Geology of the Mount Aetna Volcanic Center, Chaffee and Gunnison Counties, Colorado

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Geology of the Mount Aetna Volcanic Center, Chaffee and Gunnison Counties, Colorado

By PRIESTLEY TOULMIN III and JANE M. HAMMARSTROM

A description of a deeply eroded mid-Tertiary volcano on the southern fringes of the Mount Princeton batholith in the Sawatch Range

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Geology of the Mount Aetna Volcanic Center, Chaffee and Gunnison Counties, Colorado

By Priestley Toulmin III *and* Jane M. Hammarstrom

Abstract

The Mount Aetna volcanic center is located in the southwestern part of the Mount Princeton batholith, a quartz-monzonitic pluton of Oligocene age in the southern Sawatch Range of central Colorado. The batholith lies just west of the Arkansas River graben, the northernmost major element of the Rio Grande rift system. As presently exposed, the volcanic center consists of a deeply eroded complex of highly compacted, densely welded, propylitically altered intracaldera ash-flow tuffs, flows, and breccias that have been preserved within a trapdoorlike graben that subsided after the main stage of volcanism but before the end of intrusive magmatic activity. The earliest volcanism of which a record is preserved produced predominantly andesitic flows, breccias, and a few ash flows; these volcanic rocks were deposited on a rolling surface that exposed Precambrian and Paleozoic rocks, as well as a border facies of the Mount Princeton batholith. After an interval of erosion that exposed deeper levels of the batholith and developed a new surface of rugged high relief, great thicknesses of more silicic volcanics were deposited, largely in the form of ash-flow tuffs. Penecontemporaneous collapse formed a caldera of unknown dimensions, along the walls of which chaotic megabreccias were produced by collapse and mass sliding of the slopes. The megabreccias are preserved mostly on the western and southwestern margins of the presently exposed structure. It is likely that ash flows from the Mount Aetna center extended as far as 75 kilometers east across the Arkansas River graben to form part of the Thirtynine Mile volcanic field, the southern topographic boundary of South Park.

The igneous activity associated with the Mount Aetna volcanic center began more than 37 million years ago, perhaps about 40 million years. Comparison of radiometric data from several different bodies and map units strongly implies that a complex history of intrusion, erosion, volcanism, and tectonism took place here in an extremely short time. Some of the more silicic postvolcanic intrusives may have been emplaced as much as 4 million to 5 million years afterwards, and minor magmatic activity apparently continued to produce small dikes and minor intrusions for another 10 million years or so. These epochs, like those associated with other volcanic centers along the west side of the northernmost part of the rift zone, are distinctly older than the corresponding episodes in the San Juan volcanic field proper to the south; this early magmatism may reflect crustal stresses premonitory to the opening of this part of the Arkansas River graben–Rio Grande rift zone.

Chemically, the rocks of the complex are typical of calc-alkaline suites. In a regional context, the rocks of this complex have compositions intermediate between magmatic types recognized elsewhere (Front Range, San Juan volcanic field, Elk Mountains) and tend to blur distinctions made in those areas. Major-element compositions are consistent with local differentiation of magmas from one another, but contents of rare-earth elements suggest that plagioclase fractionation was not a dominant factor in the evolution of the volcanic rocks.

The compositions of the major rock-forming minerals vary considerably, but their ranges in the volcanic rocks and dominant quartz-monzonite units overlap one another. Much of the variation reflects both magmatic and postmagmatic processes. The younger, more silicic units (granites and rhyolitic and aplitic dikes) are distinct in both mineral chemistry and major- and trace-element rock chemistry.

INTRODUCTION

This report presents some results of a study of an assemblage of middle Tertiary igneous rocks in the southern Sawatch Range of central Colorado (fig. 1). The study, which began in the early 1960's as a part of a multidisciplinary field and laboratory study of the chemical and petrologic relations between "classic" base- and precious-metal hydrothermal mineralization and the differentiation processes exhibited by a complex suite of calc-alkaline intrusive rocks, led to the recognition of a deeply eroded, highly altered eruptive center that may have been the source of widespread volcanic deposits in the region.

The remnants of the volcanic center are preserved in a trapdoorlike subsided block, to which we shall refer as the "Mount Aetna subsided block." This block subsided along

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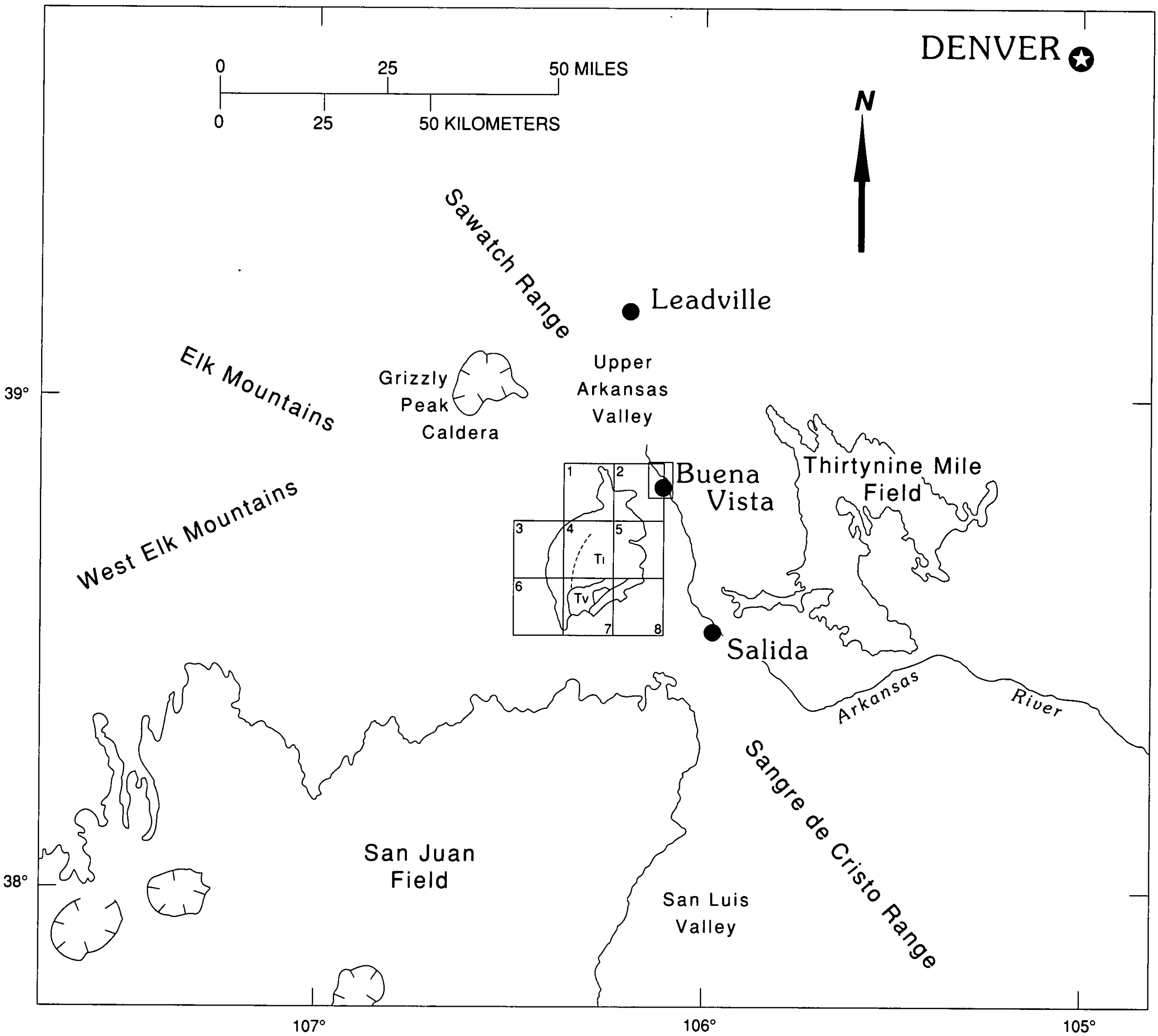


Figure 1. Mount Aetna volcanic center. The outlined U.S. Geological Survey 1:24,000-scale quadrangles are as follows: 1, Mount Yale; 2, Buena Vista West; 3, Mount Antero; 4, St. Elmo; 5, Cumberland Pass; 6, Whitepine; 7, Garfield; and 8, Maysville. Ti, Tertiary intrusives. Tv, Tertiary volcanics.

two faults that intersect at an angle of about 60 degrees; the faults are now occupied by prominent dikes of a distinctive, coarsely porphyritic rock, the Mount Aetna Quartz Monzonite Porphyry. These dikes emanate from an irregular stock of the same rock that makes up much of Mount Aetna, a prominent peak conspicuously visible from U.S. Highway 50 just east of Monarch Pass. The mountain doubtless takes its name from the famous Sicilian volcano because of the misleading resemblance to a typical stratovolcano that this view provides (fig. 2), an illusion that is heightened by the lava-flowlike appearance of the prominent light-colored talus stream that stretches from the summit to the base of the peak.

The Mount Aetna volcanic center is located near the southwestern margin of the Mount Princeton batholith, a large quartz-monzonite intrusion of middle Tertiary age that underlies most of the high peaks of the southern Sawatch Range, approximately between the latitudes of Salida and Buena Vista. Because of the southward tilting of the Mount Aetna subsided block and perhaps because of a southerly component to the regional tilting of the Sawatch Range (Bryant and Naeser, 1980), progressively higher structural levels in the batholith are exposed to the south; levels close to the original roof of the batholith may be preserved in the Mount Aetna subsided block. Paleozoic sedimentary rocks are absent from the interior of the Sawatch Range in its northern part but are more abundant as residual patches lying on the Precambrian basement rocks in that part of the range south of the prominent east-west valley of Texas Creek, at about the latitude of Buena Vista (Tweto and

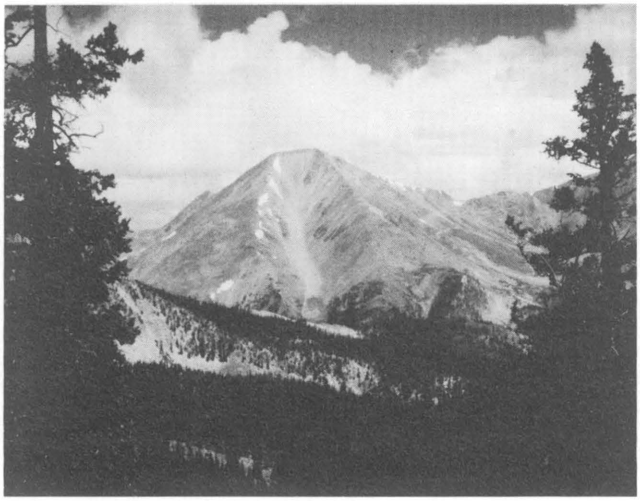


Figure 2. Mount Aetna from the southeast. The pseudovolcanic appearance engendered by the mountain's symmetrical profile and the lavalike talus stream probably suggested the name, by analogy with Mt. Etna in Sicily.

others, 1976, 1978). This relation implies a regional southward inclination to the basal Paleozoic unconformity in the central and southern Sawatch Range; the southward-opening trace of the Laramide Sawatch arch implies a northward axial tilt for that structure (Tweto, 1975; MacLachlan and Kleinkopf, 1969), so this southerly tilt in the southern part may reflect an asymmetry in the predominantly westward tilting of the Sawatch Range related to the opening of the Upper Arkansas graben-Rio Grande rift. The batholith, having been emplaced between the two events, would show the effects only of the later, southerly tilting.

No genetic relation between the volcanics and the intrusive rocks of the batholith has been demonstrated, but the compelling evidence that very little time elapsed between emplacement of the batholith and eruption of the volcanics clearly implies some sort of genetic connection. The relation of the batholithic and volcanic rocks to the younger middle Tertiary granites, porphyries, monzonite, rhyolite, and aplites is even less clear. The term "Mount Princeton batholith" [or "Princeton batholith" of Crawford (1913)] has traditionally been applied to the large intrusive body of the Mount Princeton Quartz Monzonite; in this report, we regard the Mount Pomeroy Quartz Monzonite as an integral part of the batholith as well. We will use the informal term "Mount Princeton igneous complex" to encompass all the middle Tertiary igneous rocks spatially associated with the Mount Princeton batholith, including those of the Mount Aetna volcanic center.

Previous Work

The earliest detailed geologic study of the area was by R.D. Crawford early in this century. His classic report on the Monarch and Tomichi mining districts (Crawford, 1913) describes the rocks in great and accurate detail. Dings and Robinson (1957) described the geology and ore deposits of the Garfield 15-minute quadrangle, in which the greater part of the Mount Aetna volcanic center lies, and published a geologic map at a somewhat larger scale (1:31,680). Their detailed mapping has been of great value in the present study, and many of their mapped features are presented here unchanged. At the time of these earlier studies, many of the concepts of ash-flow volcanism and caldera formation (Smith, 1960; Smith and Bailey, 1968a, b; Steven and Lipman, 1976) had not been developed, and the recognition of features diagnostic of this style of volcanism was not feasible.

The unusual assortment of beryllium minerals in the Mount Antero region has been recognized for many years; pertinent references are summarized by Adams (1953). Sharp (1976) studied the Mount Antero Granite and its pegmatites and published a detailed, large-scale geologic map; Scott and others (1975) published a geologic map of the Poncha Springs NW 7.5-minute quadrangle, which includes the easternmost part of the area shown in plate 1. Brock and Barker (1972) mapped the Mount Harvard 15-minute quadrangle, which contains the northern part of the Mount Princeton batholith.

The Mount Princeton batholith has been recognized for many years as the largest of the early to middle Tertiary plutons that are distributed along the Colorado Mineral Belt (Crawford, 1924). It has been suggested that these intrusions are cupolas on a huge Laramide (broadly interpreted) granitic-granodioritic mass underlying much of central Colorado (Crawford, 1924; Case, 1965, 1967; Tweto and Case, 1972; Steven, 1975; Isaacson and Smithson, 1976; Case and Sikora, 1984). The Mount Princeton batholith, regarded as the largest and presumably most deeply eroded of these cupolas, is composed mostly of more or less homogeneous quartz monzonite [by the older classification schemes; for example, Wahlstrom (1947)] but has a variety of associated igneous rocks along its southern fringe. Previous workers (Crawford, 1913; Dings and Robinson, 1957) regarded these as satellitic shallow intrusives, but Toulmin (1976; see also U.S. Geological Survey, 1963, p. A88, 1973, p. 142, 1975, p. 153) recognized that at least some of the supposedly intrusive rocks of these fringing bodies were of extrusive, pyroclastic origin. Brock and Barker (1965) described pyroclastic dikes cutting the Mount Princeton Quartz Monzonite in the north-central part of the batholith; if these dikes were closely related to the quartz monzonite, their character suggests a relatively shallow level of emplacement for the whole system.

Several seasons of detailed field examination and local, detailed mapping have, in general, confirmed the mapping of Crawford (1913) and of Dings and Robinson (1957), which has required only relatively minor modification. Reinterpretation of the origin of some of the map units has, however, greatly changed the implied geologic history (Toulmin, 1984). The complex suite of rocks along the southern and southwestern edges of the batholith is now seen not as a group of hypabyssal intrusive bodies composed of differentiates derived from the main batholithic magma body, but rather as remnants of a possibly very large Oligocene volcanic center that may have been the source of major ash-flows extending many tens of kilometers to the east. The volcanism followed the same petrologic path as that delineated by Steven and Lipman (1976) for the San Juan volcanic province to the southwest—early intermediate (andesitic) stratovolcanoes followed by more siliceous ash flows and associated subsidence. Perhaps partly because of its greater age, but more importantly because of strong local uplift, the Mount Aetna volcanic center has been eroded more deeply than those in the San Juan province; volcanic rocks are preserved only in a local down-faulted block, the Mount Aetna subsided block, on the southern fringe of the southwest-tilted batholith.

Acknowledgments

Many young geologists ably assisted in the fieldwork on which this report is based; they are named on plate 1. The contributions of many colleagues at the U.S. Geological Survey are gratefully acknowledged. Laboratory work on mineral separation, X-ray diffraction studies, and the like were especially facilitated by the efforts of Ed Williams, C.C. Silber, S.K. Mosburg, and B.H. Sepenuk. The expertise of J.J. McGee in microprobe matters was invaluable. Ogden Tweto, P.W. Lipman, R.L. Smith, W.E. Sharp, M.R. Brock, and Fred Barker visited the field area and offered helpful insights. Discussions with R.C. Epis (Colorado School of Mines), C.E. Chapin (New Mexico Bureau of Mines), T.A. Steven, and G.R. Scott helped put our work in the context of mid-Tertiary volcanism in central Colorado, and Scott provided us with valuable specimens of volcanic rocks from the Thirtynine Mile field. Ray Tekverk and Jan Fay, then project geologists with Gulf Resources Exploration Company, provided access to core collections and contributed stimulating discussions of local geology. Lipman and S.L. Ludington provided helpful reviews of the manuscript.

DESCRIPTION OF ROCK UNITS

The bedrock units that make up the Mount Aetna volcanic center and its immediate geologic frame range in age from Precambrian to Oligocene (pl. 1). The oldest rocks recognized are Precambrian gneisses, schists, and amphibolites. These are intruded by granites of Boulder Creek age (1.7–1.8 b.y.) (Bickford and Wetherill, 1964); Dings and Robinson (1957) mapped this rock as "granite of Pikes Peak type." Both these groups of rocks are intruded by younger Precambrian granites tentatively correlated with the 1.45-b.y.-old Silver Plume Granite.

Regionally, sedimentary rocks representing every system of the Paleozoic and Mesozoic except the Silurian are known (Dings and Robinson, 1957), but within the immediate area of the Mount Aetna volcanic center, they occur only as isolated patches of altered and metamorphosed rocks.

Tertiary igneous rocks include the batholith of the Mount Princeton Quartz Monzonite and, along its southern fringe, the Mount Pomeroy Quartz Monzonite, which probably represents a roof facies of the batholith. Volcanic deposits (the Calico Mountain and Sewanee Peak units and associated volcanic and collapse breccias) were emplaced on a rugged erosional surface on which these intrusive rocks were exposed. After subsidence of a large block of the volcanic rocks and the roof area of the Mount Princeton batholith, the coarsely porphyritic Mount Aetna Quartz Monzonite Porphyry, which is closely related chemically and petrographically to both the plutonic and volcanic rocks, intruded to form a stock and two major dikes. These rocks were intruded by a variety of minor intrusive units and by larger bodies of more leucocratic, granitic plutonic rocks (Hoffman Park and Mount Antero Granites). Surficial deposits typical of the glacial, alluvial, colluvial, and mass-wasting processes active in the Colorado Rockies abound but will not be discussed in detail.

Precambrian Rocks

Precambrian rocks within the area of plate 1 include granitic and amphibolitic gneisses, hornblende schist, amphibolite, granite, and pegmatite. These rocks have been described and mapped in detail in parts of the area by Dings and Robinson (1957), Crawford (1913), and Scott and others (1975). Except for two units, the gneissic quartz monzonite and the Silver Plume(?) Granite, they are shown undivided on plate 1.

Gneissic Quartz Monzonite

The gneissic quartz monzonite is a medium- to coarse-grained augen gneiss composed essentially of microcline, quartz, biotite, and plagioclase. The name is retained from the usage of earlier authors [Dings and Robinson, 1957; Crawford, 1913 ("quartz monzonite gneiss")], who regarded the unit as the earliest of the Tertiary intrusive rocks in the area. As the following discussion will show, the unit is of Precambrian age and forms an important part of the roof rocks and frame of the Mount Princeton batholith and of the floor on which the earliest volcanic rocks of the Mount Aetna volcanic center were deposited. Within the area of interest here, the gneissic quartz monzonite is exposed primarily in a northeasterly trending belt about 0.5 to 2 km wide, extending about 7.5 km from the eastern slopes of Mount Aetna to the west ridge of Mount Tabeguache. Similar rocks also occur within the area of Precambrian metamorphic rocks underlying the eastern and southeastern slopes of Mount Shavano, but they have not been mapped separately there. The gneiss is strongly to moderately foliated; the foliation is shown primarily by the orientation of the biotite and, to a lesser extent, by parallel orientation of the large microcline "eyes." Though locally quite variable, the foliation in general strikes northeast and dips moderately to steeply in either direction.

As noted by Pulfrey (1970, p. 16–18), who nonetheless accepted the Tertiary age assignment, the appearance of the rock is quite unlike that of any Tertiary intrusive rock in this part of Colorado but is strikingly similar to that of the coarsely porphyroblastic "gneissic quartz monzonite" of Precambrian age described by Van Alstine (1969) in the Trout Creek area, about 25 km to the northeast. The principal difference between the rocks in the two areas is that the gneisses at Trout Creek are somewhat less coarse grained than those in the Mount Aetna area. As noted by earlier workers, contact relations imply that the gneissic quartz monzonite is older than all "other" Tertiary igneous rocks in the area. Additional evidence indicating a Precambrian age for the unit is the presence of hyacinth-colored zircons, implying radiation exposure greater than is normal in Tertiary rocks, and the fact that an attempted K-Ar age determination on biotite separated from the rock gave a result of $199\pm6\times10^6$ yr, almost certainly a reset figure implying an older true age. The outcrop on Calico Mountain that apparently led Crawford (1913, p. 146) to infer a Tertiary age for this unit was described by him as showing the gneiss "in eruptive contact with quartzite and baked shale, which are penetrated by apophyses of the gneiss stock." Dings and Robinson (1957, p. 23) apparently accepted this interpretation of the exposures. Careful examination of all outcrops in the general area described by Crawford (1913, p. 145–147) revealed a few transgressive contacts between probable Pennsylvanian clastic sedimentary rocks and a bleached, sheared rock containing a few megacrysts of quartz and feldspar in a fine-grained matrix; in thin section, this rock appears to be an altered, granulated, and sheared clastic rock, perhaps originally an arkosic sandstone. A few inclusions of a similar rock were seen in Mount Pomeroy Quartz Monzonite at several places on the northern and northeastern slopes of Calico Peak. This material may represent the brecciated and altered wall zone of Paleozoic sedimentary rocks into which the batholith of Mount Princeton and Mount Pomeroy Quartz Monzonites intruded. The rock bears no resemblance to the gneissic quartz monzonite in texture or mineralogy, and the relations in this outcrop, therefore, cannot support the assignment of a post-Pennsylvanian age to the gneissic quartz monzonite. Finally, the gneissic quartz monzonite is cut by a dike of Precambrian Silver Plume(?) Granite near the head of Hunkydory Gulch.

Silver Plume(?) Granite

This granite, which was tentatively correlated with the widespread Silver Plume Granite of central and north-central Colorado by Dings and Robinson (1957), is typically a massive, gray to buff, medium-grained equigranular rock composed of microcline, plagioclase, quartz, and biotite. It underlies an area at the southwestern edge of the area shown in plate 1 and occurs in small bodies within the area mapped as "Precambrian rocks undivided" and in masses too small to show in other parts of the map area. According to Dings and Robinson (1957, p. 9), the Silver Plume(?) Granite intrudes Pikes Peak Granite near Monarch Pass, about 6.3 km south of the area of plate 1, but the "Pikes Peak Granite" of Dings and Robinson (1957) is probably of Boulder Creek age (see Bickford and Wetherill, 1964).

On the western slopes of Vulcan Mountain, just north of the main area of the Silver Plume(?) Granite, clasts in the megabreccia in a coherent area about 0.4 × 1 km are almost exclusively fragments of Silver Plume(?) Granite (pl. 1). This area is interpreted as a mass of locally derived breccia produced during collapse of the caldera wall. A dike of the Silver Plume(?) Granite cuts the gneissic quartz monzonite near the head of Hunkydory Gulch, confirming the Precambrian age of the latter unit.

Paleozoic Sedimentary Rocks

Sedimentary rocks of Paleozoic age occur in the vicinity of the Mount Aetna volcanic center as isolated, relatively small patches resting on older Precambrian basement rocks and intruded by younger Tertiary igneous rocks (pl. 1; Dings and Robinson, 1957; Crawford, 1913). Paleozoic deposits in the immediate vicinity of the volcanic center seem to be mostly Mississippian and younger; Paleozoic rocks known to be older than this are confined to the exterior fringes of the Mount Princeton batholith.

Several small patches of Paleozoic sedimentary rocks, surrounded by Calico Mountain Andesite, are exposed on the western slopes of Calico Mountain. The rocks are metamorphosed and altered limestones, siltstones, and shales and probably represent upper Paleozoic formations such as the Leadville Limestone, Belden Shale, and Minturn Formation. Their occurrence in isolated patches, and the local occurrence of fine-grained granulated lenses, might suggest that the sedimentary rocks here are large blocks in a megabreccia, as similar blocks are interpreted elsewhere in the area. The rather consistent relative positions of carbonate rocks below and west of clastic rocks suggest that the original stratigraphic relations have not been grossly disrupted, however, and the finely brecciated material may instead represent near-contact effects of the intrusion of the Mount Pomeroy Quartz Monzonite, as discussed in the section on "Gneissic Quartz Monzonite." Under this interpretation, the patches of Paleozoic rocks surrounded by Calico Mountain Andesite might be local highs on the prevolcanic surface. Large patches of talus and slide rock dominated by clastic sedimentary lithologies are found on the high ridge southwest of the Middle Fork of the South Arkansas River. The rocks are predominantly green sandstone and shale and probably belong to the Belden and Minturn Formations. Close examination reveals the presence of igneous and pyroclastic material intermingled with the sedimentary materials, which locally can be shown to be clasts in a sparse clastic-pyroclastic matrix. These areas are interpreted to be large masses of megabreccia representing the collapse of oversteepened caldera walls and will be further discussed in the section "Megabreccia." An area of sedimentary rocks of presumed Paleozoic age occurs on the lower slopes of the ridge northwest of Hoffmann Park and may be in sedimentary contact with the Precambrian augen gneiss there.

Tertiary(?)—Quartz Diorite

A biotite-hornblende-augite quartz diorite mapped by Dings and Robinson (1957) in nearby parts of the Garfield quadrangle (outside the limits of pl. 1) may be of Tertiary age and related to the igneous rocks of the Mount Princeton batholith and Mount Aetna volcanic center. In most occurrences, this rock is in contact only with Precambrian rocks, but Dings and Robinson (1957, pl. 1, p. 22) mapped one stock, about 4 km west of the volcanic center, that cuts Paleozoic sedimentary rocks; their map relations indicate a post-Ordovician age for that body. According to them, the adjacent Mount Princeton Quartz Monzonite contains inclusions of the quartz diorite (Dings and Robinson, 1957, p. 22); this quartz diorite is, therefore, older than the Mount Princeton Quartz Monzonite.

Hornblende and biotite from the quartz diorite of another body closer to the Mount Aetna volcanic center gave conflicting K/Ar age numbers (see table 6). The 115-m.y. apparent age of the hornblende may well reflect excess argon in the sample, but the 46-m.y. "age" of the biotite suggests that this quartz diorite may be pre-Tertiary and that its minerals' argon systems have been thermally reset to varying degrees.

Tertiary

Mount Pomeroy Quartz Monzonite

The Mount Pomeroy Quartz Monzonite is exposed in an east-northeast-trending band extending about 10 km from the Brittle Silver-Central Mountain area to the western slopes of Mount Antero; to the south and southwest, it is overlapped by younger volcanic rocks; and, to the northeast, it is truncated by the younger Mount Antero Granite (pl. 1). The northwestern contact is locally gradational with the Mount Princeton Quartz Monzonite and, to judge from its trace across the rugged topography, has a moderate southerly to southeasterly dip. The geometric relations suggest that the Mount Pomeroy is generally underlain by the Mount Princeton Quartz Monzonite.

Petrography

The rock is texturally variable, ranging from medium-grained granitic to rather fine-grained porphyritic. Pink, altered alkali feldspars and green, chloritized and epidosized hornblende and biotite produce an overall mottled aspect. The rock is characteristically altered, and the weathering of iron sulfides has produced a widespread limonitic surface stain. Fracturing on a decimeter scale is typical; in some places the fractures are occupied by veinlets of quartz, carbonates, clays, sericite, pyrite, and (or) epidote. In thin section, all the primary igneous minerals exhibit varying degrees of alteration. Feldspars are clouded with clay minerals and sericite, and hornblende and biotite are extensively altered to chlorite, epidote, and opaque minerals. Ragged aggregates of sphene are associated with the altered ferromagnesian minerals and are presumed to be products of alteration; we saw no typical wedge-shaped crystals of primary sphene, so characteristic of the Mount Princeton Quartz Monzonite and the Mount Aetna Quartz Monzonite Porphyry. Micrographic intergrowths of quartz and feldspar are common, as are myrmekitic patches at contacts of feldspar grains.

Point-count analysis of stained slabs of nine specimens of Mount Pomeroy Quartz Monzonite yielded the following average mode, in volume percent (one standard deviation in the last place in parentheses): quartz, 10(3); potassium feldspar, 35(6); plagioclase, 41(3); ferromagnesian silicates, 12(2); opaque minerals, 0.9(2); and other accessory minerals, 0.1(2).

Contact Relations

The contact between the Mount Pomeroy and Mount Princeton Quartz Monzonites is broadly gradational and, in many places, difficult or impossible to define in the field within a zone up to several hundred meters in width. Lithologies intermediate between typical Mount Princeton and Mount Pomeroy Quartz Monzonites occur within this zone, but nowhere has a complete, continuous transition been traced between rocks typical of the two map units. The intermediate lithologies are interpreted as hybrid rocks generated by remobilization of the Mount Pomeroy Quartz Monzonite and mixing with advancing magma of the Mount Princeton Quartz Monzonite. In some areas (for example, along the ridge between Grizzly and Pomeroy Gulches), the Mount Princeton Quartz Monzonite shows a somewhat porphyritic aspect, a high degree of alteration, abundance of interstitial granophyre, and absence or rarity of euhedral sphene crystals in a band several hundred meters wide adjacent to the contact with the Mount Pomeroy. On the high slopes west of Chalk Creek, the groundmass of the porphyritic Mount Princeton Quartz Monzonite becomes progressively finer grained as the contact with the Mount Pomeroy is approached, apparently representing a more or less continuous "megachill" phenomenon.

In some areas, such as the north end of Billings Basin and the adjacent area at the head of Grizzly Gulch, the lithologic variability of the Mount Pomeroy Quartz Monzonite can be seen to reflect a structure bordering on autointrusion, in which dikes and irregular small masses of relatively fine-grained porphyritic varieties cut through masses of coarser, more granitic-textured rock. In most such instances, both lithologies are clearly variants of the Mount Pomeroy type.

Alteration and Metamorphism

Plagioclase in the Mount Pomeroy Quartz Monzonite near its contact with the Mount Princeton Quartz Monzonite is often very dark in hand specimen and exhibits a "cloudiness" resulting from a very large content of extremely small, probably opaque inclusions. This feature and many of the associated textural characteristics of the rock are virtually identical to those described from contact-metamorphosed igneous rocks in Scotland and elsewhere (MacGregor, 1931). The tiny inclusions range from rod shaped to apparently equant and are so small that one cannot always be certain whether the material is opaque or transparent. The specks are arranged randomly in some instances and are concentrated in bands or chains in others; when in bands, they may or may not be parallel to recognizable crystallographic directions. The very fine inclusions are concentrated in the relatively fresh portions of the original plagioclase grains and are absent from recrystallized plagioclase and albitic overgrowths. As noted by MacGregor, the fine inclusions also seem to be rare or absent in portions of the plagioclase crystals that contain high concentrations of larger inclusions and alteration products, but in the Mount Pomeroy, it is not entirely clear whether this reflects a real difference in abundance or a greater difficulty in observing them. MacGregor (1931, p. 526, 536) concluded that, in the several examples examined or reviewed by him, the "clouding" consists of tiny iron-oxide grains exsolved from iron-rich portions of the plagioclase by the thermal effects of younger intrusions; we draw the same inference with respect to those in the Mount Pomeroy Quartz Monzonite. Armbrustmacher and Banks (1974) have described coarser and better developed inclusions of the same general sort in metadolerite dikes in Wyoming, which may have cooled very slowly because of prior metamorphic heating of the terrane into which they were intruded.

Origin

Several lines of evidence thus suggest that the Mount Pomeroy Quartz Monzonite represents an early-formed roof or capping facies for the Mount Princeton batholith that was altered and thermally metamorphosed by the rising magma of the main stage of the batholith not long after its initial emplacement. The complex, autointrusive character of the Mount Pomeroy and its high degree of alteration are consistent with an origin as an "advance guard" of the main mass of magma below. The chemistry and mineralogy of the unit are also permissively consistent with its being an early member of a magmatic series whose main representative is the Mount Princeton Quartz Monzonite.

Mount Princeton Quartz Monzonite

The Mount Princeton Quartz Monzonite forms a subcircular pluton 25 to 35 km across, making up the bulk of the Mount Princeton batholith (pl. 1). The rock is typically a medium-grained hypidiomorphic granular rock consisting of plagioclase, alkali feldspar, quartz, hornblende, biotite, and accessory minerals, of which sphene is the most conspicuous and characteristic. The rock generally appears massive in outcrop but in places is somewhat porphyritic. Little or no flow structure exists in the unit. Mafic concentrations or fragments, here lumped as "cognate inclusions" without genetic connotation, are irregularly distributed throughout the pluton without apparent relation to the margins.

Contact Relations, Metamorphism, and Alteration

Intrusive contacts of the Mount Princeton Quartz Monzonite with its wall rocks are usually marked by little or no contact metamorphism, endo- or exomorphic. The exception is in Taylor Gulch, just south of the area of plate 1, where Paleozoic sedimentary rocks are marmorized and hornfelsed near the contact. This is the only place where intimate invasion of the country rocks by Mount Princeton magma has been observed.

The freshest samples of the Mount Princeton Quartz Monzonite are found near the outer margins of the pluton, outside the Mount Aetna subsided block, and away from the contact with the Mount Pomeroy Quartz Monzonite within the Mount Aetna subsided block. Rocks in the outer segments tend to be finer grained than interior samples and to have white feldspars and prominent honey-yellow to root-beer-brown sphenes visible in hand specimen. Interior parts of the pluton are locally porphyritic; phenocrysts are large (up to 1 cm long) pink potassium feldspar crystals. Even where the rock is nonporphyritic, potassium feldspars in the rocks from the central portion of the pluton are pink. At the contact with the Mount Pomeroy Quartz Monzonite, the Mount Princeton is quite reddish in appearance and has the dark plagioclases typical of the Mount Pomeroy (see previous discussion in the section on "Alteration and Metamorphism" under "Mount Pomeroy Quartz Monzonite"). Two to three kilometers north of the inferred contact, the potassium feldspar is still quite reddish, but the plagioclase is generally white, sphene is ubiquitous, and the rock is somewhat coarser and generally has a more typical "Mount Princeton" aspect. Potassium feldspar retains a pinkish color in the rocks from here to the northern contact of the pluton. Pyroxene is very rare and has not been identified in hand specimen. Pyrite crystals and veins, and more rarely galena, are locally abundant.

Alteration is common; secondary clay minerals impart a chalky appearance to the feldspars, and replacement by chlorite and epidote gives a greenish tinge to the biotite and hornblende. Proximity to the Mount Pomeroy contact seems to be the controlling factor in degree of alteration; rocks from the segment of the pluton east of the easternmost dike of the Mount Aetna Quartz Monzonite Porphyry are relatively fresh. This relation implies that the intrusion of the nearby dike and the younger Mount Antero Granite had little effect on the degree of alteration of the Mount Princeton Quartz Monzonite.

Petrography

In thin section, the most variable characteristic of the quartz monzonite is the degree of alteration of feldspars. Near the Mount Pomeroy contact, both feldspars appear dusty brown in plane polarized light. Away from the contact, potassium feldspar retains this brown appearance, but plagioclase is generally clean. In the freshest samples (those that lack pink or red color in hand specimen), both feldspars are clean. An increase in the amount of interstitial graphic granite is noted as the feldspars become more cloudy.

Plagioclase is polysynthetically twinned and displays both oscillatory and normal zoning; the crystals average 3 to 6 mm in length and commonly have euhedral terminations against quartz or alkali feldspar. Although plagioclase is generally free of inclusions, large crystals commonly contain "trash zones" of minute inclusions, mostly biotite and opaques, about midway between core and rim and parallel to the outer surface of the crystal. In other cases, a distinct oval band of fine-grained sericite separates the core from the rest of the grain.

The degree of unmixing of alkali feldspar varies throughout the pluton; no coarse perthite was observed. The best-developed exsolution textures occur in the freshest rocks, away from the Mount Pomeroy contact. Clouding in feldspars near the contact may obscure perthitic textures. Carlsbad twins are common; microcline twins are extremely rare. The potassium feldspar usually forms blocky subhedral to interstitial anhedral grains. Inclusions are largely confined to 1- to 2-mm-long partially resorbed plagioclases, although sphene, opaques, and ferromagnesian silicates may also be present. Contacts against other minerals are smooth, except for contacts against plagioclase, which tend to be crinkled and to be marked by a narrow albitic rim within the plagioclase.

Quartz occurs in anhedral grains up to a few millimeters across and as thin fingers interstitial to other minerals in the rock. The absence of quartz inclusions in other minerals suggests that quartz began to crystallize late in the solidification history of the quartz monzonite.

Hornblende and biotite are present in subequal amounts. Hornblendes form green to almost colorless laths and pseudohexagonal rhombs, commonly clotted together with biotite, sphene, and (or) opaques. All hornblendes, even from the least altered rocks, are patchy in color, and most are twinned. Hornblendes from samples near the Mount Pomeroy contact are palest in color, have actinolitic compositions, and are riddled with 0.25-mm and smaller blocky magnetite grains. Patches of biotite are common in hornblende; hornblende is not observed enclosed within biotite.

Biotites are pleochroic in shades of brown. Typical habits are 1 by 2 mm or larger rectangular books and euhedral hexagons up to 2 mm across. Plagioclase and apatite inclusions, and sometimes zircons having pleochroic halos, are common in the first type; inclusions are rare in the second type. Chlorite invades biotite along cleavages and replaces hexagons from the outside in, the euhedral outline of the biotite remaining intact. Biotites in some rocks, especially those near the contact with the Mount Pomeroy Quartz Monzonite, are completely chloritized. Granular sphene occurs along biotite cleavages and grain borders; when associated with greenish-yellow epidote in chloritized biotites, it has the appearance of "green sphene" in hand specimen.

Sphene is abundant throughout the Mount Princeton Quartz Monzonite in several habits—euhedral, wedge-shaped crystals up to 1.5 mm long; partially formed wedges that are euhedral against feldspars and quartz but anhedral against biotite and hornblende; fine-grained to moderately coarsely granular rims around magnetite; and granular alteration products in ferromagnesian silicates. Apatite and magnetite are sometimes observed as inclusions in euhedral sphene.

Reflected light examination of 16 polished sections of specimens from throughout the pluton reveals that the opaque minerals are predominantly magnetite, with or without thin partial rims or lamellae of hematite. Tiny blebs of pyrite and, less commonly, chalcopyrite occur in cores of some blocky magnetites. No discrete grains of hematite, ilmenite, or sulfides were noted.

Apatite, as prisms and euhedral hexagonal grains in biotite, hornblende, and magnetite, is the other principal accessory mineral in the rock. Coarse, cigar-shaped, and blocky interstitial patches of reddish allanite, not apparently metamict, are confined to rocks in which the feldspar is highly altered.

Modal analysis of 11 samples (stained slabs) gave the following, in volume percent (one standard deviation in the last place in parentheses): quartz, 19(4); potassium feldspar, 28(2); plagioclase, 42(2); ferromagnesian silicates, 10(2); opaque minerals, 1.4(5); and other accessory minerals, 0.3(5).

Calico Mountain Andesite

The name "Calico Mountain Andesite" is proposed here for a previously unnamed assemblage of highly altered andesitic lava flows, pyroclastic breccias, laharic breccias, agglomerate, and welded ash-flow tuffs exposed in a band about 8 km long trending east-northeast from the western margin of Billings Basin to the upper reaches of Browns Creek (pl. 1). The name is derived from the prominent exposures on Calico Mountain, which serve as the type locality. The width of the band of outcrop ranges from 1 to 3 km. The northwestern contact of the unit is against the Mount Pomeroy Quartz Monzonite; to the southeast it is bounded by the Precambrian gneissic quartz monzonite. As the lithologic character of the unit leaves little doubt as to its volcanic origin and the gneissic quartz monzonite and the Mount Pomeroy Quartz Monzonite are both older than the Calico Mountain, both contacts are interpreted as basal. Similarly, inliers of the gneissic quartz monzonite and of Paleozoic sedimentary rocks within the area of the Calico Mountain Andesite are regarded as exposures of the basal contact of that formation. The Calico Mountain is essentially identical to the unit mapped by Crawford (1913) and Dings and Robinson (1957) as "andesite."

Lithology and Internal Structures

The Calico Mountain Andesite is intensely altered to an assemblage of clay minerals, chlorite, epidote, calcite, pyrite, and iron oxides. A characteristic heavy limonite stain or coating, derived from the abundant pyrite, gives the rock a variegated seal-brown to brownish-red color, from which the name of Calico Mountain is doubtless derived. In hand specimen, the typical lithology is a porphyry in the fine-grained groundmass of which are set altered phenocysts of feldspar and sparse mafic minerals a millimeter or so in greatest dimension. In much of the area underlain by the Calico Mountain, the rocks at the surface are fractured at the decimeter scale, and the surface is covered with rock fragments from 10 to 50 cm in size. This probably obscures a primary brecciated character in much of the formation, for, where well exposed, it can be seen to contain a large proportion of volcanic breccia, agglomerate, and laharic material. Fragments of welded ash-flow tuff containing readily recognizable (though now altered) collapsed pumice fragments are found throughout the unit (fig. 3), and two ash-flow units in Billings Basin are sufficiently thick and well exposed to be mapped separately (pl. 1). In the same area, well-defined beds of coarse agglomerate occur (fig. 4) but are not sufficiently continuous to permit mapping at the scale of plate 1.

Mappable internal structures in the Calico Mountain are relatively uncommon, but locally foliation, flattened pumice fragments, internal lithologic contacts, bomb- or boulder-rich horizons, or even rare, crudely developed stratification in apparently water-laid sedimentary lenses in volcanic breccias, permit observation of the attitude of what may have been initially flat or low-dipping features. These planar features all show southerly or southeasterly dips, generally flatter in exposures to the southeast than in those to the northwest. It is likely that these dips reflect, to a considerable degree, a regional southerly tilt and that initial dips were toward the axis of the band of outcrop. A contour

Figure 3. Collapsed, stretched pumice fragments in welded tuff of the Calico Mountain Andesite, Billings Basin.

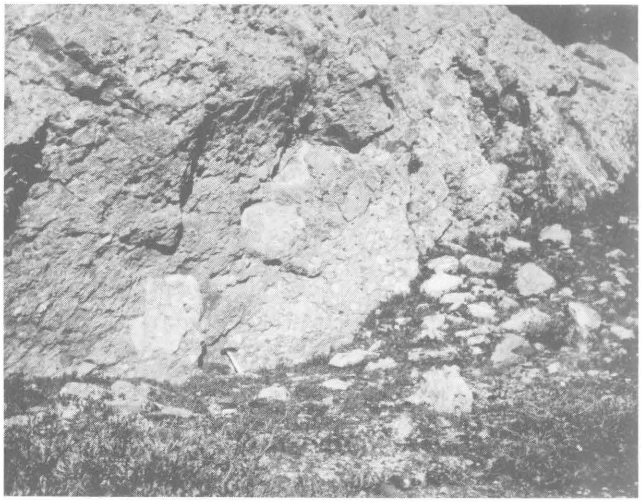


Figure 4. Agglomerate horizon in the Calico Mountain Andesite along the trail to Island Lake.

map on the base of the Calico Mountain Andesite (fig. 5) shows a troughlike configuration trending east-northeast and even suggests a crude dendritic pattern. Correction for southerly regional tilt enhances the appearance of an east-northeast-trending dendritic drainage pattern.

Contact Relations

Over most of its extent, the basal contact of the Calico Mountain Andesite is poorly exposed, but it can be located within a few to a few score meters throughout the area. The map pattern (pl. 1) shows that the erosion surface on which the Calico Mountain was deposited was one of moderate relief and rolling topography. Prevolcanic weathering is not as conspicuous as at the base of the Sewanee Peak Volcanics, discussed later (see the section "Contact Relations: Basal Rubble Zone" under "Sewanee Peak Volcanics"), but may be partly obscured by intense hydrothermal alteration. Inclusions of older rocks are not particularly abundant in the lower part of the Calico Mountain in most places, but locally, as at the southwestern edge of the southern cirque at the head of Browns Creek, where an inlier of gneissic quartz monzonite is exposed, a basal breccia is composed largely of blocks of the underlying rocks with interstitial volcanic material. Because the original upper contact of the Calico Mountain Andesite is not preserved, no estimate of the total thickness of the formation can be made, and the irregular nature of the basal contact makes an estimate of even the thickness preserved highly uncertain, but it would appear that approximately 500 to 800 m of Calico Mountain Andesite is the maximum thickness preserved.

At the southwestern end of its belt of outcrop, an eroded surface of the Calico Mountain Andesite is overlain by ash-flow tuffs and breccias of the Sewanee Peak Volcanics. This surface appears to have been of higher relief than the basal contact; it is locally well exposed and exhibits several features of interest, such as residual weathering of the underlying rocks, accumulations of cobbles and boulders of the underlying rocks (and of more angular paleotalus), and extensive incorporation of surface debris into the

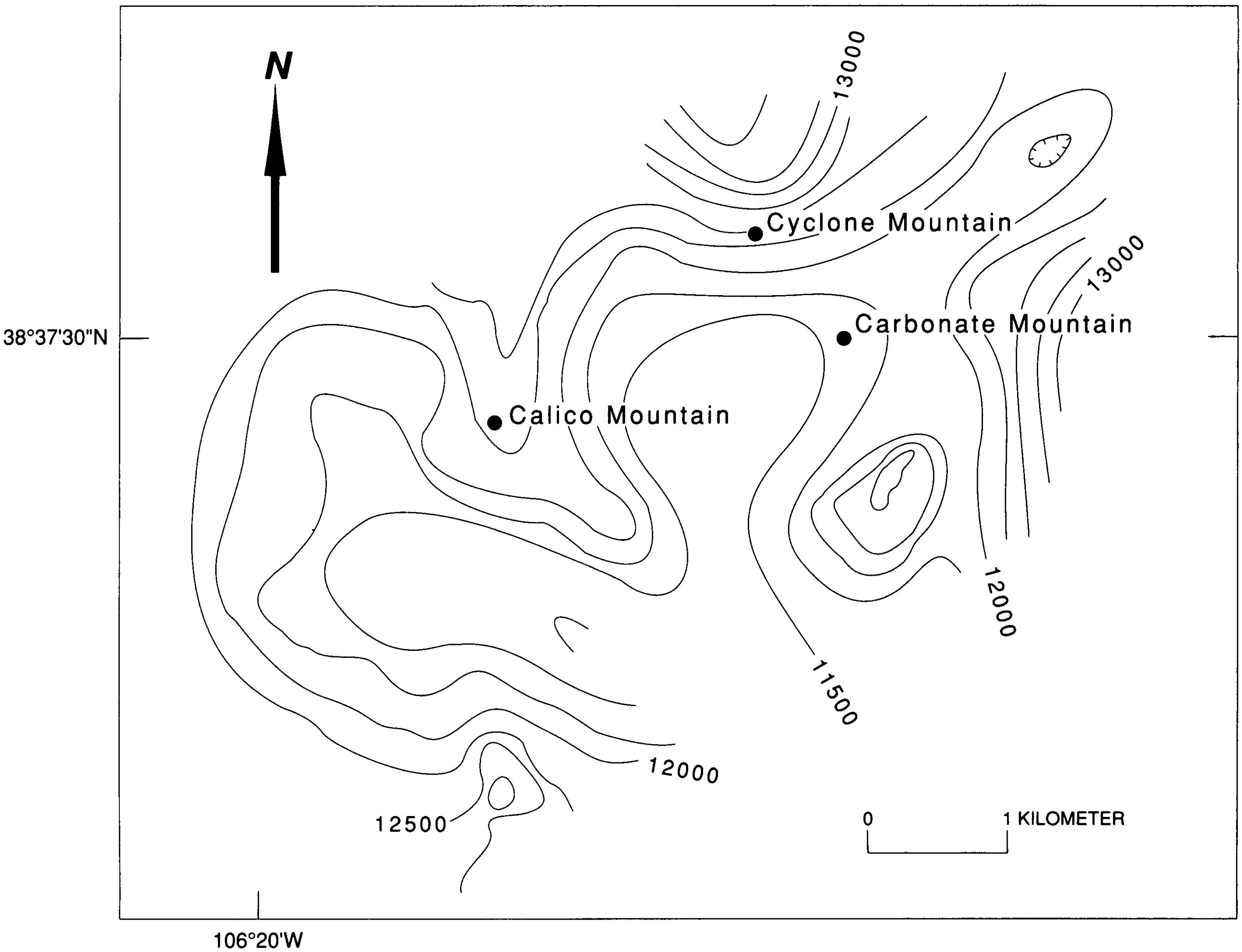


Figure 5. Structure contours on the base of the Calico Mountain Andesite. The contour interval is 250 ft.

basal portion of the overlying Sewanee Peak Volcanics. This surface cuts across several other map units and will be discussed in more detail in the section "Sewanee Peak Volcanics."

The composition of the Calico Mountain Andesite is variable, and it undoubtedly contains rocks more siliceous than andesite sensu stricto. The altered condition of most rocks in the unit, however, makes detailed chemical comparisons impossible.

Sewanee Peak Volcanics

The name "Sewanee Peak Volcanics" is here proposed for a complex assemblage of volcanic and pyroclastic breccias; densely welded and compacted ash-flow tuffs, locally apparently remobilized to form flows and flow breccias; lava flows; and rare ash-fall deposits. Lithic fragments from 1 to 5 cm in diameter are sporadically abundant throughout the unit; most of these are volcanic, but clasts of many of the prevolcanic rock types of the area are to be found. In some areas, especially near the base of the formation, the older rocks predominate, in some places as monolithologic swarms of fragments of the underlying unit and in others as randomly varied and mixed assemblies of many lithologies. The unit is discontinuously exposed in an oblong area approximately 4 by 6 km in size that extends southwestward from the vicinity of Hancock Pass and Brittle Silver Basin to the east side of Mount Aetna (pl. 1). Its extent was doubtless much greater originally but has been greatly reduced by erosion and by the emplacement of younger intrusive units. For these reasons and because of the highly irregular character of the surface on which it was deposited, we cannot make a meaningful estimate of the original thickness of the unit, but a minimum of 1.5 to 2 km is required by the present distribution and attitudes as shown on plate 1.

The rock is hard but brittle and is broken by many closely spaced joints and less systematic fractures. As a result, it tends to form steep, unstable cliffs aproned by extensive talus.

The unit is virtually identical to that which Dings and Robinson (1957) and Crawford (1913) interpreted as a shallow intrusive and mapped under the name "quartz latite porphyry." The unit is redefined here on the basis of its manifestly volcanic nature. The name is from the excellent exposures on Sewanee Peak, a rugged summit on the divide between Billings Basin and the heads of Chalk Creek and the Middle Fork of the South Arkansas River. These exposures are designated the type area.

Petrography

Because of its dense compaction and propylitic alteration, much of the Sewanee Peak Volcanics has a uniform megascopic appearance. Typically, the rocks have a dark-gray to green, very fine grained groundmass in which are set abundant phenocrysts of feldspar up to 1 or 2 mm in length, rarer biotite and hornblende crystals of about the same size, and distinctly less common quartz phenocrysts. Tiny yellow sphene crystals are visible in some hand specimens. The abundance of lithic fragments varies greatly, and the rocks range from essentially inclusion-free fine porphyry to volcanic breccia. The megascopic appearance of collapsed and stretched pumice fragments is also highly variable, as they have undergone varying degrees of compaction, deformation, and propylitic alteration. Less intensely compacted pumice fragments are usually relatively light colored and have aspect ratios of less than about 8; more highly deformed blocks appear as darker-colored streaks in the form of typical fiamme. Devitrification and alteration have destroyed most of the finer structures typical of pyroclastic rocks in thin section, but in a few instances recognizable shard structure is evident (fig. 6).

In thin section, the dense porphyry that is typical of the bulk of the unit shows a fine-grained, nearly unresolvable groundmass in which relict flow structures and pumice fragments may or may not be discerned. Where seen, flow structures swirl around and between the abundant euhedral and broken phenocrysts. Many feldspar phenocrysts are broken fragments of euhedral to subhedral crystals, though some unbroken euhedra are present. Plagioclase is by far the most abundant phenocryst mineral, constituting about 90 percent of the phenocrysts in the typical rock. Most crystals show optical evidence of compositional zoning, and microprobe analysis shows a range from core to rim of about An_{60} to An_{30}. Most crystals appear to be zoned more or less continuously, but a few plagioclase crystals show an inner core having sharply higher refractive indices than the outer part of the same crystal. These may represent xenocrysts strongly out of equilibrium with the Sewanee Peak magma or, less probably, early-formed phenocrysts that became disequilibrated with the magma as a result of

Figure 6. Shard structure in the Sewanee Peak Volcanics. The field of view is about 2 cm.

preeruptive changes in physical-chemical conditions (the outer rim seems too thick to be ascribed to posteruptive overgrowth). Though by no means typical, one plagioclase crystal was seen to contain inclusions of round biotite and prismatic apatite.

Alkali feldspar is very much less abundant than plagioclase in the "typical" Sewanee Peak Volcanics; it is estimated to make up no more than 1 or 2 percent of the phenocrysts in most specimens, though it may range up to 5 percent or so in a few. It is untwinned, does not show optically obvious zoning, and occurs in crystals of the same general size and shape as the plagioclase. Its X-ray diffraction pattern indicates monoclinic symmetry and suggests a structural state intermediate between sanidine and orthoclase.

Biotite makes up an estimated 5 to 8 percent of the phenocrysts. Biotite crystals range from 0.1 mm or so to as much as 2 to 3 mm in long dimension. They are commonly bent as a result of flowage and typically are greatly altered to an assemblage of chlorite, epidote, and finely granular sphene. Where fresh, the biotite commonly exhibits a deep russet color parallel to its slow ray, the perpendicular direction being light to medium yellow brown.

Hornblende is perhaps slightly less abundant than biotite and occurs typically in euhedral to subhedral crystals a few tenths to 2 mm across. It is pleochroic in shades of olive green and brownish yellow, rarely exhibiting a bright apple-green shade. The composition of the hornblende and biotite will be discussed in the section "Mineral Chemistry."

Among the accessory minerals, sphene occurs as euhedral, coffin-shaped crystals up to about 1.5 mm in length, which are commonly broken and occasionally optically strained, and also as a fine-grained alteration product associated with chlorite and epidote, formed from biotite and hornblende. Apatite forms small phenocrysts (no larger than a couple of tenths of a millimeter) and also is commonly included in hornblende and biotite.

Contact Relations: Basal Rubble Zone

The basal contact of the Sewanee Peak Volcanics is especially well exposed on the northern and northeastern margins of its area of outcrop. The most spectacular and informative of these exposures is at Pomeroy Pass, a saddle on the ridge that separates Billings Basin from Chalk Creek north of Sewanee Peak (the name "Pomeroy Pass" appears on older maps, but the pass is unnamed on recent U.S. Geological Survey topographic sheets). Here a thick, gently dipping red zone of lithified rubble (designated "Trz" on pl. 1) lies at the base of the steep, dark cliffs of Sewanee Peak Volcanics and separates it from the underlying Mount Pomeroy Quartz Monzonite (fig. 7). The rubble zone consists of very poorly sorted, crudely stratified clasts, cobbles, and boulders of various lithologies. Mount Pomeroy Quartz Monzonite and volcanic rocks, perhaps partly derived from the Sewanee Peak Volcanics itself, predominate, but a few clasts of other rocks, including upper Paleozoic sedimentary rocks, Mount Princeton Quartz Monzonite, and probable Calico Mountain Andesite, are also present. The base of the rubble zone is highly irregular, and its upper contact with the Sewanee Peak Volcanics is locally gradational. The character of the rubble zone also varies with the character of its base. As the rubble zone is traced southward down the side of the ridge, the southward dip of its base increases rather abruptly, and at this point, the lithologic diversity of the clasts in the rubble also increases.

Figure 7. Basal contact of the Sewanee Peak Volcanics at Pomeroy Pass. Note the well-developed rubble zone at the base; fragments, which are largely oxidized, presumably are weathered and baked clasts of the underlying Mount Pomeroy Quartz Monzonite.

Most of the material that makes up the rubble zone is reddened by pervasive iron oxides. Both the clasts and the matrix are affected. The underlying Mount Pomeroy Quartz Monzonite is unusually heavily altered and reddened, and its enrichment in iron oxides increases toward the overlying rubble zone. Clasts show red marginal shells (fig. 8). All these features suggest strongly that the rubble zone represents partially weathered debris that accumulated on the prevolcanic surface and was partly incorporated into the basal portions of the volcanics. The Oligocene climate in this area has been interpreted to have been mild and humid to subhumid (Epis and Chapin, 1975), suitable for limonitic weathering. Hydrous iron oxides in weathered material would be converted to hematite when heated by volcanic activity.

The increased lithologic diversity accompanying steepening of the paleosurface slope, noted previously, is consistent with a transition from in situ weathering to a greater degree of local transport of the accumulated material. As one follows the base of the Sewanee Peak Volcanics for 4 km or so to the southeast, the contact transgresses first

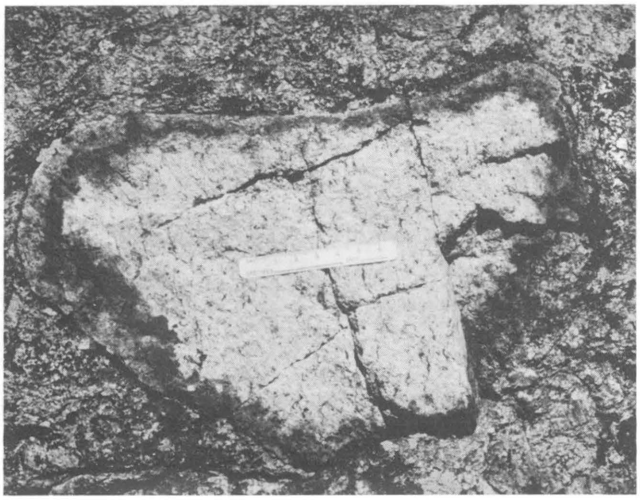


Figure 8. Hematite-rimmed clast in the basal Sewanee Peak Volcanics. The hematite rim is interpreted as a baked rind of limonite that was produced by weathering on the pre-Sewanee Peak surface.

rocks of the Calico Mountain Andesite and then of the gneissic quartz monzonite. Patches of rubble zone, or of rubble-poor but intensely weathered subjacent rocks, are found at several places along the contact (pl. 1). Where the local relief on the contact is relatively low, the weathered material incorporated into the basal Sewanee Peak is almost exclusively the underlying Calico Mountain; in areas of more rugged pre-Sewanee Peak topography, as indicated by the irregular trace of the contact, more extensive accumulations of subvolcanic rubble occur, and the lithologic diversity of the clasts is much greater both in the rubble and in the included material in the lower part of the overlying volcanics. In the vicinity of Lake Arthur, where the underlying formation is still the Calico Mountain Andesite, the rubble zone contains an enormous variety of rock types, including several that are now exposed no closer than several kilometers from this locality; farther southeast, where the Sewanee Peak overlies gneissic quartz monzonite, this polymict rubble is replaced by a thicker, monolithologic accumulation more closely resembling the megabreccia (see next section).

On the east side of the upper valley of the east fork of Tomichi Creek, southwest of Brittle Silver Mountain, a basal mass of rubble zone separates the overlying Sewanee Peak Volcanics from a floor of the Mount Princeton and the Mount Pomeroy Quartz Monzonites. The contact between the two quartz monzonite units continues into the rubble zone, where it separates areas of nearly monolithologic breccia composed respectively of the Mount Princeton and the Mount Pomeroy Quartz Monzonite (see pl. 1).

Breccias and Megabreccias

At several places along the margin of the outcrop area of the Sewanee Peak Volcanics, thick accumulations of coarse fragmental debris (designated "Tmb" on pl. 1), derived chiefly from older rock units, underlie and are interfingered with the Sewanee Peak rocks. Along the northeastern margin, the occurrences are relatively thin and discontinuous, and the distinction from the basal red rubble zone (Trz) of the Sewanee Peak is somewhat arbitrary, being based mainly on coarser clasts, a less oxidized character, and generally an apparently nonvolcanic matrix. Even here, however, the lithologic character of the breccias is quite variable. In the basin of Lake Arthur, south of Billings Reservoir, the clasts are heterogeneous and contain a significant volcanic component, though, less than a kilometer away, the clasts are almost exclusively of the gneissic quartz monzonite, and so little volcanic material is present that the contact between breccia and gneissic quartz monzonite can be mapped with confidence only where exposure is especially good. By contrast, on the southwestern side of the Sewanee Peak Volcanics, the breccias are very extensive and appear to underlie a large, originally continuous area approximately 2 km wide and 5 km long (see pl. 1). We interpret the jumble of volcanic and prevolcanic lithologies in this area as caldera-collapse meso- and megabreccias (Lipman, 1976), produced by the failure of oversteepened caldera walls penecontemporaneously with Sewanee Peak volcanism.

The east fork of upper Tomichi Creek and the adjoining southern and eastern slopes of Central Mountain show the diverse character of the megabreccia exceptionally well. Large (0.5-km) areas are underlain by single lithologic units (for example, the Mount Princeton or the Mount Pomeroy Quartz Monzonite, one or another of the Precambrian granites), which, if seen in float or small, poorly exposed outcrops, seem to be in place. On close scrutiny, however, patches of breccia are observed, and these appear to be interstitial to the larger blocks. On the ridge south of Central Mountain and in the basin at the head of the east fork of Tomichi Creek, large (greater than 20-m) blocks of Mount Princeton Quartz Monzonite are surrounded by a clastic matrix of the same material ranging in grain size from a few centimeters to less than a millimeter. On the same south ridge of Central Mountain, just east of the large north-south dike of Mount Aetna Quartz Monzonite Porphyry, Paleozoic sedimentary rocks are found as float and outcrops a few meters in size over an area a few hundred meters in extent. Incoherent attitudes from one apparent outcrop to the next and the presence of patches of sheared pyroclastic matrix indicate that this area is also a mass of very coarse breccia.

Near the southern end of this ridge, the east-facing cliffs provide spectacular exposures of the breccia that clearly reveal their complexity. Figure 9 shows an erosional pinnacle consisting of several interleaved varieties of breccia surmounted by a large block, which is probably Calico Mountain Andesite; the whole exposure, surrounded by

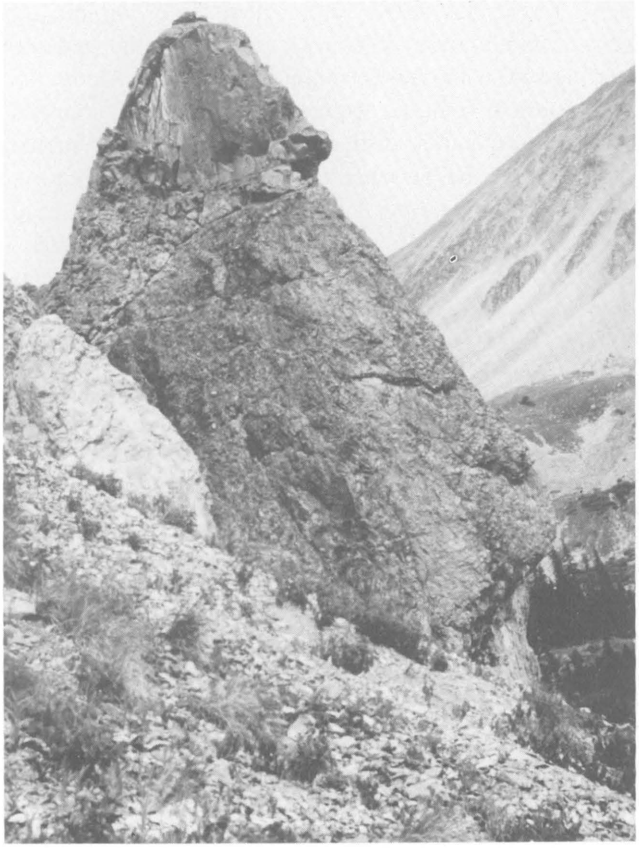


Figure 9. An exceptionally well exposed block surmounting an erosional pinnacle in the megabreccia near the major fork in Tomichi Creek.

welded tuff, suggests an environment in which slices and masses of breccia could readily have become mobilized and incorporated into still more complex breccias.

The same mass of megabreccia extends south-southeast across Tomichi Creek and underlies much of the high ridge (Continental Divide) separating the drainages of the Middle Fork of the South Arkansas River and Tomichi Creek. Except for the steep, clifflike slopes facing east toward the Middle Fork, much of this area is covered with talus and slide-rock, and outcrops are relatively sparse or uncertain. Geologic mapping, therefore, is based largely on lithologies observed in float. Large (hundreds of meters) coherent areas of consistent lithology are readily mappable in this area, but these do not necessarily represent the original distribution of bedrock map units. The geologic map (pl. 1) shows the outlines of several such areas within the megabreccia; these areas represent what are believed to be concentrations of very large blocks of exotic material incorporated within the megabreccia. On the slopes just west of the Continental Divide, between Vulcan Peak and Clover Mountain, much of the float is composed of Paleozoic sedimentary rocks, but small amounts of Precambrian granites and of Tertiary volcanic breccia are also present. A few blocks show volcanic breccia adhering to larger pieces of prevolcanic rocks; these are interpreted as patches of interblock matrix.

The huge scale of the breccia structure is readily and dramatically apparent on the steep eastern slopes of the Continental Divide in this area. On the cliffs east of the second saddle south of Vulcan Peak, for example, a 20- by 35-m block of porphyry is exposed in the cliff face, embedded in a clastic polymict breccia containing fragments of many prevolcanic units—gneissic quartz monzonite, Silver Plume(?) Granite, an older Precambrian granite probably of Boulder Creek age, and sedimentary rocks (sandstones, argillites, carbonate rocks) of probable Paleozoic age. The porphyritic rock of the large block is too altered for positive identification but is clearly volcanic; it could be from either the Calico Mountain Andesite or the lower part of the Sewanee Peak Volcanics. In places, the matrix breccia seems wholly clastic and nonvolcanic; elsewhere, however, collapsed pumice, broken euhedral phenocrysts, a fine-grained crystalline groundmass, and other textural features prove its pyroclastic origin. The extraordinary heterogeneity of the matrix breccia and the intimate blending of volcanic and clastic material in it are consistent with the proposed origin by catastrophic failure and collapse of the walls of a caldera contemporaneously with violent volcanic activity.

The degree of transport of the material comprising the unit mapped as megabreccia (Tmb) ranges considerably. In places, such as the area at the head of Tomichi Creek described above, where a coarse breccia unit abruptly passes from one dominant constituent lithology to another along the projected line of contact between the two units in the underlying bedrock, it is clear that we are dealing with a local accumulation of surface debris, perhaps in the nature of a coarse talus pile. Elsewhere, the heterogeneity of the materials bespeaks a greater degree of transport and a more complex, presumably larger source region. Nonetheless, as has been amply documented in studies of other volcanic areas (Lipman, 1976; Cruson, 1972a, b, 1973), very large blocks of rock and even of surficial materials may maintain a surprising degree of integrity in the very large scale collapse phenomena associated with caldera wall failure, and large masses of essentially uniform lithology are just as likely well within the megabreccia as near the margins.

Mount Aetna Quartz Monzonite Porphyry

Form and Contact Relations

The Mount Aetna Quartz Monzonite Porphyry forms an irregular stock and two major dikes that trend in roughly northeast-southwest and north-south directions out from the southeastern and western sides of the stock, cutting the Sewanee Peak Volcanics and older rocks (fig. 10; pl. 1). Immediately adjacent to the dikes, the wall rocks are consistently sheared parallel to the dike walls, but the dike

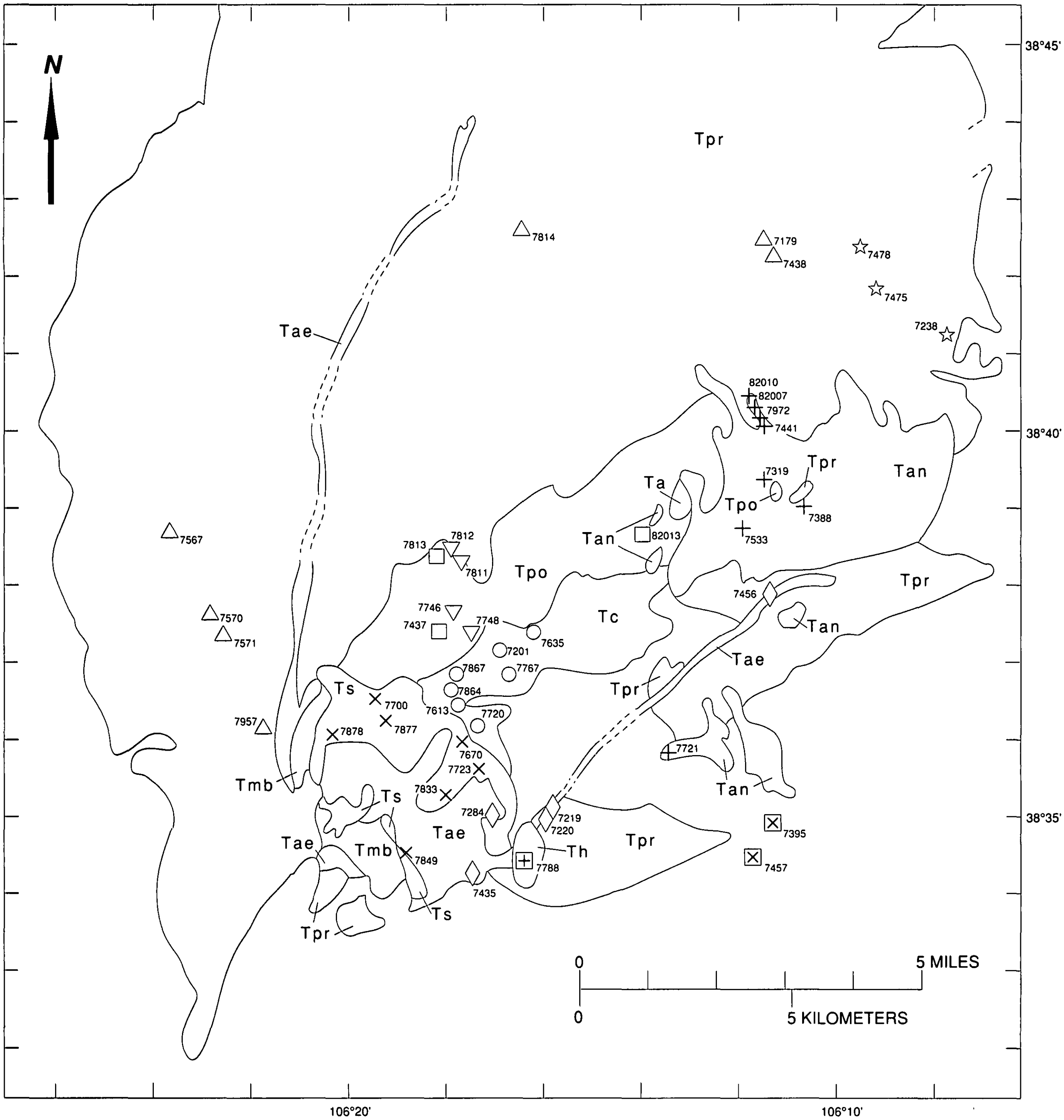


Figure 10. Analyzed samples. See plate 1 for explanation of abbreviations. Symbols designate rock units, as follows:

- ⊠ – Quartz diorite
- □ – Mount Pomeroy Quartz Monzonite
- ▽ – Transitional rock at the contact between the Mount Princeton and the Mount Pomeroy Quartz Monzonites
- △ – Mount Princeton Quartz Monzonite
- ○ – Calico Mountain Andesite
- × – Sewanee Peak Volcanics
- ◇ – Mount Aetna Quartz Monzonite Porphyry
- ⊞ – Hoffman Park Granite
- \+ – Mount Antero Granite
- ☆ – Monzonite dike, rhyolite porphyry of Raspberry Hill, and aplite dike

7814 – Sample number

rock itself is not deformed. This feature is especially well displayed on the ridge crest west of Taylor Mountain and on the lower ridge northwest of Hunkydory Gulch, where the gneissic quartz monzonite adjacent to the Mount Aetna Quartz Monzonite Porphyry dike is virtually mylonitized, though the quartz monzonite porphyry is essentially undeformed. Similar relations can be seen at many localities along the western (north-south) dike between Brittle Silver Basin and Hancock Pass.

The wedge-shaped area in the acute angle between the two major dikes of the Mount Aetna Quartz Monzonite Porphyry, which we are designating the "Mount Aetna subsided block," is the unique site of occurrence of the volcanic rocks and the Mount Pomeroy Quartz Monzonite, which we interpret as a roof facies of the Mount Princeton batholith. Along much of its length, the southeastern dike separates the Mount Princeton Quartz Monzonite on the southeast from gneissic quartz monzonite on the northwest; the latter must have formed part of the batholith's walls and may well have formed part of its roof. Along the ridge east of the upper course of Chalk Creek near Hancock and Romley (just north of the area of pl. 1), the western dike delimits a system of richly mineralized fractures in the Mount Princeton Quartz Monzonite, which is absent west of the dike. The strength of the geologic contrasts, intensity of deformation adjacent to the dike walls, and the dikes' thickness all diminish to the north and east, away from the Mount Aetna center. These observations strongly imply that the Mount Aetna dikes were emplaced along major faults bounding a subsided block that appears to have had the geometry of a trapdoor opening to the southwest. Maximum subsidence of the block must have been at least on the order of 3 km to preserve the volcanics and the batholith roof, which are completely eroded away everywhere else. Furthermore, subsidence must have been essentially complete before emplacement of the porphyry, for otherwise the dikes would have undergone the deformation that affected their sheared walls.

Petrography

Mineralogically, the Mount Aetna Quartz Monzonite Porphyry is nearly identical to the Mount Princeton Quartz Monzonite, but texturally, it is distinct from all other rocks in the area. The typical rock is very coarsely porphyritic, containing large feldspar and quartz phenocrysts in a granitic matrix, but the abundance of phenocrysts and the grain size of the groundmass vary throughout the unit. In the main stock, the rock has a light-gray cast due to the salt-and-pepper texture of a fine-grained white groundmass speckled with 0.5-mm and smaller black hornblendes and biotites. The rock is punctuated with 0.5-cm-long white plagioclase phenocrysts, rounded quartz "eyes" up to 0.5 cm long, and distinctive pink, euhedral potassium feldspar phenocrysts averaging 1 cm in length, locally ranging up to 4 cm along the length of both dikes. Rocks in the western dike, especially near Brittle Silver Basin, tend to be more altered than elsewhere, and, in places, plagioclase cores are full of coarse green epidote. The southern ends of both dikes generally have a darker gray appearance due to a denser groundmass and a greater contrast between phenocryst and groundmass grain sizes. Feldspars and quartz form the largest phenocrysts throughout the unit; potassium feldspars are coarser and tend to be more euhedral than either plagioclase or quartz phenocrysts.

In thin section, the variability of the groundmass is readily apparent. The coarsest type consists of an interlocking mosaic of anhedral quartz and feldspar grains up to 2 mm across; little size contrast is evident between the groundmass and most of the phenocrysts. Finer grained varieties have groundmass crystals on the order of tenths of millimeters across, and all gradations between the two extremes exist. Although the phenocryst abundance varies throughout the rock unit, the mineralogy does not.

Potassium feldspar phenocrysts are generally euhedral and commonly terminated; many display Carlsbad twins, but microcline twinning has not been observed. X-ray diffraction confirms that they belong to the orthoclase series. The feldspar is typically free of alteration and mostly homogeneous, displaying only rare patches of incipient perthite exsolution and faint oscillatory zoning. Some crystals have clean cores bounded by a zone of aligned euhedral to subhedral inclusions (mostly plagioclase, some sphene, and ferromagnesian silicates) and clean rims. Other crystals contain inclusions throughout; inclusions of quartz were not observed. The included plagioclases do not generally appear resorbed, nor did we observe evidence of reaction between the phenocrysts and the groundmass. Plagioclase crystals aligned along interior growth zones in the host orthoclase appear to have been incorporated during crystal growth rather than produced by exsolution. Minerals included within the phenocrysts are always smaller than corresponding ones outside. These observations imply that the phenocrysts are magmatic in origin and that some of them must have grown to about half their final size in relatively crystal-poor magma.

Plagioclase displays both normal and oscillatory zoning, the latter best developed near, but not at, the outer margins of crystals. It characteristically includes hornblende, biotite, and euhedral crystals of sphene. In altered rocks, plagioclases are commonly sericitized.

Hornblende is typically euhedral; crystals average about 2 mm in length, may be twinned, and often contain patches of biotite. Although the degree of alteration (chloritization) is variable from sample to sample, the hornblendes tend to be green or brownish green in plane light, rarely the very pale green to colorless actinolitic variety observed in the Mount Pomeroy and in parts of the Mount Princeton Quartz Monzonites.

Biotite is dark brown to reddish, commonly bent, and variably chloritized and epidosized. In some rocks, biotite is completely altered to chlorite dotted with sphene-rimmed opaque minerals.

Minor minerals are silicates, oxides, and sulfides. Sphene is ubiquitous in the porphyry, forming euhedral wedge-shaped phenocrysts up to 5 mm across; broken grains are common. Epidote occurs as an alteration product in both biotite and hornblende. Magnetite crystals are blocky to slightly rounded and range from about 0.25 mm across down to specks only a hundredth of a millimeter in size. Hematite rims and lamellae occur in magnetite in some samples. Pyrite blebs in magnetite cores are rare and are observed only in the coarse, discrete grains; no sulfides were observed outside of magnetite grains. Apatite is common as inclusions in magnetite and as euhedral phenocrysts.

A finer grained, characteristically pink (though locally greenish) variety of the Mount Aetna Quartz Monzonite Porphyry forms mappably distinct bodies mostly within the western dike in the area between Brittle Silver Mountain and Central Mountain and on the ridge south of Central Mountain. This rock is usually highly altered but has a finer grained, nearly aplitic quartz-rich groundmass in which are set phenocrysts of plagioclase, alkali feldspar, hornblende, and rather rare rounded quartz. The large pink feldspar phenocrysts so typical of most of the Mount Aetna Quartz Monzonite Porphyry are very rare. This rock may represent a late, somewhat dry differentiate of the Mount Aetna magma emplaced mainly along a central zone of weakness in the Mount Aetna dike.

Hoffman Park Granite

The Hoffman Park Granite forms a 1.5- by 0.5-km oval stock near the southern margin of the Mount Princeton batholith (pl. 1). The stock cuts the eastern dike of the Mount Aetna Quartz Monzonite Porphyry and the southeastern apophysis of the Mount Princeton Quartz Monzonite. Crawford (1913) and Dings and Robinson (1957) included it with the Mount Princeton Quartz Monzonite. Toulmin (1976) identified the stock as a separate intrusion of the Mount Antero Granite, established field relations demonstrating that it is younger than both the Mount Princeton and the Mount Aetna, and noted the association with molybdenum mineralization. Steininger and Arehart (1976) concurred on a separate identity for the rock and on the age relations in their discussion of the Mount Aetna molybdenum prospect. Recent K/Ar ages (Pulfrey, 1970; tables 5, 6; proprietary information) suggest that the Hoffman Park Granite may be slightly older than the Mount Antero Granite. The rock is also chemically and mineralogically distinct both from the Mount Princeton Quartz Monzonite and from the Mount Antero Granite and is here regarded as a separate rock unit, for which the name "Hoffman Park Granite" is proposed. The type locality is Hoffman Park.

The Hoffman Park Granite is a massive, medium-grained, pink to gray leucocratic rock composed of 5-mm-long pink potassium feldspars, similar sized white plagioclases that alter to a chalky yellowish white, 2- to 3-mm rounded quartz grains, and dark biotite. Notable differences from the Mount Princeton Quartz Monzonite are overall lighter color, slightly finer grain size and lack of porphyritic textures visible in hand specimen, absence of hornblende, less biotite and opaque minerals, and lack of prominent sphene, although sphene is noted in all thin sections of the rock.

Potassium feldspars average 4 by 2 mm in size and display string microperthite evenly developed throughout entire grains. Carlsbad twins are common; microcline twins occur sporadically. Inclusions of other minerals are scarce and are limited to plagioclase and quartz. Contacts against plagioclase and quartz are clean; no graphic granite or myrmekite was observed.

Plagioclase is twinned and slightly zoned. Variable amounts of sericite are concentrated in the cores of individual crystals.

Biotite tends to form long (up to 2 mm), thin laths pleochroic in shades of brown; most grains are partly chloritized. Inclusions of zircons 0.05 mm across have pleochroic haloes. Apatites are common within and at the margins of biotite grains.

Blocky opaque grains average 1 mm in diameter and contain inclusions of apatite. Sphene forms thin rims around opaques, as well as discrete 1-mm-long rhombs and laths. Coarse reddish-brown, nonmetamict allanite crystals were observed in a few samples.

Two samples collected on the lower slopes of the gulch draining Hoffman Park contain variably fine grained quartzofeldspathic material interstitial to the 4-mm quartz and feldspar typical of the unit as a whole. Pinkish granite from the bed of the Middle Fork of the South Arkansas River a few hundred meters below these samples shows a normal granitic texture.

Point-count analysis of a stained slab of Hoffmann Park Granite gave the following results, in volume percent: quartz, 25; potassium feldspar, 50; plagioclase, 24; biotite and opaque minerals, 1.

Mount Antero Granite

The Mount Antero Granite, a texturally variable leucogranite, is exposed in two major areas at the southeastern corner of the Mount Princeton batholith (pl. 1). The northern area, the larger of the two, covers an area of about 30 km^2 and encompasses two prominent peaks—Mount Antero and Mount White. Roof pendants of the Mount Pomeroy and Mount Princeton Quartz Monzonites occur in this stock. A band of Mount Princeton Quartz Monzonite separates the Mount Antero Granite in the vicinity of Mount Antero from the smaller area just north of the North Fork of the South Arkansas River.

Crawford (1913) described the granite near Browns Creek (North Fork area) and cited field evidence to show that the Mount Princeton Quartz Monzonite is cut by the granite. He also noted the occurrence of beryl in the granite, as well as in miarolitic cavities, where it is associated with phenacite and topaz.

The occurrences of beryllium minerals (gem-quality beryl, phenacite, and bertrandite) at Mount Antero were noted in the 1880's, and several later investigations focused on the mineral assemblages associated with beryl-bearing pegmatites, miarolites, and granite in the area (Landes, 1934; Switzer, 1939; Adams, 1953).

Dings and Robinson (1957) mapped the western parts of the two granite areas and showed that the granite is younger than the Mount Pomeroy and Mount Princeton Quartz Monzonites and the andesite (the Calico Mountain Andesite of this report). Pulfrey (1970) and Thompson and Pulfrey (1973) presented a biotite K/Ar age of 30.8 ± 1.1 m.y. and discussed the major-element and trace-metal geochemistry of the granite and related aplites and pegmatites. Sharp (1976) mapped the Mount Antero area in detail and subdivided the granite into normal, greisenized, porphyritic, contaminated hornblende-bearing and fine-grained variants; he also mapped individual aplites, pegmatites, veins, and beryl-rich areas in the granite.

Characteristic differences between the Mount Antero Granite and the other intrusive rocks of the Mount Princeton batholith are the absence of hornblende and euhedral sphene and the presence of abundant muscovite and fluorite. Sharp (1976) reported hornblende in a contaminated phase of the granite at a contact with older quartz monzonite, and several workers have reported accessory sphene in the granite. No hornblende and none of the euhedral sphene rhombs characteristic of the older rocks were noted in the samples collected for this study. The typical granite is coarse grained and appears white to pink in hand specimen. The predominant minerals are pink potassium feldspars up to 1 cm long, rounded smoky quartz, and white plagioclase. Brown biotite books, averaging 0.25 to 0.5 mm long, occur sporadically throughout the rock, usually in small clots with opaques. Some degree of chloritization is present in all samples. Tiny zircons having prominent pleochroic haloes are abundant in some samples; euhedral apatite inclusions and patches of purple fluorite are also common in biotite.

Muscovite occurs in several habits—fine (up to a few tenths of a millimeter) grains of sericite in plagioclase; irregular, plumose patches in interstices between feldspar and quartz; and coarse books intergrown with and apparently replacing biotite. In many samples, muscovite is well developed; in others, only thin shreds of muscovite were noted at biotite grain margins.

Potassium feldspars are moderately perthitic, have Carlsbad twins, and generally lack microcline twins. Plagioclases are not strongly zoned, often have oval cores outlined by sericite, and are quite albitic.

Fine-grained and porphyritic variants of the granite are small-scale local features, and, with the exception of the fine-grained granite on top of Mount Antero, which has megascopic blue beryl clots, the mineralogy of the variants is the same. The fine-grained granite is an equant mosaic of 1-mm quartz and feldspar grains along with fairly fresh brown biotite, muscovite, and accessory minerals.

The average modal composition of the Mount Antero Granite, as measured by point-count analysis of stained slabs of seven specimens, is as follows, in volume percent (one standard deviation in last place in parentheses): quartz, 28(5); potassium feldspar, 36(3); plagioclase (albite), 34(4); biotite, 2(1); opaque minerals, 0.5(2); and other accessory minerals, less than 0.1.

Minor Intrusive Bodies

Two small plugs and a variety of dikes cut the Tertiary and older rocks in the studied area.

An oblong plug about 500 by 750 m in size intrudes the Mount Pomeroy Quartz Monzonite in the upper part of Cyclone Gulch (Tgp on pl. 1). At its margins, the rock is quartz rich and granophyric in texture and carries highly altered feldspar phenocrysts 5 to 10 mm long. A few shreds of chloritized biotite and sparse opaque grains represent the mafic minerals, though, near its contact with the Mount Pomeroy Quartz Monzonite, the rock has a few phenocrysts of altered possible hornblende.

An isolated outcrop nearby is of an apparently hybrid rock best described as a porphyritic microdiorite. It has moderately abundant phenocrysts of altered hornblende, shreddy biotite, and locally fresh andesine in an altered groundmass. Its relation to the Mount Pomeroy Quartz Monzonite and the granophyric plug is not clear.

An irregular intrusive slightly over 1 km in maximum dimension occurs on Raspberry Hill (elevation 11,038 ft) in the northeastern part of the mapped area (Trp on pl. 1). It is composed of a rhyolitic porphyry whose aphanitic to micrographophyric groundmass encloses 3- to 5-mm phenocrysts of quartz, altered feldspar, and slightly smaller biotite. A whole-rock K/Ar age of 22 m.y. for this rock has been published (see table 5).

Dikes of monzonitic, quartz monzonitic, and rhyolitic composition cut the Mount Princeton Quartz Monzonite. Several of these, as well as swarms of aplite dikes, are shown on plate 1. Published ages (see table 5), if taken at face value, suggest that these rocks are significantly younger than the Mount Princeton Quartz Monzonite; some, especially the more siliceous ones, may be related to the rhyolite porphyry of Raspberry Hill.

ROCK CHEMISTRY

Major- and minor-element analyses of the principal rock types associated with the Mount Aetna volcanic center have been made, and the results are presented in tables 1 and 2. The locations are depicted in figure 10 and described in the Appendix. Figures 11 to 14 illustrate and summarize some of the more significant features of the rock chemistry. As can be seen in the Harker plots of major element oxides against SiO_2 (fig. 11), variation is in general fairly smooth and monotonic, though the data for several elements scatter rather broadly. The rocks constitute a calkalkaline suite, both petrographically and chemically (Irvine and Barragar, 1971, p. 527; Green and Ringwood, 1968, p. 106); as usual in such suites, increasing SiO_2 is associated with declining contents of Al_2O_3, Fe_2O_3, FeO, MgO, CaO, TiO_2, and P_2O_5 and with increases in the alkalis Na_2O and K_2O. The

Table 1. Major-element analyses of rocks of the Mount Princeton igneous complex
[n.d., not determined]

Map unit	Quartz diorite		Mount Pomeroy Quartz Monzonite						
Sample	7395	7457	7437	82013	7813	7748	7746	7811	7812
Analyst[1]	d	a	a	b	a	a	a	a	a
				Weight percent					
SiO_2	61.9	55.0	61.7	63.3	61.5	62.2	62.7	63.9	62.8
Al_2O_3	16.9	16.7	15.1	15.6	15.3	16.5	14.8	15.3	15.3
Fe_2O_3	2.8	3.5	3.5	2.8	3.0	2.2	3.6	2.8	2.4
FeO	3.0	5.4	3.6	2.4	3.2	2.4	3.5	2.7	3.4
MgO	1.9	3.6	2.5	1.9	2.1	2.2	3.2	2.4	2.6
CaO	5.1	6.4	3.8	3.9	3.6	3.9	4.1	3.6	3.2
Na_2O	2.9	2.9	3.4	3.2	2.8	4.0	3.0	3.5	3.7
K_2O	3.2	2.7	4.2	4.3	4.5	4.3	4.4	4.3	4.7
H_2O	.75	.60	.76	.92	1.4	.86	.76	.9	1.2
TiO_2	.83	1.2	.86	.64	.75	.73	.96	.73	.75
P_2O_5	.33	.35	.24	.21	.23	.16	.27	.22	.26
MnO	.12	.12	.08	.15	.07	.04	.1	.09	.05
CO_2	<.05	.02	.03	.09	.20	.01	.01	.03	.07
F	n.d.	n.d.	n.d.	.14	n.d.	n.d.	n.d.	n.d.	n.d.
ZrO_2	n.d.	.03	.04	.04	n.d.	n.d.	n.d.	n.d.	n.d.
BaO	n.d.	.12	.10	.12	n.d.	n.d.	n.d.	n.d.	n.d.
Total[2] ----------	99.7	98.6	99.9	99.6	98.6	99.5	101.4	100.5	100.4
				Normative values					
Q	19.0	8.4	14.3	17.9	17.5	11.5	15.5	16.3	12.5
C	.18	---	---	---	.30	---	---	---	---
Z	---	.04	.06	.06	---	---	---	.03	.03
or	19.0	16.2	24.8	25.5	27.0	25.5	25.6	25.3	27.6
ab	24.6	24.9	28.8	27.2	24.0	34.0	25.0	29.5	31.2
an	23.2	24.9	13.5	15.6	15.3	14.4	13.7	13.3	11.2
wo	---	2.11	1.56	.51	---	1.62	1.89	1.20	1.03
en	4.74	9.09	6.23	4.75	5.30	5.51	7.86	5.95	6.45
fs	2.05	5.34	2.45	1.32	2.32	1.47	2.02	1.60	3.10
mt	4.01	5.15	5.08	4.07	4.41	3.21	5.15	4.04	3.46
hm	---	---	---	---	---	---	---	---	---
il	1.58	2.31	1.64	1.22	1.44	1.39	1.80	1.38	1.42
ap	.78	.84	.57	.50	.55	.38	.61	.52	.61
fr	---	---	---	.25	---	---	---	---	---
cc	---	.05	.07	.21	.46	.02	.02	.07	.16
mg	---	---	---	---	---	---	---	---	---
Total ----------	99.3	99.3	99.2	99.0	98.6	99.1	99.3	99.1	98.8
D.I.[3]	62.6	49.5	68.0	70.6	68.5	71.1	66.2	71.1	71.4

scatter in the plot of total alkalies vs. SiO_2 precludes a meaningful application of Peacock's alkali-lime-index criterion, but the linear trend on the AFM diagram (fig. 12) is diagnostic. Probably the most obvious feature in the major-element composition of the suite as a whole is the sharp break between the true granites—the Mount Antero and the Hoffman Park and related minor units—and the other rock units. The Hoffman Park Granite seems not to differ perceptibly from the Mount Antero Granite with respect to the major elements, but many of its trace-element contents are more like those of the Mount Princeton Quartz Monzonite. The Mount Pomeroy Quartz Monzonite is generally less silicic than the Mount Princeton, and specimens from the transitional contact zone, whose affinity were equivocal in the field, are chemically more like the Mount Pomeroy than the Mount Princeton. The Mount Antero Granite is rather variable in composition; the one sample (82010) of the porphyritic facies (Sharp, 1976) is noticeably higher in Al_2O_3, MnO, and P_2O_5 and lower in K_2O and TiO_2 than other specimens of the granite but otherwise lies well within

Table 1. Major-element analyses of rocks of the Mount Princeton igneous complex—Continued

Map unit	Sewanee Peak Volcanics							Mount Aetna Quartz Monzonite Porphyry				
Sample	7670	7700	7723	7833	7849	7877	7878	7219	7220	7284	7435	7456
Analyst[1]	a	a	a	a	a	a	a	c	c	c	c	c
					Weight percent—Continued							
SiO_2	65.7	65.7	64.7	66.4	65.0	65.3	65.6	61.8	62.2	64.8	63.8	65.1
Al_2O_3	15.7	15.0	15.7	15.7	15.5	15.7	16.0	16.1	16.1	15.4	15.5	15.2
Fe_2O_3	1.8	2.7	1.8	1.3	1.4	2.3	1.9	2.3	2.4	2.4	2.5	1.8
FeO	3.0	2.4	2.9	2.4	3.2	2.2	2.9	3.5	3.0	2.2	2.4	2.4
MgO	1.3	1.4	1.3	1.1	1.2	1.1	1.2	1.8	1.8	1.4	1.6	1.3
CaO	3.1	2.5	3.0	2.8	2.9	3.0	3.0	3.7	3.5	3.1	3.3	3.1
Na_2O	3.7	3.1	3.8	3.7	3.7	3.9	4.0	3.5	3.7	3.7	3.6	3.7
K_2O	4.1	4.8	3.9	4.4	4.3	4.1	4.1	4.1	4.1	4.1	4.3	4.1
H_2O	1.1	1.2	.50	.51	.69	.33	.79	1.1	1.0	.90	.85	.79
TiO_2	.58	.58	.57	.50	.52	.53	.55	.75	.77	.60	.67	.59
P_2O_5	.23	.22	.23	.21	.22	.22	.23	.34	.33	.26	.28	.27
MnO	.08	.04	.07	.07	.09	.07	.09	.11	.11	.07	.11	.10
CO_2	.06	.02	.03	.01	.07	.06	.08	.02	.08	.06	.02	.01
F	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
ZrO_2	n.d.	n.d.	.02	.03	.03	0.03	.03	.04	n.d.	n.d.	.02	n.d.
BaO	n.d.	n.d.	.13	.12	.13	.12	.13	.15	n.d.	n.d.	.15	n.d.
Total[2] ----------	100.5	99.7	98.6	99.2	98.9	99.0	100.6	99.3	99.1	99.0	99.1	98.5
					Normative values—Continued							
Q	19.2	22.0	18.8	19.9	18.1	19.1	17.7	14.6	15.0	19.4	17.4	19.6
C	.23	.74	.31	.21	.09	---	.18	---	.19	---	---	---
Z	---	---	.04	.04	.04	.04	.04	.06	---	---	.03	---
or	24.1	28.5	23.4	26.2	25.7	24.5	24.1	24.4	24.4	24.5	25.6	24.6
ab	31.2	26.3	32.6	31.5	31.6	33.3	33.6	29.8	31.6	31.6	30.7	31.8
an	13.4	10.9	13.6	12.8	12.9	13.4	13.0	16.2	14.8	13.4	13.6	13.0
wo	---	---	---	---	---	.02	---	.07	---	---	.52	.34
en	3.22	3.50	3.28	2.76	3.02	2.77	2.97	4.51	4.52	3.52	4.02	3.29
fs	3.20	1.30	3.07	2.66	4.07	1.41	3.00	3.52	2.48	1.21	1.45	2.16
mt	2.60	3.93	2.65	1.90	2.05	3.37	2.74	3.36	3.51	3.52	3.66	2.65
hm	---	---	---	---	---	---	---	---	---	---	---	---
il	1.10	1.10	1.10	.96	1.00	1.02	1.04	1.43	1.48	1.15	1.28	1.14
ap	.54	.52	.55	.50	.53	.53	.54	.81	.79	.62	.67	.65
fr	---	---	---	---	---	---	---	---	---	---	---	---
cc	.14	.05	.07	.02	.16	.14	.18	.05	.18	.14	.05	.02
mg	---	---	---	---	---	---	---	---	---	---	---	---
Total ----------	98.9	98.8	99.4	99.4	99.2	99.6	99.2	98.8	99.0	99.1	99.1	99.2
D.I.[3]	74.5	76.8	74.7	77.6	75.4	76.9	75.4	68.8	71.0	75.5	73.8	76.0

their range. Despite the considerable degree of alteration of both units, analyses of the Calico Mountain Andesite and the Sewanee Peak Volcanics do not overlap.

The major-element compositions of the igneous rock units are not related in any simple linear fashion; least-squares mixing calculations yield unacceptably large residuals for several elements (notably Mg, Na, Ti).

In general, all rare-earth elements (REE's) decrease with increasing SiO_2 for the entire group of rocks analyzed (fig. 15; table 2), and this trend is especially regular for europium (fig. 16). Europium shows a moderate negative anomaly in most samples, and a very strong one in a few of the most SiO_2-rich granites and aplites. For the intrusive rocks, the absolute magnitude of the (negative) europium anomaly, which may be expressed as (Eu/Eu*) − 1 (where Eu* is the interpolated value between the adjacent REE's Sm and Gd), shows a regular and rather smooth increase as SiO_2 increases, except for the Mount Pomeroy Quartz Monzonite and some of the most silica-rich rocks, which show anomalously large negative anomalies. The most

Table 1. Major-element analyses of rocks of the Mount Princeton igneous complex—Continued

Map unit	Mount Princeton Quartz Monzonite							
Sample	7567	7570	7571	7814	7957	7179	7179	7438
Analyst[1]	c	c	c	c	c	c	d	c
	Weight percent—Continued							
SiO_2	68.0	67.0	65.9	67.4	68.6	65.9	67.5	66.0
Al_2O_3	15.4	15.1	15.3	15.3	15.1	15.4	15.7	15.4
Fe_2O_3	1.5	2.1	2.4	2.2	1.7	1.3	2.1	2.2
FeO	2.1	2.2	2.5	2.2	2.2	3.0	1.8	2.2
MgO	1.2	1.5	1.5	1.4	1.2	2.5	1.2	1.4
CaO	3.0	3.4	3.6	3.2	3.2	2.8	3.4	3.3
Na_2O	3.5	3.2	3.3	3.1	3.1	3.1	3.3	3.4
K_2O	4.2	3.6	3.9	4.2	4.2	4.8	3.7	4.0
H_2O	.59	.69	.61	.42	.66	.48	.43	.37
TiO_2	.47	.58	.63	.55	.54	.77	.52	.55
P_2O_5	.13	.22	.23	.19	.17	.14	.20	.22
MnO	.05	.08	.08	.05	.06	.09	.07	.05
CO_2	.01	.03	.06	.01	.52	.02	<.05	.03
F	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
ZrO_2	.02	.02	.02	n.d.	n.d.	.02	n.d.	.02
BaO	.11	.09	.10	n.d.	n.d.	.09	n.d.	.10
Total[2] ----------	100.3	99.8	100.1	100.2	101.2	100.4	99.9	99.2
	Normative values—Continued							
Q	22.8	25.1	21.9	24.2	26.6	18.6	25.3	21.9
C	---	.29	---	.31	1.23	.33	.56	.01
Z	.03	.03	.03	---	---	.03	---	.03
or	24.8	21.3	23.0	24.8	24.5	28.2	21.9	23.8
ab	29.5	27.1	27.9	26.2	25.9	26.1	27.9	29.0
an	13.9	15.4	15.4	14.5	11.3	13.0	15.6	15.0
wo	.11	---	.31	---	---	---	---	---
en	2.98	3.74	3.73	3.48	2.95	6.20	2.99	3.51
fs	1.93	1.50	1.71	1.40	1.83	3.32	.84	1.42
mt	2.17	3.05	3.48	3.18	2.43	1.88	3.05	3.22
hm	---	---	---	---	---	---	---	---
il	.89	1.10	1.20	1.04	1.01	1.46	.99	1.05
ap	.31	.52	.54	.45	.40	.33	.47	.52
cc	.02	.07	.14	.02	1.17	.04	---	.07
mg	---	---	---	---	---	---	---	---
Total ----------	99.3	99.3	99.4	99.6	99.4	99.5	99.6	99.6
D.I.[3]	77.0	73.5	72.8	75.2	77.0	72.9	75.1	74.7

negative anomaly (Eu/Eu* = 0.035) is in an aplite dike that cuts the Mount Princeton Quartz Monzonite.

The other three samples in which Eu/Eu* is less than 0.4 are all Mount Antero Granite from within about 100 m vertically of the roof of the stock near the summit of Mount Antero. Mount Antero Granite from about 1,000 m lower in the stock (east of Jennings Creek on the north wall of the valley of the North Fork of the South Arkansas River) falls exactly on the trend defined by the Mount Aetna and Mount Princeton Quartz Monzonites and the Hoffman Park Granite. The Mount Pomeroy Quartz Monzonite, which we regard also as a roof facies of a larger pluton, likewise shows a significant negative departure from the europium anomaly trend (fig. 16). In the absence of accompanying silica enrichment, simple fractionation of plagioclase seems unlikely to have produced such local anomalies in europium. Perhaps a locally oxidizing environment, resulting from volatile enrichment near the top of the magma chambers, lowered the partition coefficient of Eu between feldspar and melt by increasing Eu^{+3}/Eu^{+2} (Weill and

Table 1. Major-element analyses of rocks of the Mount Princeton igneous complex—Continued

Map unit	Calico Mountain Andesite						
Sample	7201	7613	7635	7720	7767	7864	7867
Analyst[1]	c	c	c	c	c	c	c
	Weight percent—Continued						
SiO_2	59.3	57.10	60.8	60.4	59.7	59.8	59.5
Al_2O_3	16.7	15.8	16.6	15.8	16.0	15.9	15.6
Fe_2O_3	3.4	2.7	2.2	3.2	2.2	3.3	1.8
FeO	3.0	3.7	3.0	3.9	3.8	1.9	3.6
MgO	1.7	1.8	1.8	1.8	2.2	1.3	3.1
CaO	3.1	4.7	4.2	4.9	3.8	3.7	4.5
Na_2O	4.2	2.3	3.5	3.3	3.7	3.3	1.8
K_2O	4.6	4.8	4.4	4.0	4.4	4.1	3.1
H_2O	1.1	1.6	.7	1.3	1.3	1.6	2.5
TiO_2	.91	.89	.83	.89	.91	.85	.84
P_2O_5	.30	.31	.29	.34	.30	.29	.30
MnO	.02	.10	.03	.10	.07	.07	.11
CO_2	.03	2.5	.03	1.3	.15	2.2	1.7
F	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
ZrO_2	.06	n.d.	n.d.	.05	n.d.	.05	.06
BaO	.19	n.d.	n.d.	.17	n.d.	.13	.16
Total[2] ----------	98.6	98.3	98.4	101.4	98.5	98.5	98.6
	Normative values—Continued						
Q	8.49	19.1	12.4	15.4	10.0	22.1	26.8
C	.09	4.89	---	.83	---	5.09	5.74
Z	.06	---	---	.07	---	.08	.06
or	27.6	28.8	26.4	23.3	26.4	24.6	18.6
ab	36.0	19.8	30.1	27.5	31.8	28.4	15.4
an	13.3	5.58	16.9	14.0	14.3	2.83	10.0
wo	.19	---	.92	---	.80	---	---
en	4.29	4.56	4.56	4.42	5.56	3.29	7.83
fs	1.25	3.34	2.42	3.19	3.84	---	4.00
mt	5.00	3.98	3.24	4.57	3.24	3.95	2.65
hm	---	---	.63	---	---	.63	---
il	1.75	1.72	1.60	1.67	1.75	1.64	1.62
ap	.72	.75	.70	.79	.72	.70	.72
cc	.07	5.78	.07	2.91	.35	5.08	3.92
mg	---	---	---	---	---	---	---
Total ----------	98.8	98.4	99.3	98.6	98.7	98.3	97.4
D.I.[3]	72.1	67.8	68.9	66.2	68.2	75.0	60.8

Drake, 1973) and thereby produced an "abnormally" low Eu content in the feldspar of these rocks. The large negative Eu anomaly in the porphyry of Raspberry Hill is consistent with its late emplacement and other indications of a high degree of differentiation. The europium anomaly of the quartz diorite is consistent with an early position in the sequence of plutonic magmas, though there is no compelling evidence for its close relation to them. In any event, its europium anomaly also implies a significant degree of differentiation from an earlier, unknown member.

Table 1. Major-element analyses of rocks of the Mount Princeton igneous complex—Continued

Map unit	Hoffman Park Granite	Mount Antero Granite								Monzonite dike	Quartz porphyry	Aplite porphyry
Sample	7788	7319	7388	7441	7533	7721	7972	82007	82010	7475	7238	7478
Analyst[1]	a	c	c	d	c	a	a	b	b	c	c	c
					Weight percent—Continued							
SiO_2	73.5	73.1	74.2	76.5	75.7	73.5	74.4	73.6	75.4	67.0	70.7	74.8
Al_2O_3	13.9	13.0	13.2	13.0	12.2	13.7	13.2	13.8	14.5	14.7	13.2	12.8
Fe_2O_3	.52	.28	.57	.41	.46	.49	.59	.92	.17	1.2	2.4	.12
FeO	.72	1.0	.88	.28	.60	.76	.72	.16	.28	2.8	1.4	1.4
MgO	.12	.27	.20	.00	.23	.23	.23	.25	.11	.94	.52	.04
CaO	.69	.88	.64	.65	.62	.87	.65	.78	.50	2.3	1.8	.4
Na_2O	3.7	3.8	3.8	3.8	3.6	3.8	3.6	3.9	4.4	3.3	3.7	4.2
K_2O	5.1	5.2	5.0	4.4	4.3	4.6	4.6	4.7	3.5	4.7	4.8	4.4
H_2O	.28	.47	.40	.46	.45	.31	.20	.12	.17	.85	.25	.15
TiO_2	.16	.22	.17	.11	.13	.17	.16	.15	.01	.46	.25	.08
P_2O_5	.04	.05	.06	.02	.04	.07	.05	.05	.10	.19	.06	.03
MnO	.04	.08	.07	.05	.06	.05	.06	.07	.10	.05	.03	.09
CO_2	.06	.03	.02	.08	.01	.06	.03	.05	.02	.07	.04	.03
F	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	.16	.31	n.d.	n.d.	n.d.
ZrO_2	.02	n.d.	n.d.	n.d.	.01	n.d.	.01	.01	.03	.02	.01	.01
BaO	.07	n.d.	n.d.	n.d.	n.d.	.10	n.d.	.05	.02	.12	.06	.01
Total[2] ----------	98.9	98.4	99.2	99.8	98.4	98.7	98.5	98.6	99.4	98.7	99.2	98.6
					Normative values—Continued							
Q	31.0	29.0	31.3	36.5	37.1	31.9	31.6	32.1	36.2	22.8	27.2	32.1
C	1.24	---	.57	1.04	.62	1.14	1.33	1.55	3.49	.55	---	.54
Z	.03	---	---	---	---	.02	---	---	---	.04	.03	.02
or	30.5	31.2	29.8	26.1	25.8	27.5	27.6	28.2	20.8	28.1	28.6	26.4
ab	31.7	32.7	32.4	32.2	31.0	32.6	30.9	33.5	37.4	28.3	31.6	36.1
an	2.94	3.11	2.68	2.59	2.80	3.71	2.75	2.14	---	10.1	5.27	1.64
wo	---	.34	---	---	---	---	---	---	---	---	1.33	---
en	.30	.68	.50	---	.58	.58	.58	.63	.23	2.37	1.30	.10
fs	.71	1.41	1.00	.09	.63	.81	.69	---	.55	3.53	.23	2.54
mt	.76	.41	.83	.60	.68	.72	.87	.31	.25	1.76	3.51	.18
hm	---	---	---	---	---	---	---	.72	---	---	---	---
il	.31	.42	.32	.21	.25	.33	.31	.29	.02	.88	.48	.15
ap	.10	.12	.14	.05	.10	.17	.12	.12	.24	.46	.14	.07
fr	---	---	---	---	---	---	---	.32	.52	---	---	---
cc	.14	.07	.05	.18	.02	.14	.07	.12	---	.16	.09	.07
mg	---	---	---	---	---	---	---	---	.04	---	---	---
Total ----------	99.7	99.5	99.6	99.54	99.5	99.6	99.8	99.9	99.8	99.1	99.7	99.8
D.I.[3]	93.1	93.0	93.5	94.8	93.9	92.0	93.1	93.7	94.5	79.2	87.3	94.5

[1] Rapid rock analyses in USGS Analytical Laboratories, as follows: a, 4/30/76, H. Smith, Analyst; b, J. Gillison, Analyst; c, 9/14/77, K. Coates and H. Smith, Analysts; d, XRF analyses, 7/13/65, P. Elmore, S. Botts, and L. Artis, Analysts.

[2] Oxide sums minus oxygen equivalent of F, Cl; Zr, Ba, as determined by instrumental neutron activation analysis—see table 2.

[3] Differentiation Index.

Table 2. Minor-element analyses of rocks of the Mount Princeton igneous complex

Map unit	Quartz diorite	Mount Pomeroy Quartz Monzonite		Mount Princeton Quartz Monzonite				
Sample	7457	7437	82013	7567	7570	7571	7179	7438
				Concentration[1]				
Ba	1,060	879	1,070	964	831	881	828	905
Co	26.3	17.3	13.6	10.8	9.4	9.9	9.8	8.8
Cr	28.2	23.4	11.4	10.8	7.1	6.6	6.3	6.2
Cs	.9	1.5	1.8	2.7	1.9	1.6	2.2	2.2
Hf	5.5	7.8	8.1	4.5	4.7	5.5	5.3	4.9
Rb	77	152	171	142	115	117	107	120
Sr	608	499	518	507	580	570	544	238
Ta	.69	1.49	1.46	1.65	1.41	1.36	1.49	1.43
Th	7.6	34.5	32.2	26.4	24.4	26.5	18.1	21.8
U	<3.0	7.6	4.6	6.8	4.6	4.7	3.1	4.9
Zn	103	43	94	43	58	54	37	34
Zr	210	295	275	157	149	183	168	162
Sc	22.50	11.90	10.70	7.81	7.96	7.77	7.13	7.73
Sb	<.6	.4	.2	.3	.3	.2	.4	.2
La	51	68	67	52	62	55	54	55
Ce	99	124	124	94	102	95	97	98
Pr	<68	<68	<68	<68	<68	<68	<68	<68
Nd	43	49	51	40	43	38	39	38
Sm	9.3	9.2	9.1	7.1	7.4	6.8	7.2	6.9
Eu	2.18	1.41	1.56	1.40	1.45	1.40	1.44	1.40
Gd	8.1	7.5	7.9	5.9	7.2	6.1	n.d.	7.0
Tb	1.01	.85	.30	.68	.68	.61	.87	.67
Tm	.56	.19	.42	.20	.26	.26	n.d.	.24
Yb	3.0	2.6	2.5	1.4	2.0	1.6	1.6	2.3
Lu	.47	.34	.35	.30	.29	.28	.31	.29

The lack of an obvious trend in the Eu anomalies of the Calico Mountain Andesite and the Sewanee Peak Volcanics, and their similarity to the postvolcanic Mount Aetna Quartz Monzonite Porphyry, suggests that fractionation of plagioclase was not the dominant mechanism in whatever process of differentiation may relate them.

Simmons and Hedge (1978, table 3, specimen Nos. 5–7) published, with no geologic or petrographic description, initial Sr isotopic ratios for three of the specimens described here. Their results for the specimens of the Mount Aetna Quartz Monzonite Porphyry (No. 7435, 0.70706) and the Mount Princeton Quartz Monzonite (No. 7438, 0.70767) are fairly close, but the third specimen they reported on, No. 7457, gave a somewhat different result, 0.70849. This specimen was of the quartz diorite, whose uncertain relation to the rest of the Mount Princeton igneous complex was discussed above, in the section entitled "Tertiary(?)—Quartz Diorite."

MINERAL CHEMISTRY

Similarities in mineralogy and overlap in whole rock compositions among distinct, separately mappable units in the Mount Princeton batholith and the Mount Aetna volcanic center provide a fruitful opportunity to study variations in mineral chemistry within and among the principal rock units. The major rock-forming minerals were analyzed in polished thin sections on ARL microprobes at the U.S. Geological Survey in Reston, Va. Data were reduced on-line by a computer program based on the Bence-Albee method (Bence and Albee, 1968); both natural and synthetic mineral standards were utilized. The microprobes were operated at an excitation potential of 15 kV and a beam current of 0.10 μA. A few separates of biotites and hornblendes from the quartz monzonites and granites were analyzed by conventional methods (table 3). Variation in mineral composition among rock units is shown by the microprobe data summarized in table 4; the data are presented in general order of decreasing age and increasing Differentiation Index of the rock units. Values represent averages for all samples from a particular rock unit but do not imply homogeneity within a unit.

Hornblende

Calcic amphiboles occur in all rocks of the batholith except the granites. The hornblendes all have more than 1.8 Ca per formula unit (23 oxygens) and fall close to a linear trend between $Ca_2(Fe,Mg)_5Si_8O_{22}(OH)_2$ (actinolite) and $NaCa_2(Fe,Mg)_4Al_3Si_6O_{22}(OH)_2$ (pargasite) (fig. 17), in the

Table 2. Minor-element analyses of rocks of the Mount Princeton igneous complex—Continued

Map unit	Calico Mountain Andesite				Sewanee Peak Volcanics				
Sample	7201	7720	7864	7867	7723	7833	7849	7877	7878
	Concentration[1]—Continued								
Ba	1,730	1,530	1,200	1,410	1,205	1,110	1,190	1,105	1,140
Co	10.1	13.1	10.7	10.6	7.6	6.4	7.7	6.8	6.6
Cr	12.6	15.3	9.3	8.5	15.1	12.4	16.1	11.5	13.6
Cs	.9	1.8	8.5	4.9	2.2	2.0	3.3	1.7	1.9
Hf	10.1	10.1	9.7	9.5	6.4	5.6	7.0	6.1	5.6
Rb	135	140	148	138	140	127	137	135	128
Sr	655	633	374	686	601	622	629	605	707
Ta	1.32	1.56	1.38	1.38	1.79	1.50	1.76	1.70	1.63
Th	22.3	28.7	26.7	23.2	20.2	18.0	20.5	17.5	18.0
U	4.7	5.6	6.6	5.0	5.9	4.9	6.4	3.6	3.8
Zn	25	82	78	76	72	223	67	68	93
Zr	437	344	389	409	203	193	241	218	192
Sc	11.50	11.90	10.70	11.40	6.87	5.62	6.52	6.10	6.17
Sb	.8	.6	.5	.8	.6	.4	.7	.4	.4
La	76	78	78	71	58	55	62	53	55
Ce	141	147	143	134	107	96	111	98	103
Pr	<68	<68	<68	<68	<68	<68	<68	<68	<68
Nd	60	59	62	61	48	38	47	48	44
Sm	10.8	11.0	100.9	10.5	8.1	6.9	8.3	7.4	7.9
Eu	2.24	2.18	2.15	2.23	1.79	1.55	1.76	1.62	1.72
Gd	8.9	8.2	8.2	9.0	6.2	5.0	7.1	6.2	5.6
Tb	1.22	1.04	.94	1.06	.73	.61	.70	.69	.73
Tm	.50	.47	.48	.39	.27	.33	.29	.34	.30
Yb	3.1	3.0	2.8	3.0	2.2	2.0	2.1	1.8	2.0
Lu	.40	.41	.39	.39	.30	.24	.30	.29	.29

fields of actinolite, actinolitic hornblende, and magnesiohornblende as defined by Leake (1978). The most actinolitic hornblendes occur in the Mount Pomeroy Quartz Monzonite and presumably reflect the intense alteration characteristic of this rock unit. Many analyses from this rock unit show Si contents greater than the 7.3 to 7.5 atoms per 23-oxygen anhydrous formula that Leake (1971, p. 399–400) found to be the maximum in truly igneous calciferous amphiboles. Similar compositions are encountered in rocks from the contact zone between the Mount Pomeroy and the Mount Princeton and also within the Mount Princeton Quartz Monzonite in the Mount Aetna subsided block. Hornblendes from the outer margins of the Mount Princeton body are more typically "igneous" in composition; they contain more Fe and Al and are less fluorine-rich than hornblendes from the center of the mass.

Hornblende compositions in the Mount Aetna Quartz Monzonite Porphyry overlap those in the Sewanee Peak Volcanics but have distinctly higher contents of Al, Fe, and Ti than do most hornblendes in the older Mount Pomeroy and Mount Princeton Quartz Monzonites. The Mount Aetna and the Sewanee Peak do not contain colorless or very pale green hornblendes, and all analyzed amphiboles from these two rock units have Si contents within Leake's field for igneous hornblendes. The mean compositions of amphiboles of the Mount Pomeroy, Mount Princeton, Mount Aetna, and Sewanee Peak units (table 4*A*) all plot very close to the line demarking the Si- and (Ca + Na + K)-rich limits of igneous hornblendes according to Leake (1971, figs. 3, 4).

Although high Ti content of igneous and metamorphic hornblendes has been correlated empirically with high temperature and low oxygen fugacity (for example, Helz, 1982; Wones and Gilbert, 1982), we interpret the general trend of higher titania in hornblendes from younger rocks in this area as a reflection of their lesser degree of alteration rather than as a primary magmatic signature. The colorless to pale-green, actinolitic hornblende grains in the Mount Pomeroy are typically riddled with small magnetite grains and granular sphene, which probably formed from expulsion of iron and titanium from hornblende during late magmatic or subsolidus alteration. The primary magmatic hornblende was probably richer in Fe and Ti, as suggested by "igneous" compositions of small hornblende inclusions in plagioclase, which seem to have been protected from alteration.

The compositional range in some single grains is as great as in the rock unit in which they occur; it is reflected by patchy color domains observed in thin section. These domains are anhedral, are variable in size, and bear no apparent relation to crystal morphology, twin planes, or cracks; although a paler colored rim is sometimes observed, no regular core-rim relation seems to exist. Within individual grains, darker colored patches are generally richer in Al

Table 2. Minor-element analyses of rocks of the Mount Princeton igneous complex—Continued

Map unit	Mount Aetna Quartz Monzonite Porphyry		Hoffman Park Granite	Mount Antero Granite				Monzonite dike	Quartz porphyry	Aplite porphyry
Sample	7219	7435	7788	7441	7721	82007	82010	7475	7238	7478
				Concentration[1]—Continued						
Ba	1,335	1,360	653	283	848	467	153	1,120	465	102
Co	9.4	10.4	.6	.7	1.4	1.1	.7	5.8	3.5	.5
Cr	20.5	15.3	2.6	1.6	3.5	2.3	<4	12.7	8.6	4.7
Cs	2.8	1.5	.8	3.8	2.2	3.2	12.3	1.2	1.6	5.0
Hf	6.3	5.6	5.1	4.8	4.1	3.9	6.1	5.1	4.0	4.4
Rb	128	139	162	431	315	284	628	119	162	391
Sr	733	679	117	72	238	127	37	618	218	13
Ta	1.61	1.62	1.96	8.40	3.25	3.51	17.50	1.57	2.00	7.36
Th	16.1	18.8	19.6	28.3	17.4	36.5	24.9	19.3	20.0	23.4
U	4.1	3.9	3.5	15	7.7	21.3	10.3	6.1	4.6	11.3
Zn	378	54	61	16	25	22	33	58	34	44
Zr	265	161	141	88	103	84	41	220	92	75
Sc	8.21	7.84	3.23	5.32	4.72	3.64	13.40	4.73	3.87	5.99
Sb	.5	.5	.02	.4	.1	.1	.2	1.0	1.1	.5
La	57	58	56	36	37	32	24	49	34	15
Ce	105	108	99	56	64	54	48	87	65	33
Pr	<68	<68	<68	<68	<68	<68	<68	<68	<68	<68
Nd	48	46	36	20	23	17	15	42	27	19
Sm	8.6	8.2	5.7	3.4	3.5	3.2	2.8	6.1	6.0	5.6
Eu	1.87	1.71	.93	.28	.55	.38	.17	1.31	.87	.07
Gd	7.2	7.0	4.2	4.0	2.2	4.5	4.1	4.3	5.4	6.9
Tb	.84	.63	.58	.42	.32	.41	.33	.54	.49	.79
Tm	.32	.19	.40	<.20	<.20	.34	<.30	.29	<.20	.20
Yb	2.1	2.1	2.5	2.4	1.5	2.7	2.5	1.8	1.5	4.2
Lu	.29	.27	.42	.48	.23	.45	.42	.25	.19	.57

[1] Values are reported in parts per million. All analyses performed in USGS Analytical Laboratories.
Sr analyzed by X-ray spectroscopy; R. Johnson, J.R. Lindsay, J. Lindsay, B. McCall, K. Dennen, analysts.
Pr analyzed by emission spectroscopy; J. Harris, analyst.
All other elements analyzed by instrumental neutron activation analysis; P.A. Baedecker, L.J. Schwarz, analysts.

and Ti than lighter colored patches. Ti differences between domains may reflect crystallization over a substantial range of conditions, resulting in incomplete reequilibration of early compositions. Czamanske and others (1981) reported similar variations in secondary amphiboles in granitoids from a Cretaceous-Paleocene batholith in southwestern Japan, where "late" amphiboles have more Si, less Al, and less Ti than "primary" ones. Patchiness occurs even in the least altered specimens of the Mount Princeton Quartz Monzonite, where "igneous" compositions predominate, but compositional differences within single grains are less extreme than in the more altered rocks.

As an aside, it is interesting to note that the continuous trend exhibited in figure 17 spans the actinolite-pargasite miscibility gap [proposed by Miyashiro (1973, p. 251–252)], which has been noted in low- and intermediate-pressure facies metamorphic rocks (Robinson and others, 1982, p. 69ff.). Petrographic and experimental studies (Spear, 1981; Oba, 1980) suggest the existence of a gap at temperatures not far below the solidus, but no gap in composition exists for the amphiboles in our rocks. Amphibole compositions from the plutonic and volcanic rocks of the Mount Princeton complex show a continuous trend between tremolite and pargasite when plotted in terms of the components used by Oba (1980) and (for actinolite) Oba and Yagi (1987) (fig. 18). We conclude that the environment of final equilibration for hornblendes of the Mount Princeton complex differs from the conditions at which amphibole immiscibility has been observed in these studies. Compositional patchiness in single hornblende grains may represent incomplete equilibration during crystallization (Czamanske and Wones, 1973; Grapes, 1975) or subsequent subsolidus alteration.

Chemical analyses of hornblende separates from the Mount Princeton Quartz Monzonite (table 3) show that $Fe^{+3}/(Fe^{+3} + Fe^{+2}) = 0.22$ for three magnesio-hornblendes from the western side of the intrusive, but two actinolitic hornblendes from the central part of the pluton

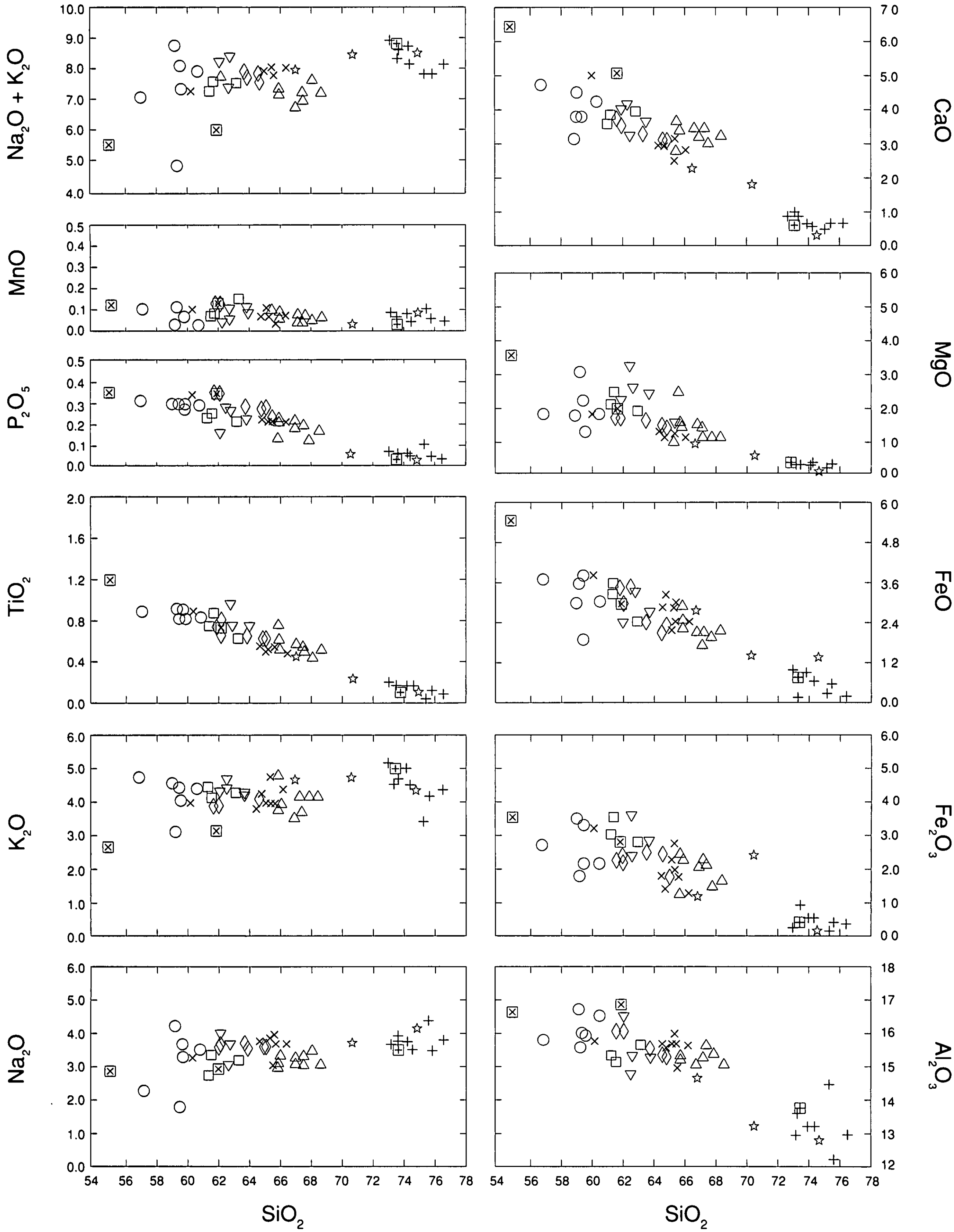


Figure 11. Harker variation diagrams for rocks of the Mount Aetna volcanic center and other rocks of the Mount Princeton igneous complex. Symbols for rock units as in figure 10.

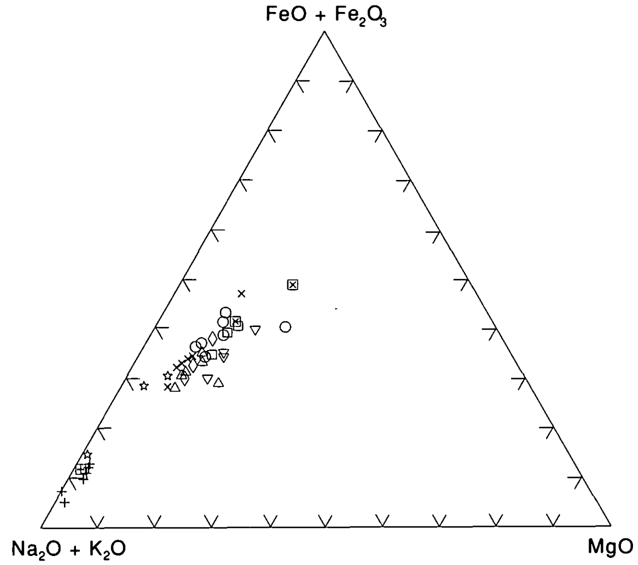


Figure 12. AFM (weight percent) diagram for rocks of the Mount Aetna volcanic center and other rocks of the Mount Princeton igneous complex. A, $Na_2O + K_2O$; F, $FeO + Fe_2O_3$; M, MgO. Symbols for rock units as in figure 10.

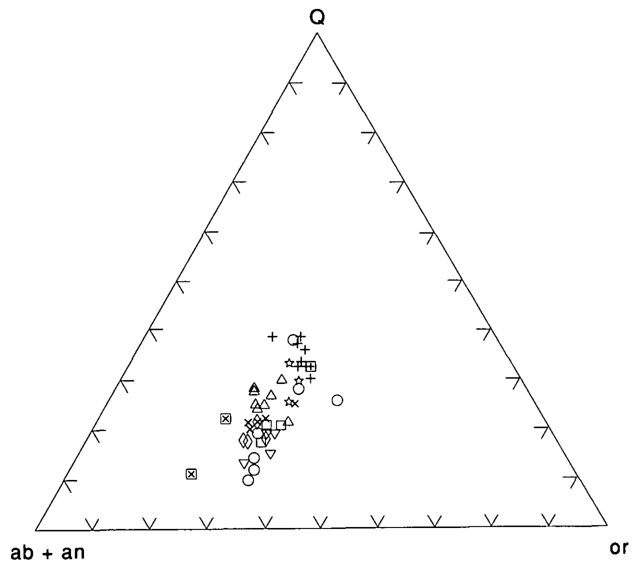


Figure 13. Normative quartz (Q), plagioclase (ab+an), and orthoclase (or) diagram for rocks of the Mount Aetna volcanic center and other rocks of the Mount Princeton igneous complex. Symbols for rock units as in figure 10.

are slightly more oxidized, having a ratio of 0.25. Water contents range from 1.42 to 2.44 weight percent total H_2O but do not vary systematically with sample location.

Biotite

Biotites are intermediate in composition between phlogopite and siderophyllite, with Fe/(Fe + Mg) = 0.31 to 0.46 (fig. 19). Al, Mn, and Fe/(Fe + Mg) tend to increase

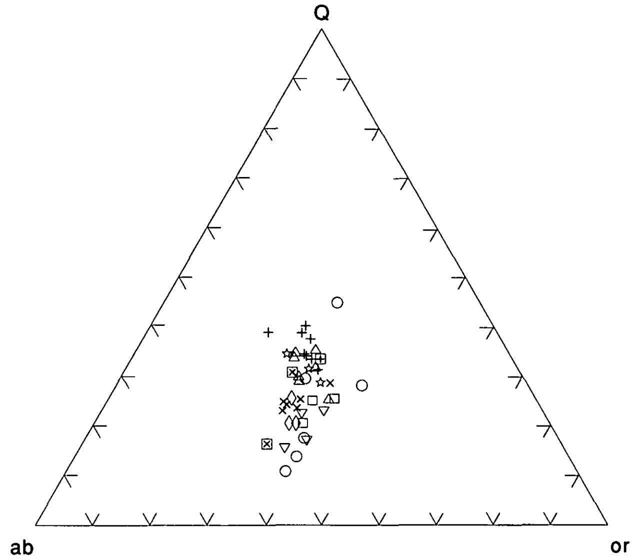


Figure 14. Normative quartz (Q), albite (ab), and orthoclase (or) diagram for rocks of the Mount Aetna volcanic center and other rocks of the Mount Princeton igneous complex. Symbols for rock units as in figure 10.

with increasing whole-rock silica content, whereas Ti and Ba generally decrease. Octahedral-site occupancies are in excess of 2.7 cations per 11-oxygen formula unit. The alkali site contains an average of about 0.93 cations, principally K^+. Fluorine occupies from 20 to nearly 50 percent of the OH site, and Cl contents are generally quite low. Like their associated hornblendes, biotites from the Mount Pomeroy and from the Mount Pomeroy-Mount Princeton contact zone tend to be more magnesian and more fluorine-rich than biotites in the Mount Princeton remote from the contact zone. Biotites in most of the Mount Princeton, the Mount Aetna, and the Sewanee Peak units are virtually indistinguishable from one another. Biotites in the Hoffman Park Granite are similar to these in Al and Fe but are distinctly richer in Mn and F and have lower Ba and Ti. Biotites in the Mount Antero Granite are distinct from biotite in all the other units—they contain more Al, Fe, Mn, and F and less Ti and Ba than do biotites of any other unit.

The presence of dark, relatively fresh euhedral biotite in the typically altered Mount Pomeroy Quartz Monzonite suggests postmagmatic recrystallization, as does the relatively fluorine-rich composition of all the Mount Pomeroy biotites. Jacobs and Parry (1976) documented fluorine enrichment in altered and secondary biotites relative to associated magmatic biotites of Basin and Range stocks, and Gunow and others (1980) demonstrated extreme fluorine enrichment in biotites from fluorine-rich environments, such as that implied by the fluorite-bearing Mount Antero Granite. Figure 20, modified from their study, shows that biotites from most rocks of the Mount Princeton complex, including the Mount Pomeroy, fall along a relatively tight trend only slightly displaced toward higher fluorine contents from the biotites of the Sierra Nevada and the Santa Rita

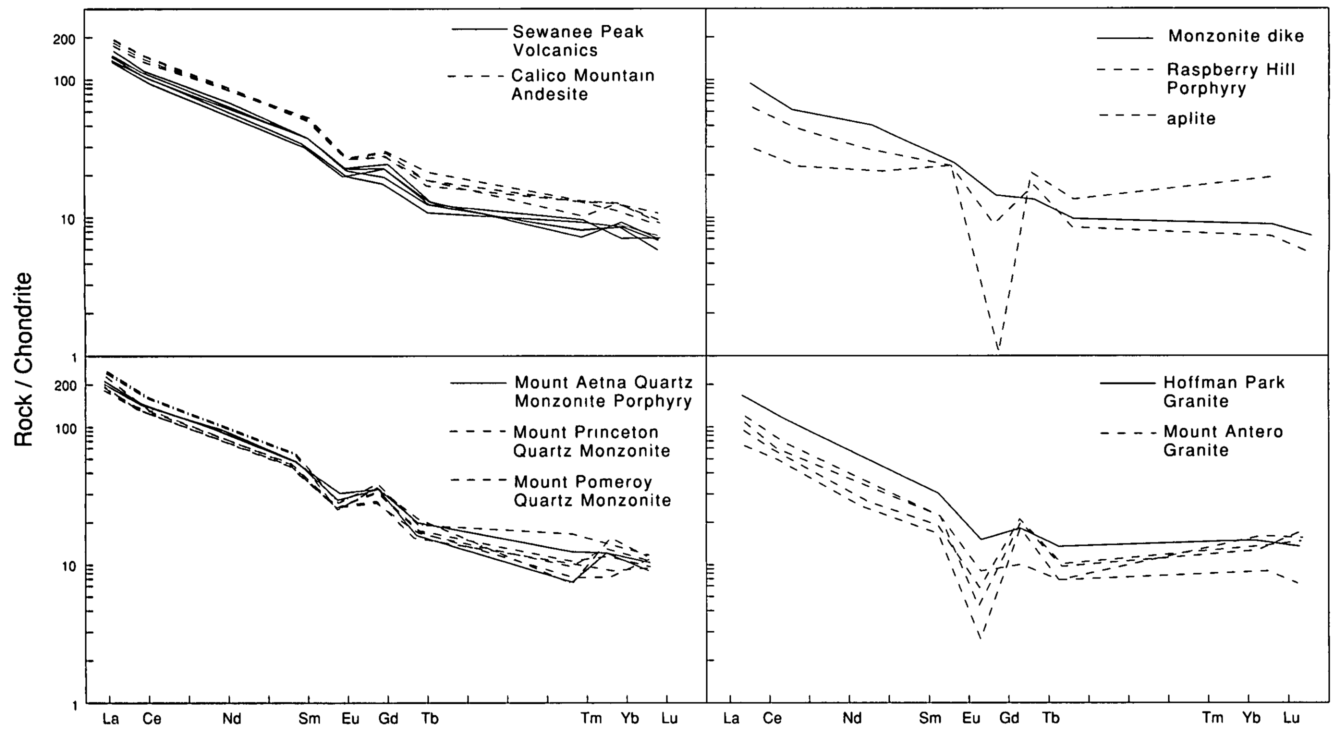
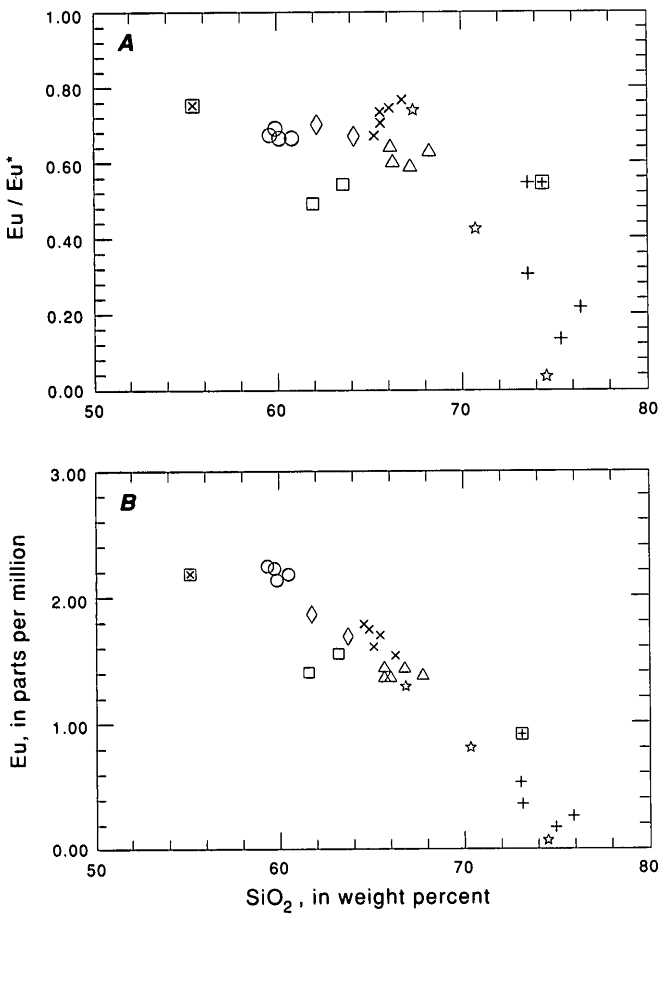


Figure 15. Chondrite-normalized rare-earth element patterns for rocks of the Mount Aetna volcanic center and other rocks of the Mount Princeton igneous complex.



(New Mexico) suites; on the other hand, the Hoffman Park and Mount Antero Granite biotites are more similar to those at Henderson. For this reason, and because the Mount Antero Granite has not produced notable fluorine enrichment in other rocks (Mount Princeton Quartz Monzonite and Mount Aetna Quartz Monzonite Porphyry) near its contacts with them, we doubt that the Mount Antero Granite magma, though fluorine rich, was an important factor in the alteration of the Mount Pomeroy micas. Nonetheless, the spatial distribution of biotite compositions in the Mount Pomeroy Quartz Monzonite and the rocks transitional between it and the Mount Princeton Quartz Monzonite is consistent with possible effects of concentration of volatiles at the base of the Mount Pomeroy Quartz Monzonite cap on the crystallizing batholith of the Mount Princeton Quartz Monzonite.

◀ **Figure 16.** Variation of Eu and the europium anomaly as functions of SiO_2 for rocks of the Mount Aetna volcanic center and other rocks of the Mount Princeton igneous complex. *A*, The europium anomaly (as measured by the ratio Eu/Eu*, where Eu* is the mean of the contents of the next lighter (Sm) and next heavier (Gd) chrondrite-normalized rare-earth elements) versus whole-rock silica content. *B*, Eu, in parts per million determined by instrumental neutron activation analysis, versus whole-rock silica content. Symbols for rock units as in figure 10.

Table 3. Chemical analyses of minerals
[In Weight percent; n.d., not determined]

Sample	7528	7529	7530	7532	7534
A. Biotites from Mount Antero Granite					
SiO_2	39.6	39.6	39.5	37.9	38.8
Al_2O_3	14.9	16.7	16.6	16.8	15.4
Fe_2O_3	2.0	4.5	3.8	3.1	4.1
FeO	12.6	11.4	10.8	11.6	11.0
MgO	12.5	10.3	10.4	12.0	12.2
TiO_2	1.64	1.28	1.48	1.73	1.80
MnO	1.52	1.90	1.45	1.35	1.54
Li_2O	.54	.83	.75	.68	.51
P_2O_5[2]	.07	.04	.04	.12	.06
CaO	.10	.09	.05	.24	.17
Na_2O	.15	.31	.30	.15	.10
K_2O	9.75	9.40	9.15	9.15	8.95
Rb_2O	.27	.25	.29	.24	.26
H_2O	1.75	1.98	2.00	n.d.	n.d.
Cl	<.1	.2	.5	1.1	.3
F	4.4	3.6	4.0	4.2	3.9
O=Cl	---	.05	.13	.29	.08
O=F	1.8	1.5	1.7	1.8	1.6
Total------	100.1	100.8	99.4	98.3	97.4

Plagioclase

Plagioclase in the Mount Princeton complex ranges from An_{61} to An_4 in composition; it is strongly zoned, and individual rock units have plagioclases with composition spans of at least 30 mol percent An. Cores are always more calcic than rims, and, in some rocks, fine-scale oscillatory zoning is superimposed on the overall normal igneous zoning pattern. The average K_2O content is about 0.5 weight percent; somewhat higher levels in plagioclases in the Mount Pomeroy Quartz Monzonite and individual specimens of cloudy feldspars in other rocks may reflect the presence of finely disseminated clays. Similarly, the highest iron concentrations are observed in the Mount Pomeroy and adjacent contact-zone plagioclases where black, clouded feldspars are common. Intermediate compositions and high iron contents are typical of black, clouded plagioclases described in other studies (Smith, 1974). The most calcic plagioclases are found in the Mount Aetna Quartz Monzonite Porphyry and in the Sewanee Peak Volcanics, but, with the exception of the granites, maximum anorthite content in plagioclase is not systematically related to whole-rock silica content. Figure 21 shows core-to-rim zoning patterns in plagioclases from the Mount Pomeroy and Mount Princeton Quartz Monzonites and the Mount Aetna Quartz Monzonite Porphyry. The overall zoning pattern is similar in all three crystals—broad core areas of nearly constant composition are rimmed by more albitic margins having a rather sharp transition. In the Mount Aetna Quartz Monzonite Porphyry, this transition is a zone of fine-scale oscillations of 3 to 5 mol percent An. In general, plagioclase in the Mount Aetna Quartz Monzonite Porphyry and the Sewanee Peak Volcanics is more complexly zoned than that in the Mount Princeton and Mount Pomeroy Quartz Monzonites, presumably as a result of a more complex thermal history.

Table 3. Chemical analyses of minerals—Continued

Sample	7179	7567	7568	7569	7570	7571	7573	7574
B. Biotites from Mount Princeton Quartz Monzonite								
SiO_2	37.9	37.6	36.8	37.2	37.0	37.2	37.1	37.2
Al_2O_3	13.7	14.1	14.2	14.0	14.4	14.4	14.2	14.6
Fe_2O_3	2.8	2.0	2.1	3.9	4.2	3.8	1.8	3.0
FeO	13.9	13.0	13.8	14.0	12.8	12.6	14.3	14.8
MgO	12.8	14.9	15.4	13.9	13.8	14.6	15.5	13.4
TiO_2	3.9	4.18	4.45	4.04	4.01	4.03	4.26	3.24
MnO	.34	.32	.30	.46	.52	.47	.32	.64
P_2O_5[2]	.08	.10	.17	.09	.12	.05	.14	.08
CaO	1.2	.38	.76	.49	.48	.22	.35	.18
Na_2O	.24	.23	.12	.16	.18	.12	.16	.12
K_2O	9.3	8.72	8.30	8.72	8.95	9.30	9.02	9.20
H_2O	2.7	1.89	2.72	2.75	2.49	n.d.	2.15	2.13
Cl	n.d.	.2	.2	.2	.7	.2	.1	<.1
F	.78	2.5	<0.1	<0.1	<0.1	<0.1	<0.1	<.1
O=Cl	---	.04	.04	.04	.2	.04	.04	.02
O=F	.33	1.0	---	---	---	---	---	---
Total -------	99.31	99.1	99.3	100.0	99.5	96.95	99.5	98.6

Table 3. Chemical analyses of minerals—Continued

Sample	7567	7569	7570	7573	7574
C. Hornblendes from Mount Princeton Quartz Monzonite[1]					
SiO_2	50.3	50.0	50.3	51.2	50.6
Al_2O_3	4.65	5.39	5.00	4.60	5.50
Fe_2O_3	2.7	3.0	2.9	3.0	3.7
FeO	8.6	9.4	9.1	8.4	9.8
MgO	16.4	15.6	16.3	16.0	14.3
TiO_2	.72	.68	.52	.72	.84
MnO	.56	.73	.73	.59	.87
P_2O_5*	.18	.20	.16	.30	.16
CaO	12.3	12.5	12.6	12.1	12.2
Na_2O	.94	.94	.85	.68	.96
K_2O	.46	.42	.40	.42	.50
H_2O	1.78	1.58	1.67	2.44	1.42
Cl	.2	.2	.2	.2	.1
F	.5	.4	.4	.6	.1
O=Cl	.05	.05	.05	.05	.02
O=F	.2	.2	.2	.3	.4
Total	100.0	100.7	100.8	100.8	101.0

[1] Analyzed by X-ray fluorescence, flame photometric, and spectrophotometric techniques in USGS Analytical Laboratories, H_2O determined by the Penfield method; 12/21/65; F.O. Simon, analyst.

* Probably represents contamination by apatite.

Potassium Feldspar

Microperthitic to cryptoperthitic potassium feldspar occurs in the quartz monzonites and as phenocrysts in the Mount Aetna Quartz Monzonite Porphyry; optically homogeneous potassium feldspar occurs in some of the volcanics as phenocrysts but is much less abundant than plagioclase. The best-developed microperthites (even textures across grains and coarsest lamellae) occur in the granites. Potassium feldspar crystals in the plutonic rocks tend to be zoned with respect to Na and Ba, which are usually concentrated in core areas. Average BaO contents in alkali feldspars generally increase as the Differentiation Index increases and age decreases (see table 4), except for the alkali feldspars in the granites, which are low in barium. Cores of phenocrysts in the Mount Aetna Quartz Monzonite Porphyry have up to 1.5 percent BaO, and up to almost 3 percent BaO is observed in phenocrysts in the Sewanee Peak Volcanics. Alkali feldspars in these two rock units are distinctive in that they have more intermediate compositions and smaller ranges of compositions within single grains than the quartz monzonites. Iron and magnesium are negligible in all the alkali feldspars; calcium varies within individual grains but generally runs 1 to 2 mol percent An.

Powder X-ray diffraction patterns reveal monoclinic symmetry for all alkali feldspars studied. Cell-edge refinements show that the alkali feldspars in the Mount Princeton Quartz Monzonite and the Mount Aetna Quartz Monzonite Porphyry are intermediate orthoclase, with slightly greater Al/Si disorder and lattice strain in the Mount Aetna Quartz Monzonite Porphyry feldspars (Kroll and Ribbe, 1983).

An attempt was made to evaluate coexisting feldspar compositions by using the two-feldspar geothermometers of Whitney and Stormer (1977) and Haselton and others (1983). Textural relations indicate early onset of crystallization of plagioclase relative to potassium feldspar, so it is unlikely that plagioclase core compositions were ever in equilibrium with potassium feldspar crystals. For most of the Mount Pomeroy and Mount Princeton Quartz Monzonites, where potassium feldspars are zoned, the inferred temperatures fall in the subsolidus range, even if a higher pressure (which would increase the temperature) is assumed. A few samples from the center of the Mount Princeton mass suggest near-solidus temperatures, as does a sample from the Mount Aetna Quartz Monzonite Porphyry stock. Only the Sewanee Peak Volcanics sample, which has a narrow range of composition, indicates truly magmatic temperatures [averages about 775 °C by Stormer's (1975) curves and about 900 °C according to the revision by Haselton and others (1983)]. Temperature estimates for the granites were low, on the order of 400 °C or below.

Sphene

Although relative sphene content is a significant discriminator for some units in the Mount Princeton igneous complex, sphene composition is not. Compositions of sphenes from the Mount Princeton Quartz Monzonite, the Mount Aetna Quartz Monzonite Porphyry, and the Sewanee Peak Volcanics overlap in composition. In all the rocks, approximately 10 percent of the titanium site is occupied by iron and aluminum in nearly equal proportions. Euhedral, magmatic sphenes carry up to 3 percent REE's, predominantly Ce and Nd. Fluorine ranges from 0.3 to 1 percent. Granular, apparently secondary sphene lacks detectable REE's, as do rare overgrowth rims on euhedral sphene crystals.

Opaque Minerals

Magnetite occurs in all the igneous rock units, most commonly in contact with or enclosed by biotite or hornblende. Magnetite is relatively pure—TiO_2 contents range from 0 to 5 weight percent, and MnO ranges from 0 to 2 weight percent. Thin hematite rims or lamellae are common, as are inclusions of apatite and zircon. Magnetite is the only opaque oxide phase noted in the Mount Aetna Quartz Monzonite Porphyry and the Sewanee Peak Volcanics, and it tends to be more titaniferous in these rocks than in any other units.

A manganese-rich ilmenite was observed in the Mount Princeton Quartz Monzonite, the Mount Antero

Table 4. Compositional ranges of rock-forming minerals in major rock units of the Mount Princeton igneous complex from electron-microprobe analyses

Map unit	Mount Pomeroy Quartz Monzonite		Mount Princeton Quartz Monzonite		Sewanee Peak Volcanics		Mount Aetna Quartz Monzonite Porphyry	
	Mean	Range	Mean	Range	Mean	Range	Mean	Range
				A. Hornblende compositions[1]				
Si	7.54	6.45–7.89	7.33	6.77–7.94	6.84	6.40–7.04	6.91	6.61–7.10
Al^{IV}	.46	.04–1.55	.67	.06–1.23	1.16	.96–1.60	1.08	.90–1.39
Al^{VI}	.07	0 – .35	.12	0 – .38	.23	0 – .35	.22	.04– .34
Fe^{+2}	1.31	0.55–1.99	1.49	.88–1.91	1.76	1.59–1.95	1.75	1.62–1.90
Mg	3.57	2.67–4.40	3.25	2.62–4.01	2.83	2.47–3.16	2.90	2.65–3.08
Ti	.04	0 – .22	.08	0 – .16	.15	.09– .29	.11	.08– .13
Mn	.01	0 – .06	.02	0 – .11	.03	0 – .10	.01	0 – .09
Mn_{M4}	.05	0 – .09	.07	0 – .12	.05	0 – .09	.06	0 – .10
Fe_{M4}	.07	0 – .29	.05	0 – .40	.05	0 – .24	.07	0 – .18
Ca	1.90	1.77–2.13	1.87	1.61–2.02	1.92	1.84–2.12	1.90	1.76–1.98
Na_{M4}	.01	0 – .11	.03	0 – .20	.03	0 – .10	.03	0 – .10
Na	.18	.04– .45	.24	0 – .44	.40	.19– .52	.42	.31– .52
K	.06	.01– .28	.09	.01– .19	.17	.11– .24	.17	.11– .24
A–site	.24	.05– .73	.34	.01– .62	.57	.34– .74	.57	.44– .70
F	.28	0 – .63	.17	0 – .51	.28	.09– .41	.28	.09– .41
Cl	.02	0 – .06	.01	0 – .06	0	0 – .05	0	0 – .05
Fe/(Fe+Mg)	.28	.15–0.45	.32	.20– .42	.39	.36– .44	.39	.36– .43
Samples................	4		15		4		4	
Analyses...............	46		110		25		20	

Granite, and the Hoffman Park Granite. This ilmenite is always present as inclusions in or adjacent to micas. The manganese content of the ilmenite increases with rock silica content, from about 20 percent MnO in the Mount Princeton Quartz Monzonite to almost 30 percent in the granites. This phase was not observed in the Mount Pomeroy Quartz Monzonite, though a Ti-rich, Mn-poor, heterogeneous opaque phase occurs in intimate intergrowths with blebby sphene in that unit. Magnetite-ilmenite assemblages suitable for the estimation of oxygen fugacity were not found, but the common association of magnetite, sphene, and quartz indicates that the magmas were relatively oxidizing, probably in the high-fO_2 part of the magnetite stability field; if we assume that the effective activity of the hedenbergite component in the magma was not greater than 0.1, then the equation of Wones (1981, fig. 6, table 2) predicts an oxygen fugacity less than 1 log unit below the magnetite-hematite buffer at magmatic temperatures.

Rare pyrite, occasionally enclosing tiny blebs of chalcopyrite, has been noted in magnetite in the Mount Aetna Quartz Monzonite Porphyry and as discrete grains rimmed by an iron-rich, presumably hydrated alteration product in the Mount Pomeroy Quartz Monzonite.

Apatite

Euhedral, hexagonal apatite crystals are ubiquitous in biotite in the Mount Princeton Quartz Monzonite. Apatite was observed in all rock units in biotite and quartz; it occurs as rods in plagioclase and as inclusions in or at the margins of magnetite grains. Microprobe analyses of a few samples show that apatite compositions are slightly variable, but they are generally fluorine-rich (1.5–3.3 percent F, less than 0.5 percent Cl) and contain up to a percent or so of REE's.

RADIOMETRIC DATING

Radiometric age determinations of several rocks closely related to the Mount Aetna volcanic center have been published (table 5). Many of these determinations were made by methods now known to be unreliable indicators of the actual time of emplacement or crystallization, though the ages determined may in some cases be interpretable as the times of specific postmagmatic events, such as the time of cooling through a known or estimated temperature.

Table 4. Compositional ranges of rock-forming minerals in major rock units of the Mount Princeton igneous complex, from electron-microprobe analyses—Continued

Map unit	Mount Pomeroy Quartz Monzonite		Mount Princeton Quartz Monzonite		Sewanee Peak Volcanics		Mount Aetna Quartz Monzonite Porphyry		Hoffman Park Granite		Mount Antero Granite	
	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range
					B. Biotite compositions[2]							
Si	2.87	2.80–2.96	2.85	2.73–2.96	2.80	2.68–2.86	2.81	2.70–2.89	2.90	2.80–3.01	2.95	2.88–3.02
Al^{iv}	1.11	1.04–1.17	1.14	1.01–1.26	1.20	1.14–1.32	1.18	1.11–1.29	1.10	.99–1.18	1.05	.98–1.12
Al^{vi}	.02	0 – .06	.06	0 – .24	.04	0 – .09	.05	0 – .11	.09	.04– .12	.42	.22– .66
Fe^{+2}	.82	.66–1.00	1.01	.79–1.19	1.02	.91–1.11	.94	.75–1.11	1.02	.87–1.12	.96	.84–1.07
Mg	1.84	1.65–2.02	1.54	1.29–1.76	1.56	1.40–1.70	1.66	1.44–1.95	1.53	1.39–1.68	1.15	.85–1.43
Ti	.21	.11– .35	.22	.03– .33	.23	.20– .29	.21	.16–1.25	.13	.10– .15	.09	.06– .12
Mn	.02	0 – .03	.03	0 – .05	.03	0 – .05	.02	.01– .04	.09	0 – .13	.11	.08– .16
M	2.91	2.79–2.98	2.86	2.76–3.00	2.88	2.77–3.06	2.89	2.84–2.95	2.88	2.80–2.94	2.73	2.63–2.82
K	.86	.77– .92	.92	.81–1.03	.87	.67– .93	.87	.77– .98	.93	.87– .96	.95	.83–1.00
Na	.04	.01– .07	.02	0 – .06	.04	0 – .09	.04	0 – .09	.01	0 – .02	.02	.01– .05
Ca	0	0 – .03	0	0 – .04	0	0 – .05	0	0 – .04	0	0	0	0 – .01
Ba	.01	0 – .04	0	0 – .03	.01	.01– .02	.02	.01– .03	.01	.01	0	0 – .01
A	.92	.82– .97	.95	.81–1.08	.93	.73–1.06	.92	.83–1.01	.94	.89– .97	.98	.87–1.03
F	.44	.15– .58	.23	.11– .49	.27	.18– .37	.27	.15– .41	.72	.62– .91	.88	.46–1.27
Cl	.01	.01– .03	.02	0 – .05	.01	0 – .02	.02	0 – .03	.01	0 – .02	.01	0 – .04
Fe/(Fe+Mg)	.31	.25– .37	.40	.32– .47	.40	.36– .42	.36	.28– .43	.40	.34– .45	.46	.38– .53
Samples................		4		17		3		6		1		10
Analyses...............		21		123		27		33		8		37

Direct radiometric dating of the volcanic rocks has proved difficult, in large part owing to the difficulty of obtaining suitably fresh, unaltered samples. A number of new determinations have been made on the Tertiary intrusive rocks (table 6), but these, too, are of somewhat uncertain significance because of alteration and apparent thermal or chemical disturbance of their isotopic systems. Analytical details and descriptions of the dated materials are available in open file reports of the U.S. Geological Survey (Sutter and others, in press).

Conventional K/Ar ages on biotite and hornblende separated from several rock units generally show older "ages" for hornblende samples than for coexisting biotites. This common relation presumably reflects the lower "closing temperature" for argon diffusion in biotite than in hornblende, but additional effects of excess argon and thermal or chemical disturbance, revealed by $^{40}Ar/^{39}Ar$ studies, limit the precise quantitative interpretation of the time of crystallization from these data.

The combined $^{40}Ar/^{39}Ar$ and K/Ar data, however, do permit certain conclusions of geologic significance. First, the igneous activity must have begun no later than 37 m.y. ago, for that "age" is preserved by the more retentive argon systems of several samples. Second, the entire sequence of events from emplacement of the Mount Princeton batholith through erosion, volcanism, subsidence of the Mount Aetna block, and intrusion of the Mount Aetna Quartz Monzonite Porphyry seems to have taken place over a very short period of time, for the most reliable indicated "ages" span only about 1 m.y. at most. It must be remembered that these ages, especially the Ar/Ar numbers, refer to the times when the samples cooled through their respective blocking temperatures, not to times of emplacement or crystallization. It seems likely that the close agreement of hornblende closing times in the Mount Princeton Quartz Monzonite and the Mount Aetna Quartz Monzonite Porphyry may reflect continued or repeated high temperatures throughout much of the igneous history of the center; as a result, final cooling through the hornblende blocking temperature occurred more or less contemporaneously for all the rocks. Clearly, those parts of the Mount Pomeroy and Mount Princeton Quartz Monzonites near the prevolcanic erosion surface must have fallen well below hornblende closing temperatures (thought to be on the order of 520–530,°C) before volcanism occurred, but suitable samples for analysis were not available from these areas. In summary, igneous activity at the

Table 4. Compositional ranges of rock-forming minerals in major rock units of the Mount Princeton igneous complex, from electron-microprobe analyses—Continued

Map unit	Mount Pomeroy Quartz Monzonite	Mount Princeton Quartz Monzonite	Sewanee Peak Volcanics	Mount Aetna Quartz Monzonite Porphyry	Hoffman Park Granite	Mount Antero Granite
			C. Feldspar compositions			
Plagioclase:						
An	13 - 48	17 -53	28 -60	16 -61	8–15	6 -16
Ab	50 - 86	49 -95	39 -68	38 -84	82–91	81 -92
Or	1 - 4	1 - 4	1 -4	1 - 7	1- 4	1 - 2
Percent FeO	.02– [3]1.31	.05– .52	.17– .39	.07– .44	---	---
Percent MgO	0 - .40	0 - .08	.11– .20	.05– .15	---	---
Samples	4	12	3	3	1	2
Analyses	30	160	17	77	5	19
Potassium feldspar:						
An	0 - 3	0 - 3	1 -2	0 - 2	0	0 -2
Ab	5 - 30	7 -38	22 -30	4 -27	6– 8	5 -11
Or	68 - 95	62 -93	65 -86	71 -93	92–94	86 -95
Cs	0 - 3	0 - 3	1 -6	1 - 5	0– 1	1
Percent FeO	.05– .26	.02– .40	.08– .14	0 - .08	---	.03– .13
Percent MgO	0 - .24	0 - .02	.09	0	---	0 - .06
Samples	4	6	1	2	1	2
Analyses	7	46	7	13	4	2

[1] Hornblende formulas calculated on the basis of 23 oxygens, total iron as FeO.
[2] Biotite formulas calculated on the basis of 11 oxygens, total iron as FeO.
[3] Only one crystal showed FeO content >0.6 weight percent.

Mount Aetna volcanic center must have begun at least 37 m.y. ago, but its duration and the precise dates of volcanism are not yet well defined.

DEVELOPMENT OF THE COMPLEX

The oldest volcanic deposits in the Mount Aetna volcanic center are those of the Calico Mountain Andesite. These rocks were deposited on a rolling surface of moderate relief cut across rocks of Precambrian and Paleozoic age intruded by the Mount Pomeroy Quartz Monzonite and perhaps by the Mount Princeton Quartz Monzonite, though we have found no direct evidence that the Mount Princeton Quartz Monzonite had been exposed at the time of Calico Mountain volcanism. This surface is presumed to be essentially continuous with the late Eocene surface described by Epis and Chapin (1975), which, though generally of low relief, had "appreciably greater relief" near the Laramide Sawatch uplift (Epis and Chapin, 1975, p. 53). We know neither the location of the focus of Calico Mountain volcanism nor the type(s) of volcanic center(s) that may have produced the formation, but by analogy with the well-documented relations in the younger and much better preserved volcanic centers in the San Juan Mountains (Steven and Lipman, 1976), it seems reasonable to infer one or more central stratovolcanoes of generally andesitic composition. As was described earlier, in the section "Calico Mountain Andesite," the Calico Mountain Andesite has been preserved in a band that may represent a paleovalley extending northeastward from the general area of Mount Aetna, where an intersection of major structural elements served as a focus for younger igneous activity; it seems plausible that the parent volcano was located in this same general area. The Calico Mountain is made up of intercalated lava flows, laharic and volcanic breccias, and relatively minor welded ash-flow tuffs (insofar as the proportions can be determined through the alteration and poor

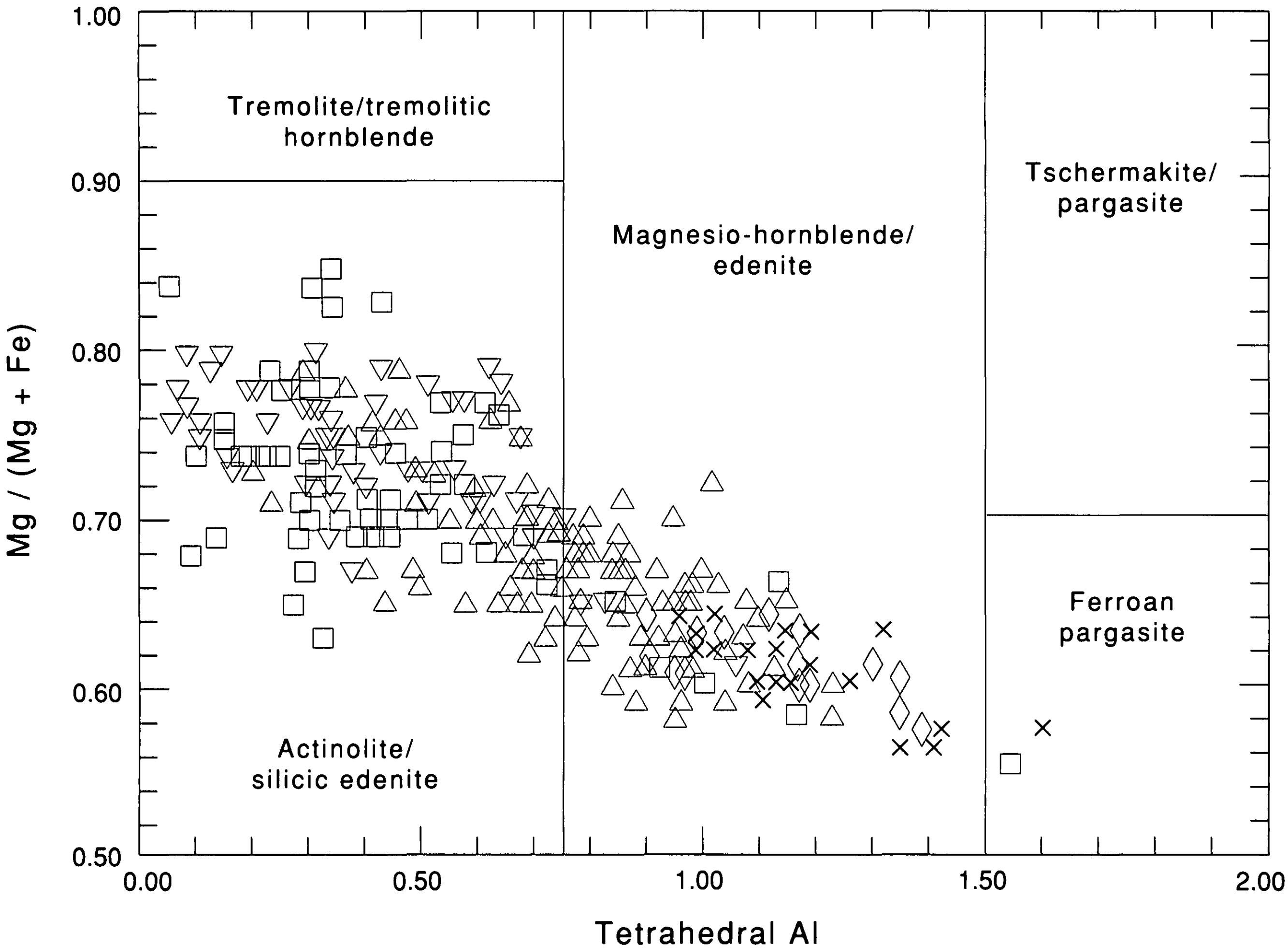
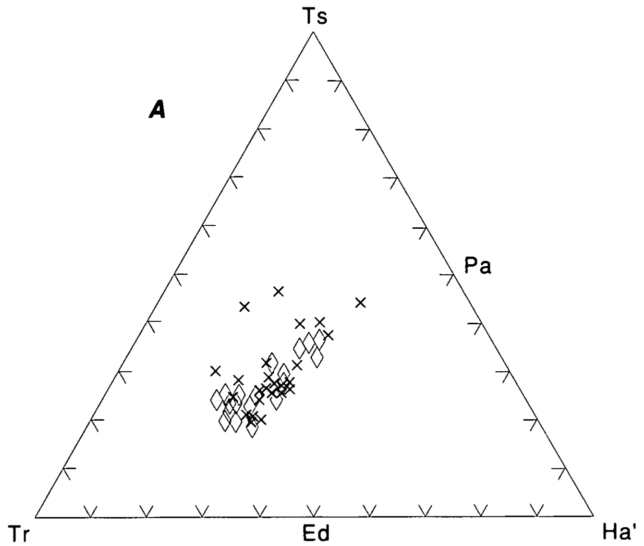


Figure 17. Range of amphibole compositions from rocks of the Mount Aetna volcanic center and other rocks of the Mount Princeton igneous complex plotted in terms of tetrahedral aluminum content and Mg/(Mg + Fe). Cations are calculated on the basis of 23 oxygens per formula unit. Amphibole names are based on Leake (1978). Symbols for rock units as in figure 10.

exposure). Although it has not been possible to document regional trends in the constitution of the unit in any quantitative way, it may be significant that the only pyroclastic units of mappable extent and continuity, and by far the best exposures of agglomerate, in the Calico Mountain are in the southwestern part of the belt of exposure, closest to the presumed vent (fig. 3; pl. 1).

The contact between the Calico Mountain Andesite and the overlying Sewanee Peak Volcanics is part of a more rugged surface of erosion, which laid bare not only the same rocks exposed on the pre-Calico Mountain surface but also cut more deeply into the underlying batholith, thereby exposing the Mount Princeton Quartz Monzonite beneath its carapace of Mount Pomeroy Quartz Monzonite. Eruption of the ash flows and breccias of the Sewanee Peak buried extensive accumulations of talus and other fragmental surface deposits of both local and transported material; we infer a heterogeneous, rugged, youthful surface on which pockets of residual soil were interspersed among talus, sliderock and landslide deposits, and coarse gravels, perhaps not too different from the present-day surface in the area. Recognizable remnants of this surface survive today mostly to the north and east of the Mount Aetna Quartz Monzonite stock, in the Billings Basin and Hunkydory Gulch areas; farther to the southwest, as one approaches the western marginal fault-dike, all coherent trace of the surface is lost in the chaotic collapse breccia marking the caldera wall.

Eruption of the Sewanee Peak Volcanics is interpreted to have taken place through multiple vents and to have led to the formation of a caldera by catastrophic subsidence as the magma was withdrawn from a presumably rather shallow reservoir. The size, and even the central location, of this structure is not certain. The juxtaposition of thick, highly compressed, propylitized welded ash-flow tuffs and breccias with great marginal masses of megabreccia and mesobreccia of the sort shown by Lipman (1976) to characterize caldera-wall collapse breccia is strong evidence for the existence of such a structure. Subsequent to, or possibly in the late stages of, the Sewanee Peak eruptive



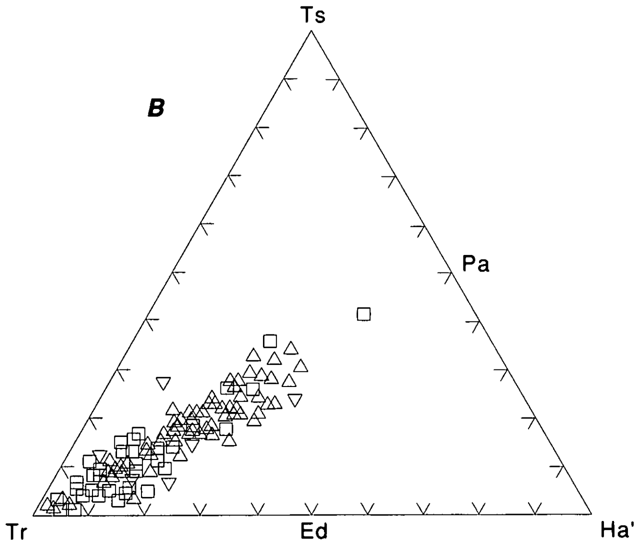


Figure 18. Compositions of amphiboles from rocks of the Mount Aetna volcanic center and other rocks of the Mount Princeton igneous complex in terms of components defined by Hallimond (1943) and used by Oba (1980) to illustrate a possible miscibility gap between tremolite (actinolite) and pargasite. *A*, Hornblendes from the Sewanee Peak Volcanics and from the Mount Aetna Quartz Monzonite Porphyry. *B*, Hornblendes from the Mount Pomeroy Quartz Monzonite, the Mount Princeton Quartz Monzonite, and the contact between the Mount Pomeroy and the Mount Princeton Quartz Monzonites. The components are defined as follows:

Tr = tremolite
$Ca_2(Mg, Fe^{2+})_5Si_8O_{22}(OH)_2$

Ha′ = hastingsitelike component of Hallimond (1943)
$(Na, K)_2Ca_2(Mg, Fe^{2+}, Mn)_5Si_6Al_2O_{22}(OH)_2$

Ts = tschermakite
$Ca_2(Mg, Fe^{2+},Mn)_3Al_2Si_6O_{22}(OH)_2$

The locations of the end-member compositions edenite (Ed) and pargasite (Pa) are shown for reference. Symbols for rock units as in figure 10.

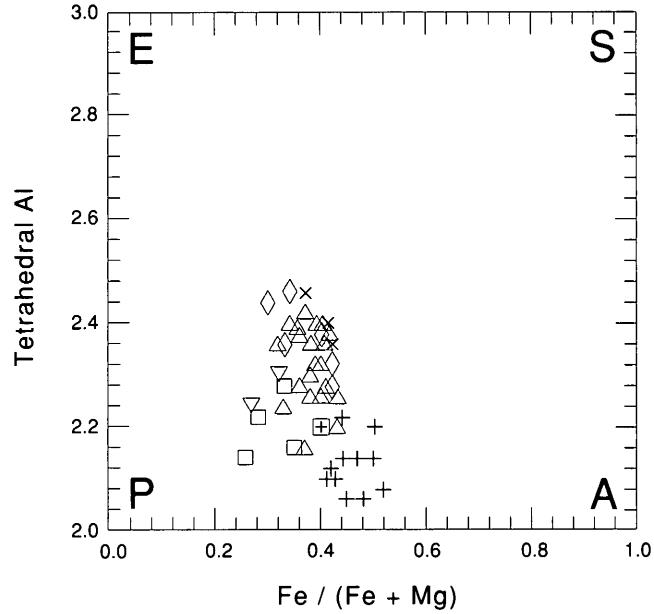


Figure 19. Biotite compositions in terms of end-member micas—

P, phlogopite $K_2Mg_6Al_2Si_6O_{20}(OH)_4$
A, annite $K_2Fe_6Al_2Si_6O_{20}(OH)_4$
E, eastonite $K_2Mg_5Al_4Si_5O_{20}(OH)_4$
S, siderophyllite $K_2Fe_5Al_4Si_5O_{20}(OH)_4$

Compositions are defined by Fe/(Fe + Mg) and tetrahedral aluminum. Formulas were calculated on the basis of 22 oxygens and total iron treated as FeO. Each point represents the average composition for a given sample. Symbols for rock units as in figure 10.

episode, the Mount Aetna block subsided in trapdoor fashion, as Steven and Lipman (1976) have noted is characteristic of some generally small-volume eruptions in the San Juan field. Subsidence took place along two faults whose locations are marked today by large dikes of the Mount Aetna Quartz Monzonite Porphyry and was essentially complete at the time of emplacement of the Mount Aetna Quartz Monzonite Porphyry. The two faults strike essentially N. 45° E. and due north, approximately parallel to the regional grain of the Precambrian basement and to the eastern front of the Sawatch Range in this latitude, which locally reflects the western boundary of the Arkansas River graben, the northern element of the Rio Grande rift system, respectively. Although no independent evidence of major rifting at this time has been found, Varga and Smith (1984, p. 8692) have suggested that early rift-related tensional stresses (Tweto, 1979) may have played a role in localizing early Oligocene volcanic centers (Bonanza, Mount Aetna, Grizzly Peak) along the west side of the northern Rio Grande Rift. Subsidence of the Mount Aetna subsided block was greatest in the southwest, near the intersection of the two structures, so that the regional southerly tilt is enhanced and deviated somewhat westward within this "trapdoor" structure.

Although the boundary faults of the subsided block were sufficiently open to guide the intrusion of the magma,

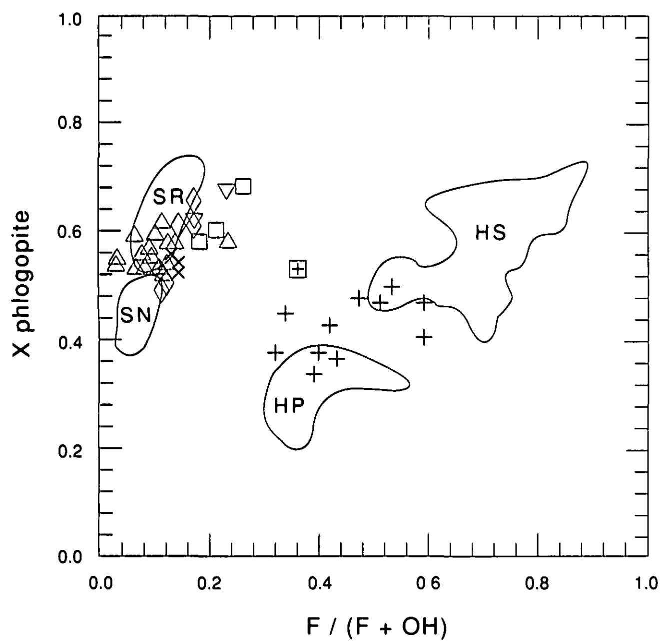


Figure 20. Average biotite compositions in terms of fluorine content, assuming F + Cl + OH = 4 for a 22-oxygen formula unit, and mole fraction (×) of phlogopite, which is defined as Mg/M-site sum. Fields for primary magmatic and alteration biotites given by Gunow and others (1980) are as follows:

SN—Primary magmatic biotites from the Sierra Nevada and the Coast and Transverse Ranges batholiths,
SR—Biotites from the Santa Rita porphyry copper deposit, which includes primary, hydrothermal, and vein biotite compositions,
HP—Biotites that have retained their primary cationic composition from granite and porphyry at the Henderson molybdenum deposit, and
HS—Secondary or hydrothermal biotites from Henderson.

Symbols for rock units as in figure 10.

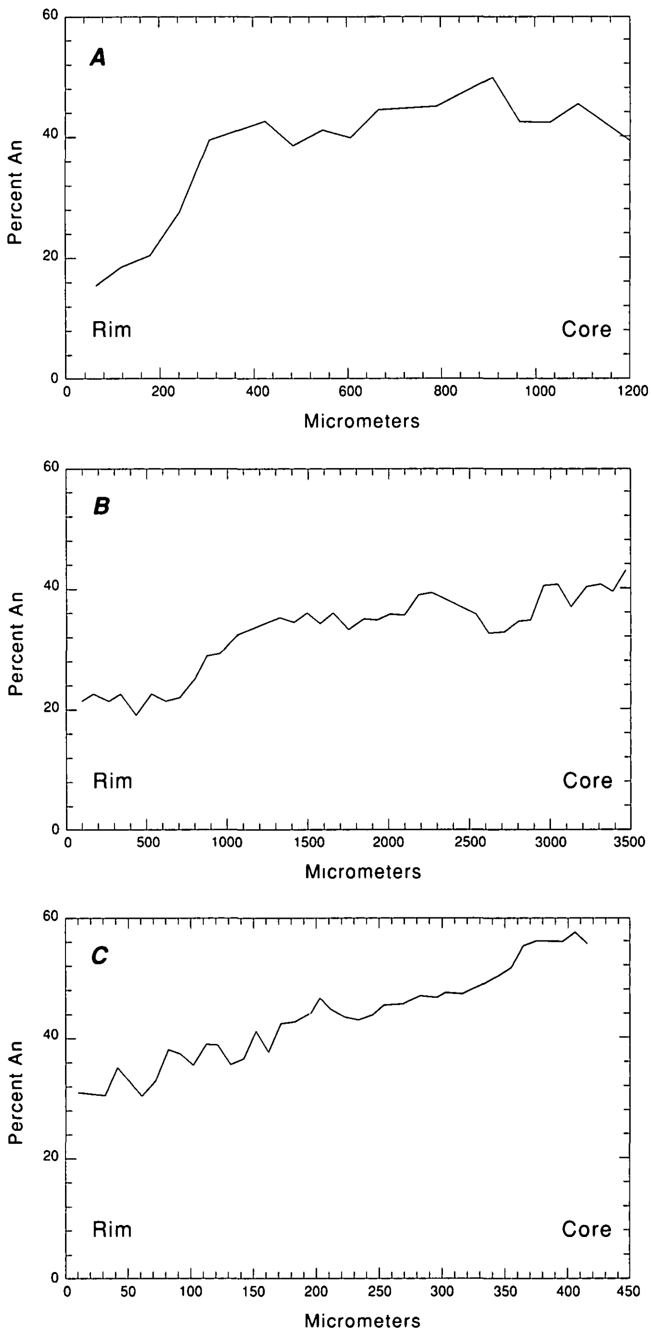


Figure 21. Compositional zonation in plagioclase crystals from rocks of the Mount Princeton igneous complex. *A*, Sample 8023, Mount Pomeroy Quartz Monzonite. *B*, Sample 7706, Mount Princeton Quartz Monzonite. *C*, Sample 7219, Mount Aetna Quartz Monzonite Porphyry.

the emplacement of the Mount Aetna Quartz Monzonite stock seems to have had no perceptible effect on the attitude of the block. The Mount Aetna apparently intruded the caldera shortly after collapse, but we have found no evidence for its having caused resurgent doming. The final magmatic event in the vicinity of the Mount Aetna volcanic center was the intrusion of the Hoffman Park Granite stock, which cut the southeastern fault-dike. Farther to the northeast, emplacement of the Mount Antero Granite was probably roughly contemporaneous.

The main volcanic activity at the Mount Aetna volcanic center apparently took place in a brief time span during the very early Oligocene, about 37 m.y. ago, synchronously with volcanism at the Bonanza center (Varga and Smith, 1984). Related magmatic activity probably began even earlier and continued into the lower twenties of millions of years before the present. Magmatism followed the general pattern characteristic of the San Juan and West Elk fields (Lipman and others, 1969, 1970), in which early intermediate (andesitic) central volcanoes are succeeded by more silicic explosive volcanism, but at Mount Aetna, as at the Bonanza center (Varga and Smith, 1984, p. 8692), corresponding stages in the activity occurred several million years earlier than in the San Juan and West Elk fields.

REGIONAL RELATIONS

The Mount Princeton batholith, with which the Mount Aetna volcanic center is integrally tied, is located at

Table 5. Published radiometric age determinations for rocks associated with the Mount Aetna volcanic center

Rock unit	"Date" (m.y.)	Method	Reference[1]
Mount Princeton Quartz Monzonite.	37±2	Whole-rock K/Ar.	(1)
Quartz monzonite porphyry dike.	25±1	---do.---	(1)
Rhyolite dike	26.2±1.0	---do.---	(1)
Porphyry of Raspberry Hill.	22±1	---do.---	(1)
Mount Antero Granite ..	30.8±1.1	Biotite K/Ar ..	(2)

[1] (1) Quoted and slightly corrected by Marvin and Coles (1978) from Olson and Dellechaie (1976); data also in Limbach (1975).
(2) Thompson and Pulfrey (1973, p. 118) quoted from Pulfrey (1970).

a tectonic-magmatic nexus near the intersection of several major trends of fundamental significance. The northeast-southwest-trending Colorado Mineral Belt is marked by a series of igneous bodies extending from the Colorado Front Range front north of Boulder southwest across the State to the San Miguel district; some authors (for example, Simmons and Hedge, 1978) depict it as including the Mount Princeton batholith on its southeastern margin. The Sangre de Cristo Range marks a narrow, well-defined band of tectonic and, to a lesser degree, magmatic activity along the eastern margin of the San Luis Valley-Rio Grande rift zone in south-central Colorado; this structural trend is generally regarded as extending north-northwest only as far as the Poncha Pass area, where it is apparently truncated by the northward extension of the Rio Grande rift zone (the Upper Arkansas Valley) and, to its west, by the Sawatch Range,

Table 6. Radiometric age determinations made in connection with the present study

Number	Rock unit	"Age" (m.y.)	Method	Reference[1]	Remarks
64B76	Mount Princeton Quartz Monzonite..........	34.9±1.0	K/Ar:biotite	(1)	
		41.1±0.9	K/Ar:hornblende	(1)	
7438	---do.---	36.6±1.1	K/Ar:biotite	(1)	
		34.8±1.7	K/Ar:hornblende	(1)	
		[2]36.3±0.3	$^{40}Ar/^{39}Ar$:hornblende	(2)	Total gas age 38.8 m.y.
		[3]29 ca.	$^{40}Ar/^{39}Ar$:orthoclase	(2)	
7569	---do.---	41.1±1.2	K/Ar:hornblende	(1)	
		34.8±0.8	K/Ar:biotite	(1)	
		[2,4]37.1±0.3	$^{40}Ar/^{39}Ar$:hornblende	(2)	
		[5]34.4±0.3	$^{40}Ar/^{39}Ar$:biotite	(2)	
7570	---do.---	36.9±1.1	K/Ar:hornblende	(1)	
		34.5±0.8	K/Ar:biotite	(1)	
		[5]36.4	$^{40}Ar/^{39}Ar$:hornblende	(2)	Discordant Ar-release spectrum.
		[5]34.5±0.3	$^{40}Ar/^{39}Ar$:biotite	(2)	Nearly concordant Ar-release spectrum.
		[3]34 ca.	$^{40}Ar/^{39}Ar$:orthoclase	(2)	
7574	---do.---	[2,4]35.4±0.3	$^{40}Ar/^{39}Ar$:hornblende	(2)	Total gas age 36.1 m.y.
		[6]34.6±0.3	$^{40}Ar/^{39}Ar$:biotite	(2)	Total gas age 34.5 m.y.
		[3]32 ca.	$^{40}Ar/^{39}Ar$:orthoclase	(2)	
7723	Sewanee Peak Volcanics.......................	33.9	K/Ar:biotite	(1)	
		[4]35.7±0.3	$^{40}Ar/^{39}Ar$:hornblende	(2)	Maximum closure age. Total gas age 36.7 m.y.
		[5]33.6±0.3	$^{40}Ar/^{39}Ar$:biotite	(2)	
7435	Mount Aetna Quartz Monzonite Porphyry....	37.2±1.7	K/Ar:hornblende	(1)	
		36.0±1.1	K/Ar:biotite	(1)	
		[6]36.1±0.3	$^{40}Ar/^{39}Ar$:hornblende	(2)	Total gas age 37.2 m.y.
		[6]34.0±0.3	$^{40}Ar/^{39}Ar$:biotite	(2)	Total gas age 33.9 m.y.
7788	Hoffman Park Granite	33.2±0.7	K/Ar:biotite	(1)	
7457	Quartz diorite....................................	115±6	K/Ar:hornblende	(1)	
		46.3±1.4	K/Ar:biotite	(1)	
7436	Gneissic quartz monzonite	199±6	...........No...........	(1)	

[1] (1) Analyses by R.F. Marvin, H.H. Mehnert, Lois Schlocker, and Carl Hedge, U.S. Geological Survey.
(2) Analyses by J. Sutter and M. Kunk, U.S. Geological Survey.
[2] Preferred age based on high-temperature steps in Ar-release spectrum; no distinct plateau.
[3] Time of cooling through approx. 150 °C.
[4] Ar-release spectrum indicates excess Ar.
[5] Total gas age.
[6] Age based on Ar-release spectrum plateau.

which occupies the core of a major north-plunging anticlinorium. It is interesting to note, however, that a chain of nearly contemporaneous igneous centers continues the trend smoothly to the north-northwest—the Mount Princeton batholith in the Sawatch Range and the Whiterock, Snowmass, and Sopris plutons in the Elk Mountains, along with a host of minor intrusions and a belt of north-northwest- to northwest-trending faults, merge into the Grand Hogback monocline, which marks the northeastern margin of the Colorado Plateau here.

The east-west band of intrusive and extrusive igneous rocks of the West Elk Mountains, whose petrologic and tectonic similarity to the San Juan volcanic province has been noted by Lipman and others (1969), projects directly into the northern border zone of the Mount Princeton batholith and the poorly defined hinge zone in the Sawatch uplift mentioned in the "Introduction" of this report. The Mount Princeton-Mount Aetna magmatic system is also adjacent to the northeastern corner of the San Juan-Bonanza volcanic field; its location at the juncture of these several features raises the question of the possible petrologic and genetic relations between the igneous rocks here and those of the other groups.

Simmons and Hedge (1978, p. 379) discerned two distinct rock suites in the Colorado Mineral Belt—a "silica oversaturated granodiorite suite ...[that has] Sr contents less than 1,000 ppm, subparallel REE patterns and initial $^{87}Sr/^{86}Sr$ greater than 0.707" and a "silica saturated, high alkali monzonite suite" having contrasting geochemical characteristics. The trace-element and Sr-isotope characteristics of the Mount Princeton-Mount Aetna rocks are consistent with an assignment to the granodiorite suite of Simmons and Hedge, but the major-element chemistry is more equivocal. Thus, while plots of total alkali oxides versus silica and normative Q–(ab + an)–or (Simmons and Hedge, 1978, figs. 2, 3) show an clear distinction between their two groups, corresponding data for the Mount Princeton-Mount Aetna rocks straddle that boundary continuously. Similarly, on a normative Q–ab–or plot, the Mount Princeton-Mount Aetna rocks fall between the "high-pressure" and "low-pressure" fields of the San Juan ash-flow tuffs delineated by Lipman and others (1978, fig. 4) and show a much more restricted range of variation in K/Na than do the San Juan rocks. Comparison of Harker silica-variation diagrams shows that the Mount Princeton-Mount Aetna rocks are about 1 percent richer in K_2O and poorer in CaO (at corresponding SiO_2 contents) than are the rocks of the San Juan and Elk Mountains suites (Lipman and others, 1969, fig. 3), although they are indistinguishable from those in the mid-Tertiary Elk Mountains group on an AFM plot as shown by Mutschler and others (1981, fig. 3).

Several authors (Epis and Chapin, 1975; Steven, 1975) have suggested that volcanic centers in the Sawatch Range may have been the sources for some of the volcanic rocks of the Thirtynine Mile volcanic field, at the southern end of South Park and, in particular, of the very widespread Wall Mountain Tuff, which extended eastward across the Front Range to the Great Plains near Castle Rock, Colo. Though the Mount Aetna center may have been the source for some of the ash flows of the Thirtynine Mile volcanic field, we do not believe that it was the source for the Wall Mountain Tuff. The Wall Mountain Tuff is a high-silica rhyolite (Epis and Chapin, 1974, table 1) unlike any of the volcanic rocks of the Mount Aetna center. Correlation of distal and caldera-facies ash flows on the basis of bulk composition is somewhat uncertain because of the possibility of phenocryst segregation during flow, but the composition of phenocryst minerals should provide a more reliable indication. Desborough and others (1973) have shown the usefulness of microprobe analyses of biotite in this regard. We have made microprobe analyses of biotites from only one specimen of Wall Mountain Tuff, but these showed a considerable range of composition, which did not overlap that of biotite from the Sewanee Peak Volcanics. Partial analyses of several specimens of Wall Mountain Tuff (G.A. Desborough, U.S. Geological Survey, written commun., 1973) confirm this finding with respect to Fe and Mg. The Wall Mountain Tuff apparently lacks hornblende, which is common in the Sewanee Peak. Certain other ash flows in the Thirtynine Mile field, such as the Badger Creek Tuff, which fills a paleovalley well aligned with the Mount Aetna center (Epis and Chapin, 1975), resemble those of the Sewanee Peak more closely in petrography and rock and mineral composition, but the presently accepted age of 33 m.y. for the Badger Creek (Epis and Chapin, 1974) is incompatible with such a correlation. We think it likely that some flows in the Thirtynine Mile field were derived from the Mount Aetna center, but further work will be required to resolve these ambiguities.

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APPENDIX

Locations of Analyzed Samples

Sample	Quadrangle	West longitude[1]	North latitude[1]	Location
		Mount Pomeroy Quartz Monzonite		
7437	St. Elmo	106–19–55	38–37–33.5	Billings Basin, just east of portal of Pride of the West Mine.
7746, 7748	Garfield	106–19–12.8	38–37–20.2	Slope east of Billings Lake, just southwest of prospect pit, 11,840 ft.
7811	St. Elmo	106–19–43.5	38–38–23.4	Grizzly Gulch, near contact with Mount Princeton Quartz Monzonite on slope northeast of lake, 12,093 ft.
7812	---do.---	106–19–48.1	38–38–27.4	Grizzly Gulch, near contact with Mount Princeton Quartz Monzonite, outflow gully at northern end of lake, 12,093 ft.
7813	---do.---	106–19–50.6	38–38–18.2	Grizzly Gulch, knoll west of northern end of lake, 12,093 ft.
82013	---do.---	106–16–00	38–39–05	Along road, 800 m east of California Mine, near fork in jeep trail.
		Mount Princeton Quartz Monzonite		
7179, 7438	Mount Antero	106–14–21.9	38–42–46.1	Quarry at Cascade, north of Chalk Creek, near the western pond about 450 m west-northwest of Chalk Lake.
7567	Cumberland Pass	106–24–29.1	38–38–42.6	Tunnel Gulch, western side of cut at southern portal of Alpine Tunnel.
7568	---do.---	106–24–20.3	38–38–14.6	Along road to southern portal of Old Alpine Tunnel, about 1 km south of portal.
7569	---do.---	106–24–08.2	38–37–57.1	Along road to southern portal of Old Alpine Tunnel, about 1.6 km south of portal.
7570	---do.---	106–23–49.0	38–37–41.7	Along road to southern portal of Old Alpine Tunnel, 2.3 km southeast of portal on western side of creek.
7571	Whitepine	106–23–32.4	38–37–28.4	Cliffs along road to southern end of Alpine Tunnel east of intersection with pack trail to Williams Pass.
7573	Cumberland Pass	106–24–52.6	38–41–19.1	Northern slope of hill, 12,724 ft, southern side of North Fork Chalk Creek, about 2.8 km southeast of Tincup Pass.
7574	Mount Yale	106–16–00.5	38–48–31.2	Slope south of Rainbow Lake.
7814	St. Elmo	106–18–33.1	38–42–46.3	Along Chalk Creek road, across valley from mouth of Coal Camp Creek.
7957	Whitepine	106–22–54.4	38–36–11.8	Ridge west of Central Mountain, east of Tomichi Pass, elevation 12,050 ft.
		Mount Aetna Quartz Monzonite Porphyry		
7219	Garfield	106–18–19.5	38–35–12.2	Center of dike crossing ridge northwest of Taylor Mountain.
7220	---do.---	106–18–18.7	38–35–11.5	Southeastern contact of dike crossing ridge northwest of Taylor Mountain.
7284	---do.---	106–19–11.5	38–35–09.8	Mount Aetna summit.
7435	---do.---	106–19–30.2	38–34–16.9	Talus stream west of Mount Aetna.
7456	Mount Antero	106–14–28.8	38–38–08.1	Dike in southern wall of Brown's Creek gulch, about 0.75 km northwest of peak, 13,712 ft, at elevation 12,800 ft.
		Sewanee Peak Volcanics		
7670	Garfield	106–19–41.1	38–36–08.2	About 90 m southwest from ridge 30 m northwest of outlet from first lake south of North Fork Reservoir (known locally as Lake Arthur).
7700	---do.---	106–20–54.1	38–36–47.6	Just above base of cliffs at northern side of talus at head of Chalk Creek, just south of Hancock Lake, elevation 12,025 ft.
7723	---do.---	106–19–18.3	38–35–30.1	100 m east of small lake north of Mount Aetna, just south of knob, 12,065 ft.
7833	---do.---	106–20–01.5	38–35–06.8	Northern side of Middle Fork South Arkansas River valley, on southwestern flank of Mount Aetna, about 1,500 m N. 81° E. from peak, 12,842 ft, at elevation 11,650 ft.
7849	---do.---	106–20–43.5	38–34–32.5	Gulch southeast of Vulcan Mountain, just below mine workings, elevation 12,070 ft.
7877	---do.---	106–21–09.5	38–36–17.7	Ridge west from Chalk Creek Pass, 60 m vertically above pass.
7878	---do.---	106–21–40.3	38–36–07.9	About 15 m vertically above saddle south of Van Wirt Mountain, on southern side.

Sample	Quadrangle	West longitude[1]	North latitude[1]	Location
				Rhyolite porphyry of Raspberry Hill
7238	Mount Antero	108–11–27.2	38–41–25.6	About 150 m northeast of Raspberry Mountain summit, at contact with Mount Princeton Quartz Monzonite.
				Monzonite dike
7475	Mount Antero	106–12–45.1	38–42–06.6	Dike on southern side of northeast-trending ridge southeast of upper Tie Gulch, about 15 m below crest.
				Aplite dike
7478	Mount Antero	106–12–45.1	38–42–28.5	Western lip of Tie Gulch, elevation 9,030 ft.
				Calico Mountain Andesite
7201	Garfield	106–18–57.4	38–37–05.1	About 400 m S. 60° W. from summit of Calico Mountain.
7613	---do.---	106–19–36.2	38–36–24.2	Outcrop in easternmost talus pile from high cliffs west of North Fork Reservoir.
7635	---do.---	106–18–25.1	38–37–28.1	Western wall of Cyclone Creek gulch on eastern flank of Calico Mountain, 700 m N. 40° E. from summit of Calico Mountain.
7767	---do.---	106–18–41.5	38–36–48.0	Calico Mountain, due south of summit, elevation 11,650 ft.
7864	---do.---	106–19–54.0	38–36–30.4	Ridge south-southeast of Island Lake.
7867	---do.---	106–19–30.2	38–36–49.9	Slope east of first lake north of Island Lake (known locally as Lake Ellis).
				Quartz diorite
7395	Maysville	106–14–19.2	38–34–57.8	Divide between the North Fork of the South Arkansas River and Lost Creek, northwest of peak, 11,178 ft.
7457	---do.---	106–14–42.2	38–34–20.1	Lost Creek basin, elevation 10,300 ft, about 150 m west of road.
				Mount Antero Granite
7319	Mount Antero	106–14–29.1	38–39–22.3	Mount White, 2 km S. 10° E. of Antero summit, elevation 13,150 ft.
7388	---do.---	106–13–51.1	38–39–13.5	South-trending ridge 2,000 ft east-southeast of western summit of Mount White.
7441	Mount Antero	106–14–52.3	38–40–03.0	Open cut at top of Antero road, knob 0.77 km south-southwest of Mount Antero summit.
7528	---do.---	106–14–50.5	38–39–06.8	Just north of saddle north of Antero knob southwest of western summit of Mount White, elevation 12,800 ft.
7529	---do.---	106–14–51.3	38–39–04.7	Crestline of ridge south of knob southwest of western summit of Mount White, elevation 12,740 ft.
7530	---do.---	106–14–51.0	38–39–03.3	Crestline of ridge south of knob southwest of western summit of Mount White, elevation 12,650 ft.
7532	---do.---	106–14–55.1	38–38–58.6	Western side of ridge south of knob southwest of western summit of Mount White, elevation 12,250 ft.
7533	---do.---	106–14–55.6	38–38–56.3	Western side of ridge south of knob southwest of western summit of Mount White, elevation 12,100 ft.
7534	---do.---	106–14–56.3	38–38–55.2	Western side of ridge south of knob southwest of western summit of Mount White, elevation 11,985 ft.
7721	Garfield	106–16–30.4	38–35–57.4	About 0.5 km east of Jennings Creek, by North Fork road.
7972	Mount Antero	106–14–50.8	38–39–58.7	Along road at Antero workings.
82007	---do.---	106–14–49.5	38–40–02.6	Southeast-trending ridge at workings on knob south of Mount Antero.
82010	---do.---	106–14–59.3	38–40–02.2	Workings at knob south of Mount Antero.
				Hoffman Park Granite
7788	Garfield	106–18–52.6	38–34–40.3	Hoffman Park below Uncle Sam Mine.

[1] Degrees–minutes–seconds.