Geochronology of the central Colorado volcanic field

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Abstract

The central Colorado volcanic field (CCVF) consists of at least ten late Eocene/Oligocene (38–29 Ma) eruptive centers and their volcanic products dispersed over approximately 22,000 km^2 in the Southern Rocky Mountains. The CCVF originally covered most of the Sawatch Range, southern Front Range, Wet Mountains, northern Sangre de Cristo Range, and the areas between. Outflow aprons extended onto the High Plains to the east, merged with the San Juan volcanic field to the southwest, and overlapped the Colorado Mineral Belt on the north and west. The CCVF was severely dissected by Neogene faulting and erosion leaving widely scattered remnants, the largest of which is the Thirtynine Mile volcanic area (previously known as the Thirtynine Mile volcanic field), located between South Park and the Arkansas River. Most of the larger erosional remnants, including the Thirtynine Mile remnant, consist of a combination of products of local eruptive centers and regional ignimbrites erupted from caldera sources in or near the Sawatch Range.

We have developed a time-stratigraphic framework for the CCVF using ^{40}Ar/^{39}Ar dating and paleomagnetic characterization of regional ignimbrites (ash-flow tuffs) as stratigraphic markers to correlate remnants of the volcanic field. ^{40}Ar/^{39}Ar ages of sub-caldera plutons and non-caldera rhyolitic and andesitic volcanism help flesh out this framework. Our interpretation of the eruptive history of the CCVF is based on our database of 83 single-crystal laser-fusion analyses of sanidine, 45 resistance-furnace step-heating analyses of other phases (biotite, hornblende, groundmass), and paleomagnetic study of 40 sites.

Caldera volcanism in the CCVF was active between 36.7 and 32.9 Ma. erupting seven regional ignimbrites that spread mainly eastward along paleovalleys on the late Eocene erosion surface. Four caldera centers have been recognized in the Sawatch Range (Grizzly Peak, Mount Aetna, Bonanza, and Marshall Creek); three of these calderas erupted four of the regional ignimbrites (Antero Tuff, 33.8 Ma; Badger Creek Tuff, 33.8 Ma; Thorn Ranch Tuff, 33.7 Ma; and Gribbles Park Tuff, 32.9 Ma). Caldera sources have not yet been determined for three other regional ignimbrites (Wall Mountain Tuff, 36.7 Ma; tuff of Stirrup Ranch, 36.5 Ma; and East Gulch Tuff, 33.7 Ma). Two ignimbrites (Fish Canyon Tuff, 27.8 Ma; and Carpenter Ridge Tuff, 27.4 Ma) erupted from the San Juan volcanic field and lapped onto the CCVF. Other eruptive centers within the CCVF include Cripple Creek (32.5–30.9 Ma), Silver Cliff–Rosita Hills (35.4–32.0 Ma), Guffey (36.1 Ma), Waugh Mountain (31.6 –31.3 Ma), and Nathrop (30.4–28.9 Ma). Dated plutons in the Sawatch Range are Mount Princeton batholith (34.3 Ma), Mount Aetna Quartz Monzonite (34.1 Ma), and Mount Antero Granite (29.6 Ma). Three fossiliferous sedimentary deposits were also dated; they are Antero Formation (33.8 Ma), Pitch-Pinnacle Formation (33.7–32.9 Ma), and Florissant Formation (34.1 Ma).

Compilation of more than 300 chemical analyses from the literature and from student theses indicate that rocks of the CCVF are calc-alkaline to alkaline in composition and relatively rich in potassium. Ignimbrites are dacites, trachydacites, and rhyolites. Lavas are dominantly trachyandesites and trachydacites. Alkalinity increases eastward toward the Rocky Mountains–High Plains boundary. Cripple Creek and the Silver Cliff-Rosita Hills centers erupted highly alkaline rocks and are precious metal mining districts of the Great Plains Margin type. A-type granites and topaz rhyolites were emplaced along the flanks of the Rio Grande rift between about 30 and 29 Ma.

Introduction

The central Colorado volcanic field (CCVF) is defined as the middle Tertiary (38–29 Ma) eruptive centers and their volcanic and volcaniclastic products in the Sawatch Range, southern Mosquito and Front ranges, the Wet Mountains and Wet Mountain Valley, the northern Sangre de Cristo Range, South Park, and the ignimbrite (ash-flow tuff) remnants in the Castle Rock area of the High Plains (Figs. 1, 2A). The CCVF was once continuous, but has been eroded to a number of discontinuously exposed remnants that share many common physical, temporal, and geochemical characteristics, typically including the presence of one or more regional ignimbrites. The largest remnant of the CCVF, the Thirtynine Mile volcanic area (previously known as Thirtynine Mile volcanic field; Epis and Chapin 1968, 1974), includes the Guffey eruptive center and is located between the southern Mosquito and Front ranges. Laramide-age plutons are excluded from the CCVF because they belong to the older, much studied, Colorado Mineral Belt. The northeastern corner of the generally younger San Juan volcanic field to the southwest laps onto the southwestern edge of the CCVF.

Steven and Epis (1968) and Steven (1975) compiled geologic data and existing radioisotopic ages of middle Tertiary volcanic rocks in Colorado and concluded that: “A widespread volcanic field covered much of the Southern Rocky Mountains in middle Tertiary time, 40 to 25 m.y. ago…” (Steven 1975). Subsequent block faulting and erosion led to the present situation of widely scattered outcrops of rocks of similar age and lithology (Steven and Epis 1968). Many workers have studied the San Juan field, which is the largest fragment of the composite middle Tertiary volcanic field, but previous studies on the Thirtynine Mile volcanic area and other fragments of the CCVF vary from rudimentary to detailed. The purpose of this paper is to pull together remnants of the CCVF into a useful stratigraphic and geochronologic framework using correlation and dating of regional ignimbrites.

In 1989 we began a systematic effort to date and correlate ignimbrites in the CCVF using a combination of ^{40}Ar/^{39}Ar geochronology of sanidine and paleomagnetic studies. We had recently used this approach successfully to develop a chronology and stratigraphic framework of sanidine-bearing regional ignimbrites in the Mogollon–Datil volcanic field in New Mexico (McIntosh 1991; McIntosh et al 1990, 1991, 1992a,b). The work in the CCVF was "moonlighted" between more pressing duties in New Mexico. Our initial goal was to establish precise ages for the seven largest regional ignimbrites. Although the stratigraphic sequence of these ignimbrites had already been established (Epis and Chapin 1974), published K-Ar and fission-track ages were few, and some were inconsistent and violated established stratigraphic order. As the project developed we used ^{40}Ar/^{39}Ar geochronology and paleomagnetism to correlate the regional ignimbrites among many isolated fragments of the CCVF. Dating of plutons and intracaldera facies ignimbrites helped to determine source calderas for some of the regional ignimbrite outflow sheets. As the geochronology database grew we began to fill in the developing time-stratigraphic framework by dating volcanic rocks other than ignimbrites, including rhyolite lavas and intermediate eruptive centers.

In addition to the volcanic record, we applied ^{40}Ar/^{39}Ar geochronology to fossiliferous volcaniclastic sequences. Single-crystal ^{40}Ar/^{39}Ar ages from sanidine in pumice and crystal grains in these rocks provide constraints for their depositional ages. Dated units include the Florissant Formation (MacGinitie 1953; Gregory 1994), well known for fossil plants and insects; the Pitch-Pinnacle Formation (Gregory and McIntosh 1996; Gregory 1994), which contains a recently discovered rich fossil flora; and the widely distributed Antero Formation. Establishing accurate ages for these fossiliferous formations is important to paleontologists and climatologists because they were deposited close to the time of dramatic global cooling near the Eocene–Oligocene boundary (Wolfe 1992).

Geologic setting and previous work

The central Colorado volcanic field was built upon a widespread surface of relatively low relief carved in middle to late Eocene time across Laramide uplifts and constructed across the synorogenic sedimentary fill of adjacent basins (Epis and Chapin 1968, 1975; Steven and Epis 1968). Barriers to long-distance movement of pyroclastic flows were negligible before subsidence of the upper Arkansas and San Luis Basins of the Rio Grande rift, which began between approximately 30 and 26 Ma (Chapin and Cather 1994) and was accompanied by rise of rift-flank uplifts like the Sangre de Cristo and Sawatch ranges. The drainage net on the late Eocene surface was utilized by pyroclastic flows to travel long distances, at least 140 km in the case of the Wall Mountain Tuff (Chapin and Lowell 1979) and more than 100 km in the case of the younger flows from the San Juan field that emplaced the Fish Canyon and Carpenter Ridge Tuffs. The drainage divide in late Eocene time was along, or west of, the Laramide Sawatch uplift (Fig. 2A), which was later split longitudinally by subsidence of the upper Arkansas rift basin.

Large-volume silicic ignimbrite caldera volcanism in the CCVF was centered in the area of the Sawatch uplift between 37 and 33 Ma. At least seven large-volume regional ignimbrite sheets (Table 1) were erupted from calderas in the Sawatch uplift area during this time interval. The bulk of these pyroclastic flows traveled eastward to become part of the stratigraphic sequences preserved in the Thirtynine Mile volcanic area and in smaller erosional fragments of the CCVF, such as Cripple Creek and Silver Cliff–Rosita Hills. At least one ignimbrite, the Gribbles Park/upper Bonanza Tuff, was emplaced southward as far as the Baca graben of the San Luis Basin, where it has been identified in cuttings from wells northeast of Alamosa (Gries and Brister 1989; Brister and McIntosh 2004 this volume). Little is known of the possible distribution of CCVF ignimbrites to the west of the Sawatch uplift. Erosion has removed the middle Tertiary volcanic cover of the Elk Mountains and northern West Elk Mountains revealing numerous subvolcanic plutons (Obradovich et al. 1969; Steven 1975). The only known exposure of outflow-facies CCVF ignimbrites west of the Sawatch uplift is a small outcrop of the Grizzly Peak Tuff reported by Fridrich et al. (1991), about 50 km west-northwest of the Grizzly Peak caldera, on the north flank of Mount Sopris. Two younger regional ignimbrites, The Fish Canyon and Carpenter Ridge Tuffs, lapped onto the CCVF from the San Juan volcanic field between 27.8 and 27.4 Ma, and are exposed along Saguache Creek at the southern terminus of the Sawatch Range (Bruns et al. 1971, fig. 2).

The ignimbrite stratigraphy of the CCVF was first established in the Thirtynine Mile volcanic area, where seven regional ignimbrites were mapped and described by R. C. Epis and students at the Colorado School of Mines and C. E. Chapin and students at the New Mexico Institute of Mining and Technology. The stratigraphy of these ignimbrites is summarized in Table 1 and Figures 3 and 4; more complete descriptions are available in Epis and Chapin (1974). Four of the seven ignimbrites (Wall Mountain, Stirrup Ranch, East Gulch, and Thorn Ranch tuffs) are simple cooling units. Two ignimbrites (Badger Creek and Gribbles Park Tuffs) are multiple-flow, compound cooling units that are more variable in composition and welding. The seventh ignimbrite unit (Antero Formation) includes an ignimbrite facies consisting of nonwelded tuffs with minor interbeds of tuffaceous sedimentary strata and a sedimentary facies consisting mainly of tuffaceous clastic sedimentary deposits derived by erosion of the ignimbrite facies (Fig. 2C). Outcrops of ignimbrites within the Thirtynine Mile volcanic area all represent outflow facies and are generally confined to paleovalleys rather than forming widespread sheets typical of ignimbrites in the San Juan volcanic field (Steven et al. 1974; Lipman et al. 1973) and elsewhere. An eighth large volume ignimbrite in the CCVF, the Grizzly Peak Tuff, is known chiefly from intracaldera facies within the Grizzly Peak caldera (Fridrich et al. 1991, 1998). The Grizzly Peak Tuff may have originally had a widespread outflow sheet in the northern CCVF, but erosion has removed all but two tiny outcrops (Fridrich et al. 1998).

^{40}Ar/^{39}Ar dating and paleomagnetic correlation studies detailed below indicate that some outcrops in the CCVF previously mapped as Badger Creek Tuff were miscorrelated. Paleovalley-filling ignimbrites exposed near the Arkansas River and mapped as Badger Creek Tuff are in fact distal facies of Fish Canyon and Carpenter Ridge Tuffs (Table 1) erupted from the San Juan volcanic field. A thick, but local, ignimbrite sequence in the Trout Creek paleovalley, also mapped as Badger Creek Tuff, is in fact an older, previously unrecognized unit herein termed the tuff of Triad Ridge. These new correlations reveal that the Badger Creek Tuff is much smaller in geographic extent than previously thought and confined mainly to the Salida–Waugh Mountain paleovalley (Fig. 2C). The Badger Creek Tuff is apparently a densely welded, late-stage phase of the same series of eruptions that produced the Antero Formation ignimbrites (Lowell 1969, 1971; Shannon et al. 1987).

Source calderas for four of the seven CCVF regional ignimbrites have been recognized in and near the Sawatch Range (Fig. 2). The remaining calderas were probably located in the same area, but have been obscured by erosion, downfaulting, or overprinting by younger caldera volcanism. The northernmost caldera, near Independence Pass, is the Grizzly Peak caldera (Fridrich 1986, Fridrich and Mahood 1984, 1987; Johnson and Fridrich 1990; Fridrich et al. 1991, 1998), source of the predominantly intracaldera facies Grizzly Peak Tuff. The Mount Aetna caldera (Shannon

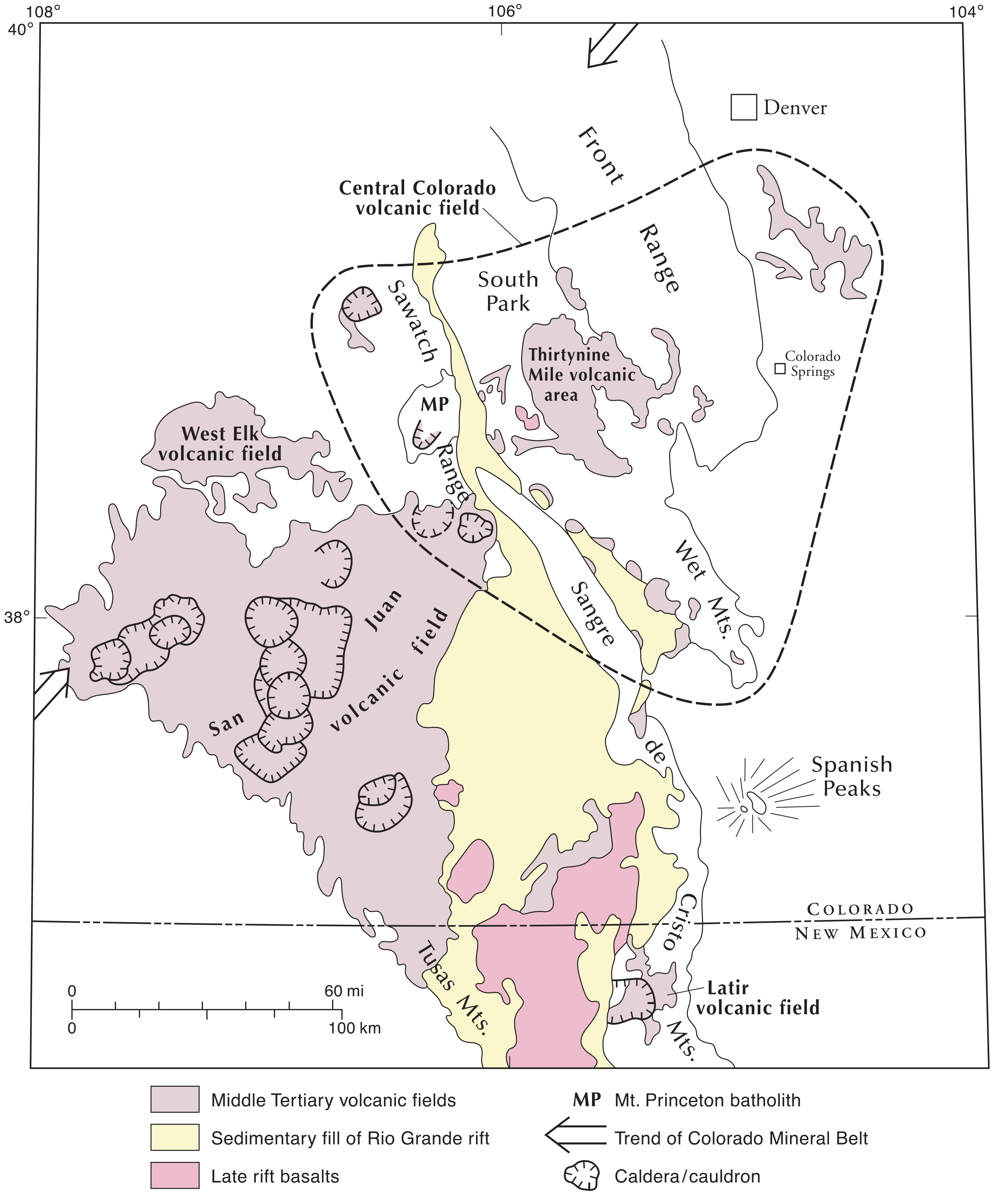


FIGURE 1—Map of the Southern Rocky Mountains showing erosional remnants and inferred original extent of the central Colorado volcanic field (CCVF) and adjacent volcanic fields. Modified from Lipman (2000).

1988, 1989; Shannon et al. 1987; Toulmin and Hammarstrom 1990), northwest of Salida, erupted the Antero and Badger Creek Tuffs. The southernmost caldera in the Sawatch Range, the Bonanza caldera (Karig 1965; Bruns et al. 1971; Varga and Smith 1984), is the source of Gribbles Park Tuff/upper Bonanza and contains the Bonanza mining district (Burbank 1932). A newly recognized caldera, herein named the Marshall Creek caldera, is present northwest of the Bonanza caldera and is the source of the Thorn Ranch Tuff (Fig. 2A,D). A recent paper by Gregory and McIntosh

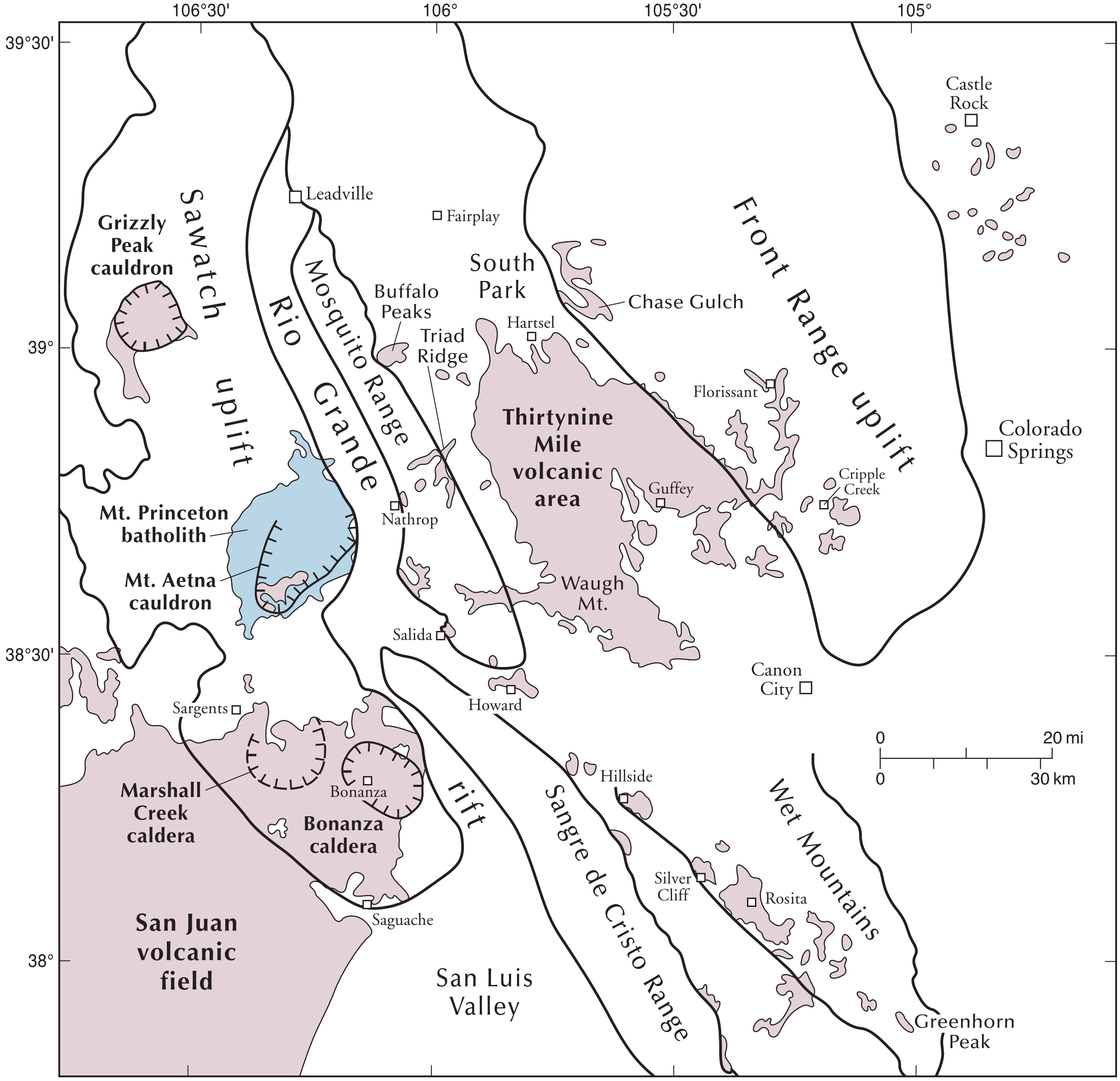


FIGURE 2A—Sketch map of the central Colorado volcanic field-showing major geologic features, known calderas, and distribution of CCVF outcrops. Base map modified from Shannon et al. (1987) and Colorado Geologic Highway Map (Western Geographics 1991).

(1996) described the fossil flora of the Pitch-Pinnacle Formation, an apparent moat deposit in this largely unmapped caldera. Recognition of the Marshall Creek caldera is based upon ^{40}Ar/^{39}Ar dating and paleomagnetic correlation of proximal deposits of the Thorn Ranch Tuff, on dating of clasts in the Pitch-Pinnacle Formation, on recognition of megabreccia blocks of various formations, and on reinterpretation of mapping by Olson (1983). Sources for the Wall Mountain, Stirrup Ranch, and East Gulch tuffs have not yet been identified, but their outflow distribution (Fig. 2B,D) indicates that they were also erupted from calderas in the Sawatch Range.

The largest erosional remnant of the central Colorado volcanic field is the Thirtynine Mile volcanic area. This erosional remnant occupies a high plateau between the southern Mosquito Range on the west, the Front Range on the east, South Park on the north, and the Arkansas River canyon on the south. The most voluminous and areally extensive volcanic unit exposed in this area is the lower member of the Thirtynine Mile Andesite (Figs. 2,3), a breccia complex of predominantly fragmental intermediate to mafic rocks that covers approximately 2,600 km^2 to an average depth of 150 m (Epis and Chapin 1974). The lower Thirtynine Mile breccia complex is an enigmatic unit with an incompletely understood origin. It was termed the "basic breccia and agglomerate" unit in the Pikes Peak sheet mapped by Cross (1894). The unit is somewhat similar to the Conejos Formation of the San Juan volcanic field, which has been described by Lipman (1975) as aprons of lava flows and breccias (termed "vent-facies") surrounding widely scattered central volcanoes and grading laterally into mudflow breccias and other sedimentary deposits (termed "volcaniclastic facies"). The lower Thirtynine Mile Andesite, in contrast, consists mainly of a chaotic mix of breccias of various

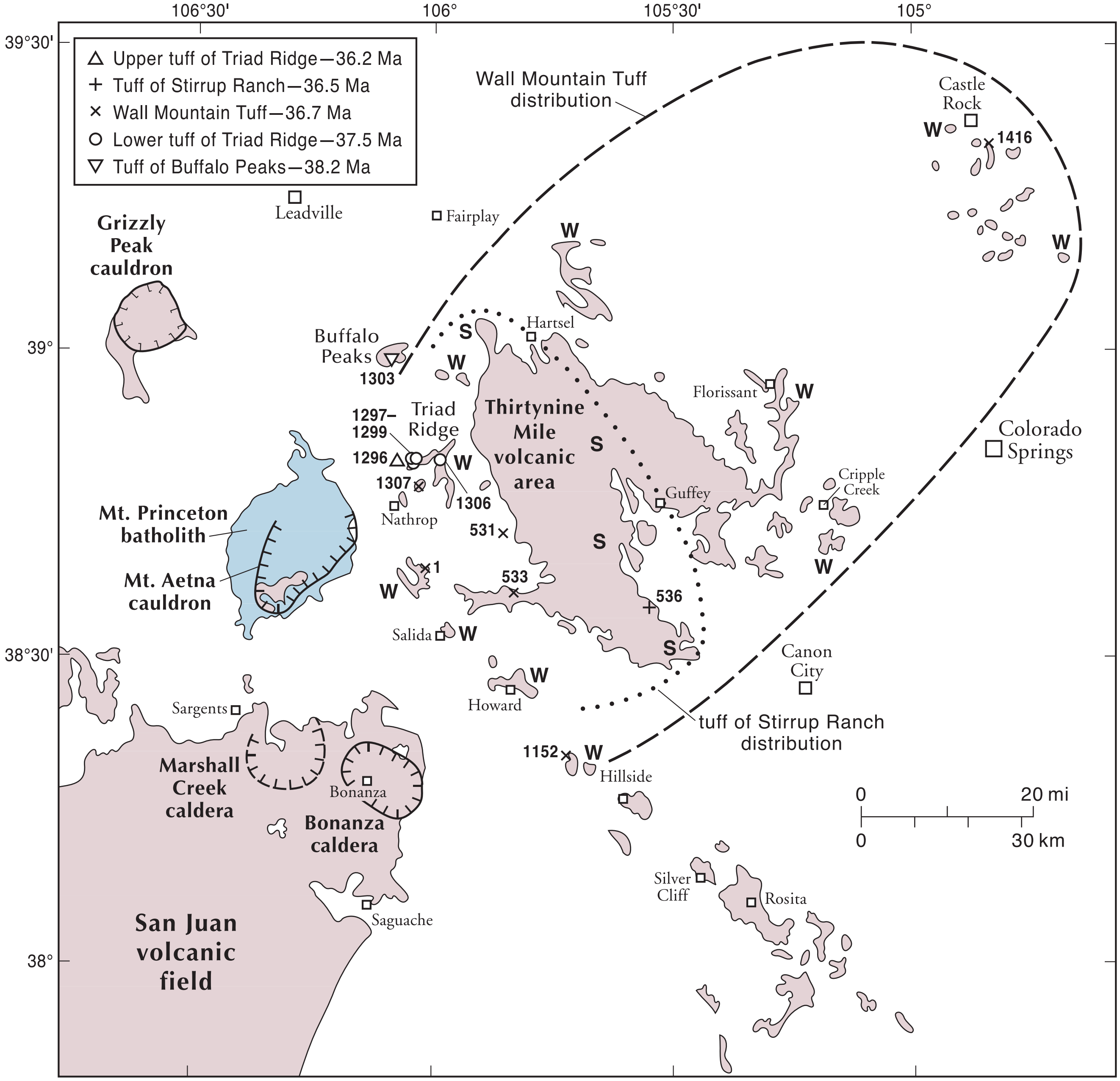


FIGURE 2B—Sketch map of the central Colorado volcanic field-showing inferred distribution and sample locations for 38.2–36.2 Ma ignimbrites, including Wall Mountain Tuff and tuff of Stirrup Ranch. Base map modified from Shannon et al. (1987) and Colorado Geologic Highway Map (Western Geographics 1991). Unit-name initials indicate locations where outcrops of regional ignimbrites are known but were not sampled.

types derived from small, widely scattered breccia vents, several of which are well exposed and have been described by Wycoff (1969) and Chapin and Wycoff (1969). The breccia vents form small (0.8 km diameter by 150 m high) cones in which all rocks are breccias, including breccia dikes and brecciated plugs that seal the vent. Monolithologic, intermediate-composition breccias erupted from these vents comprise about 60% of the lower Thirtynine Mile Andesite, heterolithic epiclastic debris-flow breccias make up about 30%, and autobrecciated lava flows comprise about 10%. The breccia complex is chaotically stratified due to its construction as coalescing series of deposits filling channels and topographic low areas. The unit weathers to low, rounded, sparsely vegetated hills of purplish-brown breccias in which no one deposit can be followed for more than a few hundred meters. A possible analog is the Mehrten Formation on the west slope of the Sierra Nevada in northern California, described by Curtis (1954), who developed a model for brecciation in vents. Other authors who have interpreted andesitic breccias as products of subterranean fragmentation and eruption as breccias include Durrell (1944) and Parsons (1967). The lower Thirtynine Mile breccia complex buried the Wall Mountain and Stirrup Ranch tuffs and largely disrupted the drainage system on the late Eocene surface. Lakes formed along the west and north (upslope) edges of the breccia complex resulting in deposition of fossiliferous lacustrine and low-energy fluvial strata of the Antero and Florissant Formations (Figs 2C).

In contrast, the upper member of the Thirtynine Mile Andesite (Figs. 3,4), consists of basaltic trachyandesite (shoshonitic basalt of Goldmann 1989) flows and interbedded breccias that form a ring of mountains surrounding the

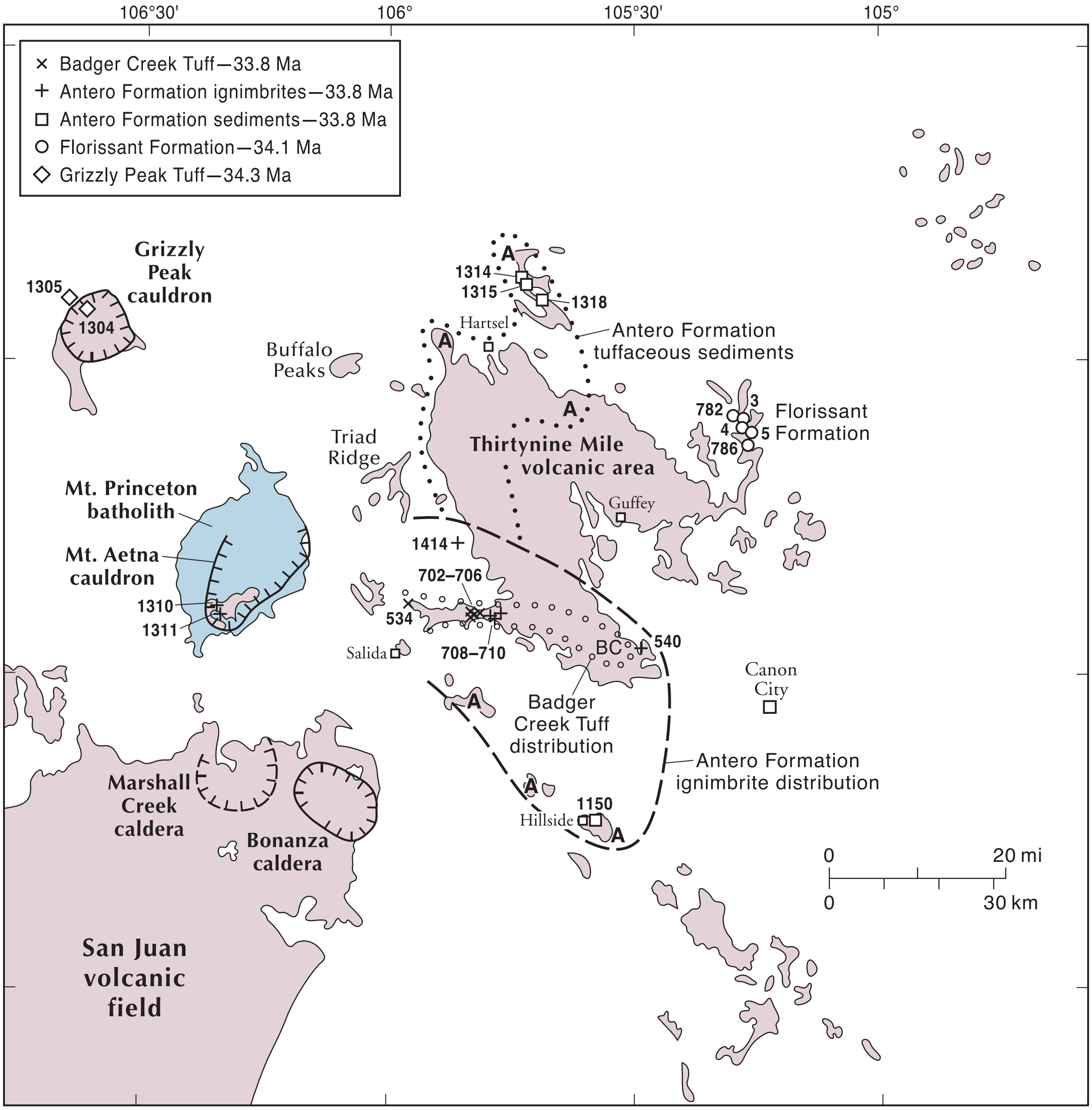


FIGURE 2C—Sketch map of the central Colorado volcanic field-showing inferred distribution and sample locations for 34.3–33.8 Ma ignimbrites and related units, including Badger Creek Tuff and Antero Formation. Base map modified from Shannon et al. (1987) and Colorado Geologic Highway Map (Western Geographics 1991). Unit-name initials indicate locations where outcrops of regional ignimbrites are known but were not sampled.

Guffey volcanic center. The upper member rests on the lower member, is more mafic in composition, and forms bold, well-stratified outcrops. Remnants of the large (16 by 26 km basal dimensions) stratovolcano formed by the upper member surround a complex of domes, plugs, and flows of intermediate to silicic composition that are partly contemporaneous with the lower member. ^{40}Ar/^{39}Ar ages of three samples of the intrusive facies range from 37 to 36 Ma (Table 2). The only available age for extrusive facies of the upper member is a 35 Ma K-Ar date (recalculated following Steiger and Jäger 1977) on a basalt flow high on Thirtynine Mile Mountain (Marvin et al. 1974, p. 28). Geochemical studies by Goldman (1989), Wobus et al. (1990), and students of the Keck Geology Consortium have characterized the rocks of the Guffey volcanic center as latites, trachytes, and quartz trachytes overlain by a thick series trachybasalt and shoshonitic flows and lahars, the latter intruded by basalt dikes and small rhyolitic plutons. Samples from the lower Thirtynine Mile Andesite, however, are largely from volumetrically minor felsic rocks that form conspicuous outcrops, whereas fragmental rocks forming the bulk of the unit are mostly unsampled. A comprehensive study of the lower Thirtynine Mile Andesite is needed.

Smaller fragments of the central Colorado volcanic field (Table 1, Fig. 4) consist of eruptive centers of relatively local extent, subvolcanic plutons, volcanic sequences preserved in paleovalleys, lava flows, and tuffaceous sedimentary deposits. The Cripple Creek and Silver Cliff–Rosita Hills volcanic centers are alkaline eruptive complexes containing small, but deep, subsidence structures described as diatremes or cauldrons, and surrounded by a variety of volcanic and intrusive rocks (see Appendices 1, 2, and 3 for ref-

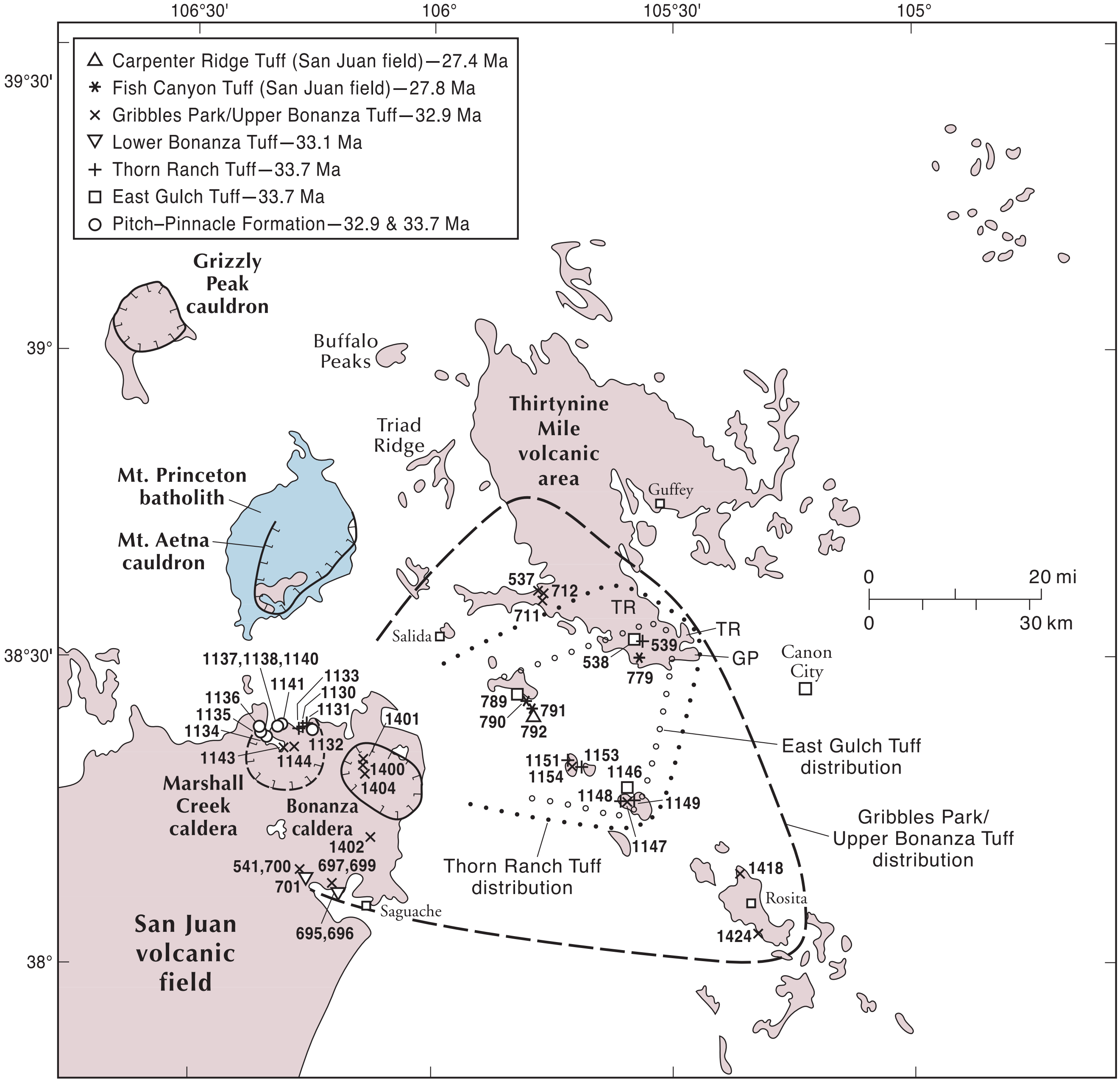


FIGURE 2D—Sketch map of the central Colorado volcanic field-showing inferred distribution and sample locations for 33.7 Ma ignimbrites and related units, including Gribbles Park/upper Bonanza Tuff, Thorn Ranch Tuff, and East Gulch Tuff. Base map modified from Shannon et al. (1987) and Colorado Geologic Highway Map (Western Geographics 1991). Unit-name initials indicate locations where outcrops of regional ignimbrites are known but were not sampled.

erences). The Buffalo Peaks, Florissant, Salida–Waugh Mountain, and Trout Creek paleovalleys contain key stratigraphic sections that have elsewhere largely been lost to erosion. The onset of rifting, beginning approximately 30 Ma, led to intrusion of highly evolved alkaline, high-silica magmas such as the Mount Antero Granite and the topaz rhyolites near Nathrop (Fig. 2; Appendix 4). Basaltic flows northeast of Salida (Fig. 2E) at Herring Park (8.5 Ma, ^{40}Ar/^{39}Ar) are considered to be part of a younger episode of rift related bimodal volcanism, rather than part of the CCVF sequence.

^{40}Ar/^{39}Ar geochronology

As described above, sample collecting for this project extended over a period of 12 yrs. Sample locations were initially selected to determine the precise ages of regional ignimbrites exposed in the Thirtynine Mile volcanic area, the largest erosional remnant of the central Colorado volcanic field. Subsequent sampling addressed lateral correlation among regional ignimbrites. Once the regional chronostratigraphic framework began to be better established, further sampling focused on intracaldera/outflow ignimbrite correlation problems, as well as timing of smaller volume rhyolitic and intermediate volcanism. At many of the sample locations in this study, oriented core samples for paleomagnetic analysis were also collected.

Our initial efforts at ^{40}Ar/^{39}Ar dating of CCVF ignimbrites involved incremental heating of bulk sanidine separates, an approach that had yielded flat age spectra and precise ages for ignimbrites in the Mogollon–Datil volcanic field in New Mexico (McIntosh et al 1990, 1992a,b). As further detailed below, age spectra from most of the initial samples of CCVF ignimbrites were discordant (Fig. 5).

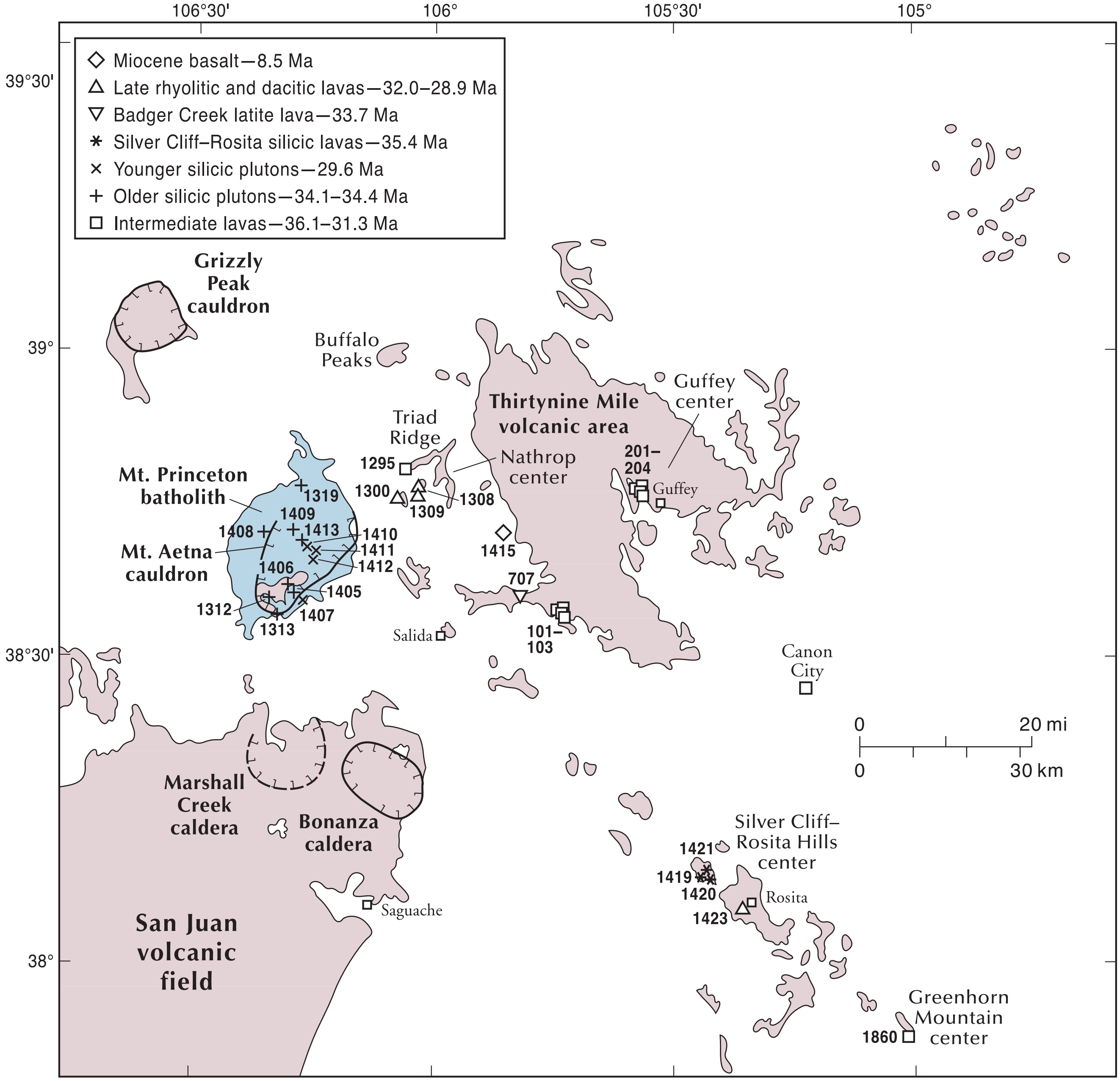


FIGURE 2E—Sketch map of the central Colorado volcanic field-showing inferred distribution and sample locations for plutons and lavas. Base map modified from Shannon et al. (1987) and Colorado Geologic Highway Map (Western Geographics 1991).

Subsequently, single-crystal ^{40}Ar/^{39}Ar analyses revealed that incompletely degassed K-feldspar contaminant grains mixed with phenocrysts were responsible for anomalous bulk-sample age spectra (McIntosh et al. 1992c). Single-crystal methods were therefore adopted for all subsequent ^{40}Ar/^{39}Ar analyses of sanidine bearing ignimbrites, lavas, or sedimentary units. In total 83 samples were dated by laser-fusion methods. Incremental heating methods were used for 45 bulk samples of groundmass concentrate or K-bearing minerals other than sanidine, prepared mostly from plutonic rocks or volcanic units lacking sanidine phenocrysts.

^{40}Ar/^{39}Ar bulk-sample incremental-heating pilot study—methods and results

Our initial attempts to date CCVF ignimbrites were made at the U.S. Geological Survey argon geochronology laboratory in Reston, Virginia. The ten ignimbrite samples selected for the pilot study included at least one sample of each of the seven largest regional ignimbrites in the CCVF; most of the samples are from densely welded facies. Bulk sanidine separates were prepared from each of the ten pilot study samples, and 250 mg aliquots of each sample were irradiated in the USGS TRIGA reactor facility along with Fish Canyon Tuff sanidine as a neutron flux monitor (FC-1, Assigned age = 27.84 Ma, Deino and Potts 1990). The bulk sanidine separates of the pilot study were analyzed by the incremental heating method in a resistance-furnace on line with a VG 1200 mass spectrometer. Procedures used were identical to those described in McIntosh et al. 1990.

Eight of the ten samples in the incremental-heating pilot study yielded discordant spectra, contrasting sharply with the flat, concordant age spectra similar to results from sanidine phenocrysts from the Mogollon–Datil volcanic field (McIntosh et al. 1990) and elsewhere (e.g., Bove et al 1999). Only two of the ten pilot samples (Fig. 5a) yielded flat spec-

TABLE 1—Summary of ^{40}Ar/^{39}Ar dated units in the central Colorado volcanic field.

Unit	Caldera	Facies	Maximum dimension (km)	Maximum thickness (m)	Silica range (anhydrous)	Polarity	Mineral	n	Age ±2σ (Ma)
Regional ignimbrites									
Gribbles Park Tuff	Bonanza	outflow	60	180	60–75	N	san	14	32.88 ± 0.08
Gribbles Park Tuff	Bonanza	intracaldera	?	?	?		san	3	32.99 ± 0.20
lower Bonanza Tuff	Bonanza	pre-caldera?	?	?	?		san/bio	4	33.11 ± 0.29
Thorn Ranch Tuff	Marshall Pass	outflow	80	75	76–79	R	san	5	33.66 ± 0.14
Thorn Ranch Tuff	Marshall Pass	intracaldera	?	?	?		san	3	33.61 ± 0.17
East Gulch Tuff	?	outflow	?	20	75–77	R	san	2	33.71 ± 0.10
Badger Creek Tuff	Mount Aetna	outflow	70	100	66–68	R	san	5	33.81 ± 0.11
Antero Formation	Mount Aetna	outflow	80	110	66–68	R	san	4	33.76 ± 0.10
Antero/Badger Creek	Mount Aetna	intracaldera	?	?	?		san	1	33.66 ± 0.13
tuff of Stirrup Ranch	?	outflow	60	90	73	N	san	1	36.50 ± 0.16
Wall Mountain Tuff	?	outflow	150	150	69–74	N	san	5	36.69 ± 0.09
Local ignimbrites									
Grizzly Peak	Grizzly Peak	intracaldera	?	?	57–77		san	2	34.31 ± 0.12
upper tuff of Triad Ridge	?	outflow					san	1	36.22 ± 0.32
lower tuff of Triad Ridge	?	outflow	16	300		N	bio,hbl	4	37.49 ± 0.22
tuff of Buffalo Peaks	?	outflow					hbl	1	38.18 ± 0.32
Exotic ignimbrites									
Carpenter Ridge Tuff	Bachelor	outflow	120	200	60–75	R	san	1	27.38 ± 0.12
Fish Canyon Tuff	La Garita	outflow	150	200	66–71	N	san	3	27.83 ± 0.15
Sedimentary units									
Pitch-Pinnacle		tuffaceous	15	200		(younger xtals)	anorth	2	32.89 ± 0.21
Formation		sediments				(older xtals)	san	6	33.73 ± 0.20
Antero Formation		tuffaceous sediments	80	600	67–71		san	3	33.76 ± 0.15
Florissant Formation		tuffaceous sediments	20	50		N	san	5	34.05 ± 0.08
Silicic centers									
Nathrop—rhyolite of		lava dome	4.3	300	68–76	(younger flow)	anorth	1	28.88 ± 0.21
Bald Mountain						(older flow)	san	1	30.35 ± 0.08
Nathrop—rhyolite Ruby Mountain		intrusives	1.8 x 1.2	180	74–77		san	1	30.08 ± 0.08
Cripple Creek		diatreme complex					san		32.5 to 30.91[1]
Rosita Hills–Pringle Latite		plug and dikes	1.7 x 1.3	?	64–66		san	1	31.99 ± 0.56
rhyolite of Silver Cliff		flow complex	3.3 x 2.3	76	75–76		san	3	35.39 ± 0 .12
Intermediate centers									
basalt of Herring Park		lava flow	3.5	85			gm	1	8.50 ± 0.09
andesite of Waugh Mountain		lava flows	22	370	53–55		gm	1	31.28 ± 0.21
latite of Waugh Mountain		lava flows and domes		8	200		hbl, gm	3	31.57 ± 0.33
andesite of Greenhorn Mountain		lava flows	4	18			hbl	1	33.40 ± 0.57
latite of East Badger Creek		lava flow	4.2	90			hbl	1	33.68 ± 0.12
andesites of Guffey		intrusions					hbl	3	36.09 ± 0.49
dacite of Triad Ridge		lava flow	2.6	15	63		san	1	36.14 ± 0.10
Plutonic units									
Mount Antero Granite		pluton	20		74–77		bio, musc	3	29.59 ± 0.13
Mount Aetna ring dike		ring dike					kspar	1	34.13 ± 0.18
Mount Aetna Quartz Monzonite		intrusive complex			67–69		bio,hbl	2	34.07 ± 0.90
Mount Aetna Quartz Monzonite		intrusive complex					bio	2	34.0 ± 0.3[2]
Mount Princeton batholith		pluton	67 x 38		65–68		bio	4	34.31 ± 0.21
Mount Princeton batholith		pluton					bio	3	34.5 ± 0.3[2]

Notes

Fields left blank were not determined.

Minerals: **san** = sanidine, **anorth** = anorthoclase, **bio** = biotite, **hbl** = hornblende, **musc** = muscovite, **gm** = groundmass

All data from this study unless otherwise noted.

Published data: [1]Kelley et al. 1999; [2]Toulmin and Hammarstrom 1990

tra that met plateau criteria (Fleck et al. 1977; McIntosh et al. 1990) and provided precise plateau ages. The plateau ages of these two well-behaved samples (36.67 ± 0.10 Ma for sample 533 of Wall Mountain Tuff, and 36.66 ± 0.14 Ma for sample 531 of tuff of Stirrup Ranch) are consistent with stratigraphic relationships and also agree closely with weighted mean ages of subsequent single-crystal laser-fusion analyses of the same units. The eight discordant age spectra ranged from moderately climbing (Fig. 5B) to highly disturbed (Fig. 5C). Although radiogenic yields of individual steps are nearly all in excess of 99% and K/Ca values are generally consistent, none of the age spectra meet plateau criteria, nor do the data form well-defined isochrons.

These eight discordant age spectra are all apparently due to contamination of the 250-mg bulk sanidine separates by small amounts of older K-feldspar crystals incorporated into the ignimbrite shortly before eruption or during eruptive transport. The older K-feldspar contaminant crystals clearly did not lose their inherited argon, in spite of heating within the densely welded ignimbrite sampled in the pilot study. Given the abundance of discordant spectra observed in the pilot study of CCVF ignimbrites, the bulk-sample,

TABLE 2—^{40}Ar/^{39}Ar results from central Colorado volcanic field samples.

Unit	Locality	Min	Sample	Lab	Irrad	Analysis	n	%^{39}Ar	K/Ca	Age ± 2σ (Ma)
Miocene lava										
basalt of Herring Park	Herring Park	gm	1415	7505	62	FSH	9	100.0	1.4	8.50 ± 0.09
San Juan ignimbrites (<29 Ma)										
Carpenter Ridge Tuff	Kerr Gulch quarry	san	792	146	3	LF(4)	7		42.0	27.38 ± 0.12
Fish Canyon Tuff	head of Echo Canyon	san	779	163	3	SCLF	8		66.9	27.71 ± 0.14
	Alkali Gulch box	san	790	147	3	LF(5)	6		72.1	27.93 ± 0.11
	Kerr Gulch quarry	san	791	148	3	LF(5)	6		68.4	27.79 ± 0.15
			unit mean				3		69.1	27.83 ± 0.15
late CCVF lavas (31-29 Ma)										
rhyolite of Bald Mountain	Bald Mountain	anorth	1308	6180	45	SCLF	13		0.7	28.88 ± 0.21
	Bald Mountain	san	1309	6181	45	SCLF	15		67.4	30.35 ± 0.08
rhyolite of Ruby Mountain	Sugarloaf Mountain	san	1300	6175	45	SCLF	15		102.4	30.08 ± 0.08
Pringle Latite	Rosita Gulch	san	1423	7514	62	SCLF	13		17.0	31.99 ± 0.56
CCVF Pulse Three: Bonanza Interval (32.8 Ma)										
Gribbles Park Tuff (outflow facies)	Two Creek	san	537	9454	93	SCLF	15		27.2	32.91 ± 0.11
	Saguache Creek	san	541	9458	93	SCLF	11		27.5	32.85 ± 0.12
	west of Windy Peak	san	1143	915	11	SCLF	6		27.8	32.81 ± 0.20
	west of Windy Peak	san	1144	916	11	SCLF	7		34.2	32.79 ± 0.19
	NE of Hillside	san	1147	957	11	SCLF	12		26.0	32.95 ± 0.20
	Oak Creek	san	1154	1030	11	SCLF	13		25.9	32.96 ± 0.18
	Bills Creek	san	711	5260	34	SCLF	10		26.7	32.94 ± 0.14
	Two Creek	san	712	5261	34	SCLF	10		26.7	32.98 ± 0.14
	NE of Silver Cliff	san	1418	7509	62	SCLF	15		27.5	32.82 ± 0.09
	South of Rosita	san	1424	7515	62	SCLF	8		27.3	32.70 ± 0.12
(upper Bonanza Tuff facies)	Saguache Creek	san	700	5250+	93	SCLF	25		26.2	33.01 ± 0.11
	Saguache Creek	bio	700	9460	93	FSH-total gas	15		7.2	*44.16 ± 7.18* [#]
	Findley Ridge unit 7	san	699	5249+	93	SCLF	24		27.4	32.89 ± 0.09
	Findley Ridge unit 7	bio	699	9462	93	FSH–plateau	8		11.2	*33.24 ± 0.24* [#]
	Findley Ridge unit 5	san	697	5248+	93	SCLF	25		28.6	32.90 ± 0.10
	Findley Ridge unit 5	bio	697	9464	93	FSH–plateau	8		18.9	*33.30 ± 0.13* [#]
	Columbia Gulch	san	1402	7508	62	SCLF	15		28.9	32.88 ± 0.09
	unit mean (Gribbles Park + upper Bonanza)					14		25.9	32.88 ± 0.08	
(lower Bonanza Tuff facies)	Saguache Creek	san	701	5251	34	SCLF	10		29.9	32.83 ± 0.11
	Findley Ridge unit 2	san	696	5247	34	LF(1-2)	10		12.4	33.23 ± 0.16
	Findley Ridge unit 2	bio	696	9466	93	FSH–plateau	5		10.2	*33.41 ± 0.17* [#]
	Findley Ridge unit 1	bio	695	9480	93	FSH–plateau	12		10.8	*33.21 ± 0.12* [#]
	Findley Ridge unit 1	plag	695	5246	34	SCLF	10		0.1	*34.19 ± 1.21* [#]
			unit mean				4		12.7	33.11 ± 0.29
Gribbles Park Tuff (intracaldera)	Superior Mill	san	1400	7506	62	LF(1-5)	13		32.0	32.92 ± 0.13
	Bear Creek	san	1401	7507	62	LF(2-5)	14		25.6	33.17 ± 0.10
	Rawley Gulch	bio	1404	7518	62	FSH–plateau	8	88.1	7.2	*33.32 ± 0.25* [#]
			unit mean				3		28.8	32.99 ± 0.20
Pitch-Pinnacle Formation	Pinnacle Mine Road	san	1141	914	11	SCLF	2		17.0	32.90 ± 0.22
	Pinnacle Mine Road	san	1137	955	11	SCLF	4		43.4	32.88 ± 0.64
			unit mean				2		230.2	32.89 ± 0.21
CCVF Pulse Two: Antero Interval (34.3–33.4 Ma)										
Thorn Ranch Tuff (outflow facies)	South Tallahassee Creek	san	539	52358+	138	SCLF	29		43.2	33.59 ± 0.14
	NE of Hillside	san	1148	52363+	138	SCLF	37		30.5	33.73 ± 0.09
	NE of Hillside	san	1149	9599	11	SCLF	10		29.0	33.49 ± 0.20
	Falls Gulch	san	1151	1027	11	SCLF	5		63.6	33.75 ± 0.22
	Oak Creek	san	1153	52364+	138	SCLF	14		49.2	33.60 ± 0.12
			unit mean				5		43.1	33.66 ± 0.14
Thorn Ranch Tuff (intracaldera facies)	Marshall Pass road	san	1130	52360+0	138	SCLF	38		31.4	33.54 ± 0.12
	Marshall Pass road	san	1131	52361+	138	SCLF	22		29.6	33.63 ± 0.10
	Marshall Pass road	san	1133	951	11	SCLF	7		25.3	33.75 ± 0.22
			unit mean				3		28.8	33.61 ± 0.17
East Gulch Tuff	South Tallahassee Creek	san	538	52357+	138	SCLF	15		34.1	33.69 ± 0.15
	SE of Howard	san	789	52359+	138	SCLF	7		5.3	*33.90 ± 0.19* [#]
	NE of Hillside	san	1146	52362+	138	SCLF	15		50.2	33.72 ± 0.12
			unit mean				2		42.2	33.71 ± 0.10
Badger Creek Tuff	Longs Gulch	san	534	9452	93	SCLF	15		83.6	33.80 ± 0.10
	East Badger Creek	san	706	5255	34	SCLF	10		79.2	33.80 ± 0.13
	East Badger Creek	san	705	5254	34	SCLF	8		75.9	33.83 ± 0.13
	East Badger Creek	san	703	5253	34	SCLF	5		64.5	33.82 ± 0.14
	East Badger Creek	san	702	5252	34	SCLF	10		71.0	33.81 ± 0.12
			unit mean				5		74.8	33.81 ± 0.11
Badger Creek latite lava	East Badger Creek	san	707	5256	34	SCLF	10		13.4	33.68 ± 0.12
Antero Formation (ignimbrite facies)	Gardner Peak	san	540	4946	93	SCLF	15		78.5	33.87 ± 0.10
	East Badger Creek	san	710	5259	34	SCLF	10		59.5	33.75 ± 0.12

TABLE 2—continued

Unit	Locality	Min	Sample	Lab	Irrad	Analysis	n	%^{39}Ar	K/Ca	Age ± 2σ (Ma)
	East Badger Creek	san	709	5258	34	SCLF	2		36.8	*33.96 ± 0.25* #
	East Badger Creek	san	708	5257	34	SCLF	10		75.7	33.87 ± 0.14
	Herring Park	san	1414	7521	62	SCLF	15		73.8	33.73 ±0.05
			unit mean				4		71.9	33.76 ± 0.10
Antero Formation (volcaniclastic facies)	NE of Hillside	san	1150	960	11	SCLF	12		65.5	33.65 ± 0.19
	Chase Gulch	bio	1314	6213	45	FSH-total gas	11		34.1	*140.89 ± 2.44* #
	Chase Gulch	san	1315	6186	45	SCLF	6		70.8	33.78 ± 0.12
	Chase Gulch	san	1318	6187	45	SCLF	15		93.9	33.78 ± 0.09
			unit mean				3		76.7	33.76 ± 0.15
Mount Aetna intracaldera tuff	Chalk Creek Pass	san	1310	6182	45	SCLF	7		62.7	*34.34 ± 0.40* #
	Chalk Creek Pass	san	1311	6183	45	SCLF	6		76.1	33.66 ± 0.13
			unit mean				1		69.4	33.66 ± 0.13
Pitch-Pinnacle Fm (older xtals)	Pinnacle Mine road	san	1141	914	11	SCLF	8		20.6	33.67 ± 0.22
	Pinnacle Mine road	san	1138	2007	20	SCLF	22		48.6	33.72 ± 0.10
	Pinnacle Mine road	san	1140	918	11	SCLF	2		59.2	33.75 ± 0.37
Pitch-Pinnacle Fm (clasts)	Pinnacle Mine road	san	1137	2006	20	SCLF	14		50.1	33.38 ± 0.25
	Pinnacle Mine road	san	1134	952	11	SCLF	2		80.3	33.85 ± 0.21
	Indian Creek	san	1135	953	11	SCLF	5		67.7	33.93 ± 0.21
	Marshall Creek	plag	1132	950	11	SCLF	11		0.1	*35.1 3± 0.58* #
	Indian Creek	plag	1136	954	11	SCLF	12		0.2	*34.11 ± 0.59* #
			unit mean				6		54.4	33.73 ± 0.20
Grizzly Peak Tuff (intracaldera facies)	Grizzly Park Reservoir	san	1304	6176	45	SCLF	13		84.1	34.27 ± 0.09
	Lincoln Gulch Road	san	1305	6177	45	SCLF	12		84.8	34.36 ± 0.11
			unit mean				2		84.5	34.31 ± 0.12
Florissant Formation	Florissant Monument	san	786	1668	17	SCLF	8		43.7	33.98 ± 0.12
	Florissant Monument	san	5	1671	17	SCLF	20		43.3	34.01 ± 0.13
	Florissant Monument	san	782	1669	17	SCLF	10		42.8	34.07 ± 0.12
	Florissant Monument	san	4	1670	17	SCLF	20		59.9	34.14 ± 0.12
	Florissant Monument	san	3	1672	17	SCLF	18		47.0	34.03 ± 0.13
			unit mean				5		47.3	34.05 ± 0.08
CCVF Pulse One: Wall Mountain Interval (36.7-35.4 Ma)										
rhyolite lava at Silver Cliff	White Hills	san	1419	7510	62	SCLF	5		61.5	35.41 ± 0.23
	White Hills	san	1420	7511	62	SCLF	1		33.5	35.35 ± 0.19
	White Hills	san	1421	7512	62	SCLF	2		71.5	35.41 ± 0.16
			unit mean				3		55.5	35.39 ± 0.12
Stirrup Ranch Tuff	North Fork, Tallahassee Creek	san	536	4945	93	SCLF	3		27.7	36.50 ± 0.16
Wall Mountain Tuff	Badger Creek	san	531	4941	93	SCLF	15		24.9	36.61 ± 0.11
	Falls Gulch	san	1152	1028	11	SCLF	12		26.3	36.78 ± 0.21
	Browns Canyon Road	san	1	1657	17	SCLF	38		26.2	36.70 ± 0.04
	Bald Mountain	san	1307	6179	45	SCLF	14		25.5	36.66 ± 0.10
	Quarry south of Castle Rock	san	1416	7540	62	LF(1-6)	15		23.7	36.78 ± 0.11
			unit mean				5		25.3	36.69 ± 0.09
Younger plutons (30 Ma)										
Mount Antero Granite	East of Shavan	K-spar	1407	7478	62	FSH - total gas	14		39.1	*28.65 ± 0.53* #
Mount Antero Granite	East of Shavano	alt. biot.	1407	7477	62	FSH - plateau	6	83.9	3.1	*29.12 ± 0.18*#
Mount Antero Granite	West side of Mount Antero	K-spar	1411	7525	62	FSH - total gas	12		164.0	*26.77 ± 0.23* #
Mount Antero Granite	West side of Mount Antero	bio	1411	7533	62	FSH - plateau	6	68.0	10.1	29.64 ± 0.11
Mount Antero Granite	West side of Mount Antero	musc	1411	75341	62	FSH - plateau	5	67.8	389.6	29.58 ± 0.14
Mount Antero Granite	West side of Mount Antero	K-spar	1412	7529	62	FSH - total gas	12		195.7	*27.77 ± 0.24* #
Mount Antero Granite	West side of Mount Antero	bio	1412	7536	62	FSH - plateau	6	76.1	42.9	29.60 ± 0.12
Mount Antero Granite	West side of Mount Antero	musc	1412	7535	62	FSH - plateau	10	93.0	302.7	29.53 ± 0.10
			unit mean				3			29.59 ± 0.13
Older plutons (34 Ma)										
Mount Aetna ring dike	West of St. Elmo	K-spar	1408	7480	62	FSH - plateau	4	72.6	65.7	34.13 ± 0.18
Mount Aetna ring dike	West of St. Elmo	hbl	1408	7481	62	FSH - total gas	11	0.1		*42.74 ± 0.72* #
Mount Aetna Quartz Monzonite	SE of Chalk Creek Pass	hbl	1312	6210	45	FSH - plateau	4	65.7	0.1	33.40 ± 0.52
Mount Aetna Quartz Monzonite	Middle Fork, S. Arkansas River	bio	1313	6211	45	FSH - plateau	6	79.1	5.6	34.28 ± 0.29
Mount Aetna Quartz Monzonite	Middle Fork, S. Arkansas River	hbl	1313	6212	45	FSH - total gas	9		0.1	*36.42 ± 0.73* #
			unit mean				2			34.07 ± 0.90

TABLE 2—continued

Unit	Locality	Min	Sample	Lab	Irrad	Analysis	n	%^{39}Ar	K/Ca	Age ± 2σ (Ma)
Mount Princeton batholith	Hunkydory Gulch	K-spar	1405	7519	62	FSH - plateau	2	54.2	112.5	*31.67 ± 0.27* #
Mount Princeton batholith	Hunkydory Gulch	bio	1405	7520	62	FSH - plateau	6	65.2	28.3	34.21 ± 0.13
Mount Princeton batholith	Baldwin Creek	K-spar	1413	7537	62	FSH - total gas	12		21.4	*30.05 ± 0.36*#
Mount Princeton batholith	Baldwin Creek	bio	1413	7538	62	FSH - plateau	5	54.8	17.1	34. 30 ± 0.19
Mount Princeton batholith	Baldwin Creek	hbl	1413	7539	62	FSH - total gas	11		0.1	*38.23 ± 2.04* #
Mount Princeton batholith	Alpine Lake	K-spar	1409	7523	62	FSH - total gas	12		39.1	*31.69 ± 0.30* #
Mount Princeton batholith	Alpine Lake	bio	1409	75229	62	FSH - plateau	7	90.2	7.5	34.42 ± 0.16
Mount Princeton batholith	Alpine Lake	hbl	1409	7524	62	FSH - total gas	11		0.2	*34.55 ± 1.21* #
Mount Princeton batholith	Cottonwood Lake	bio	1319	6214	45	FSH - plateau	8	92.9	11.1	34.51 ± 0.30
Mount Princeton batholith	Cottonwood Lake	hbl	1319	6215	45	FSH - plateau	3	90.7	0.1	*38.24 ± 0.52* #
			unit mean				4			34.31 ± 0.21
Lavas and tuffs from intermediate centers										
andesite of Waugh Mountain	Stony Face Mountain	gm	103	51966-01	133	FSH - plateau	3	62.0	1.4	31.28 ± 0.21
latite of Waugh Mountain	Stony Face Mountain	hbl	101	51952-01	133	FSH - plateau	4	90.8	0.1	31.61 ± 0.27
latite of Waugh Mountain	Stony Face Mountain	gm	101	51964-01	133	FSH - plateau	3	63.7	1.8	31.74 ± 0.21
latite of Waugh Mountain	Stony Face Mountain	gm	102	51965-01	133	FSH - plateau	8	97.8	1.7	32.44 ± 0.69
			weighted mean				4			31.57 ± 0.33
andesite of Greenhorn Mtn.	Greenhorn Mountain	gm	1860	9733-01	98	FSH - plateau	9	100.0	1.5	33.40 ± 0.57
andesitic intrusives at Guffey	Guffey Area	hbl	201	7216-01	58	FSH - plateau	5	29.5	0.5	*38.12 ± 2.92*#
andesitic intrusives at Guffey	Guffey Area	hbl	202	7217-01	58	FSH - plateau	5	76.2	0.2	36.06 ± 0.49
andesitic intrusives at Guffey	Guffey Area	hbl	203	7218-01	58	FSH - plateau	10	100.0	0.1	35.97 ± 0.69
andesitic intrusives at Guffey	Guffey Area	hbl	204	7219-01	58	FSH - plateau	10	100.0	0.1	36.92 ± 1.59
		weighted mean					3			36.09 ± 0.49
dactite of Triad Ridge	Triad Ridge, summmit	san	1295	6173	45	SCLF	13		14.2	36.14 ± 0.10
upper tuff of Triad Ridge	Triad Ridge, north side	san	1296	6174	45	SCLF	2		13.2	36.22 ± 0.32
lower tuff of Triad Ridge	Triad Ridge, north side	bio	1297	6205	45	FSH - plateau	4	90.9	8.3	37.34 ± 0.18
lower tuff of Triad Ridge	Triad Ridge, north side	hbl	1297	6206	45	FSH - plateau	3	88.7	0.1	37.32 ± 0.39
lower tuff of Triad Ridge	Triad Ridge, north side	bio	1298	6207	45	FSH - plateau	6	90.8	9.9	37.48 ± 0.14
lower tuff of Triad Ridge	Triad Ridge, north side	bio	1299	6208	45	FSH - plateau	9	99.6	20.1	37.62 ± 0.15
lower tuff of Triad Ridge	Triad Ridge, north side	san	1306	6178	45	SCLF	14		789.7	*257.49 ± 65.4*#
		weighted mean					4			37.49 ± 0.22
tuff of Buffalo Peaks	Mesa east of Buffalo Peaks	hbl	1303	6209	45	FSH - plateau	3	87.6	0.1	38.18 ± 0.32

Notes:

Min = mineral dated (**san**=sanidine, **bio**=biotite, **anorth**=anorthoclase, **hbl** = hornblende, **K-spar** = K-feldspar, **plag** = plagioclase, **gm** = groundmass); **Sample** = sample number; **Lab** = laboratory analysis number (**+** denotes multiple analyses); **Irrad** = irradiation batch number; **Analysis** = type of analyses (**SCLF** = single-crystal laser-fusion, **LF** = multi-crystal-laser fusion, number in parentheses denote crystals per fusion; **FSH** = furnace step-heating, plateau or total gas denotes treatment of age spectrum); **n** = number of fusion analyses or heating steps used in age calculation; **%^{39}Ar** = percent of released ^{39}Ar in age plateau for furnace step-heating analyses; **K/Ca** = ratio calculated from K-derived ^{39}Ar and Ca-derived ^{37}Ar; **Age (Ma)** = weighted mean age; **± 2 σ** = two sigma uncertainty in weighted-mean age, **#** and ***italics*** denote rejected age determinations considered to be inaccurate or imprecise.

Sample preparation and irradiation:

Sanidine, hornblende, biotite and groundmass concentrate separated using standard techniques (crushing, sieving, magnetics, heavy liquids and hand-picking).

Samples were packaged and irradiated in machined Al discs for 7 hrs in D-3 position, Texas A&M University Research Reactor

Neutron flux monitor Fish Canyon Tuff sanidine (FC-1). Assigned age = 27.84 Ma (Deino and Potts 1990) relative to Mmhb-1 at 520.4 Ma (Samson and Alexander 1987).

Instrumentation:

Mass Analyzer Products 215-50 mass spectrometer on line with automated all-metal extraction system.

Single or multiple crystals of sanidine were fused by 10-watt or 50-watt Synrad CO$_2$ laser.

Hornblende, biotite and groundmass concentrate samples were step-heated by a double-vacuum resistance furnace.

Reactive gases from the sanidine analyses were removed during a 2 minute reaction with 2 SAES GP-50 getters, one operated at ~ 450° C and one at 20° C. Gas also exposed to a W filament operated at ~ 2000° C and a cold finger operated at – 140° C

Reactive gases from the hornblende, biotite and groundmass concentrate were removed during a 15 min reaction with 3 SAES GP-50 getters, two operated at ~ 450° C and one at 20° C. Gas also exposed to a W filament operated at ~ 2000 °C and a cold finger operated at – 140° C

Analytical parameters:

Electron multiplier sensitivity averaged 7.13 x 10^{-17} moles/pA for those samples analyzed by the laser.

Electron multiplier sensitivity averaged 1.33 x 10^{-16} moles/pA for those samples analyzed by the furnace.

Total system blank and background for the total fusion samples averaged 294, 5.9, 1.1, 2.0, 2.0 x 10^{-18} moles

Total system blank and background for the incrementally heated samples averaged 1730, 37.4, 1.6, 6.3, 9.4 x 10^{-18} moles

J-factors determined to a precision of ± 0.1% by CO$_2$ laser-fusion of 4 single crystals from each of 4 or 6 radial positions around the irradiation tray.

Correction factors for interfering nuclear reactions were determined using K-glass and CaF$_2$ and are as follows: $(^{40}Ar/^{39}Ar)_K$ = 0.0002 ± 0.0003; $(^{36}Ar/^{37}Ar)_{Ca}$ = 0.00028 ± 0.000011; and $(^{39}Ar/^{37}Ar)_{Ca}$ = 0.00089 ± 0.00003.

Age calculations:

Weighted mean and error calculated by weighting each age analysis by the inverse of the variance, using the method of Samson and Alexander (1987).

Total gas ages and errors calculated by weighting individual steps by the fraction of ^{39}Ar released. Decay constants and isotopic abundances following Steiger and Jäger (1977).

All errors reported at ± 2 σ, unless otherwise noted.

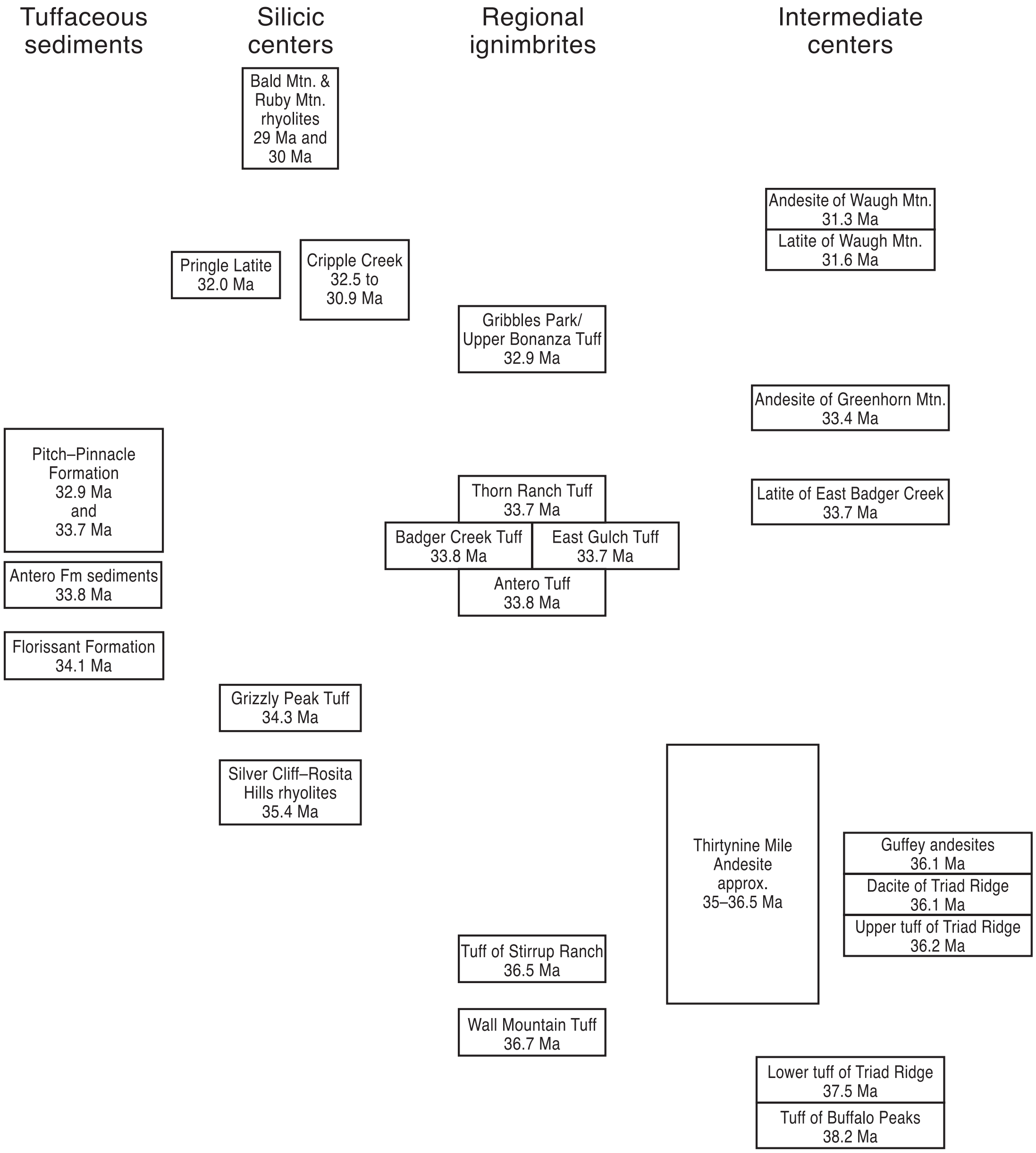


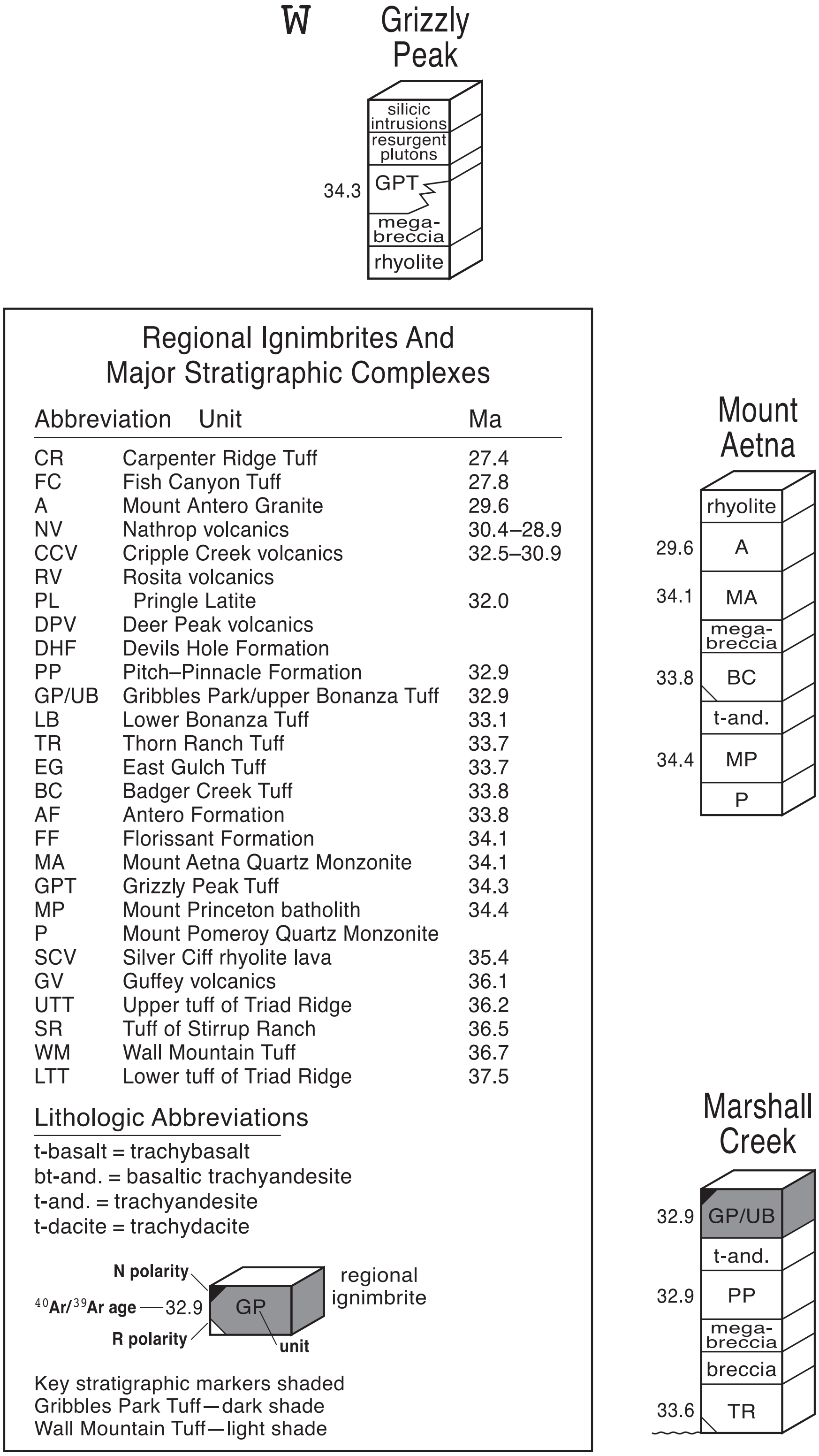
FIGURE 3—Two-dimensional summary of the key units of central Colorado volcanic field stratigraphic framework.

incremental heating approach was abandoned in favor of single-crystal methods. As described below, subsequent single crystal analyses have confirmed the presence of K-feldspar contaminant crystals in some CCVF ignimbrite samples. Anomalously old K-feldspar contaminant crystals in other ignimbrites elsewhere have been revealed by single-crystal laser-fusion studies (e.g. Spell et al. 2001) and have also been interpreted from discordant age spectra (e.g., McIntosh et al. 1990).

^{40}Ar/^{39}Ar laser-fusion analyses—methods and results

The first single-crystal laser-fusion analyses of CCVF ignimbrites were performed on the pilot study samples at the Berkeley Geochronology Center using an argon-ion laser extraction system on line with an MAP 215 mass spectrometer. As reported in McIntosh et al. (1992c), these initial laser fusion analyses confirmed the presence of older K-feldspar contaminant grains in some of the samples.

All subsequent ^{40}Ar/^{39}Ar analyses, including reanalysis of the pilot study samples, were performed at the New Mexico Geochronology Research Laboratory. Sanidine separates, typically 10–20 mg, were prepared from all sanidine-bearing samples, including 66 samples of ignimbrites, 9 samples of lavas, and 16 samples of ash- or pumice-rich sedimentary units. Sanidine separates were irradiated over the course of 12 irradiation batches in the D-3 position at the Nuclear Science Center reactor, College Station, Texas, using Fish Canyon Tuff sanidine as a neutron-flux monitor (FC-1, assigned age = 27.84 Ma, Deino and Potts 1990). For nearly all of the sanidine separates, 15 or more single crystals were individually fused by CO_2 laser. For seven separates with unusually small (< 0.3 mm) crystals, 2–6 crystals were simultaneously fused for some or all of the analyses. Analyses were performed on an MAP 215-50 mass spectrometer. Following corrections for blank, mass discrimination, and post-irradiation isotopic decay, ages were calculated using decay constants and isotopic abundances reported by Steiger and Jäger (1977). All errors are reported at 2σ, unless otherwise noted. K/Ca ratios were calculated from measured ratios of K-derived ^{39}Ar and Ca-derived ^{37}Ar.



Regional Ignimbrites And Major Stratigraphic Complexes

Abbreviation	Unit	Ma
CR	Carpenter Ridge Tuff	27.4
FC	Fish Canyon Tuff	27.8
A	Mount Antero Granite	29.6
NV	Nathrop volcanics	30.4–28.9
CCV	Cripple Creek volcanics	32.5–30.9
RV	Rosita volcanics	
PL	Pringle Latite	32.0
DPV	Deer Peak volcanics	
DHF	Devils Hole Formation	
PP	Pitch–Pinnacle Formation	32.9
GP/UB	Gribbles Park/upper Bonanza Tuff	32.9
LB	Lower Bonanza Tuff	33.1
TR	Thorn Ranch Tuff	33.7
EG	East Gulch Tuff	33.7
BC	Badger Creek Tuff	33.8
AF	Antero Formation	33.8
FF	Florissant Formation	34.1
MA	Mount Aetna Quartz Monzonite	34.1
GPT	Grizzly Peak Tuff	34.3
MP	Mount Princeton batholith	34.4
P	Mount Pomeroy Quartz Monzonite	
SCV	Silver Ciff rhyolite lava	35.4
GV	Guffey volcanics	36.1
UTT	Upper tuff of Triad Ridge	36.2
SR	Tuff of Stirrup Ranch	36.5
WM	Wall Mountain Tuff	36.7
LTT	Lower tuff of Triad Ridge	37.5

Lithologic Abbreviations

t-basalt = trachybasalt
bt-and. = basaltic trachyandesite
t-and. = trachyandesite
t-dacite = trachydacite

Key stratigraphic markers shaded
Gribbles Park Tuff—dark shade
Wall Mountain Tuff—light shade

FIGURE 4—Three-dimensional depiction of the ignimbrite-based time-stratigraphic framework of the central Colorado volcanic field.

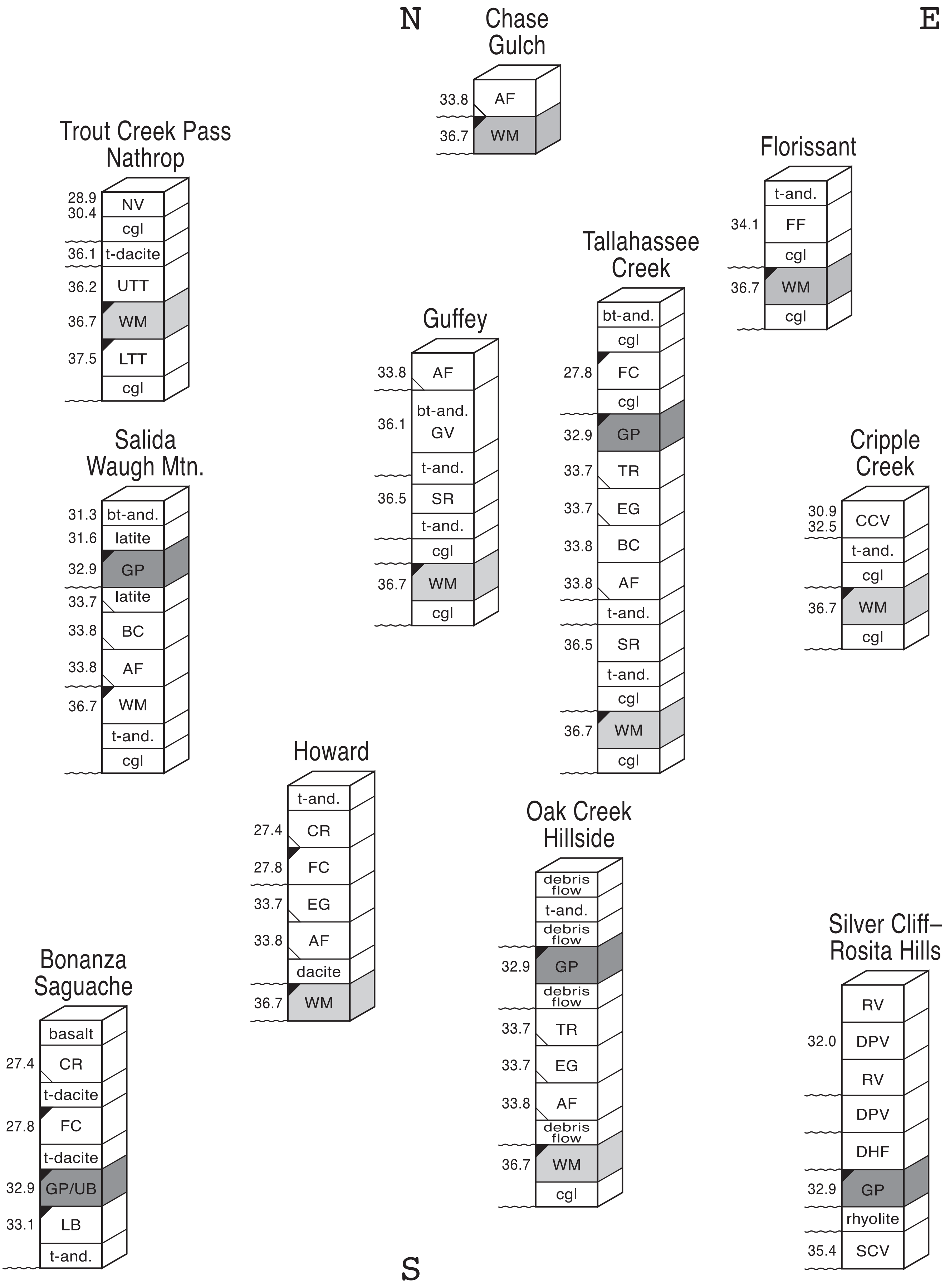


FIGURE 4 continued

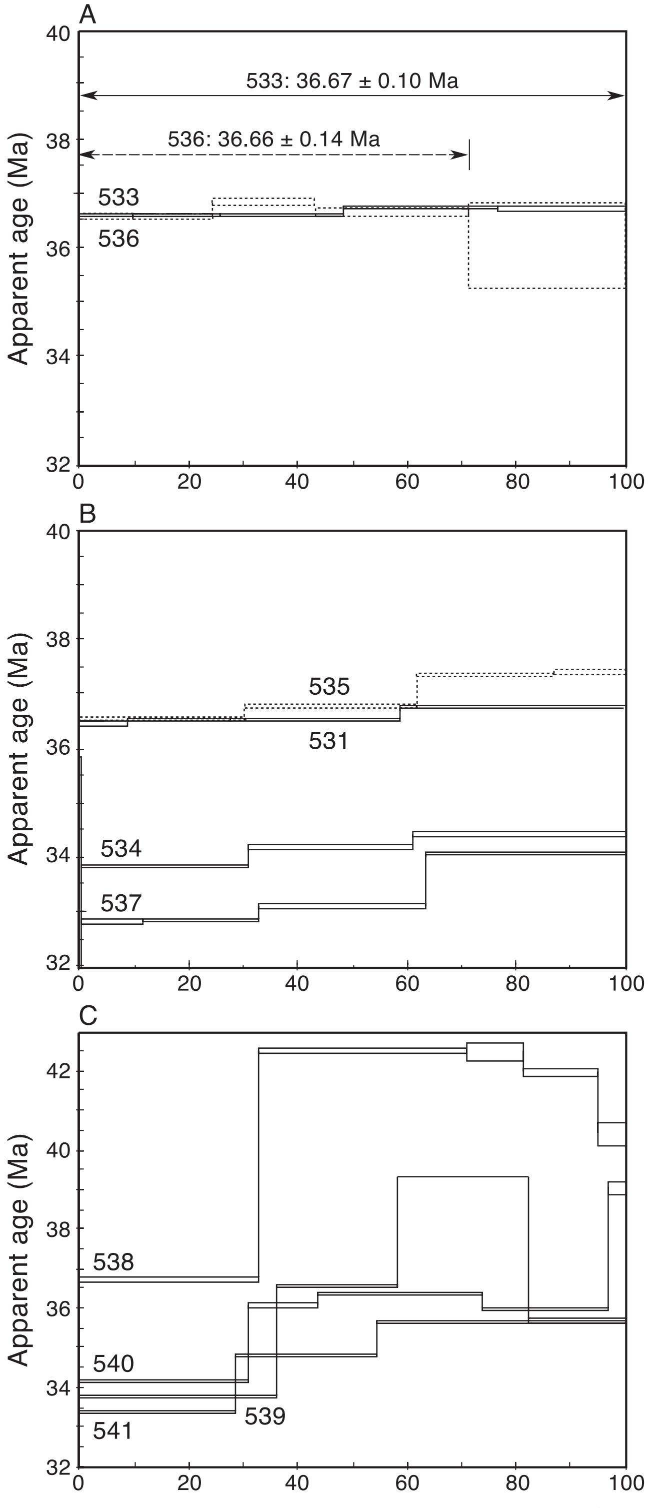


FIGURE 5—Age spectra from pilot study of ten incrementally heated bulk sanidine separates. Discordant, climbing spectra are atributed to contamination by older K-feldspar.

Procedural details of sample preparation, irradiation, and analytical methods are summarized in Table 2 footnotes and in Figures 3–10. Results are summarized in Tables 1 and 2. Analytical data, age spectra, and age-probability plots for individual samples are compiled in Appendix 5.

^{40}Ar/^{39}Ar laser-fusion results from ignimbrites and lavas—Individual sanidine crystals from CCVF ignimbrites and lavas tend to yield precise, well-grouped single-crystal ^{40}Ar/^{39}Ar ages, similar to results from phenocrystic sanidine from ignimbrites and lavas elsewhere (e.g. Deino and Potts 1990; Walter et al. 1994). Ages of single crystals generally have 2 σ analytical precision of ± 0.1–0.5%, high radiogenic yields (95–100%), and K/Ca values (32–60). In some cases, these well-behaved crystals are accompanied by one or more crystals that yield low-precision ages (2σ analytical error > ± 2%), generally with small ^{39}Ar signals (^{39}Ar < 10^{-15} moles), low radiogenic yields (< 90%), or anomalous K/Ca values (< 5 or > 100). Reasons for these low-precision analyses vary. Many reflect small crystal size or incomplete fusion by the laser. K/Ca ratios and signal size identify others as plagioclase or quartz crystals inadvertently included in the sanidine mineral separate. Some of these flawed analyses may alternatively be related to large melt inclusions, observed optically in some grains.

After exclusion of these low-precision analyses, single-crystal ages from all of the nine lava samples and most of the 66 ignimbrite samples are unimodal and tightly grouped. Figure 6 depicts single-crystal laser-fusion results from eight sites in the Thorn Ranch Tuff, which are representative of the range of results observed in this study. Age-probability distribution diagrams of these data from most samples in this study show generally gaussian distributions consistent with the single-crystal ages being a single population representative of eruption age (e.g., Fig. 6, samples 1133, 1151, 1131, and 539). Weighted-mean ages for these single-population samples are generally precise, with 2 σ errors ranging from ± 0.25% to ± 0.86%. As detailed in the following sections, these weighted mean ages are invariably consistent for multiple samples of individual units and also agree closely with established stratigraphy. Tightly grouped, unimodal, gaussian age-probability distributions are typical of sanidine from most ignimbrites, lavas, and pyroclastic-fall deposits elsewhere that have been dated by single-crystal laser-fusion ^{40}Ar/^{39}Ar methods (e.g. Deino and Potts 1990; Walter et al. 1994).

Single-crystal analyses from a small minority of samples yield multimodal ages interpreted as representing a mixture of primary, eruption-age sanidine phenocrysts and older K-feldspar contaminant grains (e.g., Fig. 6, samples 1149, 1130, 1148, and 1153). Ages of the primary sanidine phenocrysts from these samples, after exclusion of data from low-precision analyses, are tightly grouped and tend to have gaussian age distributions, high radiogenic yields, and K/Ca values similar to the results from uncontaminated samples described above. In addition to these well-behaved data, the ages of one or more crystals from these samples are discordant, exceeding the mean age of the tightly grouped sanidine phenocrysts by 0.3–1100 Ma. In some cases the crystals with aberrant ages also have K/Ca values distinct from the sanidine crystals that have tightly grouped ages. These anomalously old crystals are interpreted as K-feldspar contaminant grains containing inherited argon, which was not entirely lost at the time of emplacement, in spite of dense welding of some of the sampled ignimbrites. Some or all of the anomalously old contaminant crystals may have suffered partial loss of ^{40}Ar by reheating after incorporation into the ignimbrite. The ages and K/Ca values of the oldest contaminant grains suggest derivation from Precambrian basement rocks, which are common in the area of the CCVF. Younger contaminant grains in some samples have age and K/Ca values consistent with derivation from stratigraphically lower ignimbrites, particularly Wall Mountain Tuff (e.g. Fig. 6, sample 1149).

Single-crystal ^{40}Ar/^{39}Ar analyses of some of the pilot study samples with discordant bulk-separate spectra failed to directly identify contaminant grains, yielding only well-grouped single-crystal ages with a mean value near or below the youngest part of the age spectrum. These presum-

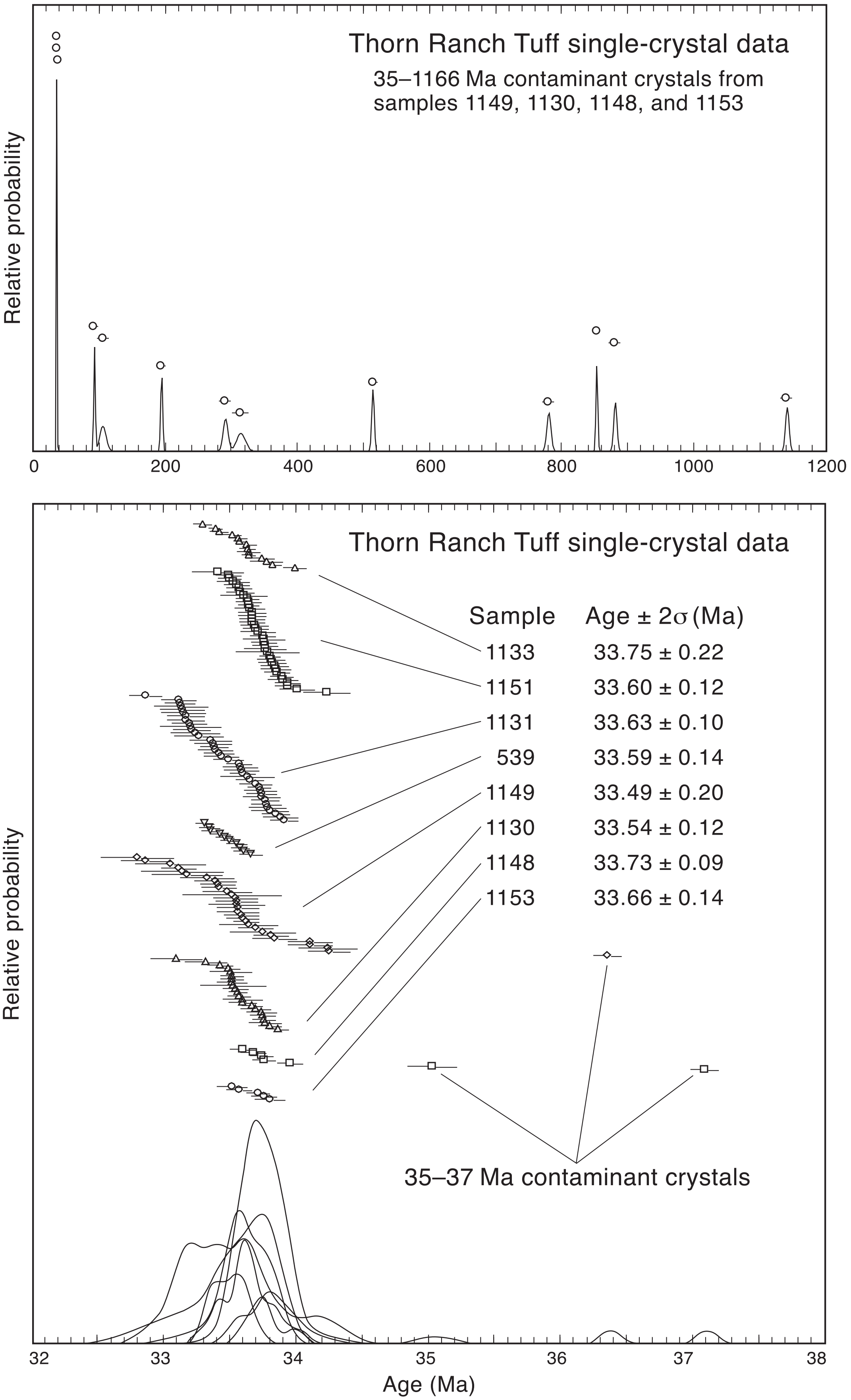


FIGURE 6—Examples of laser-fusion results from single-crystal laser fusion of sanidine from eight samples of Thorn Ranch Tuff. Four of the eight samples contain anomalously old contaminant grains, ranging in apparent age from 35 Ma to 1166 Ma.

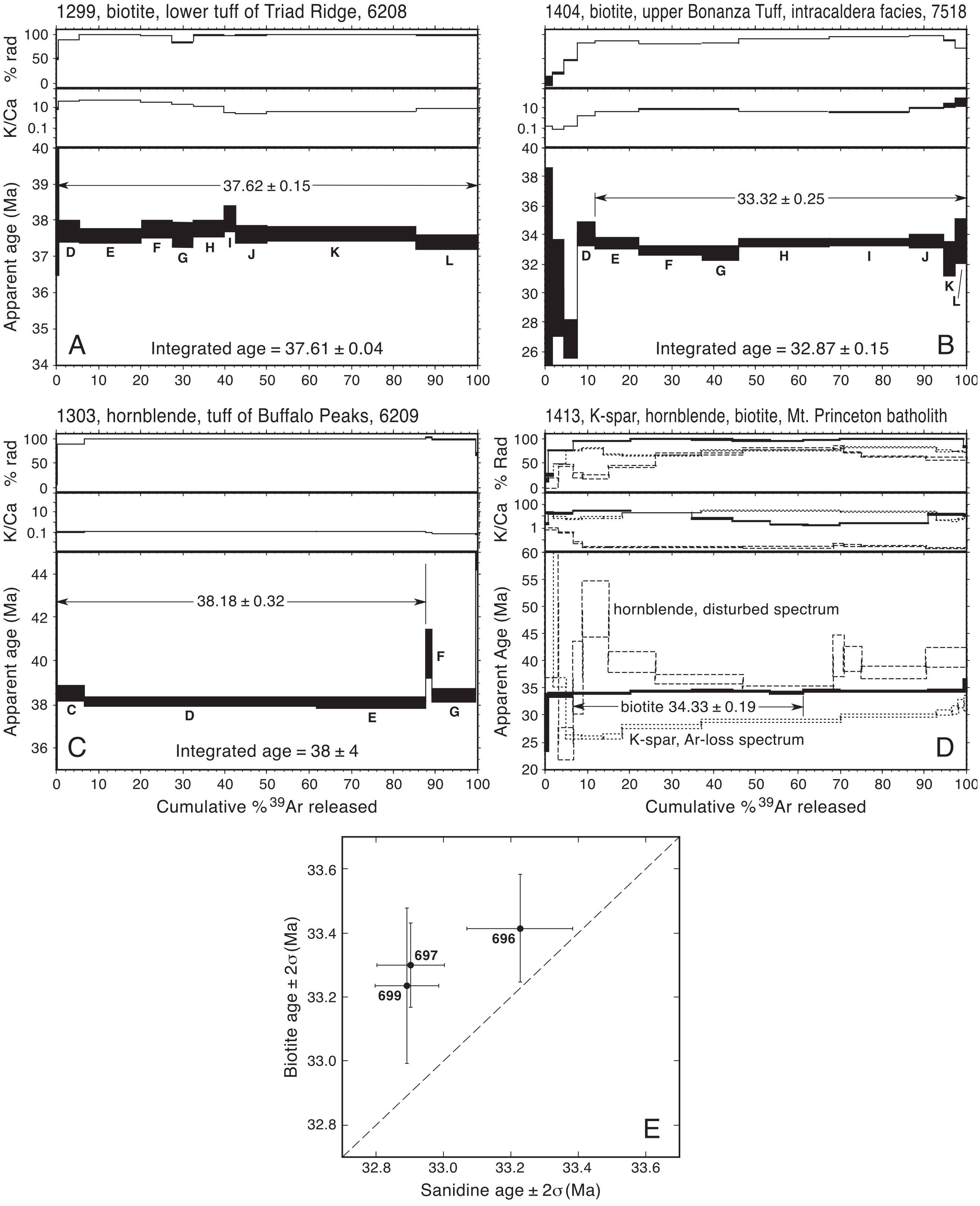


FIGURE 7—Examples of step-heating results from sanidine-free CCVF mafic units: (**A**) flat age spectrum of biotite from lower tuff of Triad Ridge; (**B**) slightly disturbed age spectrum of biotite from intracaldera-facies Bonanza Tuff; (**C**) nearly flat spectrum of hornblende from tuff of Buffalo Peaks; (**D**) age spectra of hornblende, biotite, and K-feldspar separates from granitic sample of Mount Princeton batholith; (**E**) comparison between biotite plateau ages and sanidine single-crystal laser-fusion ages for three samples from which both phases were analyzed. Biotite ages are systematically 0.15–0.3 m.y. older than sanidine ages.

ably reflect low levels of contamination by older grains, which were not detected during single-crystal analysis. Because of the small number of crystals (typically 15) used for single-crystal analyses, older K-feldspar contaminant grains apparently tend to be removed during mineral separation and crystal selection procedures.

Weighted-mean laser-fusion ages were calculated for each sanidine separate, excluding results from older contaminant grains and low-precision analyses. Weighted-mean ages and errors were calculated using the method of Samson and Alexander (1987). Isochron methods of calculating weighted mean ages from the laser-fusion results were not employed because of uniformly high radiogenic yields. Tables 1 and 2 and Figures 8 and 9 present weighted-mean ages and K/Ca values for each sample and for each unit. The mean ages show good agreement among different samples from each ignimbrite and agree closely with established stratigraphic order.

The seven largest regional ignimbrites in the CCVF were erupted in three distinct, brief pulses: near 36.7 Ma (Wall Mountain Tuff and tuff of Stirrup Ranch), near 33.7 Ma (Antero Formation and Badger Creek, East Gulch, and Thorn Ranch tuffs), and near 32.9 Ma (Gribbles Park/Bonanza Tuff). The $^{40}Ar/^{39}Ar$ results generally confirm the stratigraphy proposed by Epis and Chapin (1974) but also reveal a few errors in previously published lateral correlations of ignimbrite outcrops in some published maps, as further discussed below. Ignimbrite units not formerly identified in the CCVF include the 37.5–36.2 Ma tuffs exposed on and near Triad Ridge, southeast of Buena Vista, and distal facies of 27.8 Ma Fish Canyon Tuff and 27.4 Ma Carpenter Ridge Tuff erupted from the San Juan volcanic field and emplaced in paleovalleys along the course of the modern Arkansas River. Weighted-mean ages for nine dated sanidine-bearing lavas (Fig. 2E) are near 36.1–35.4 Ma, 33.7 Ma, and 32–29 Ma (Fig. 9). The significance and implications of the weighted mean ages of dated sanidine-bearing ignimbrites and lavas are discussed in following sections.

Single-crystal sanidine $^{40}Ar/^{39}Ar$ results from volcaniclastic units—Single-crystal laser-fusion analyses of K-feldspar crystals separated from reworked pumice and ash-rich layers and volcanic clasts within the Florissant, Pitch-Pinnacle, and Antero Formations (Fig. 10) yield results similar to those from contaminated regional ignimbrites. Radiogenic yields of individual crystals tend to be slightly lower (typically >90-95%), and analytical uncertainties (± 2σ) of individual crystals tend to be slightly higher (typically 0.25–1.3%). The lower yield and less precise ages are in part a function of crystal size, which tends to be somewhat smaller in the sedimentary units compared to regional ignimbrites.

Laser-fusion ages for sanidine crystals from three samples of sedimentary facies of the Antero Formation are nearly identical to results from Antero Formation ignimbrite facies. All of the sanidine crystals from Antero Formation sedimentary facies have unimodal age distributions near 33.8 Ma (Table 2; Fig. 10); no contaminant crystals were identified in these samples. Similarly, all sanidine crystals from five samples of the Florissant Formation have tightly clustered unimodal age distributions near 34.1 Ma and lack older contaminant crystals (Table 2; Fig 10).

Slightly more complicated results were obtained from eight samples of ash-and pumice-rich beds and volcanic clasts in the Pitch-Pinnacle Formation. A few of the K-feldspar crystals have ages near 32.9 Ma and K/Ca values near 30, whereas the majority of the crystals have ages clustering near 33.7 Ma and K/Ca values near 50 (Fig. 10; Table 2; Appendix 5). In addition, about 20% of the analyzed grains are significantly older, ranging from 430 to 915 Ma, with K/Ca values near 1000 (Table 2; Appendix 5). The youngest crystals (32.9 Ma) were interpreted by Gregory and McIntosh (1996) as being derived from the 32.9 Ma Gribbles Park Tuff, and therefore constitute evidence for a depositional age less than or equal to 32.9 Ma for at least part of the Pitch-Pinnacle Formation caldera-fill sequence.

The depositional age, provenance, and climatic significance of dated ash-and pumice-rich Antero, Florissant, and Pitch-Pinnacle Formations are further discussed below.

$^{40}Ar/^{39}Ar$ incremental-heating analyses of bulk samples—methods and results

Bulk-sample incremental-heating $^{40}Ar/^{39}Ar$ methods were used to analyze 45 non-sanidine mineral separates and groundmass concentrates from 37 different samples (Table 2; Appendix 6). Most of these analyses were attempts to date a variety of units that generally lack phenocrystic sanidine, including 19 samples of ignimbrites and lavas, one ash-rich sedimentary unit, and 12 samples of plutons. Ten biotite separates, six hornblende separates, and four groundmass concentrates were prepared from the 20 volcanic and sedimentary samples. Four of the biotite separates were obtained for comparative purposes from samples of Gribbles Park/upper Bonanza Tuff containing coexisting sanidine dated by single-crystal laser fusion (samples 696, 697, 699, and 700 in Table 2). A total of 30 K-feldspar, biotite, muscovite, and hornblende separates were obtained from 12 coarse-grained plutonic samples; step-heating of multiple minerals from plutonic samples was performed in hopes of assessing potentially extended cooling histories of the plutons.

Mineral separation and sample irradiation methods were generally similar to those used for sanidine separates (Table 2 footnotes). Following irradiation, samples were heated in 7–5 steps in a double-vacuum, low-blank resistance furnace, then analyzed using the same MAP 215-50 mass spectrometer used for analysis of laser-heated samples. Following corrections for blank, mass discrimination, and post-irradiation isotopic decay, ages for each analysis were calculated using decay constants and isotopic abundances reported by Steiger and Jäger (1977). Then age spectra and isochrons were plotted for each incrementally heated sample. Where age spectra met plateau criteria, plateau ages were calculated. Results are summarized in Table 2 and age spectra from four representative samples are shown in Figure 7. Procedural details of sample preparation, irradiation, analytical parameters and plateau selection criteria are summarized in Table 2 footnotes. Analytical data, age spectra, and isochrons for all step-heated samples are compiled in Appendix 6.

Age spectra from the majority of mineral separates and groundmass concentrates from the volcanic rocks tended to be reasonably precise and concordant, with the exception of some initial steps with generally low radiogenic yields and poor precision. Most of the age spectra from the analyzed volcanic rocks met or approached plateau criteria (e.g., Fig. 7A,B,C) , allowing calculation of the plateau ages reported in Table 2. Total gas ages are reported for two discordant age spectra from biotites (Table 2). One of these (Gribbles Park/upper Bonanza Tuff sample 700, Table 2) has low radiogenic yields and low K/Ca values suggesting alteration of the biotite. The other discordant spectrum is from biotite from sample 1314 of a reworked ash-rich sedimentary facies of the Antero Formation (Table 2). The high degree of discordance of this age spectrum probably reflects a mixture of detrital grains with varied provenance and age. Plateau ages for the biotite and hornblende separates and for groundmass concentrates tend to be significantly less precise than weighted-mean ages of sanidine phenocrysts, but are nonetheless considered to be reasonably accurate estimates

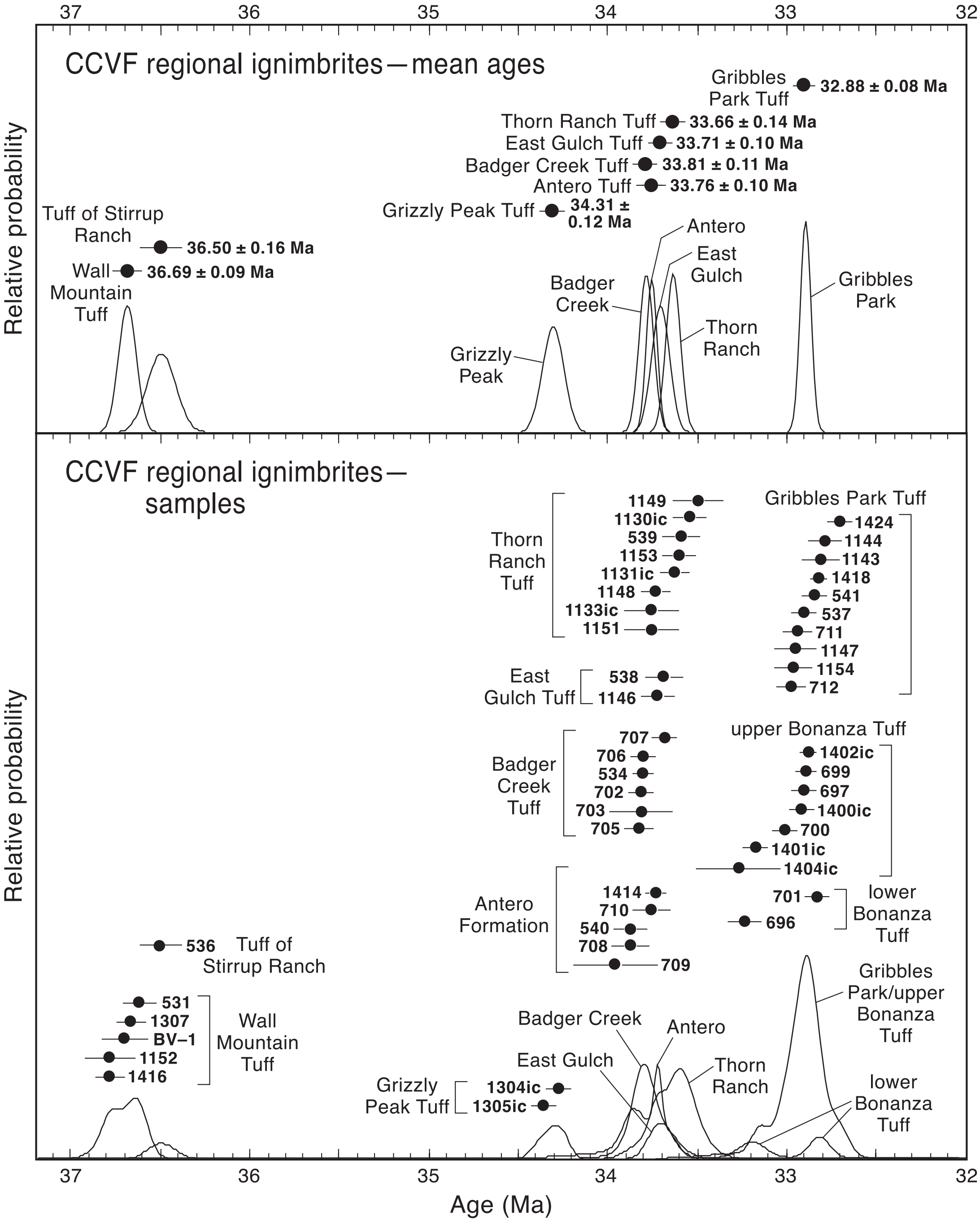


FIGURE 8—Age-probability distribution diagram summarizing $^{40}Ar/^{39}Ar$ results from the central Colorado volcanic field ignimbrites. The age-probability distribution diagram is similar to a histogram but takes into account uncertainties of individual data points. The diagram was constructed using the method of Deino and Potts (1992), by summing the model gaussian-probability curves for each date. Geomagnetic polarity time scale (GPTS) is after McIntosh et al. (1992b).

of eruption age. For the three samples with successfully dated biotite/sanidine pairs (samples 696, 697, and 699, Table 2), biotite plateau ages are systematically 0.15–0.3 m.y. older than the respective weighted-mean sanidine phenocryst age (Fig. 7E). This small but significant systematic difference between sanidine and biotite ages has been observed elsewhere and may be due to some combination of ^{39}Ar recoil and small amounts of excess ^{40}Ar in the biotite (Heizler 2001).

Age spectra of mineral separates from the plutonic rocks are generally less concordant than those from the volcanic rocks (e.g., Fig. 7D). The hornblende spectra are slightly to strongly discordant and irregularly shaped, perhaps in part due to ^{39}Ar recoil artifacts related to incipient chloritization. For most of the plutons, biotite and muscovite have relatively flat age spectra, many of which meet or approach plateau criteria (Table 2, Fig. 7D). Biotite separates yielded relatively precise plateau ages for seven of the ten pluton samples (Table 2, Fig. 9). Results from one biotite (sample 1407, Table 2) were rejected because of observed alteration of the biotite. Plateau ages of coexisting muscovite from two of the pluton samples (samples 1411 and 1412, Table 2) agree closely with the biotite ages. For the one pluton (sample 1408, Table 2) that failed to yield separable biotite, the K-feldspar age spec-

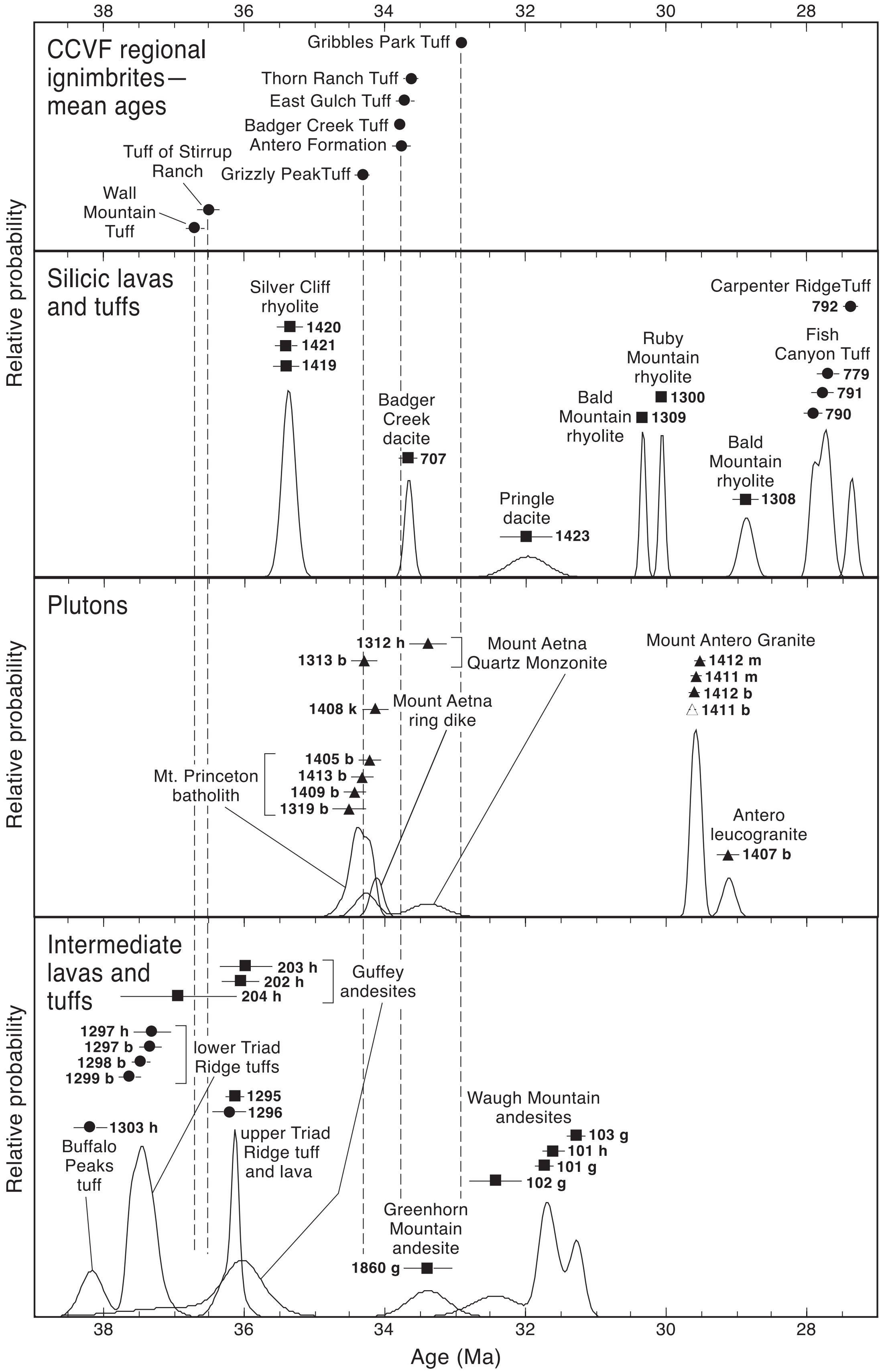


FIGURE 9—Age-probability distribution diagram summarizing $^{40}Ar/^{39}Ar$ results from the central Colorado volcanic field plutons and non-regional silicic and intermediate units.

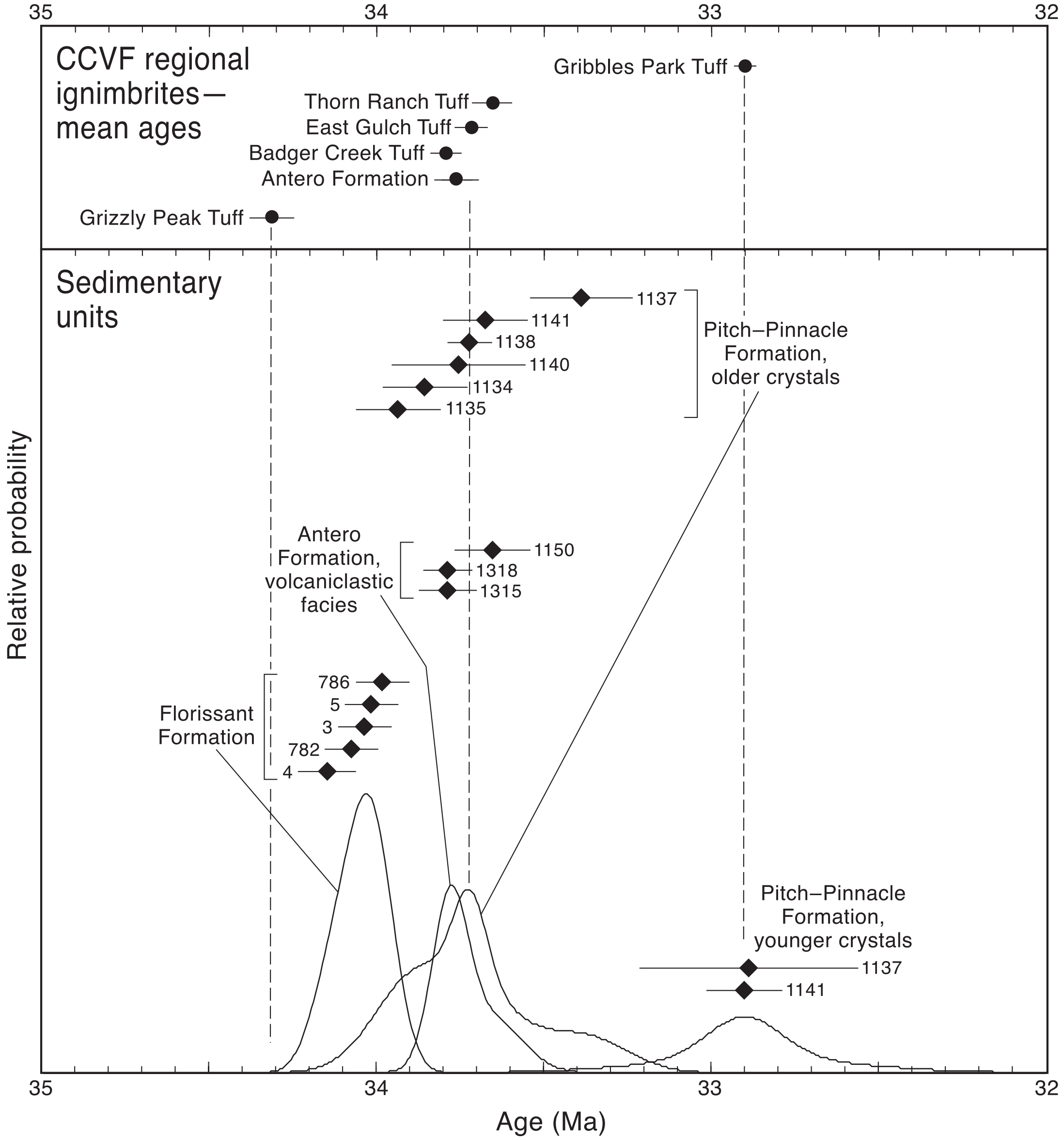


FIGURE 10—Age-probability distribution diagram summarizing $^{40}Ar/^{39}Ar$ results from the central Colorado volcanic field tuffaceous sedimentary units.

trum is flat and satisfies plateau criteria. K-feldspar separates from the other plutons are discordant and strongly rising (e.g., Fig. 7D), possibly reflecting protracted cooling within the closure temperature range of the K-feldspars (typically approximately 150–250 °C). The seven biotite, two muscovite, and one K-feldspar plateau ages are considered to be reasonably accurate estimates of the intrusion ages of their respective pluton samples. Seven of the nine well-dated pluton samples have intrusion ages near 34 Ma, and two have intrusion ages near 30 Ma (Table 2; Fig. 9).

Paleomagnetic methods and results

Oriented samples for paleomagnetic study were collected at many of the sample localities visited in the early stages of this study. Seven to ten field-drilled oriented cores were collected at each of 40 sites, primarily in regional ignimbrites. Samples were prepared and analyzed using sampling and analytical procedures identical to those reported in McIntosh (1991). Alternating field demagnetization procedures allowed isolation of what is interpreted to be primary thermoremanent magnatization directions for most of the sampled sites. Paleomagnetic data are summarized in Table 3.

Individual regional ignimbrites appear to have consistent paleomagnetic remanence directions and polarities, although the lack of distinctive unit-mean directions (compared, for example, with paleomagnetic data from ignimbrites of the Mogollon-Datil volcanic field (McIntosh 1991)) makes paleomagnetic remanence direction less useful than might be desired for correlation of individual ignimbrite sheets. Regional CCVF ignimbrites from the oldest (36.7–36.5 Ma) and youngest (32.9 Ma) eruptive pulses have normal paleomagnetic polarity, and ignimbrites from the middle (33.7 Ma) eruptive interval have reversed polarity. As described in detail below, paleomagnetic polarity has proven useful in helping to address some ignimbrite correlation problems, especially testing (and disproving) correlations between reverse polarity Badger Creek Tuff and lithologically similar normal-polarity ignimbrites near the Arkansas River and on Triad Ridge.

TABLE 3—Paleomagnetic results from CCVF samples.

Unit	Sample	Demag (mT)	n	K	Inclination (deg)	Declination (deg)	α^{95} (deg)
Fish Canyon Tuff	790	20	8	266.5	44.9	53.0	3.4
Fish Canyon Tuff	791	10	8	1564.0	68.9	23.1	1.4
Fish Canyon Tuff	779	0	10	206.1	54.5	3.5	3.4
Gribbles Park Tuff	537	50	6	52.6	50.4	315.0	9.3
Gribbles Park Tuff	711	40	8	1837.2	63.3	335.4	1.3
Gribbles Park Tuff	712	40	8	1170.7	55.7	337.6	1.6
Gribbles Park Tuff	780	20	8	458.9	58.9	332.4	2.6
upper Bonanza Tuff	541	80	4	173.9	62.4	350.9	7.0
upper Bonanza Tuff	697	50	8	230.6	44.8	345.0	3.7
upper Bonanza Tuff	698	10	8	86.3	47.8	337.3	6.0
upper Bonanza Tuff	699	50	9	1.8	17.1	335.7	57.9
upper Bonanza Tuff	700	5	9	1507.7	56.3	349.1	1.3
lower Bonanza Tuff	542	30	8	91.9	42.7	351.9	5.8
lower Bonanza Tuff	695	10	8	8.7	38.0	341.7	19.8
lower Bonanza Tuff	696	20	8	199.5	86.1	140.4	3.9
lower Bonanza Tuff	701	50	8	728.4	48.8	353.7	2.1
Thorn Ranch Tuff	781	50	8	147.0	-70.3	179.4	4.6
Thorn Ranch Tuff	539	10	4	205.1	-69.9	165.2	6.4
East Gulch Tuff	538	40	5	78.3	-55.1	190.5	8.7
East Gulch Tuff	789	5	8	970.5	-68.9	162.5	1.8
Badger Creek Tuff	534	30	8	33.0	-60.8	152.6	9.8
Badger Creek Tuff	702	5	8	601.6	-55.2	171.4	2.3
Badger Creek Tuff	703	20	8	707.2	-54.6	177.7	2.1
Badger Creek Tuff	704	10	8	848.5	-54.9	173.6	1.9
Badger Creek Tuff	705	30	8	318.3	-51.3	171.6	3.1
Badger Creek Tuff	706	10	6	814.4	-54.7	169.0	2.4
latite of East Badger Creek	707	50	6	84.2	-48.3	174.3	7.3
Antero Formation tuff	540	50	8	101.5	-61.9	155.3	5.5
Antero Formation tuff	708	10	8	208.5	-60.0	156.7	3.9
Antero Formation tuff	709	40	9	138.3	-59.3	161.4	4.4
Antero Formation tuff	710	5	8	32.7	-61.5	178.3	9.8
Florissant Formation	782	0	8	26.6	49.8	25.3	10.9
Florissant Formation	783	0	8	8.7	39.6	3.6	19.9
Florissant Formation	784	0	8	6.3	53.4	20.8	23.9
Florissant Formation	787	0	8	18.7	87.2	21.1	13.2
tuff of Stirrup Ranch	535	30	6	1.3	53.9	155.5	66.6
tuff of Stirrup Ranch	536	30	6	31.0	-42.3	239.2	12.2
Wall Mountain Tuff	531	50	8	118.5	55.1	347.4	5.1
Wall Mountain Tuff	533	30	8	222.5	55.4	336.8	3.7
lower tuff of Triad Ridge	532	40	8	902.3	47.6	351.5	1.9

Examples of regional correlations and solutions of stratigraphic problems

Wall Mountain Tuff/Badger Creek Tuff relationships

Eruption of the Wall Mountain Tuff at 36.69 ± 0.09 Ma and its emplacement along valleys on the late Eocene surface from the upper Arkansas Valley to the High Plains in the Castle Rock area (Fig. 2B) produced the first regional stratigraphic unit of middle Tertiary volcanism in central Colorado. With few exceptions, the unit rests directly upon pre-volcanic rocks ranging in age from Proterozoic to early Eocene. Erosion rapidly re-entrenched the valleys, leaving remnants of the densely welded Wall Mountain Tuff along the valley margins and occasionally on interfluves. Fluvial aggradation of the valleys formed the Castle Rock Conglomerate (Welch 1969; Morse 1985) on the High Plains and the Tallahassee Creek Conglomerate (Chapin and Epis 1974) within the Thirtynine Mile volcanic area (Figs. 3, 4). Andesitic debris flows, flow breccias, and occasional lava flows continued aggradation of the valleys and began construction of the main Thirtynine Mile volcanic pile. Renewed pyroclastic eruptions emplaced a second regional ignimbrite, the tuff of Stirrup Ranch tuff, at 36.50 ± 0.16 Ma. The Tallahassee Creek Conglomerate and from 5 to 260 m of andesitic breccias separate the Wall Mountain and Stirrup Ranch tuffs. The tuff of Stirrup Ranch was eroded to scattered remnants before being buried by continuing andesitic volcanism.

The Wall Mountain and Stirrup Ranch tuffs are so similar lithologically as to be difficult to distinguish when stratigraphic relationships are not exposed. Both tuffs are low-silica calc-alkalic rhyolites (Shannon et al. 1987). Fresh, glass-clear sanidine and fresh to intensely argillized plagioclase (andesine) are the dominant minerals. The sanidine to plagioclase ratio ranges from 0.9 to 4.4 and averages about 2.0 (Chapin and Lowell 1979). Quartz is not present as a phenocryst; biotite is the dominant mafic mineral followed by clinopyroxene and hornblende. Accessory minerals include orthopyroxene, magnetite, sphene, allanite, apatite, and zircon (Shannon et al. 1987). The Wall Mountain Tuff is about 27 m thick at the type locality (sec. 32 T16S R73W, east-central Black Mountain 15-minute quadrangle; Epis et al. 1979b) but is as much as 150 m thick in some exposures in paleovalleys in the western part of the CCVF. Outcrops of the tuff of Stirrup Ranch are relatively thin, and slumping in many cases has disaggregated the outcrops to boulders of various orientations. Both tuffs generally weather reddish brown and exhibit distinct eutaxitic fabrics formed by stretched pumice and gas cavities. Primary and secondary flow structures are prominent features of Wall Mountain

Tuff outcrops in some paleovalleys (Chapin and Lowell 1979).

Volcanism, erosion, and sedimentation competed for dominance on an abbreviated time scale as construction of the CCVF volcanic pile began. Within about 200,000 yrs, the Wall Mountain Tuff was deposited, the valleys were reentrenched and were then filled with fluvial conglomerates and andesitic debris flows before the tuff of Stirrup Ranch was emplaced, probably from the same source as the Wall Mountain Tuff. Poor exposures, cut-and-fill structures, and inversion of topography led to conflicting interpretations of stratigraphic relationships by early mappers in central Colorado. One of these stratigraphic problems was recently resolved by a combination of ^{40}Ar/^{39}Ar dating and paleomagnetic correlation and provides a good example of the power of combining these methods.

A paleovalley containing as much as 320 m of dacitic ignimbrites is followed by US–285 on the west side of Trout Creek Pass. These dacitic ignimbrites, called the andesitic tuff of Castle Rock Gulch by DeVoto (1971) and the tuff of Triad Ridge herein, form a complex outcrop pattern with the Wall Mountain Tuff in Mushroom and Castle Rock gulches along the west edge of the Antero Reservoir 15-minute quadrangle. DeVoto (1971) interpreted the outcrop relationships to indicate that the tuff of Castle Rock Gulch is overlain by the Wall Mountain Tuff (his Agate Creek Tuff, now abandoned). However, Epis and Chapin (1974) and Scott et al. (1978) correlated the tuff of Castle Rock Gulch with the Badger Creek Tuff based on a striking lithologic similarity and the fact that nowhere else in the Thirtynine Mile volcanic area did anything more than a few meters of ash or debris flows underlie the Wall Mountain Tuff. Field relationships along Mushroom and Castle Rock gulches are ambiguous and either interpretation could be justified in the field. The conflict was resolved when ^{40}Ar/^{39}Ar dating revealed that the lower portion of the tuff of Castle Rock Gulch (here termed lower tuff of Triad Ridge) is older (37.49 ± 0.22 Ma) than the Wall Mountain Tuff (36.69 ± 0.09 Ma) and has normal magnetic polarity, whereas the Badger Creek Tuff is younger (33.81 ± 0.11 Ma) and has reverse polarity. The Wall Mountain Tuff apparently filled sharply incised valleys carved into the tuff of Triad Ridge. Careful re-examination of the field relationships confirmed that DeVoto's interpretation was correct. The tuff of Triad Ridge (tuff of Castle Rock Gulch) is apparently a thick, proximal accumulation of ignimbrites that was confined mainly to paleovalleys along what is now the southern Mosquito Range (also known as the Arkansas Hills). ^{40}Ar/^{39}Ar ages of the uppermost ignimbrite (here termed upper tuff of Triad Ridge, 36.22 ± 0.32 Ma) and overlying dacitic lava (dacite of Triad Ridge, 36.14 ± 0.12 Ma) are somewhat younger than Wall Mountain Tuff. These age data suggest an unconformity within the Triad Ridge sequence that was not recognized in the field, and upon which Wall Mountain Tuff was either not deposited or not preserved.

The Badger Creek Tuff is a multiple-flow compound cooling unit of crystal-rich ignimbrites. Lowell (1969) measured 95 m of Badger Creek Tuff in the Salida–Waugh Mountain paleovalley where it rests on Proterozoic rocks, the Wall Mountain Tuff, Tallahassee Creek Conglomerate, or the Antero Formation and is locally overlain by a dacite lava flow and the Gribbles Park Tuff. The Badger Creek Tuff has a distinctive "salt and pepper" appearance caused by abundant black biotite and hornblende crystals mixed with light-pink and white pumice lapilli which, in the more densely welded zones, form lenses of black glass (piperno). Strongly zoned plagioclase crystals (andesine) comprise 70–80% of the phenocrysts; sanidine is present but only to the extent of 2–5%. Gray and brown accessory lithic lapilli are moderately abundant. The tuff has a slabby weathering habit and often crops out as rounded hills or moderate slopes of yellowish-gray to buff rock, although it tends to be light gray to reddish brown when fresh. The Badger Creek Tuff is easily confused with the tuff of Triad Ridge but the correlation fails on age, paleomagnetism, and stratigraphic position.

Other outcrops of Badger Creek-like tuffs are present along the Arkansas River near Howard. Taylor et al. (1975) assigned these outcrops to the Badger Creek Tuff and described them as pinkish-gray crystal-rich ignimbrite containing abundant biotite, sanidine, hornblende, quartz, plagioclase, sphene, magnetite, and sparse purplish-brown rock fragments in a glass-shard groundmass. The sanidine-plagioclase ratio does not fit the Badger Creek Tuff, but when dealing with multiple-flow compound cooling units it is tempting to make allowances for lithologic variations. The outcrops in question are paleovalley fills resting on Paleozoic rocks and overlain by local lava flows and a then unknown tuff from outside the area. ^{40}Ar/^{39}Ar dating and paleomagnetic correlation confirms a correlation of the Badger Creek-like tuff (27.83 ± 0.15 Ma, normal polarity) with the Fish Canyon Tuff (27.84 Ma, normal polarity) erupted from the La Garita caldera (Steven and Lipman 1976; Lipman 2000) in the San Juan volcanic field, approximately 100 km to the southwest. The overlying, then unknown, tuff is correlated with the Carpenter Ridge Tuff (27.35 Ma, Lipman 2000)) on the basis of ^{40}Ar/^{39}Ar age (27.38 ± 0.12 Ma), reverse magnetic polarity, lithology, and stratigraphic position. The Carpenter Ridge Tuff was erupted from the Bachelor caldera in the central San Juan Mountains (Lipman et al. 1973; Lipman 2000).

An additional outcrop of nonwelded Fish Canyon Tuff (dated at 27.71 ± 0.14 Ma, normal polarity) is interbedded with the conglomerate of Fear Creek (Epis and Chapin 1974) where it forms a conspicuous white band high on the north side of the Arkansas River canyon 27 km further east. The conglomerate of Fear Creek fills a southeast-trending paleovalley 1–2 mi wide and as much as 100 m deep incised into the Gribbles Park Tuff (32.88 ± 0.08, normal polarity) and is overlain by the undated basaltic andesite of Waugh Mountain (Epis and Chapin 1974).

Thus, there are at least three dacitic, crystal-rich, plagioclase-dominant, biotite- and hornblende-bearing ignimbrites in the central Colorado volcanic field. Lack of exposed stratigraphic relationships with regional Cenozoic units at some localities and the difficulties commonly encountered in interpreting stratigraphic relationships in multiply incised paleovalley sequences have created confusion. The long-distance transport of ignimbrites from eruptive centers as much as 100 km outside the Thirtynine Mile volcanic area is also a contributing factor.

Gribbles Park Tuff/upper Bonanza Tuff relationships

The Gribbles Park Tuff is a multiple-flow, compound-cooling unit of low-silica, relatively crystal-poor (13–32% phenocrysts) rhyolites characterized by abundant sanidine (6–14%), subordinate plagioclase (1–8%), and biotite (0.3–5%) with trace amounts of pyroxene, hornblende, and sphene (Lowell 1969, 1971; Epis and Chapin 1974). Dark-brown and gray accessory lithic fragments are abundant, as are large pumice lapilli. Lowell (1969) measured 180 m of Gribbles Park Tuff along the north side of Two Creek in the Salida–Waugh Mountain paleovalley. Here, the Gribbles Park section consists of three main members, which in ascending order are dark brownish-purple, pinkish-gray, and purplish-red on fresh surfaces, with thicknesses of 73, 70, and 34 m, respectively. A distinctive pinkish-orange unwelded tuff, approximately 3 m thick, occurs between the purple and gray members. The main members are moderately to densely welded. Black vitrophyre zones occur locally at the base of the lower member. Outcrops of the gray member commonly have a distinctive brittle fracture and ring when hit with a hammer.

The Gribbles Park Tuff is widely distributed and crops out from southern South Park to the northern Wet Mountain Valley and from the Saguache–Marshall Creek area on the west to Tallahassee Creek on the east (Fig. 2D). Westward forking paleovalleys and the maximum thickness of the Gribbles Park Tuff near the west end of the Salida–Waugh Mountain paleovalley indicate a source to the west, with the Bonanza caldera long considered a possibility. Our dating and paleomagnetic work confirm this correlation, which was originally suggested by Bruns et al. (1971).

The Bonanza caldera (Fig. 2) is located in the southern Sawatch Range at the extreme northeast corner of the San Juan volcanic field. Base-metal mineralization in the Bonanza mining district provided impetus for a number of geological studies including Burbank's 1932 U.S. Geological Survey Professional Paper on the geology of the ore deposits, Karig's 1965 paper on geophysical evidence for a caldera at Bonanza, the 1971 paper by Bruns et al. on stratigraphic relations with the San Juan volcanic field, and Varga and Smith's 1984 paper on the evolution of the Bonanza caldera. The oldest Tertiary unit of the Bonanza volcanic center is a complex suite of andesitic lavas, and debris-flow breccias with minor ignimbrites and airfall and water-lain tuffs. These rocks, given the formal name Rawley Andesite by Bruns et al. (1971), after a more restricted term used by Burbank (1932), are similar in origin to the widespread Conejos Formation (Lipman et al. 1970) of the San Juan volcanic field as well as the lower Thirtynine Mile Andesite of the central area of the CCVF (Epis and Chapin 1974).

The Bonanza Tuff (Mayhew 1969), originally the Bonanza Latite of Burbank (1932), overlies the Rawley Andesite and consists of an upper and lower ignimbrite sequence. The best exposures are on Findley Ridge, about 7 km northwest of the town of Saguache (Fig. 2). Findley Ridge is a remnant of a paleovalley (see fig. 8 of Bruns 1971 and fig. 6 of Varga and Smith 1984) in which an unusually thick and complex series of ignimbrites accumulated. Marrs (1973) measured approximately 150 m of ignimbrites and designated Findley Ridge as a principal reference section. Marrs (1973) subdivided the section on Findley Ridge into eight ignimbrite flow units based on mineralogy and topographically expressed cooling breaks. Units one through four of the measured section of Marrs (1973) total 69 m in thickness and are crystal-rich (22–42% phenocrysts, Table 4) trachydacites in which plagioclase (andesine An 26-52) dominates over sanidine about 2.7/1. They also contain abundant biotite (2–4%) and as much as 2.3% pyroxene (Table 4). We obtained an ^{40}Ar/^{39}Ar age of 33.21 ± 0.12 Ma on biotite from unit one and a 33.32 ± 0.16 Ma age on sanidines from unit two (Table 2). A sample of lower Bonanza Tuff along Saguache Creek yielded an age of 32.83 ± 0.11 Ma on sanidine (Table 2). Beginning with unit five of Marrs (1973), the composition of ignimbrites on Findley Ridge becomes more silicic and more variable between units. Sanidine and plagioclase become subequal in units five and six and then sanidine dominates in unit seven, which is crystal poor and mineralogically identical to Gribbles Park Tuff elsewhere, A slight angular unconformity and a prominent black vitrophyre mark the base of unit five. In contrast to the increasingly rhyolitic trend in units one through seven, the uppermost ignimbrite on Findley Ridge, unit eight of Marrs (1973), has mineralogy and field characteristics typical of lower Bonanza Tuff. It is crystal rich (44%), plagioclase dominant, contains 2% pyroxene, and is similar in texture to lower Bonanza Tuff. This anomalous reversal in compositional trend, not seen elsewhere above Gribbles Park Tuff, is interpreted as a consequence of Findley Ridge preserving a caldera-proximal paleovalley sequence. Apparently, a late-stage eruption produced lower-Bonanza-like ignimbrite that was emplaced above the Gribbles Park Tuff within the Findley Ridge paleovalley. Outside of this paleovalley, this uppermost "last gasp" ignimbrite was either never emplaced or has been eroded. Ignimbrite sequences in other areas exhibit more-silicic-to-less-silicic trends similar to the compositional trend at the top of the Findley Ridge section; in several cases these "normally zoned" trends have been interpreted as a consequence of progressive emptying of a vertically zoned magma chamber (e.g., Hildreth 1979).

The stratigraphic complication in the Findley Ridge sequence has some analogues elsewhere in the CCVF. As discussed in a previous section, the 36.50 ± 0.16 Ma tuff of Stirrup Ranch is lithologically virtually identical and chronologically indistinguishable from the underlying 36.69 ± 0.09 Ma Wall Mountain Tuff, but separated from it stratigraphically by the Tallahasse Creek Conglomerate and basal breccias of the lower Thirtynine Mile Andesite. Similarly, in the Trout Creek paleovalley, it appears that the ignimbrite eruptions that produced the multi-flow tuff of Triad Ridge apparently both preceded and followed emplacement of the Wall Mountain Tuff, thus confusing stratigraphic relationships in that area. The emplacement of ignimbrite sequences in paleovalleys may enhance chances of preserving relatively small-volume units erupted 10^5–10^6 yrs after eruption of larger volume regional ignimbrites, yielding locally complex stratigraphic relationships. Incision and topographic inversion further complicate stratigraphic relationships in many paleovalleys.

Units five and seven in the Findley Ridge section of Marrs (1973) yielded ^{40}Ar/^{39}Ar sanidine ages of 32.90 ± 0.10 Ma and 32.89 ± 0.09 Ma , respectively (Table 2). Biotite apparent ages were slightly older, 33.30 ± 0.13 Ma and 33.24 ± 0.24 Ma, respectively, probably reflecting small amounts of excess ^{40}Ar in the biotites (Heizler 2001). The sanidine results suggest that the upper Bonanza Tuff is at most 300 k.y. younger than the lower Bonanza Tuff. We correlate units five, six, and seven of measured section on Findley Ridge with Gribbles Park Tuff on the basis of ^{40}Ar/^{39}Ar age, magnetic polarity (normal), distinctive northwesterly paleomagnetic declination (Table 3), and lithologic similarity. Unit seven (samples 541, 699, Appendix 1) is a distinctive light-gray to lavender-gray rhyolite in which vapor-phase crystallization has modified the matrix such that the tuff has a brittle fracture and a notable ring when hit with a hammer. Phenocrysts are less abundant (10–16%) in unit seven, sanidine dominates, and it contains traces of hornblende and only about 1% biotite. Marrs (1973) commented that unit seven is a very distinctive ignimbrite and probably came from a different source. Unit seven at Findley Ridge is lithologically identical to Lowell's (1969) member G of the Gribbles Park Tuff, a readily recognizable stratigraphic unit in the CCVF. Samples of Gribbles Park Tuff members P and G of Lowell (1969) (samples 712 and 537, Table 2) yielded ^{40}Ar/^{39}Ar sanidine ages of 32.98 ± 0.14 Ma and 32.91 ± 0.11 Ma, respectively, within analytical error of the ages determined for units five and seven of the measured section of Marrs (1973).

The crystal-rich, dacitic lower Bonanza Tuff and crystal-poor, rhyolitic upper Bonanza Tuff are also distinct geochemically. Atkinson (2000) analyzed 12 samples of the upper Bonanza Tuff and compared them with 11 samples of lower Bonanza Tuff analyzed by Jamison (1996) and Skinner (1997). Atkinson (2000) found clear distinctions in Zr/Nb, Zr/Yb, La/Nb, Ti/Zr, and Ce/Yb between the upper and lower Bonanza Tuff. She concluded that the distinct separa-

TABLE 4—Phenocryst mineralogy of regional ignimbrites. Range of values and average (in parentheses) given for point–counted modal analyses: **n** = number of thin sections counted; **#** = approximate visual estimates; ***** = samples from outside CCVF; **tr** = trace. Accessory minerals: **o** = oxides; **sp** = sphene; **al** = alunite; **zr** = zircon; **ap** = apatite.

Unit	n	Phenocryts	Quartz	Sanidine	Plagioclase	Biotite	Hornblende	Pyroxene	Accessory	Source
Carpenter Ridge	6*	6–18(10)		2.4–4.8 (3.6)	0.2–27.9(9.0)	0.2–3.9(1.2)	0–0.6(0.2)	0–1.4(0.2)	o	Lipman 1975
	7*	8–10(9)		4–5(4.3)	3–5(3.6)	1–2(1)			o	Smith, unpublished
Fish Canyon (outflow)	6*	34–36(36)	0–3.0(2.2)	0–6.0(4.5)	18–28(22.2)	2.4–5.0(3.5)	1.4–3.0(2.3)		sp,o	Lipman 1975
Gribbles Park (upper Bonanza)	6	13–32(16)		6.5–14.4(9.9)	1.2–8.1(3.1)	0.3–4.7(2.1)	0.2–1.9(0.7)		sp,o	Lowell 1969
	6	16–47(35)		10–24(15)	2–26(15.7)	1–5(3.3)	tr	0–2(1)	o	Marrs 1973
	#	15		9	5	tr	tr		o	Varga and Smith 1984
Bonanza (lower)	9	22–42(32)		5–12(7.2)	11–30.3(19.5)	2–4(3.1)		0–2.3(0.7)	o	Marrs 1973
	#	30		9	18	2	tr	tr	ap,o	Varga and Smith 1984
Thorn Ranch	#	20–25	~ 2	~ 10	~ 2	~ 1			o	Epis and Chapin 1974
East Gulch	10	12–23(17)	1–3(2)	7–17(12)	1–3(2.3)	0–1(tr)			o	Smith unpublished
Badger Creek	8	31–37(34)		0.2–1.7(0.7)	22–28(25.1)	5.5–7.0(6.2)	0.6–2.4(1.5)		sp,o	Lowell 1969
	3	33.6	0.2	2.1	24.7	4.1	1.3		sp,al,zr,ap,o	Shannon et al. 1987
Antero Formation	8	11–30(22)		tr–1.7(0.9)	7.4–20.0(14.3)	2.8–7.7(5.7)	0.2–0.9(0.5)		sp,o	Lowell 1969
Stirrup Ranch	#	15–25		~ 13	~ 7	~ 1.5			o	Epis and Chapin 1974
Wall Mountain	6	21–33(26)		12–18(15.2)	4.5–11.6(9.3)	1.4–3.5(2.2)	tr[1]	tr[1]	o	Lowell 1969
	13	7–29(22)		4.7–21.0(13.5)	1.9–10.1(4.8)	0.3–2.3(1.3)			o	Niesen 1969
	7	14–19(16)		7.2–10.8(8.7)	5.0–7.9(6.7)	0.3–1.8(1.1)			o	Tobey 1969
	2	18.1		11.5	4	1.1		0.6	sp,al,zr,ap,o	Shannon et al. 1987
Triad Ridge (upper)	#	20–35			~ 25	~ 6	~ 1.5		o	Smith 1982
Triad Ridge (lower)	#	20–35		~ 0.7	~ 25	~ 6	~ 1.5		o	Smith 1982

tion in incompatible trace element ratios argues against a common source for the two magma types and that the upper Bonanza Tuff was not derived by simple fractionation of the magma that generated the lower Bonanza Tuff. Atkinson (2000) also analyzed two samples of the rhyolitic Spring Creek pluton (a rhyolitic stock) and three samples of the Porphyry Peak Rhyolite (three exogenous domes), both of which are located along the northern ring fracture zone of the Bonanza caldera. She found these late-stage intrusive bodies to be very similar geochemically to the upper Bonanza Tuff. Analysis of lineated pumice and fluidal flow textures in both the lower and upper Bonanza Tuff by Varga (1982) (see Varga and Smith 1984, fig. 6) indicates that tuffs of both sequences were erupted from the northern margin of the Bonanza caldera in the vicinity of the Spring Creek and Porphyry Peak intrusions.

In the future, we recommend that the name Bonanza Tuff be restricted to the lower crystal-rich dacitic unit, and that Gribbles Park Tuff be used for the upper crystal-poor rhyolitic unit.

Thorn Ranch Tuff/Marshall Creek caldera

The Thorn Ranch Tuff (Epis and Chapin 1974) is overlain by the Gribbles Park Tuff and rests upon the Antero Formation or, where present, the East Gulch Tuff (Figs. 3, 4). The Thorn Ranch Tuff crops out from the Badger Creek valley southeastward through the Waugh Mountain and Tallahassee Creek areas and southward into the northern Wet Mountain Valley near Hillside (Fig. 2D). The Thorn Ranch Tuff is a simple cooling unit of nonwelded to moderately welded tuff that weathers pinkish white to reddish brown. It is high-silica rhyolite containing 15–25% phenocrysts of sanidine, plagioclase, quartz, and biotite (Table 4). Abundant Precambrian lithic fragments and brown aphanitic accessory lithic fragments carried in a matrix of devitrified glass shards and pink and white pumice give the Thorn Ranch Tuff a distinctive appearance. Spherulitic replacement of pumice by vapor-phase minerals to yield a “birds nest” texture is common. The Thorn Ranch Tuff forms prominent reddish-brown caprocks with well-developed columnar jointing on mesas near the confluence of the three forks of Tallahassee Creek. It exhibits reverse magnetic polarity and ranges up to about 75 m in thickness. The mean of five $^{40}Ar/^{39}Ar$ sanidine dates of outflow facies Thorn Ranch Tuff samples gives an age of 33.66 ± 0.14 Ma (Table 2).

During an investigation of fossil flora in lacustrine strata near the Pitch-Pinnacle uranium mine in the southern Sawatch Range, between Marshall Pass and the community of Sargents (Fig 2a), Gregory and McIntosh (1996) recognized geologic features indicative of a caldera collapse structure. Further reconnaissance, supplemented by $^{40}Ar/^{39}Ar$ dating and paleomagnetic correlation of ignimbrites, provided evidence that the caldera is the source of the Thorn Ranch Tuff. Sampling and analysis (Table 2) of three samples of outcrops of Thorn Ranch Tuff along the Marshall Pass Road (Twl unit of Olson 1983) yielded an average $^{40}Ar/^{39}Ar$ age of 33.61 ± 0.17 Ma, which agrees closely with 33.66 ± 0.14 Ma mean age for outflow-facies Thorn Ranch Tuff in the Thirtynine Mile volcanic area. The outcrops along the Marshall Pass Road contain numerous large clasts of Precambrian rocks indicative of proximity to an eruption center

The Continental Divide south of Marshall Creek is capped by the Gribbles Park/upper Bonanza Tuff (Twb unit of Olson 1983) from which Gregory and McIntosh (1996) obtained $^{40}Ar/^{39}Ar$ ages of 32.81 ± 0.20 Ma and 32.79 ± 0.19 Ma, which are close to the 32.88 ± 0.08 Ma $^{40}Ar/^{39}Ar$ mean age of 14 samples of outflow facies Gribbles Park Tuff and upper Bonanza Tuff (Table 2). Outcrops of upper Bonanza Tuff dated by us along CO–114 west of Saguache are only about 20 km to the southeast. Sanidines from pumice in sandstones in the Pitch-Pinnacle Formation, a partly lacustrine unit within the Marshall Creek caldera, yielded a bimodal distribution of ages with the majority of grains near 33.7 Ma and a minority of grains near 32.9 Ma (Gregory and McIntosh 1996). Thus, it is likely that the sandstones in the Pitch-Pinnacle Formation were derived in part by erosion of the 33.7 Ma Thorn Ranch Tuff and the 32.9 Ma Gribbles Park/upper Bonanza Tuff. The high mean K/Ca values of the 33.7 Ma sanidines in the Pitch-Pinnacle Formation (Table 2) suggest that some crystals may also have been derived from the 33.8 Ma Badger Creek Tuff.

The Pitch-Pinnacle Formation overlies, and is interbedded with, a megabreccia of differing rock types mapped by Olson (1983) as various Paleozoic formations and volcanic rocks. In some areas, large allochthonous blocks occur in various orientations surrounded by a tuffaceous clayey matrix (Gregory and McIntosh 1996). An ignimbrite clast and an ignimbrite slide block from the megabreccia yielded ^{40}Ar/^{39}Ar ages of 33.93 ± 0.21 Ma and 33.85 ± 0.21 Ma (Gregory and McIntosh 1996). These blocks may have been derived from the lithologically similar 33.8 Ma Badger Creek Tuff.

Badger Creek Tuff/Mount Aetna cauldron

The Mount Aetna cauldron in the Sawatch Range, northwest of Salida, was identified by Shannon et al. (1987) as the source of the Badger Creek Tuff. Our dating confirms that correlation with an ^{40}Ar/^{39}Ar age of 33.66 ± 0.13 Ma for the Mount Aetna intracaldera tuff, in close agreement with the 33.81 ± 0.11 Ma mean age of five samples of outflow Badger Creek Tuff. It is also likely that the Antero Formation tuffs (33.76 ± 0.10 Ma) were also erupted from the Mount Aetna caldera. The Mount Aetna intracaldera and Badger Creek and Antero outflow tuffs all have reverse polarity. The Mount Aetna cauldron was suggested as a possible source of the Wall Mountain Tuff by Epis and Chapin (1974) but this now seems highly unlikely.

Mount Princeton batholith/Wall Mountain Tuff controversy

Several workers have inferred that the Mount Princeton batholith and/or the Mount Aetna cauldron complex were the source of the Wall Mountain Tuff. The Trout Creek and Salida–Waugh Mountain paleovalleys (Fig. 2) converge toward the Mount Princeton batholith and their tributaries fork to the west indicating east-flowing drainage systems (Chapin et al. 1970; Epis and Chapin 1975). The black vitrophyre zone at the base of the Wall Mountain Tuff is thickest in these paleovalleys, as is the total thickness of the unit. The occurrence of the tuff of Triad Ridge beneath the Wall Mountain Tuff in the Trout Creek paleovalley and a dacitic porphyry flow beneath the Wall Mountain Tuff in the Browns Canyon fork (Van Alstine 1969) of the Salida–Waugh Mountain paleovalley indicate proximity to a pre-Wall Mountain eruptive center. The above features point to the Mount Princeton batholith area as the probable source of the Wall Mountain Tuff; proving it, however, is another matter. We now know that the Mount Aetna cauldron that collapsed within the Mount Princeton batholith was the source of the Badger Creek Tuff and Antero tuffs. Could an older caldera have erupted the Wall Mountain Tuff and been obliterated by erosion and the development of the Mount Aetna cauldron?

To evaluate the Mount Princeton batholith as a potential source area we sampled and dated several intrusions. The Mount Princeton batholith yielded an ^{40}Ar/^{39}Ar age of 34.31 ± 0.21 Ma (mean of four biotite dates), apparently too young to have been a source of the Wall Mountain Tuff (36.69 ± 0.09 Ma). The Mount Aetna intracaldera tuff gave an ^{40}Ar/^{39}Ar age of 33.66 ± 0.13 Ma (sanidine, one date) within error of the mean age of the Mount Aetna Quartz Monzonite (34.07 ± 0.90 Ma, n = 2) that intrudes it. The sequence of ages of Mount Princeton batholith, Mount Aetna intracaldera tuff, and Mount Aetna Quartz Monzonite agree with field relationships as mapped by Dings and Robinson (1957), Sharp (1976), and Shannon (1988); they also agree well with the age of the outflow ignimbrites, the Badger Creek Tuff (33.81 ± 0.11 Ma) and Antero Formation tuffs (33.76 ± 0.10 Ma). Remnants of an older stock, the Mount Pomeroy Quartz Monzonite (Dings and Robinson 1957), are present near the southern edge of the Mount Princeton batholith. Our attempts to date it were unsuccessful due to discordant biotite and hornblende ages.

Our 34.3 Ma biotite dates from Mount Princeton batholith are significantly younger than some other published dates from Mount Princeton. Shannon (1988) reported fission-track dates from sphene from Mount Princeton batholith of 39.4 ± 3.2 Ma and 41.2 ± 3.2 Ma and from zircon of 36.6 ± 0.4 Ma. Toulmin and Hammarstrom (1990) reported two ^{40}Ar/^{39}Ar hornblende dates from the Mount Princeton pluton of 36.3 ± 0.3 Ma and 37.1 Ma. More recently Fridrich et al. (1998) reported a ^{208}Pb/^{232}Th zircon date from Mount Princeton of 36.6 Ma. These dates agree well with our 36.69 ± 0.09 Ma ^{40}Ar/^{39}Ar sanidine age for the Wall Mountain Tuff.

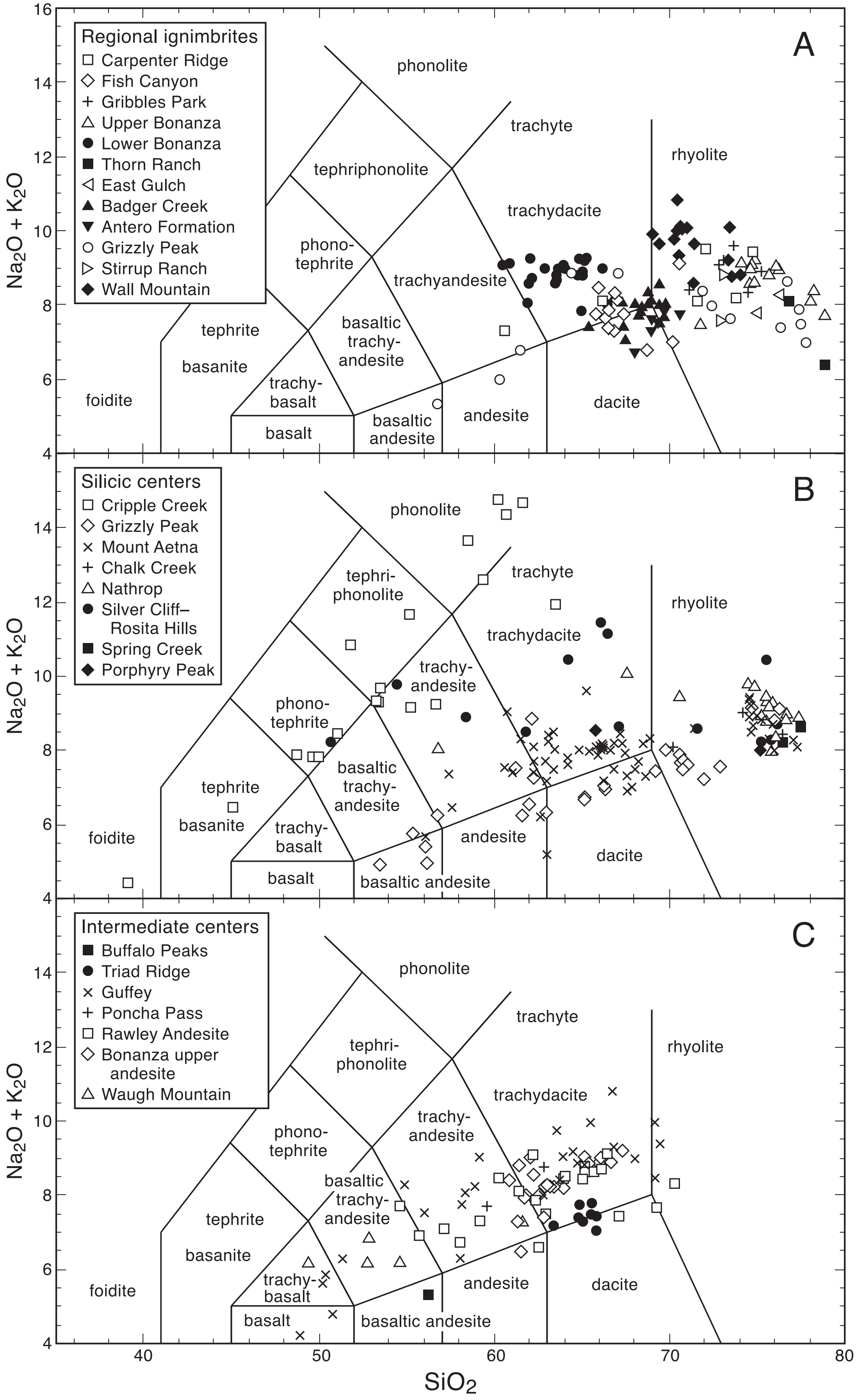
Further work is required to clarify whether the Mount Princeton batholith was indeed the source of the Wall Mountain Tuff. The proximal nature of Wall Mountain Tuff outcrops in the paleovalleys along the east side of the upper Arkansas graben and the distribution of the Wall Mountain Tuff (Fig. 2B) seem to require a source in the Sawatch Range. If our biotite ages are accurate, they may imply that the caldera source of the Wall Mountain Tuff was either completely obliterated by intrusion of the younger Mount Princeton batholith or that the remnants have not yet been recognized. Alternatively, our biotite ages may reflect a protracted cooling history for the Mount Princeton batholith or reheating by subsequent intrusions.

Geochemistry of central Colorado volcanic rocks

Approximately 360 chemical analyses (Appendix 4) were compiled from the literature to better characterize individual volcanic units, to examine trends between volcanic centers, and to aid in correlation of regional units. The analyses were performed over a long time interval in different laboratories by various analysts using various methods. In spite of the weaknesses in utilizing such data, several trends are clearly evident and the clustering of analyses of regional ignimbrite units gives some confidence in the data, at least in a reconnaissance sense. Total alkalies, SiO_2, and the sources of the data are listed in Appendix 4. All analyses are reported water and volatile free and summed to 100%.

Figure 11A compares compositions of regional ignimbrites on a total alkalies vs. silica diagram (Le Bas et al. 1986). Note the very significant difference in composition between the lower and upper Bonanza tuffs and the similarity in composition of the upper Bonanza and Gribbles Park Tuffs. Also noteworthy is the tight clustering of compositions of the three dacitic tuffs (Badger Creek; Triad Ridge, Fig 11C; and Fish Canyon) that caused such confusion among mappers in the Thirtynine Mile volcanic area. Also of interest is the extremely wide range in composition of fiamme from the Grizzly Peak Tuff as reported by Fridrich (1986) and Fridrich and Mahood (1987).

Figure 11B compares compositions of rocks from silicic


A
Regional ignimbrites
□ Carpenter Ridge
◇ Fish Canyon
+ Gribbles Park
△ Upper Bonanza
● Lower Bonanza
■ Thorn Ranch
◁ East Gulch
▲ Badger Creek
▼ Antero Formation
○ Grizzly Peak
▷ Stirrup Ranch
◆ Wall Mountain
phonolite
trachyte
rhyolite
tephriphonolite
trachydacite
phono-tephrite
trachyandesite
tephrite
basaltic trachy-andesite
basanite
trachy-basalt
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basaltic andesite
andesite
dacite
B
Silicic centers
□ Cripple Creek
◇ Grizzly Peak
× Mount Aetna
+ Chalk Creek
△ Nathrop
● Silver Cliff–Rosita Hills
■ Spring Creek
◆ Porphyry Peak
phonolite
trachyte
tephri-phonolite
rhyolite
trachydacite
trachy-andesite
phono-tephrite
basaltic trachy-andesite
tephrite
basanite
trachy-basalt
foidite
andesite
dacite
basalt
basaltic andesite
C
Intermediate centers
■ Buffalo Peaks
● Triad Ridge
× Guffey
+ Poncha Pass
□ Rawley Andesite
◇ Bonanza upper andesite
△ Waugh Mountain
phonolite
trachyte
tephri-phonolite
rhyolite
trachydacite
trachy-andesite
phono-tephrite
basaltic trachy-andesite
tephrite
basanite
trachy-basalt
foidite
andesite
dacite
basalt
basaltic andesite
$Na_2O + K_2O$
16
14
12
10
8
6
4
40
50
60
70
80
SiO_2

volcanic centers exclusive of regional ignimbrites. High-silica rhyolites and evolved granites form a tight cluster between about 74 and 78% SiO_2. These include the topaz rhyolites near Nathrop and Chalk Creek, Mount Antero Granite, Porphyry Peak and Spring Creek intrusions in the Bonanza district, and rhyolites at Silver Cliff. The Cripple Creek eruptive center stands out, because the total alkalies in its phonolitic rocks soar to values in excess of 14% at relatively modest silicia contents. Rocks of the Grizzly Peak and Mount Aetna eruptive centers range from basaltic andesite to rhyolite.

Figure 11C illustrates the compositional range of rocks at intermediate volcanic centers and major "andesitic" stratigraphic units. Rocks of the Guffey volcanic center and vicinity in the Thirtynine Mile volcanic area include a wide range in compositions from basalt to rhyolite. In the Bonanza area, the Rawley Andesite, which underlies the lower Bonanza Tuff, and the upper andesite that overlies the Gribbles Park/upper Bonanza Tuff, both show a wide range in composition, but are mainly trachyandesites and trachydacites.

Rocks of the central Colorado volcanic field are relatively alkalic with the highest values in the Cripple Creek and Silver Cliff–Rosita Hills centers that are closest to the Rocky Mountains–High Plains boundary. Both eruptive centers are precious-metal mining districts containing diatremes, small cauldrons, and breccia pipes. In their discussion of the relationship of magmatism and mineralization to tectonic setting at Cripple Creek, K. D. Kelley et al. (1998) point out that these alkaline rocks are part of a north-south belt of alkaline igneous rocks, some of which host important gold deposits. The belt extends from Canada to Mexico along the eastern edge of the Cordillera. McLemore (1996) has called such gold deposits "Great Plains Margin-alkaline related" deposits. As rocks of the central Colorado volcanic field become more alkalic to the east, mineralization changes from base- and precious-metal deposits of the Sawatch Range to precious-metal deposits of Cripple Creek and Silver Cliff–Rosita Hills. In between are molybdenum prospects related to highly evolved granites and rhyolites along the flanks of the Rio Grande rift.

Summary

The central Colorado volcanic field consists of widely scattered erosional remnants of a once continuous compositional diverse volcanic field now tied together by regional ignimbrites and the late Eocene erosion surface upon which they rest. $^{40}Ar/^{39}Ar$ dating and paleomagnetic correlation of the regional ignimbrite units reported herein provide the basis for a geochronologic and stratigraphic framework of the CCVF (Figs. 3, 4). At least four caldera centers were active in the Sawatch Range erupting five large-volume ignimbrites between 34.3 and 32.9 Ma. Four other large-volume ignimbrites, ranging in age from 37.5 to 33.7 Ma, apparently erupted from calderas in or near the Sawatch Range that have since been obliterated by erosion or buried by younger rocks. Two younger regional ignimbrites, Fish Canyon and Carpenter Ridge tuffs, lapped onto the CCVF from the San Juan volcanic field between 28.8 and 27.4 Ma. Eastward draining valleys incised into the late Eocene surface provided distribution routes for the ignimbrites but also resulted in confusing outcrop relationships, resolved in some cases only by $^{40}Ar/^{39}Ar$ dating and paleomagnetic correlation.

The oldest regional ignimbrite, the Wall Mountain Tuff (36.69 ± 0.09 Ma), was found to have been preceded by a thick, proximal dacite tuff dated at 37.49 ± 0.22 Ma and herein named the tuff of Triad Ridge. Rapid erosion of this tuff and deposition of the Wall Mountain Tuff in narrow canyons carved into it, together with the fact that the Wall Mountain Tuff was deposited on prevolcanic bedrock throughout the rest of the CCVF, caused conflicting stratigraphic interpretations for many years. The tuff of Triad Ridge and the Fish Canyon Tuff (27.83 ± 0.15 Ma) are dacite units previously misidentified as Badger Creek Tuff (33.81 ± 0.11 Ma). These three tuffs are so similar mineralogically and in outcrop characteristics as to be indistinguishable when stratigraphic control is missing. Identification of the tuff of Triad Ridge and Fish Canyon Tuff reduced the Badger Creek Tuff from being considered a widespread unit to being confined within the Salida–Waugh Mountain paleovalley.

Recognition that the Gribbles Park Tuff (32.88 ± 0.08 Ma) and the upper Bonanza Tuff are the same unit is an important regional correlation and identifies the source caldera for the Gribbles Park Tuff. The source for the Thorn Ranch Tuff (33.66 ± 0.14 Ma) was found to be a previously unknown caldera in a largely unmapped area in the Sawatch Range west of Marshall Pass. Called herein the Marshall Creek caldera, its recognition is based on $^{40}Ar/^{39}Ar$ dating and paleomagnetic correlation of outcrops of Thorn Ranch Tuff along Marshall Creek that contain abundant large blocks of Precambrian rocks. Gregory and McIntosh (1996) had previously identified sanidine crystals from the Thorn Ranch Tuff and overlying Gribbles Park/upper Bonanza Tuff in the Pitch-Pinnacle Formation, a tuffaceous sedimentary and partly lacustrine unit we think is probably a moat deposit in the Marshall Creek caldera. Recognition of megabreccia blocks of diverse lithologies in the same area also indicates the probable presence of a caldera. Unknown to us, Tom Steven of the U.S. Geological Survey has mentioned a probable "Marshall Pass caldera" to colleagues for many years (P. W. Lipman pers. comm. 2000).

The Mount Aetna cauldron was confirmed as the source of the Badger Creek Tuff and Antero Formation tuffs. The 33.66 ± 0.13 Ma $^{40}Ar/^{39}Ar$ age of the intracaldera tuff compares well with the 33.81 ± 0.11 Ma mean age of five samples of outflow Badger Creek Tuff and the 33.76 ± 0.10 Ma mean age of four samples of Antero Formation tuffs. Both intracaldera and outflow tuffs have reverse polarity. We also dated several plutons in the Mount Aetna area including the Mount Aetna Quartz Monzonite (34.07 ± 0.90 Ma), Mount Aetna ring dike (34.13 ± 0.18 Ma), Mount Princeton batholith (34.31 ± 0.21Ma), and Mount Antero Granite (29.59 ± 0.13 Ma). Attempts to date the Mount Pomeroy Quartz Monzonite were unsuccessful.

The source of pumice and ash beds in the Florissant Formation is still unknown. The 34.05 ± 0.08 Ma mean age of five samples from the Florissant Formation does not fit any of the regional ignimbrites that we have dated. The Antero Formation had previously seemed a likely correlative but the Antero tuffs (33.76 ± 0.10 Ma) are significantly younger. Fallout from a pyroclastic eruption at a silicic dome in the Guffey area may be a possibility, but needs further investigation.

Volcanic rocks of intermediate chemical composition in the central Colorado volcanic field have been informally termed andesites by many workers. But rocks of the CCVF are relatively alkalic as shown in Figure 11. Most intermediate rocks are trachyandesites and trachydacites. Rocks of the major eruptive centers have very wide ranges in composition: basalt to rhyolite at Guffey and basaltic andesite to

FIGURE 11—Classification of volcanic rocks of the central Colorado volcanic field using the IUGS classification scheme of Le Bas et al. (1986). The chemical data and sources are listed in Appendix 4. All analyses were recalculated water and volatile free and summed to 100%. Total alkali versus silica plots of geochemical data from: (**a**) regional ignimbrites; (**b**) non-regional units erupted from dominantly silicic centers; and (**c**) non-regional units erupted from dominantly intermediate centers.

high-silica rhyolite at the Mount Aetna and Grizzly Peak cauldrons. Rocks at Cripple Creek are a conspicuous anomaly with total alkalies rising to more than 14% at only intermediate silica values. Rocks of the Silver Cliff–Rosita Hills centers are also notably high in alkalies. Both Cripple Creek and Silver Cliff–Rosita Hills are closest to the Rocky Mountains–Great Plains boundary, long known as an alkalic gold province (Lindgren 1915; North and McLemore 1988; Mutschler et al. 1985). Also noteworthy is the relatively low alkali content of rocks of the Grizzly Peak cauldron that lies within the Laramide Colorado Mineral Belt. Perhaps this older magmatism had used up some of the alkalies in the source region.

The total alkalies vs. silica diagram also shows the significant difference in composition between the lower and upper Bonanza Tuff and the similarity in composition of the Gribbles Park and upper Bonanza Tuff, now known to be correlative. Also of interest is the tight clustering of points for the Badger Creek, Fish Canyon, and tuff of Triad Ridge—three tuffs which are virtually indistinguishable in the field, yet widely different in age.

Two distinctive lithologic characteristics of nearly all CCVF ignimbrites are intermediate phenocryst contents, mostly between 10% and 35%, and the presence of sanidine phenocrysts as the dominant feldspar. In contrast, ignimbrites of the San Juan and Mogollon–Datil volcanic fields vary in phenocryst content from as low as one or two percent to nearly 50%. Ignimbrites in the San Juan field are mostly plagioclase dominant whereas ignimbrites in the CCVF and Mogollon–Datil field are mainly sanidine dominant. A geochemical and isotopic comparison of rocks from these three volcanic fields might reveal heterogeneities in the lithosphere of the Rocky Mountain region.

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