mantle magmas ponded or transited to higher crustal levels.

Crustal sites and time scales for such magma-chamber processes are critical uncertainties, and volatile-rich upper-crustal silicic magma bodies must be geologically ephemeral, either erupting or solidifying rapidly. The volatile-rich low-density upper part of such a chamber, with a high proportion of liquid, would be unstable in the upper crust (high volatile content, low density) and likely to either erupt or solidify if maintained as a closed system. But the life of high-temperature subsolidus plutons can likely be much prolonged if they are rejuvenated recurrently by the rise of additional mafic magma.

Such processes, which are especially well documented for the Fish Canyon–La Garita system in the San Juan region (Lipman et al., 1978; Riciputi et al., 1995; Bachmann et al., 2002), are probably common at other multicyclic caldera centers in the SRMVF and elsewhere. Analogous triggering of smaller-scale explosive eruptions by injection of mafic magma has been inferred for the 1991 eruption at Pinatubo in the Philippines (Pallister et al., 1992) and Montserrat in the Caribbean (Murphy et al., 2000; Annen et al., 2006).

A related topic is the relative degree of preservation in subvolcanic plutons of compositional and structural evidence for early incremental assembly of separate magma batches versus late overprinting by magma movements during shallow mixing and fractionation, recurrent volcanic eruptions, associated recharge, solidification of the residua, and subsolidus recrystallization.
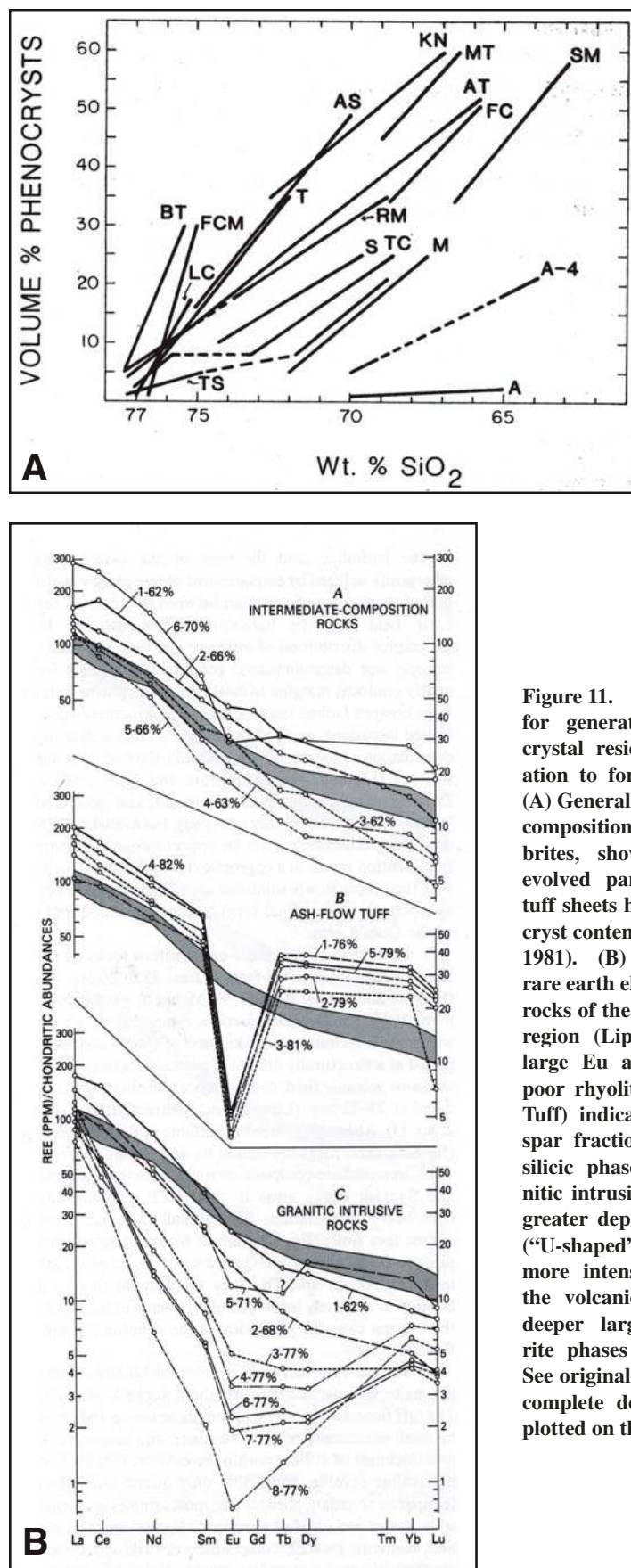

Figure 11. Petrologic evidence for generation of large-volume crystal residues during fractionation to form silicic ignimbrites. (A) Generalized plot for large compositionally zoned ignimbrites, showing that the most evolved parts (highest SiO$_2$) of tuff sheets have the lowest phenocryst contents (Fig. 17 in Hildreth, 1981). (B) Chondrite-normalized rare earth element (REE) plots for rocks of the Questa-Latir volcanic region (Lipman, 1988), showing large Eu anomalies for crystal-poor rhyolite ignimbrite (Amalia Tuff) indicative of extreme feldspar fractionation. Small-volume silicic phases of associated granitic intrusive rocks display even greater depletion of middle REE ("U-shaped" patterns), indicating more intense fractionation than the volcanic rocks. In contrast, deeper larger-volume granodiorite phases lack a Eu anomaly. See original publications for more complete documentation of data plotted on these diagrams.

Most plutons in the SRMVF solidified at their exposed locations after peak volcanism, and these thus preserve mainly records of late consolidation in the subvolcanic environment, with earlier phases of incremental assembly and associated volcanic episodes largely obscured. The sequential record of incremental assembly provided by volcanism for earlier stages of upper-crustal magmatic evolution and the composite record of late-stage consolidation that characterize many plutons probably overlap but are largely complementary.

To be sure, lower parts of some layered plutons, which may never have erupted volcanically, preserve a record of early mafic input and other assembly processes (e.g., Wiebe, 1994; Wiebe and Collins, 1998; Sisson et al., 1996; Miller and Miller, 2002), but the frequency of their preservation remains unclear. For example, roof-to-floor tilt-block exposures of two Tertiary granitic plutons of similar age and dominant compositions in southern Nevada have strongly contrasting compositions and structures (Miller and Miller, 2002). A 10-km-thick pluton consists dominantly of thick granitic units, while a smaller, thinner pluton (~3 km vertically) preserves a voluminous record of mafic input into a felsic chamber. Fractionation, convection, and late consolidation processes probably commonly overprint early incremental-assembly features in large long-lived chambers dominated by high rates of magma supply.

OVERVIEW

Cordilleran magmatism is viewed as a prolonged multistage process that generates diverse upper-crustal plutonic and volcanic products as functions of tectonic setting, duration of magmatic pulses, crustal structure and composition, fluctuating magma-power input, and magma-chamber dynamics in the upper crust. Interactions with thick crust, presence of preexisting lithospheric-scale structural controls, areally focused input of mantle melts, and large-scale fractionation are considered critical to the localized generation and emplacement of voluminous silicic volcanic and plutonic bodies discontinuously along continental-margin arcs during intense episodic magmatic flare-ups. As seen in many recent discussions and models (Fig. 12), Cordilleran magmatism is initiated by the rise of mantle-generated basalt that stalls or ponds at varied levels in the crust, depending on density and thermal structure. Basalt is commonly a major eruptive product along volcanic arcs constructed on oceanic or thin continental crust, but little or no basalt rises through thick crust without modification, unless regional extension is severe. Cordilleran activity is accordingly dominated by intermediate-composition and silicic magmas. Depending on varied crustal structure and the time span, episodicity, and scale of magmatic power input, various igneous loci have undergone a broad spectrum of evolutionary histories, but most contain distinct waxing and waning stages, and many Tertiary volcanic areas include a peak-power-input episode of ignimbrite eruptions (Fig. 12; Table 5).

Waxing Stage

During waxing stages of Cordilleran magmatism, when thermal gradients are initially near the normal cratonic geotherm, mantle basalt ponds mainly in the lower and middle crust, where relatively small volumes of intermediate-composition derivative magmas (mainly calc-alkaline andesite) are generated by assimilation, melting, and mixing with crustal components (Hildreth and Moorbath, 1988; Johnson, 1991). The rise of andesitic melts in small episodic batches initially leads to eruptions of compositionally relatively uniform lavas (commonly with low crystal contents) from geographically scattered central volcanoes, without prolonged storage or crystal fractionation in upper-crustal chambers (Fig. 12: I-A, III-A). Mantle production of basalt is probably at rates more nearly steady state than the intermittent surface eruptions. With time, the focusing of magmatism at favorable structural sites leads to clusters of volcanic vents, rising thermal gradients in the crust, initial storage and shallow fractionation of magma in the upper crust, and small-volume eruptions of more-evolved compositions (commonly crystal-rich dacite). During repeated episodic rise of magma batches, some magma begins to stall in the subvolcanic environment and solidifies as small, texturally variable plutons that are compositionally similar to associated dominant andesite and dacite erupted as lava. During this stage of relatively low-power magma input, upper-crustal bodies grow incrementally as small stocks along conduits beneath central volcanoes and as flanking laccoliths at levels of near-neutral density (Fig. 12: I-A, III-A). In the absence of periods when large volumes of melt are present, emplacement structures can be preserved. Large shallow magma chambers or plutons do not form at this stage, and many of the intermediate-composition lavas may have erupted directly from middle- or lower-crustal sites. Erosional levels in the SRMVF are insufficiently deep to directly investigate middle-crustal processes, and the Tertiary age of magmatism precludes any readily detectable seismic tomographic signature for such activity.

With continued magmatism, the subvolcanic geotherm slowly rises, and broad portions of the crustal column gradually change in physical and compositional character. Mantle magma-power input increases and becomes focused along favorable crustal structures during the transition from precursor andesitic volcanism to more silicic ignimbrites. Higher crustal temperatures also permit more interaction between mantle-derived basalt and crustal country rocks, which leads to generation of larger volumes of melt capable of rising into the upper crust and more fractionated magma. As increasing proportions of the rising magma stall in the subvolcanic crust, large composite plutons assemble in multistage increments (Fig. 12: II). As magma production increases, incremental open-system input to growing upper-crustal plutons maintains near-solidus temperatures for time intervals far longer than if emplacement proceeded rapidly as closed systems followed by conductive or convective cooling.

Ignimbrite Stage

Eventually, growing and coalescing shallow plutons at structurally favored loci in the upper crust permit segregation of a melt-rich volatile-enhanced cap of sufficient volume and areal extent to initiate large ignimbrite eruptions and attendant caldera subsidence (Fig. 13). Density, thermal, and structural considerations require that such volatile-rich upper-crustal silicic magma bodies are geologically short-lived; they either erupt or solidify. In parts of the SRMVF, such as Questa or Bonanza, only a single ignimbrite erupted, and this was followed by prolonged emplacement of small lava flows and solidification of shallow plutons during waning phases of the magmatic locus. In other places, such as the central, western, and southeastern San Juan caldera clusters, geologically rapidly erupted ignimbrite sequences from clustered or multicyclic calderas attest to more sustained periods of episodic high-power magma input at upper-crustal levels. At sites of recurrent ignimbrite eruptions, the emplacement of less-evolved caldera-fill lavas of small volume documents intermittent consolidation of the subcaldera magma chamber between briefer periods when eruptible magma was present on a caldera-wide scale.

Large-volume ignimbrite magmas of evolved phenocryst-poor rhyolite (to >1000 km^3) appear to be a signature of shallow fractionation in thick mature crust, as indicated both by phenocryst assemblages and by liquid compositions that plot at experimentally determined low pressures for simple granite-rhyolite systems. Such continental rhyolites commonly are closely associated with dacite, both as zonations within single tuff sheets and in sequential large eruptions.
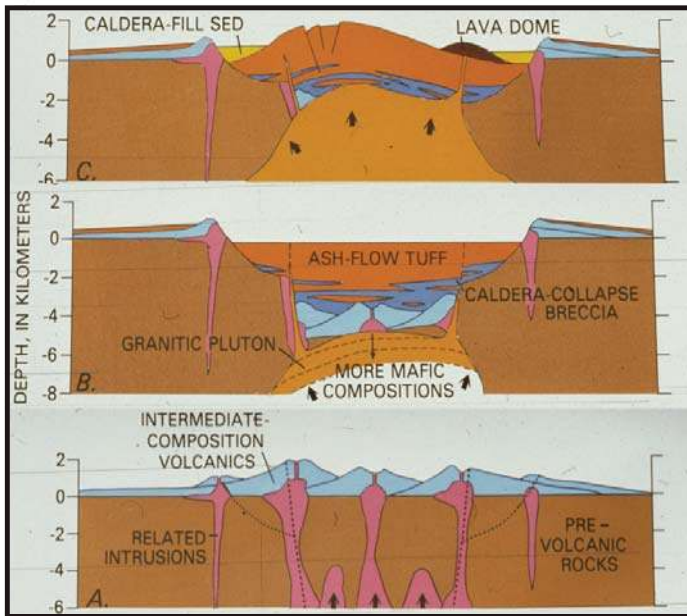
I. Caldera evolution, San Juan region (Lipman et al., 1978)
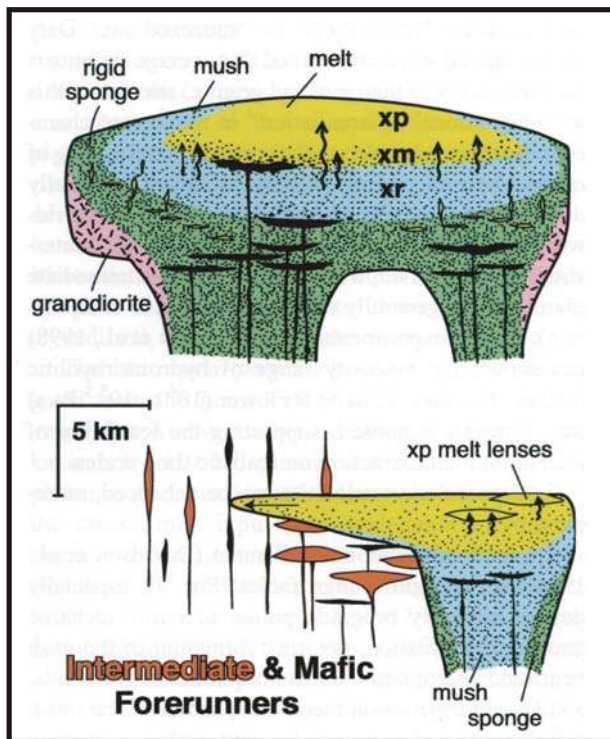
II. Precaldera evolution, Long Valley system
(Hildreth, 2004): xp, crystal-poor mobile melt (0-5%);
xm, intermediate crystal content; xr, crystal-rich (15-55%)
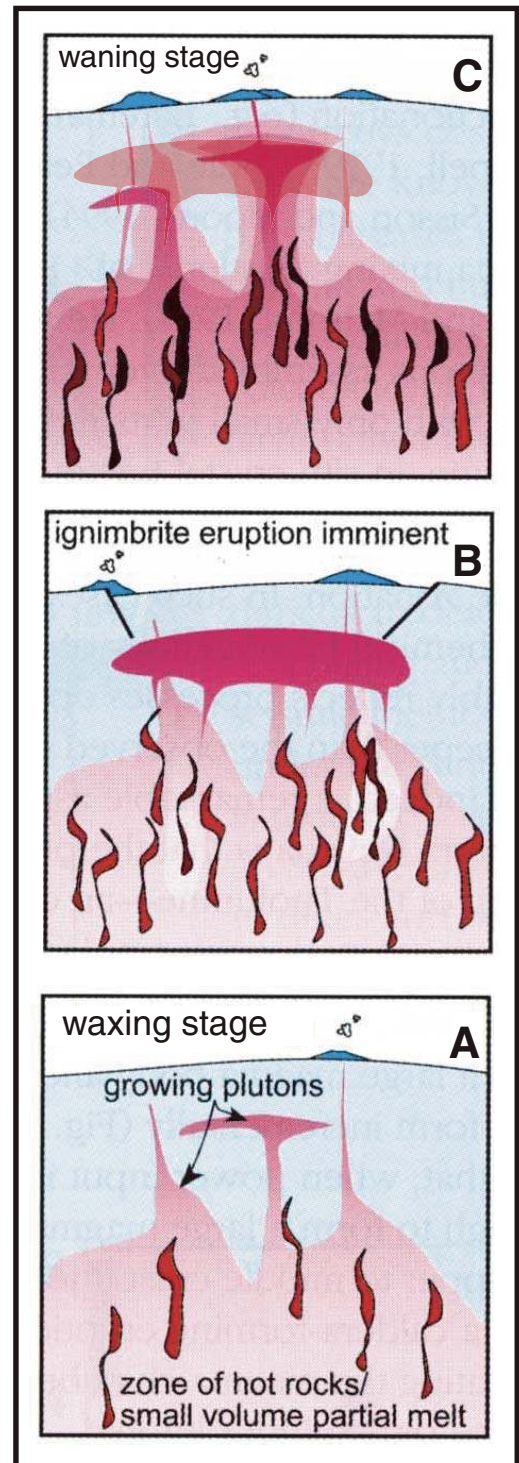
III. Magma-chamber growth (rearranged
and modified from Glazner et al., 2004)

Figure 12. Models of magma-chamber evolution in relation to volcanic eruptions and evolution of underlying plutons. (I) Inferred caldera growth and ignimbrite-related magma-chamber evolution, San Juan volcanic region (Lipman et al., 1978). (II) Inferred evolution of Long Valley magmatic system preparatory to ignimbrite eruption and caldera formation (Hildreth, 2004). (III) Model of pluton growth rearranged from Glazner et al. (2004, their Fig. 6) to reconcile more unified volcanic-plutonic evolution with inferred dichotomy between ignimbrite volcanism and pluton growth inferred by these authors. See original publications for more detailed discussion of interpretations illustrated by these diagrams.

TABLE 5. ESTIMATED MID-TERTIARY MAGMA VOLUMES, SAN JUAN VOLCANIC REGION (×10³ km³)

Age	Lava flows and breccias		Ash-flow tuff		Estimated intrusive volumes		Total
(Ma)	Per m.y.	Cumulative	Per m.y.	Cumulative	Per m.y.	Cumulative	Per m.y.
36		0		0	0	0	0
35	1	1		0	0.3	0.3	1.3
34	2	3		0	0.7	1	2.7
33	2.5	5.5	0.5	0.5	2	3	5
32	3	8.5	0.5	1	2	5	5.5
31	4	12.5		1	3	8	7
30	4	16.5		1	5	13	9
29	3	19.5	1	2	10	23	14
28	2	21.5	3	5	15	38	20
27	1.5	23	7	12	30	68	38.5
26	1	24	2.5	14.5	10	78	13.5
25	0.5	24.5		14.5	5	83	5.5
24		24.5		14.5	5	88	5
23	0.5	25	0.5	15	5	93	6
22		25		15	3.5	96.5	3.5
21		25		15	2.5	99	2.5
20		25		15	1	100	1
Total:	25		15		100		140

Examples include the Sapinero Mesa, Fish Canyon, and Carpenter Ridge Tuffs in the San Juan region, and ignimbrites of the La Pacana caldera in the Andes (Lindsay et al., 2001; Schmitt et al., 2003). In general, the more evolved the rhyolite, the lower its crystal content. In contrast, associated dacites in the SRMVF are overwhelmingly crystal rich (20%–40%). Such recurrent alternation of dacite and rhyolite during ignimbrite vol-

canism is interpreted to indicate continued presence or rapid regeneration of voluminous crystal mush, compositionally similar to granodiorite, in the source chambers throughout peak volcanism. Such associations also strongly suggest highly efficient separation of liquid from a crystal residue, perhaps critically related to the volatile phase (Sisson and Bacon, 1999; Bachmann and Bergantz, 2004). Alternative interpretation

of such SRMVF rhyolitic melts, dominantly as low-degree partial melting of Proterozoic crust, seems to be precluded by isotopic compositions that, though slightly elevated in the most-evolved Tertiary rhyolites, should be drastically more radiogenic if derived primarily from old crustal rocks (Johnson, 1991; Riciputi et al., 1995).

Such evolved compositions and volumes of rhyolite are unknown in intra-oceanic and young volcanic arcs. Recent experimental results indicate that rhyolitic melts are a normal end-stage differentiate from fractionation of moderately water-rich basaltic magma (Sisson et al., 2005); modeling suggests that such processes can occur within the lower crust (Annen et al., 2006). Such high-pressure melts may well contribute to the growth of upper-crustal chambers, but they would seem likely to stall and crystallize within the crust as volatiles separated at lower pressures unless small batches rose rapidly to the surface soon after generation. The widespread sequence of precursor lavas in the SRMVF from aphyric or crystal-poor andesite succeeded by porphyritic dacite and locally crystal-poor rhyolite may record progressive crystallization and fractionation in stalled mantle-derived magmas prior to inception of ignimbrite eruptions.

Other large ignimbrites in continental volcanic fields consist of monotonously uniform less-evolved compositions (Hildreth, 1981); these typically are crystal-rich dacites, such as the Fish Canyon Tuff from the SRMVF, dacite tuffs from
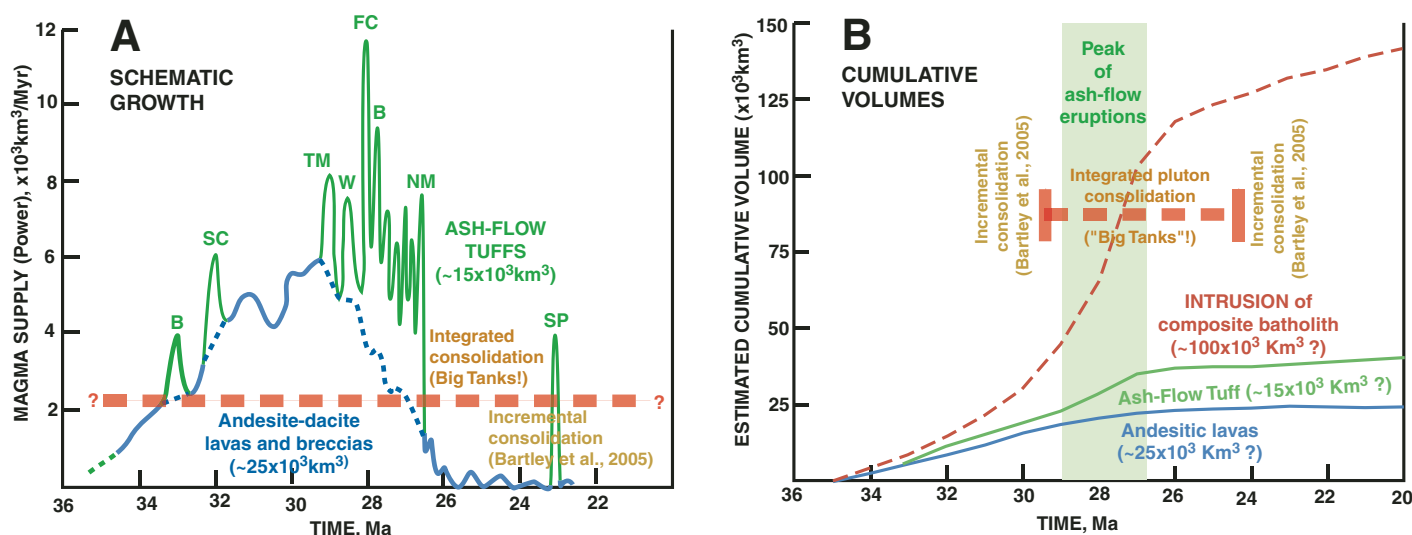

Figure 13. Volume and power input versus time for mid-Tertiary magmatism in the Southern Rocky Mountain volcanic field (interpreted volumes are from Table 5). (A) Schematic growth of the volcanic field, showing variations in magma supply with time in relation to frequent eruption of intermediate-composition lavas (blue lines) and more episodic eruption of voluminous ignimbrite sheets (green lines). (B) Plot of cumulative volumes, including intrusions that are inferred from gravity data to be at least three times greater in volume than the volcanic deposits. Red dashed lines demark inferred times of highest magma-power input, during which large integrated magma chambers ("large tanks") are inferred to have been capable of supplying recurrent ignimbrite eruptions. At lower magma-power input, plutons are inferred to have solidified more nearly concurrently with incremental magma additions, precluding sustained presence of "large tanks."

the Indian Peaks volcanic field in Utah (Best et al., 1989; Maughan et al., 2002; Christiansen, 2005), the Atana ignimbrite of La Pacana (Lindsay et al., 2001), and the Cerro Galan ignimbrite in Argentina (Francis et al., 1989). Such tuffs, which have mineralogy and bulk compositions similar to granodiorite, have been interpreted as representing rejuvenation and eruption of near-solidus batholithic-scale chambers, events triggered by mafic inputs (Bachmann et al., 2002; Bachmann and Bergantz, 2003).

Under conditions of high-power input to growing subvolcanic chambers during the ignimbrite stage, large volumes of melt can accumulate, fractionate, permit convective flow, and modify the density structure of initially emplaced subhorizontal magma bodies. Modest-scale ballooning or diapiric rise of evolved melt leads to pluton geometries that are vertically elongate, steep-sided, and characterized by upward concentration of evolved melt and volatiles, which sets the stage for ignimbrite eruptions. Such upper-crustal processes would obscure compositional and textural features of initial incremental emplacement, especially at upper levels in an evolving chamber.

Contrasts between relatively primitive arc systems dominated by andesitic compositions and small plutons versus more silicic volcanic fields and associated batholiths probably reflect intertwined contrasts in crustal thickness and magmatic-power input. Lower power input would lead to a Cascade- or Aleutian-type arc, where intermediate-composition magmas erupt directly from middle- and lower-crustal storage without the development of large shallow plutons. Andean and Rocky Mountain systems begin with similar intermediate-composition volcanism, but increasing magma production, perhaps triggered by abrupt changes in plate boundary conditions and localized by structural flaws in thick crust, leads to the development of larger upper-crustal reservoirs, more silicic compositions, large ignimbrites, and batholiths.

Waning Stage

As magma supply from the mantle decreases, amounts of eruptible magma diminish in upper-crustal chambers, chambers become smaller, and eruptions dominantly generate lava flows. Resurgent uplift of some caldera floors records rise of residual magma without accompanying ignimbrite eruption (Fig. 12: I-C, III-C). Much erupted magma is intermediate composition: dacite similar to late-erupted parts of ignimbrite sheets or andesite similar to lavas erupted earlier during waxing stage of volcanism. Some SRMVF caldera systems appear to have never developed large silicic upper-level chambers,

or large postvolcanic granitic intrusions, as evidenced by dacitic ignimbrite compositions, dominance of intermediate-composition eruptions in caldera-fill sequences, and absence of present-day gravity expression (e.g., Plataro: Fig. 6). At others, in contrast, small volumes of evolved crystal-poor rhyolite erupted as flows and domes indicate continued shallow crystal fraction, especially as intervals between eruptions increase.

Emplacement of small silicic intrusions and local surface rhyolite flows commonly continues long after peak ignimbrite eruptions (Table 4); some in the Sawatch Range are as young as 29 Ma (Mount Antero Granite, Nathrop Rhyolite), 8.5 m.y. after initial large-volume ignimbrite generation (Fig. 8). Late rhyolites in the San Juan region, localized in the vicinity of earlier ignimbrite calderas, are also present at Platoro (at 23 Ma), Silverton (as young as 10 Ma), and Lake City (19 Ma). The total span of the San Juan magmatic pulse, including such rhyolites, is thus ~15 m.y. Some small intrusive bodies of rhyolite, granite, and aplite emplaced during waning stages of magmatism are more evolved than the previously erupted silicic ignimbrites in the SRMVF, presumably because high thermal gradients in the aftermath of peak upper-crustal magmatism permitted sustained crystal fractionation. These are characterized by especially low contents of compatible elements like Sr and Ba and by chondrite-normalized depletion of middle rare earth elements (REE) making "U-shaped" plots (Lipman, 1988; Hannah and Stein, 1990). Contrary to prior inferences of relatively higher fractionation for rhyolites than associated granites (Halliday et al., 1991; Bachmann and Bergantz, 2004), such intrusions, especially those hosting molybdenum deposits, are more evolved than any large-volume rhyolitic ignimbrites, as evidenced by their depletion of Sr, Ba, and middle REE contents (Fig. 11).

One unresolved issue, which can only be considered briefly here, is the location and identity of the residue complementary to such evolved compositions. Intermediate-composition lavas and shallow granodioritic intrusions in the SRMVF typically lack Eu anomalies or broader REE enrichment. Is crystal residue from rhyolite fractionation therefore present at deeper levels than those sampled by erupted andesitic-dacitic lavas or presently exposed in subvolcanic plutons? Alternatively, do the much larger volumes of nonerupted magma in a vertically extensive pluton dilute effects of trace-element fractionation in the shallow volcanically erupted portions to levels that are obscure in later-emplaced magmas, either volcanic or plutonic? Additionally, because the SRMVF volcanic rocks are widely interpreted (from isotopic data) as blends

of mafic mantle melts with small-fraction partial melts from the lower or middle cratonic crust (Lipman et al., 1978; Johnson, 1991; Riciputi et al., 1995), could continuing open-system recharge buffer trace-element compositions of the large-volume crystal mush in subvolcanic magma chambers, maintaining a residua with little or no Eu anomaly?

Another interpretive problem is the geometry and overall size of the upper-crustal batholith beneath a volcanic region, such as the San Juan Mountains, during waning stages versus that at the time of peak volcanism. Large-scale caldera collapse and requirements for storage of residua from fractionation of evolved magmas show that high-level "large-tank" magma chambers existed, but resurgent intracaldera uplift and other intrusive activity at many calderas document further evolution of the underlying magmatic system. Additional magma from mantle and lower-crustal sources was almost certainly added during waning stages. Though difficult to quantify, peak volumetric assembly of the subvolcanic batholith seems likely to have coincided with peak volcanic throughput during the ignimbrite stage of activity (Fig. 13B), but completion of pluton assembly and solidification likely was prolonged.

These interpretations suggest that the central San Juan calderas or the Mount Princeton-Aetna subcaldera intrusions could be shallow analogs of the Tuolomne Intrusive Suite in the Sierra Nevada or the Butte Granodiorite in Montana. The San Juan gravity low is geometrically comparable to the Boulder batholith, and the composite SRMVF could be analogous, on a somewhat smaller scale, to a segment of the Sierra Nevada batholith.

Similar interpretations have been recently advanced for the well studied Altiplano-Puna volcanic complex (APVC), a representative segment of the central Andes (de Silva, 1989; Lindsay et al., 2001; Schmitt et al., 2003; de Silva et al., 2007; de Silva and Gosnold, 2007). The SRMVF and APVC are similar in geometric scale, eruptive style, and petrology. Both involved eruption of numerous dacite to rhyolite ignimbrites with volumes >100 km³ (about 30 in the SRMVF, at least 15 in APVC). 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 60 km or more across. Area covered in both regions is on the order of 70,000 to 100,000 km², during eruptive activity of ~10 m.y. (37–26 Ma in the SRMVF, 10–1 Ma in the APVC). Cumulative magmatic volume of ignimbrites is about 15,000 km³ for the SRMVF, about 12,000 km³ for the APVC,

and estimated peak magma-production rates are as high as 8,000 km³/m.y. for the SRMVF, 12,000 km³/m.y. for the APVC. Calderas in both areas are associated with pre-and post-caldera andesitic to dacitic lava eruptions, though the pre-ignimbrite volcanism in the APVC is less well known because of smaller amounts of post-volcanic 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 APVC and the SRMVF lie along the east margins of broad long-lived Cordilleran magmato-tectonic zones, associated with plate convergence and low-angle subduction. The APVC 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 SRMVF, plausibly because of its greater age.

One puzzle emerging from such interpretations of large upper-crustal magma bodies is the limited geophysical evidence for voluminous magma beneath Quaternary calderas. Calderas in the western United States, such as Long Valley, Yellowstone, and Valles, are all characterized by various geophysical signatures of elevated subsurface temperatures that extend deep into the crust and perhaps into the lithospheric mantle (e.g., Iyer, 1984; Steck et al., 1998; Miller and Smith, 1999). At Long Valley, cupolas inferred to contain small proportions of magma have been identified at depths of 6–9 km beneath the resurgent dome (Sanders et al., 1995), and crustal seismic-wave delays at depths of 20–25 km beneath Long Valley have been interpreted as indicative of deeper residual melt (Dawson et al., 1990; Weiland et al., 1995). No signature has been detected, however, for any voluminous shallow bodies of largely liquid magma comparable to the crystal-poor rhyolite that discharged during the caldera-forming eruptions (Hauksson, 1988); such a low-rigidity magma body should produce a large shadow zone through which seismic waves could not penetrate. Generally similar observations have been made for young restless calderas elsewhere in the world (Newhall and Dzurisin, 1988; Masturyono et al., 2001). A regional mid-crustal anomaly detected beneath the central Andes has been interpreted as a layer of magma extending over an area of ~45,000 km², containing 20% melt at a depth of 17–19 km (Zandt et al., 2003; de Silva et al., 2007), but even for this region of young Cordilleran ignimbrite volcanism, no data available thus far have identified shallower bodies that could lead directly to a future caldera eruption.

The rapid evolution in multistage calderas of the SRMVF as described here, in combination with thermal cooling models for shallow magma chambers, suggests that upper-crustal magma bodies may be active over long time intervals (10^5–10^6 yr) but exist much of the time in a high-temperature but near-solidus state, with only minor residual melt (Bachmann et al., 2002). Greatly diminished rates of eruptive activity at large young calderas like Long Valley since shortly after ignimbrite eruption have led to the assessment that the subcaldera chamber there is "moribund" (Hildreth, 2004), but longer repose periods between ignimbrite eruptions at multicyclic calderas elsewhere suggest that the moribund state of a large upper-crustal magma chamber may be stable and/or reversible for time periods of up to several million years. Resurrection (reincarnation?) of such high-temperature bodies by addition of water-rich basaltic magma from the mantle during relatively brief periods of high-power magma input may regenerate an eruptible cap of silicic magma geologically rapidly (Bachmann and Berganz, 2004). Just how rapidly is a critical question that remains to be evaluated, but has potential significance for evaluating recurrence intervals of large-scale and potentially catastrophic explosive eruptions.

TOPICS FOR FURTHER STUDY

Despite intensive field mapping and laboratory study in the SRMVF and elsewhere in the Cordilleran region, much remains to be done. Some promising current directions include: (1) dating subvolcanic plutons by multiple high-resolution methods, distinguishing crystallization versus eruption ages, and exploring whether prolonged crystallization histories are present compared to Sierran intrusive complexes like the Tuolomne Intrusive Suite; (2) detailed study of equilibrium, or lack thereof, in phenocryst populations within individual eruptive and intrusive units; (3) petrologic, chemical, and isotopic comparisons between late-erupted material at tops of ignimbrite sheets and subvolcanic intrusions spatially associated with source calderas. And always, the need continues for improved field constraints on rigorously analyzed materials.

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