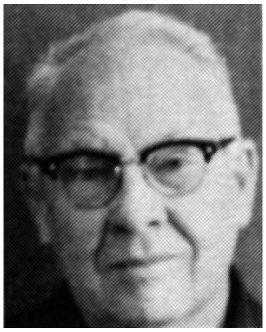
Colorado Scientific Society

The Volcanoes of Colorado

A Colorado Scientific Society
Symposium Honoring
Thomas A. Steven

University of Northern Colorado
School of Chemistry, Earth Sciences, & Physics
Greeley, CO 80639
May 19, 2007

Thomas A. Steven



The Colorado Scientific Society is pleased to honor Tom Steven with the *Volcanoes of Colorado Symposium*. We are honoring Tom because, among the 170+ scientific and technical articles he has authored or co-authored, are a host geologic maps and reports dealing with the genesis and evolutionary trends of magmas and ores in complex volcanic systems, most notably in the San Juan Mountains of Colorado. This work established the first detailed history of the evolution of the rocks of the San Juan volcanic field and their role in the formation of associated mineral deposits. His finely crafted reports and maps are models of quality research and presentation. They present complex ideas in comprehensible form and are noted for their complete documentation, imaginative interpretations, and multidisciplinary approach to science, based on "reading" the rocks.

Tom is a past president of the Colorado Scientific Society and is retired from an exemplary 42-year career with the US Geological Survey where he received the Department of Interior Meritorious Service Award. He also is recipient of the prestigeous Dibblee Medal, awarded by the Dibblee Geological Foundation for excellence in field geology and geologic mapping.

Tom and his wife, Grace, have lived in the Denver area since 1952. After retirement, he continued working on reports at the USGS as a Scientist Emeritus. In addition, he initiated other projects, including an investigation of the geomorphic evolution of the San Juan Mountains. Tom also began writing poetry and has published a 100-page book of poems about growing up in California, the beauty of the scenery he has been privileged to witness as a field geologist, and philosophical meanderings about concepts in geology, science management, and life.

SOUTH MOUNTAIN AND LITTLE ANNIE MINING CAMP, SUMMIT DISTRICT, COLORADO.

Program

Morning Talks

9:00 Welcome and Introduction

9:15 *Peter Lipman*: Large Ignimbrite-caldera Eruptions in the Southern Rocky Mountains Volcanic Field: Comparisons with the Central Andes of South America and Relation to Assembly of Subvolcanic Batholiths

9: 55 *John Ghist*: Let's Go Ogle Colorado Volcanoes with Google Earth

10: 30 Break

10:45 *Paul Morgan*: Cenozoic volcanism, heat flow, and uplift in the Southern Rocky Mountains.

11:25 *Peter Modreski*: Zeolites, chalcedony, and friends; postmagnmatic minerals in mafic to silicic volcanics of Colorado- who, where, why, and when.

12:05 Lunch Break

Afternoon Talks

1:30 *William C. McIntosh and Charles E. Chapin:* Geochronology of the early southern rocky mountain volcanic field

2:10 *Robert M. Kirkham*: Deciphering the tectonic evolution of west-central, south-central and central Colorado using upper and middle Cenozoic volcanic rocks.

2:50 Break

3:05 *Michael J. Kunk & Robert M. Kirkham*: ^{40}AR/^{39}Ar dating results of volcanic rocks in west-central Colorado and their application to geologic problems.

3:45 *Emmett Evanoff & Ed Larson*: Tuffs of the White River Sequence of Colorado and adjacent states.

4:25 Wrapup and Discussion.

LARGE IGNIMBRITE-CALDERA ERUPTIONS IN THE SOUTHERN ROCKY MOUNTAINS VOLCANIC FIELD: COMPARISONS WITH THE CENTRAL ANDES OF SOUTH AMERICA AND RELATION TO ASSEMBLY OF SUBVOLCANIC BATHOLITHS

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INTRODUCTION

Volcanoes and upper-crustal plutons in diverse geologic settings tend to share common features of mineral and chemical composition, emplacement age, and magmatic volume. Voluminous silicic ignimbrites associated with caldera sources, widespread components of Cordilleran arcs, have commonly been interpreted as broadly concurrent with assembly of upper-crustal batholiths. Tertiary ignimbrites in the western USA and elsewhere, with volumes to 1-5x10^3 km^3, record multi-stage histories of magma accumulation, fractionation, and solidification in upper parts of large subvolcanic plutons that were sufficiently liquid to erupt. Individual calderas, to 75 km across with 2-5 km subsidence, are direct evidence for shallow magma bodies comparable to the largest granitic plutons. Nested polycyclic calderas that erupted compositionally diverse tuffs, some with repose intervals of 100 ka or less, document deep composite subsidence and rapid evolution in subvolcanic magmas. Most ignimbrite compositions are more evolved than the associated plutons, requiring that subcaldera chambers retained voluminous residua from fractionation. Geophysical data show that low-density upper-crustal rocks, inferred to be plutons, are 10 km or more thick beneath many calderas.

Aternatively, some recent field and geochronologic studies have been interpreted as indicating that individual Mesozoic Cordilleran plutons grew and solidified incrementally in small batches during >10^6-year intervals, without presence of voluminous eruptible magma ("large tank") at any stage during pluton growth and batholith assembly. Such growth of plutons in small increments would minimize close associations with large ignimbrite calderas and suggest that batholith growth is largely unrelated to surface volcanism. Linked to these interpretations are inferences that ignimbrite eruptions record ephemeral magma chambers that (1) grow rapidly due to exceptionally high magmatic power input to the upper crust, (2) evacuate nearly completely during ignimbrite eruption, and (3) leave little geologic record in the form of crystallized crustal plutons.

How to reconcile these alternatives? Many large continental arcs record a broadly unified time-space-composition evolution of upper-crustal magmatic systems. Such volcanic fields, especially those containing ignimbrite-caldera episodes, commonly contain compositionally diverse eruptive products erupted over multimillion-year intervals. A common pattern is initial eruptions of intermediate-composition lavas from central volcanoes, followed by eruption of one or more large-volume ignimbrites of more silicic composition; concurrent caldera subsidence is located centrally within the area of prior lava vents. Such progressions of surface volcanism can be interpreted as providing instantaneous sequential snapshots of changing magma-chamber process through time. In contrast, subvolcanic plutons exposed in eroded volcanic terranes represent time-integrated and partly homogenized end products, as successive magmatic pulses accumulated, fractionated, and consolidated in the upper crust. Such perspectives combine evidence for prolonged growth and incremental pluton assembly with presence of large-volume eruptible chambers during peak magmatic input.

SOUTHERN ROCKY MOUNTAINS VOLCANIC FIELD

Exemplifying large-scale ignimbrite volcanism is the composite mid-Tertiary volcanic field of the Southern Rocky Mountains (SRMVF). From 38 to 23 Ma, this region of about 100,000 km^2, that had been the site of Precambrian-cored uplifts in the late Cretaceous, was blanketed by thick volcanic sequences erupted from multiple centers, including 30 large-volume regional ignimbrites and associated calderas (Fig. 1). The SRMVF was a locus of discontinuous mid-Tertiary Cordilleran magmatism, similar in composition and eruptive history to silicic volcanism farther west in the Basin-Range province and south into the vast Sierra Madre Occidentale of Mexico. The SRMVF is also comparable in size, composition, and magmatic duration to younger ignimbrite terranes such as the Altiplano-Puna Volcanic Complex of the Central Andes.

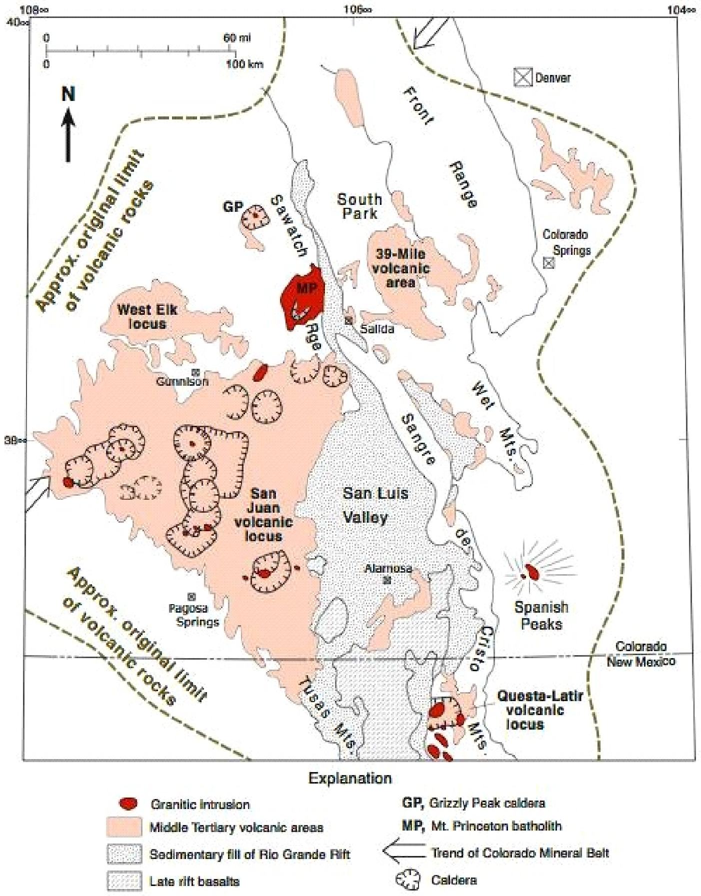

Figure 1. *Map of Southern Rocky Mountains volcanic field, showing ignimbrite calderas, major erosional remnants and inferred original extent of mid-Tertiary volcanic cover, caldera-related granitic intrusions, and later sedimentary fill of the Rio Grande rift zone. Arrows indicate trend of late Cretaceous-early Tertiary (Laramide) intrusions of the Colorado Mineral Belt.*

In the Southern Rocky Mountains, the rapid sequential eruption of multiple ignimbrite sheets of large volume and diverse compositions from overlapping caldera sources requires recurrent regeneration of “large tanks” of eruptible magma. Rhyolitic tuffs, even though mostly crystal poor, have petrologic signatures of strong feldspar fraction (e.g., depleted compatible elements such as Sr, Ba, and Eu), despite low phenocryst contents of the erupted tuffs. Similarity of the crystal-poor rhyolites, some with volumes on the order of 1000 km^3 (e.g., Sapinero Mesa and Carpenter Ridge Tuffs), to matrix (melt) compositions in crystal-rich dacites thus documents efficient separation of rhyolitic liquids from crystal residues in upper-crustal chambers.

Volumes of SRMVF tuffs and dimensions of calderas provide further insights into geometry of the associated magma chambers. Where exposures are most favorable, minimum subsidence was commonly greater than 2 km (without exposing caldera floor), as documented by depth of the unfilled caldera basin plus thick intracaldera tuff. Total subsidence at many SRMVF calderas was thus likely 3 km or more. To erupt as much as 5,000 km^3 of homogenous dacite (Fish Canyon Tuff) from a chamber below a caldera subsidence as much as 75 km across (La Garita caldera) requires presence of a low-aspect-ratio body of eruptible crystal-rich magma in the upper crust. Such an enormous lenticular or tabular magma volume must have accumulated incrementally over a sustained interval, at least several hundred thousand years as documented by zircon U-Pb ages. During this prolonged assembly process, successive pulses of magma, which are unlikely to have been identical, were mixed to achieve the striking homogeneity of the Fish Canyon Tuff along with associated precursor and successor lavas. Recurrent outpourings of intermediate-composition lavas (andesite, mafic dacite) during inception and waning of ignimbrite caldera cycles in SRMVF also show that voluminous mantle inputs continued in the roots of the systems during and after peak explosive volcanism.

Shallow granitic intrusions associated with ignimbrite calderas in the SRMVF vary in composition, texture, structure, and age relative to host calderas, providing insights about multi-stage processes involved in pluton assembly and subsequent evolution concurrently with prolonged surface volcanism. Most common in the SRMVF are granodiorite and mafic granite, chemically equivalent to andesite and dacite; silicic granites are rare and small. Most intrusions are more mafic than associated ignimbrites, especially where the tuff is silicic. Where an ignimbrite is compositionally zoned, associated intrusion compositions tend to be close to the more mafic last-erupted tuff. A few plutons are zoned, becoming more silicic upward, and others progress toward more evolved compositions with time. None of the subvolcanic plutons associated with the SRMVF retain large-scale evidence for mingling of silicic and mafic magma such as that preserved deep in some plutons elsewhere. Shallow levels of large silicic magma chambers may be too dynamic to preserve records of the recharge and mingling by mafic magma that seems an essential component of overall pluton evolution.

Intrusions geographically associated with calderas have solidification ages varying from indistinguishable from the associated ignimbrite to millions of years younger, documenting prolonged magma-chamber evolution during waning stages of a cycle that culminated with ignimbrite eruption. Compositions of intrusions are most similar to erupted tuffs if closely linked in time; younger intrusions tend to be more compositionally diverse.
Textures of caldera-related plutons vary greatly within short distances, from medium-grained holocrystalline to dense aphanitic, difficult to distinguish from intermediate-composition lava. Most common are fine-grained variably porphyritic holocrystalline plutons that are texturally

similar to central intrusions in cores of the intermediate-composition central volcanoes that preceded the caldera-forming ignimbrites. Indeed, some caldera-related plutons likely represent the cores of postcollapse volcanic edifices whose lavas fill calderas. Not surprisingly, the shallowest intrusions tend to be the finest-grained, the most texturally variably, and in places some difficult to distinguish reliably from volcanic country rocks. Other intrusions, especially the largest and deepest, have more uniform medium to coarse granitic textures, merging in appearance with Mesozoic Cordilleran plutons.

As exposed in rugged terrain, the largest caldera-related plutons appear to be plug-shaped at present outcrop levels, with equant to weakly elongate shapes and steep marginal contacts. Marginal contacts are typically sharp, without mixed zones or conspicuous contact metamorphism, consistent with shallow emplacement into cool country rocks. Roof contacts locally dip gently, but floors indicative of relatively thin sill or laccolithic geometry are absent. Nevertheless, the largest intrusions, such as Mount Princeton (25x35 km) and the clustered plutons (20x40 km) in the Questa area must have a broadly lenticular overall geometry to remain within the upper crust.

Total buoyant uplift associated with resurgent caldera intrusions is a few hundred meters at most, inadequate to account for any substantial volume of the inferred batholith. In addition to local resurgence within some calderas, some modest broad uplift along the crest of the San Juan gravity low is suggested by locally increased outward dips (a few degrees at most) of ignimbrite sheets and by graben faults, beyond limits of individual calderas. Volcanic and underlying strata exposed adjacent to margins of larger plutons in the SRMVF typically are abruptly truncated, without deflection or other structural evidence of deformation involved in generating space for intrusion. In the absence of major buoyant uplift, much of the space for pluton emplacement at upper-crustal levels must have come from large-scale stoping, for which caldera subsidence is perhaps one manifestation. At lower intrusive levels (>2-3 km?), gravitational loading of the upper crust by volcanic eruptions and associated pluton emplacement seems necessarily to have generated substantial subsidence beneath the evolving volcanic-plutonic system. Such crustal subsidence beneath a batholith, in effect represents simple material exchange, as magma from the mantle and lower crust is transferred to solidify at shallower levels.

VOLCANO-PLUTONIC MODEL

Cordilleran arc magmatism is viewed as a prolonged multi-stage process, which generates diverse upper-crustal plutonic and volcanic products as functions of tectonic setting, duration of magmatic pulses, crustal structure and composition, fluctuating magma-power input, and magma-chamber dynamics in the upper crust. As common to many recent discussions and models, Cordilleran magmatism is initiated by rise of mantle-generated basalt that stalls or ponds at varied levels in the crust, depending on density and thermal structure. Basalt is widely erupted in oceanic arcs, but little basalt rises through thick crust without modification, unless regional extension is severe. As magma production increases, incremental open-system input to growing upper-crustal plutons maintains near-solidus temperatures, for time intervals far longer than if emplaced rapidly as closed systems followed by conductive or convective cooling. Cordilleran activity is accordingly dominated by intermediate-composition and silicic magmas. Depending on the time-span, episodicity, and scale of magmatic power input, various igneous loci have undergone a broad spectrum of evolutionary histories, but most contain distinct waxing and waning stages, and many Tertiary Cordilleran arcs include a peak power-input episode of ignimbrite eruptions (Fig. 2).

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

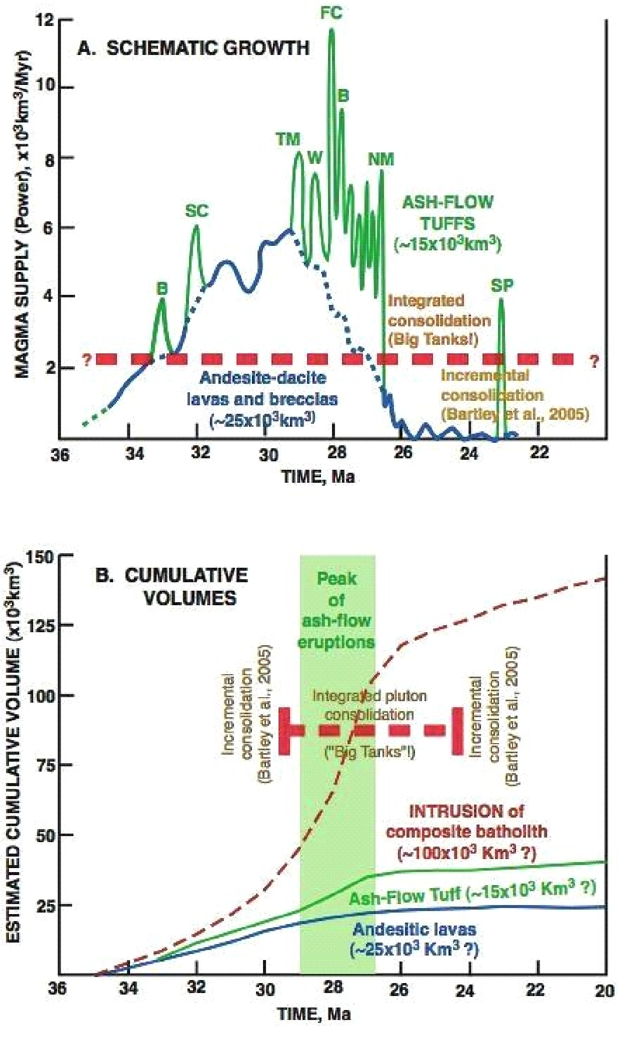

Figure 2. *Estimated volume and power input versus time, mid-Tertiary magmatism in the SRMVF.* ***A.*** *Schematic growth of the volcanic field, showing variations in magma supply with time, in relation to frequent eruption of intermediate-composition lavas (blue lines) and more episodic voluminous ignimbrite sheets (green lines).* ***B.*** *Cumulative volumes, including intrusions that are inferred from gravity data to be at least three times greater in volume than the volcanic deposits. Heavy red-dashed lines mark inferred times of highest magma-power input, during which large integrated magma chambers ("large tanks") are inferred to have supplied recurrent ignimbrite eruptions. At lower magmatic power, plutons are inferred to have solidified more nearly concurrently with incremental magma additions, precluding sustained presence of "large tanks."*

Large-volume ignimbrite magmas of evolved rhyolite (to >1,000 km^3) are signatures of shallow fractionation processes in thick mature crust. Such continental rhyolites commonly are closely associated with crystal-rich dacite, both as zonations within single tuff sheets and as sequential large-volume eruptions. In general, the more evolved the rhyolite, the lower its crystal content. These associations require highly efficient separation of liquid from a crystal residue, perhaps critically related to a voluminous volatile phase. Contrasts between relatively primitive arc systems dominated by andesitic compositions and small upper-crustal plutons, versus more silicic volcanic fields and associated batholiths, probably reflect intertwined contrasts in crustal thickness and magmatic power input. Lower power input leads to a Cascade- or Aleutian-type arc system, with much intermediate-composition magma erupting directly from middle- and lower-crustal storage, but without development of large shallow plutons. Andean and Southern Rocky Mountain systems begin with similarly intermediate-composition volcanism, but increasing magma production, perhaps triggered by abrupt changes in plate boundary conditions and localized by structural flaws in thick crust, leads to development of larger upper-crustal reservoirs, more silicic compositions, large ignimbrites, and batholiths.

A continuing uncertainty is the geometry and overall size of the upper-crustal batholith beneath a volcanic region such as the San Juans during waning stages, versus that at times of peak ignimbrite volcanism. Large-scale caldera collapse and requirements for storage of residua from fractionation of evolved ignimbrite magmas show that high-level "large-tank" magma chambers existed, but resurgent intracaldera uplift and long-continued post-ignimbrite activity at many caldera sites document further evolution of the underlying magmatic system. Additional magma from mantle and lower crustal sources was surely added during waning stages. Though difficult to evaluate rigorously, peak volumetric assembly of the subvolcanic batholith likely coincided with the ignimbrite stage, even though completion of assembly and solidification commonly is prolonged in the plutonic environment.

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LET'S GO OGLE COLORADO VOLCANOES WITH GOOGLE EARTH

John M. Ghist

Modern technology is opening the door on many new and exciting ways of learning, teaching, and studying geology. One of these technological advances is Google Earth. It shares a lot of the aspects with GIS which has been around for a number of years and with a little tweaking can do most of what GIS does at a fraction of the cost, or at no cost at all. It is available to anyone with a relatively recent computer and can open up a world (no pun intended) of information about our planet.

Volcanoes have always been a fascination for people; sometimes with deadly consequences. They are always a popular part of introductory geology classes. Google Earth allows interactive 3D viewing of the Earth's features and the ability to gain a spatial understanding of many Earth processes that have not been easily available before. A quick scan through the Internet reveals that it is increasingly becoming utilized in many college curriculums as well as some high school Earth Science classes.

For this symposium, we will be using Google Earth to take a brief tour to a few significant volcanoes in the western United States before zeroing in on Colorado and many of its interesting volcanic features. We will then “fly” up the Rio Grande Rift, visit some of Tom Steven’s favorite haunts like Creede and perhaps Marysvale and then stop at a number of locales like Thirtynine Mile field, the San Juans, Dotsero, and others.

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CENOZOIC VOLCANISM, HEAT FLOW AND UPLIFT IN THE SOUTHERN ROCKY MOUNTAINS

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Volcanism is a surface manifestation of thermal perturbations at depth that are often associated with surface heat flow anomalies, which may be temporally delayed with respect to volcanism if conduction is the primary mechanism of heat transport. If thermal anomalies are volumetrically large, thermal expansion results in isostatic uplift. The Southern Rocky Mountains have significant Cretaceous and Cenozoic volcanism, very high heat flow and uplift, but the interrelations among these phenomena are complex. Major mid-Tertiary volcanism was probably associated with significant advection of heat into the lithosphere, including the crust. This volcano-thermal high was followed by a period of cooling before relatively minor late-Tertiary volcanism (with the exception of the Jemez Lineament), and brittle-style faulting associated with the Rio Grande rift, especially in Colorado. However, surface heat flow remains very high in the Southern Rocky Mountains of Colorado, a property that has been attributed to high radiogenic upper crustal plutonic rocks. Although this explanation is consistent with radiogenic heat production measurements, it does not explain young (<10 Ma) uplift of the Southern Rocky Mountains and Colorado Plateau based on vesicular basalt paleo-altimetry data. There appears to be a complex interplay of mechanisms through which heat and mass transfer in the lithosphere during the past 100 Ma have been recorded in volcanism and uplift in the southern Rocky Mountains and no simple model of lithospheric response is satisfactory to explain all observations.

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ZEOLITES, CHALCEDONY, AND FRIENDS: POSTMAGMATIC MINERALS IN MAFIC TO SILICIC VOLCANICS OF COLORADO—WHO, WHERE, WHY, AND WHEN

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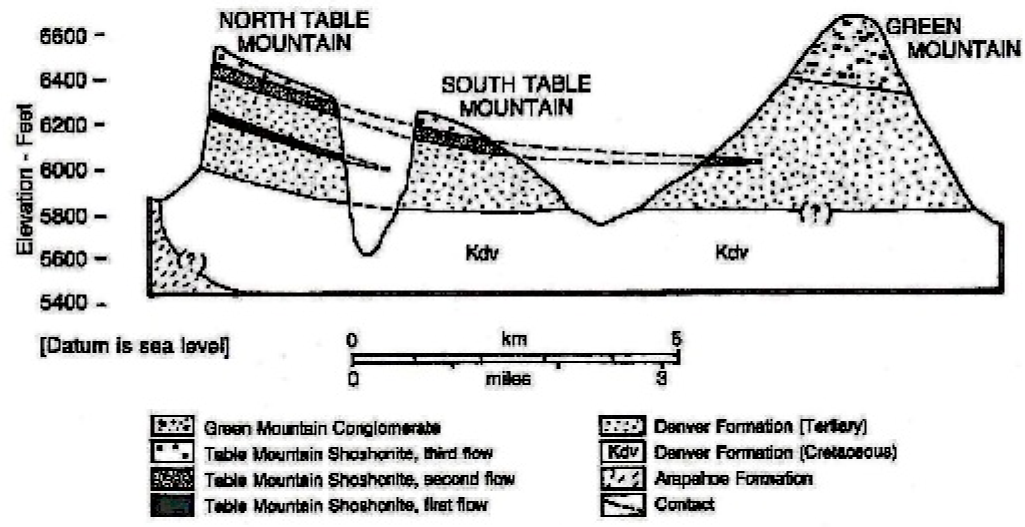
Volcanic rocks, because of the open spaces they contain due to vesicles, breccias, and fractures, and due to their labile, readily-leachable physical and chemical nature, often are host to secondary minerals formed from cooling hydrothermal waters or ground water. Zeolite minerals, quartz and its varieties (chalcedony, agate), opal, calcite, and other minerals all occur in the environments these rocks provide.

At the high-temperature end of the postvolcanic spectrum are minerals that occur in lithophysae in rhyolite, such as at Ruby Mountain, Chaffee County, where topaz, spessartine, quartz, and sanidine occur in a 30 Ma topaz rhyolite. Similar (but finer-grained) topaz-garnet mineralization occurs in rhyolite at Silver Cliff, Custer County.

The earliest-Paleocene lavas that cap North and South Table Mountain (Figure 1), overlooking Golden, Colorado, are a classic locality for zeolite and associated minerals, first described in the 1870s and 1880s following the Hayden survey of the territories of the U.S. The mineralogy and the history of geologic and mineralogic studies of this area was summarized by Kile and



Geologic section of the Golden area. Section NNW to SSE-SE, through the approximate centers of North and South Table Mountains. Vertical exaggeration approximately 12:1 (based on Van Horn, 1967, and Scott, 1972).

Figure 1. Geologic cross section, North and South Table Mountains and Green Mountain; from Kile and Modreski (1988).

Modreski (1988) and subsequently updated by Kile (2004); see also Bartos (2004) and Modreski (2005). The zeolite minerals occur principally in a highly vesicular zone in the upper one-third of the second of the three main lava flows exposed on the Table Mountains (recent geologic mapping by Harald Drewes has shown what appears to be a small tongue of an additional lava flow exposed just below the second flow at one location on the north side of North Table Mountain). The 64 ±1 Ma lavas are shoshonite, which is a K-rich basaltic trachyandesite (Obradovich, 2002; Scott, 1972).

The most abundant zeolite minerals in the Table Mountain lavas are thomsonite, chabazite, and analcime (Figure 2), but some 10 other zeolite minerals have also been found to occur in the vesicular lava, including cowlesite, garronite, gonnardite, laumontite, levyne, mesolite, natrolite, offretite, phillipsite, and stilbite, as well as the non-zeolite minerals apophyllite, aragonite, calcite, chlorite, opal, and phlogopite. With the exception of crystals of phlogopite and chlorite lining vesicles, most of these minerals probably formed from ambient-temperature ground water. However, the earliest generation of zeolites, which include yellow to orange-tinted thomsonite, laumontite, and stilbite, all with relatively elevated iron and magnesium contents, may have formed at slightly elevated temperatures in the not-quite-cooled lava. A related suite of zeolite minerals are found in volcanic-derived sandstone and conglomerate of the Cretaceous to Paleocene Denver Formation.

Another well-known Colorado occurrence of zeolite and associated minerals in vesicular lava (quartz latite of the Conejos Formation) is near Treasure Falls just west of Wolf Creek Pass. Analcime, chabazite, heulandite, laumontite, mordenite, natrolite, and wellsite occur here, along with calcite, celadonite, nontronite, opal, pyrite, quartz (amethyst, agate), and saponite (Hampson, 2004).

Colorado has numerous occurrences of agate in silicic volcanic rocks. The best known and most studied is in the Twin Mountains area north of Del Norte, Saguache County, where agate-filled "thunder eggs" occur in an Oligocene rhyolite flow (Lipman, 1976). The mineralogy and somewhat enigmatic origin of these interesting structures, associated with spherulitic devitrification of the rhyolite, was studied and discussed by Kile (2002).

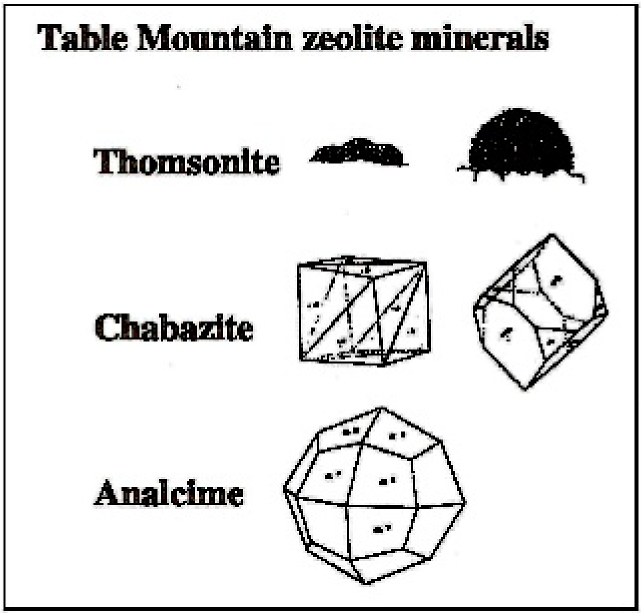


Figure 2. Morphology of the most common zeolite minerals from the Table Mountains

For details about these and many other related mineral occurrences, the interested reader is referred to Eckel (1961) and its updated version, Eckel (1997).

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GEOCHRONOLOGY OF THE EARLY SOUTHERN ROCKY MOUNTAIN VOLCANIC FIELD

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The early (pre-San Juan) part of the Southern Rocky Mountain volcanic field (ESRMVF), 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 ESRMVF (elsewhere referred to as the Central Colorado volcanic field) 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 ESRMVF was severely dissected by Neogene faulting and erosion leaving widely scattered remnants, the largest of which was 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 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 ESRMVF using ^{40}Ar/^{39}Ar dating and paleomagnetic characterization of regional ignimbrites (ash-flow tuffs) as stratigraphic markers to connect 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. All ages stated in this abstract are relative to Fish Canyon Tuff sanidine at 28.02 Ma.

Caldera volcanism in the ESRMVF was active between 36.9 and 33.1 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, 34.0 Ma; Badger Creek Tuff, 34.0 Ma; Thorn Ranch Tuff, 33.9 Ma, Gribbles Park Tuff, 3.1 Ma). Caldera sources have not yet been determined for three other regional ignimbrites (Wall Mountain Tuff, 36.9 Ma; tuff of Stirrup Ranch, 36.7 Ma; East Gulch Tuff, 33.7 Ma). Two ignimbrites (Fish Canyon Tuff, 28.0 Ma, and Carpenter Ridge Tuff, 27.5 Ma) erupted from the San Juan volcanic field and lapped onto the ESRMVF. Other eruptive centers within the ESRMVF include Cripple Creek (32.7–31.1 Ma), Silver Cliff-Rosita Hills (35.6–32.2 Ma), Guffey (36.3 Ma), Waugh Mountain (31.8 – 31.5 Ma), and Nathrop (30.65-29.1 Ma). Dated plutons in the Sawatch Range are Mount Princeton batholith (34.5 Ma), Mount Aetna Quartz Monzonite (34.3 Ma), and Mount Antero Granite (29.8 Ma). Three fossiliferous sedimentary deposits were also dated; they are Antero Formation (34.0 Ma), Pitch-Pinnacle Formation (33.9–33.1 Ma), and Florissant Formation (34.3 Ma).

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^{40}AR/^{39}AR DATING RESULTS OF VOLCANIC ROCKS IN WEST-CENTRAL COLORADO AND THEIR APPLICATION TO GEOLOGIC PROBLEMS

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Late Cenozoic volcanic rocks are widespread in west-central Colorado. ^{40}Ar/^{39}Ar age spectrum and laser fusion dating results have been used to determine the timing of the volcanic activity. The age data are used to determine rates of incision of the Colorado and Roaring Fork Rivers, and to constrain the timing of salt tectonism and regional landscape collapse in the Carbondale and Eagle collapse centers. Our data indicates that the volcanic activity occurred in pulses during the intervals 24 to 22 Ma, 16 to 13 Ma, 11 to 9 Ma, and 8 to 7 Ma. In addition there has been sporadic, volumetrically small volcanic activity, widely spaced in both space and time, during the last 4 m.y.

Ages and elevations of basaltic flows, which were erupted upon river gravels along the Colorado River, have been used to calculate apparent average incision rates in Glenwood Canyon. During the interval from 7.8 to 3.0 Ma incision occurred at an average rate of about 24 mm/k.y. In the last 3 m.y. the average apparent incision rate has increased by an order of magnitude to 242mm/k.y. Similar data from the Roaring Fork River indicate that it has had an average apparent incision rate of 291 mm/k.y. during the last 1.36 m.y., consistent with the increased rate in the Colorado River during the same interval.

An erosional surface of relatively low relief has been postulated for the west central portion of Colorado during the middle Miocene. Included in this area are the towns of Carbondale and Eagle, which are surrounded by large areas (>3600 km^2) of landscape collapse. The formation of the Carbondale and Eagle collapse centers is thought to be due to the removal of evaporates by the Colorado River and its tributaries and associated salt tectonism. Argon data from basaltic flows both within and outside of the collapse centers, together with paleomagnetic, geochemical, isotopic data, modern geological mapping, and the postulated low relief erosion surface allow for estimates of the timing and rate of landscape collapse in these centers to be made. The data indicate that although some of the collapse occurred prior to ca 13.8 Ma, most occurred in the last 10-8 m.y., and that the rate of collapse increased during the last 3 m.y.

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Tuffs of the White River Sequence of Colorado and Adjacent States

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The upper Eocene - lower Oligocene White River Sequence of the Great Plains and middle Rocky Mountains records the start of widespread explosive volcanism in the Western United States. The White River is composed primarily of claystones, mudstones and siltstone with approximately 60% fine-grained volcanic sediments. Given the thickness and distribution of the White River Sequence, the White River contains an estimated 25,000 cubic kilometers of volcaniclastic sediment. Most of this sediment is within mudrocks that were reworked by wind and water, and mixed with locally derived materials (epiclasts) derived from the Rocky Mountains. However, the White River contains about two dozen distinct and widespread tuffs, or lithified volcanic ashes.

The White River tuffs include two major types. First are the white tuffs that have mineral component that suggests rhyolite to dacite source volcanoes. Second are the “black” tuffs that have a mineral composition suggesting andesitic volcano sources. Both black and white tuffs typically have volcanic glass that is altered (in some cases completely) into smectite clays, but the mineral suites are typically well preserved and are diagnostic for each tuff. White tuffs are much more common than black tuffs, and range in thickness from 0.1 m to as much as 3 m thick. The tuffs have unique stratigraphic positions relative to biostratigraphic and magnetostratigraphic zones, have unique mineral suites, and mineral geochemistries. These features allow the tuffs to be widely correlated, in some cases over several hundreds of kilometers. Many of the tuffs have also been radiometrically dated using single-crystal 40Ar/39Ar laser-fusing techniques. Their ages range from about 35.5 to 29 Ma. The tuffs are excellent stratigraphic time-lines, allowing for high-resolution temporal calibration of biostratigraphic zone boundaries and geomagnetic polarity zones.

The sources of the tuffs are known in general, and a few of the younger very large (with thicknesses >2m) tuffs are correlated to distinct volcanic eruptions in Nevada and Utah. Crystal sizes in individual tuffs decrease toward the northeast, suggesting sources areas to the southwest. White River white tuffs older than about 31 Ma are rhyolitic to rhyodacitic in composition, while those younger than 31 Ma are predominantly dacitic. This temporal pattern of tuff compositions reflects similar changes in late Eocene and early Oligocene volcanism in the Basin and Range. Only one White River tuff in northeast Colorado has been related to the contemporaneous volcanism in Colorado. Mineral suites, geochemistry of minerals, radiometric ages, and magnetic polarity of the three largest tuffs in the upper White River, the lower Whitney, upper Whitney, and Nonpariel tuffs centered in western Nebraska, are identical to the huge Windous Butte, Cottonwood, and Wah Wah welded ash flows of southeast Nevada and southwestern Utah. These eruptions produced volumes between 3000 and 5000 cubic kilometers of proximal welded ash flows, and deposited ash-fall deposits of as much as 1.5 m thick in the Great Plains.