Calderas of the San Juan Volcanic Field, Southwestern Colorado

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By THOMAS A. STEVEN *and* PETER W. LIPMAN

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Eighteen major ash-flow tuff sheets were deposited and perhaps as many related calderas developed during emplacement of an underlying shallow batholith in late Oligocene time

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CONTENTS

ILLUSTRATIONS

TABLE

CALDERAS OF THE SAN JUAN VOLCANIC FIELD, SOUTHWESTERN COLORADO

By THOMAS A. STEVEN and PETER W. LIPMAN

ABSTRACT

Calderas in the San Juan volcanic field in southwestern Colorado formed largely in late Oligocene time (30-26 m.y. ago) in response to recurrent large-volume ash-flow eruptions. The ash-flow deposits overlie a coalescing assemblage of early Oligocene (35-30 m.y.) andesitic stratovolcanoes that formed the southwest part of a widespread composite volcanic field in the southern Rocky Mountains. A nearly one-to-one relationship exists between large-scale pyroclastic eruptions and calderas: 18 major ash-flow sheets have been identified; 15 calderas are known, 2 are postulated on indirect evidence, and another one may possibly be identified in the northeast part of the volcanic field. In general, the different caldera cycles confirm the successive stages of development described by Smith and Bailey in 1968, except that few calderas demonstrate all stages of activity. On the other hand, almost every stage is exceptionally well developed in one or more of the calderas.

The development of the calderas is believed to chronicle the emplacement of successive segments of an underlying shallow batholith that is indicated by a major gravity low having sharp marginal gradients. Early calderas in the eastern part of the field formed in areas of clustered andesitic volcanoes and are not clearly associated with the main gravity low. These early calderas are believed to have formed above local high-level magma chambers that developed in the roots of the volcano clusters before the main body of the batholith rose to shallow depths. Post-collapse volcanics are largely of andesitic composition, indicating that only limited volumes of silicic differentiates formed at the tops of these chambers and that these differentiates were depleted by the ash-flow eruptions.

The western San Juan caldera complex also formed in an area of clustered earlier andesitic volcanoes, but are above the western part of the batholith indicated by gravity data. Large volumes of silicic differentiates formed within the batholith and were spread widely by ash-flow eruptions. Five calderas formed within a period of about 2 m.y. (in the interval from 29 to 27 m.y. ago), and contrasting lithologies of the ash-flow sheets related to the calderas require sequential development of cupolas and magmatic differentiation within them. Postsubsidence lavas that were erupted after emplacement of the most voluminous of these ash-flow sheets were largely of mafic quartz latite to andesite compositions, indicating temporary depletion of silicic differentiates in the source magma chamber. In the same area, a sixth caldera formed 4-5 m.y. later in response to eruption of a petrologically distinct ash-flow tuff believed to have had an origin different from the earlier ash-flow tuffs.

Development of the central San Juan caldera complex began about 28 m.y. ago, during the period of ash-flow eruptions and caldera collapses in the western San Juan Mountains, and was largely complete by the end of the Oligocene, 26 m.y. ago. During this 2-m.y. span, recurrent pyroclastic eruptions caused deposition of eight major ash-flow sheets and formation of at least seven calderas. The calderas are above the main eastern segment of the gravity low and are believed to mark the culminating upward movement of magma in this part of the batholith. Contrasting lithologies of sequential ash-flow sheets, which were derived from clustered and, in some places, nested caldera sources, require rapid development of successive cupolas above the batholith of and local differentiation within them. Most of the postsubsidence lavas that were erupted late in the different caldera cycles are coarsely porphyritic quartz latites compositionally related to the associated ash-flow tuffs; apparently even the most voluminous ash-flow eruptions did not deplete the silicic differentiates at the top of this part of the batholith. Concurrent eruption of andesitic rocks from scattered volcanoes not closely associated with the calderas is evidence of the presence of more mafic undifferentiated magma at depth, however.

The life span of the batholithic magma chamber, as indicated by ash-flow eruptions and caldera subsidence, appears to have been brief. Voluminous andesitic material was erupted from widely scattered centers throughout early Oligocene time (35-30 m.y. ago). Toward the end of this period, the first local magma chambers 10-30 km across had risen to shallow depths beneath some of the major volcano clusters, and had differentiated sufficiently to supply large volumes of silicic ash. Within the next 4 m.y. (30-26 m.y.), the main batholith rose to shallow depths in segments indicated by the main caldera complexes; vast quantities of ash were erupted and numerous calderas collapsed into the partly evacuated magma chambers. However, within another 4 m.y. (by 22 m.y. ago), the batholith had congealed sufficiently to allow a younger, petrologically distinctive magma to penetrate to comparably shallow depths and retain its compositional identity.

INTRODUCTION

The San Juan Mountains, southwestern Colorado (fig. 1), consist mainly of volcanic rocks that form the largest remnant of a major composite volcanic field that covered most of the southern Rocky Mountains in middle Tertiary time (Steven and Epis, 1968; Steven, 1975). This remnant is an eroded volcanic plateau (Steven, 1968), in which coalescing early andesitic volcanoes were widely overlain by the silicic tuffs of 18 major and several minor ash-flow sheets and by related lavas and breccias (Lipman and others, 1970). The sources of all the larger ash-flow sheets were near-surface magma chambers that were rapidly evacuated during voluminous pyroclastic eruptions, thereby causing collapse of overlying calderas. This paper reviews the history of the ash-flow field and its related calderas and summarizes the general relations that seem common to most individual cycles of pyroclastic eruption

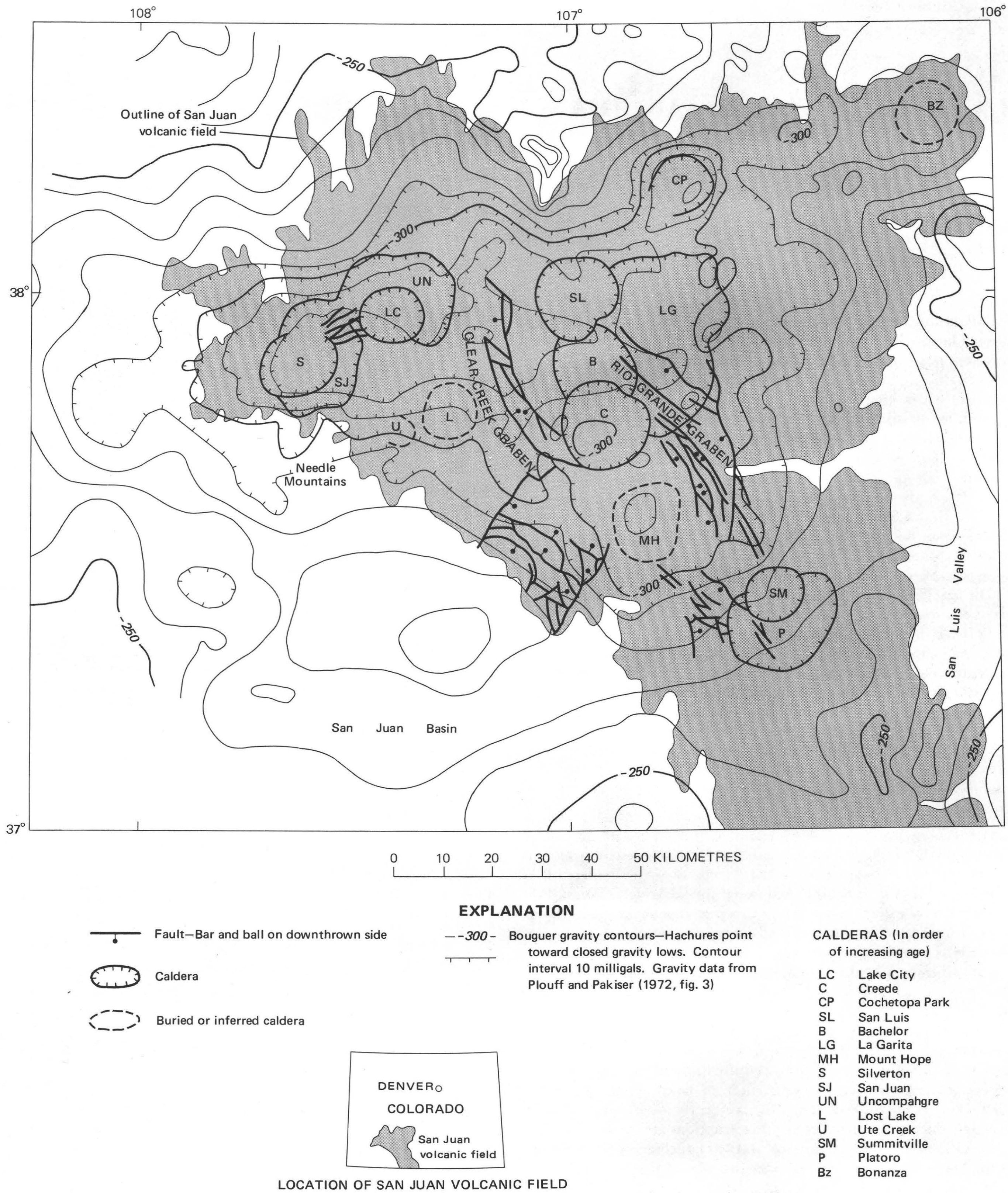

FIGURE 1.—Calderas in the San Juan volcanic field (patterned) in relation to Bouguer gravity field.

and caldera subsidence in the San Juan field.

The sequence of events we have determined for each of the calderas conforms well to the succession of stages in the development of a typical resurgent caldera described by Smith and Bailey (1968), although few of the San Juan calderas demonstrate all stages of activity. On the other hand, almost every stage is exceptionally well developed in one or more of the San Juan calderas.

GENERAL GEOLOGY

The general evolution of the San Juan volcanic field has been described by Lipman, Steven, and Mehnert (1970) and will be outlined only briefly here. Volcanic activity began in latest Eocene or earliest Oligocene time, probably between 40 and 35 m.y. ago.[1] The early rocks are largely intermediate in composition (andesite, rhyodacite, and mafic quartz latite) and were erupted from many scattered stratovolcanoes. These volcanoes were especially active in the interval from 35 to 30 m.y. ago, and the products derived from them coalesced into a composite volcanic field covering more than 25,000 km^2.

About 30 m.y. ago the character of volcanic activity changed markedly to predominantly pyroclastic eruptions, and large-volume quartz latitic and rhyolitic ash flows spread widely from many centers. Most of the larger sheets show evidence of compound cooling, and evidently were formed by many individual ash flows that followed one another in rapid succession. The earliest ash flows came largely from the northeastern and southern parts of the San Juan field, and were erupted from clusters of the early stratovolcanoes; caldera collapse resulting from the ash-flow eruptions largely destroyed the upper parts of these volcanoes. Postsubsidence eruptions around these early calderas were largely of intermediate-composition lavas and breccias that commonly are virtually indistinguishable from the early intermediate rocks of the composite volcanic field.

Beginning about 29 m.y. ago, ash-flow eruptions broke out in the western part of the San Juan volcanic field where five calderas formed in less than 2 m.y. The first two of these calderas are largely covered and are imperfectly understood, but the last three evolved in a manner generally similar to the early calderas farther east. They developed in an area of clustered andesitic central volcanoes whose vent areas were largely destroyed by caldera subsidence. Postsubsidence eruptions here were also mainly of intermediate-composition lavas and breccias that closely resemble those of the early volcanoes.

About 28 m.y. ago, while ash flows were still erupting and calderas forming in the western San Juan Mountains, major pyroclastic eruptions began in the central part of the San Juan volcanic field. A sequence of eight major ash-flow sheets formed, and caldera subsidences have been identified or inferred at all the ash-flow source areas. Postsubsidence eruptions around most of the central San Juan calderas were of viscous quartz-latitic and rhyolitic lavas closely related in composition to the ash-flow tuffs. Although some more mafic volcanoes were active during this same interval, they were not closely associated in space with the developing calderas. Ash-flow activity terminated in the central San Juan Mountains about 26.5 m.y. ago.

In early Miocene time, about 25 m.y. ago, the character of the erupted material changed from the andesitic and derivative rocks that formed the early San Juan volcanoes and succeeding ash-flow tuffs to fundamentally basaltic materials with some associated high-silica alkali-rich rhyolites. This change approximately coincided with inception of basin-and-range faulting in the adjacent San Luis Valley segment of the Rio Grande trough (Lipman and Mehnert, 1975). Fundamentally basaltic eruptions in the San Juan field continued intermittently until about 5 m.y. ago. The only large-volume rhyolitic ash-flow tuff deposited during the period of fundamentally basaltic activity is the Sunshine Peak Tuff, about 22.5 m.y. old (Mehnert and others, 1973a), which formed from ash flows that accumulated in and around the concurrently developing Lake City caldera in the western part of the San Juan volcanic field.

In all, 15 calderas are now known in the San Juan volcanic field, and indirect evidence suggests that at least two and perhaps three more exist.

A large negative Bouguer gravity anomaly underlies the area containing most of the calderas (fig. 1), and is believed to reflect a major underlying batholith (Plouff and Pakiser, 1972). Sharp gradients at the margins of the anomaly indicate that the top of the batholith is relatively shallow. The change from eruption of intermediate-composition rocks by widely scattered early stratovolcanoes to eruption of the more silicic ash flows probably took place as this batholith rose and differentiated beneath the central part of the field. When the roofs of the more differentiated and gas-charged cupolas of the batholith failed, great volumes of ash were erupted rapidly, and unsupported segments collapsed to form the calderas. The sequential development of the calderas is believed to reflect the progressive emplacement of the different high-level plutons of a composite batholith.

The calderas in the San Juan volcanic field became comprehensible to us only after the complex stratigraphy of the related ash-flow units and associated rocks was determined by regional mapping of the Durango 1°×2° quadrangle (Steven, Lipman, Hail, and others, 1974) and

[1]Except where otherwise noted, all specific age designations are from Lipman, Steven, and Mehnert (1970) or Steven, Mehnert, and Obradovich (1967).

adjacent parts of the Montrose 1°×2° quadrangle. This regional work has led to major revisions in stratigraphic nomenclature established by earlier studies of local areas (Steven, Lipman, and Olson, 1974; Lipman and others, 1973). The volcanic stratigraphy of the ash-flow units as understood in 1975 is given in table 1. For a more complete summary of the total volcanic stratigraphy, the reader should consult the above references and particularly the explanation of the Durango quadrangle map.

EARLY EASTERN CALDERAS

The oldest calderas in the eastern part of the San Juan field—the Bonanza caldera and the nested Platoro and Summitville calderas—are widely separated and the related ash-flow sheets do not overlap. Thus, the relative ages of eruption and caldera development at the two centers are uncertain (table 1). All these cycles are younger than the dated rocks in the early intermediate-composition volcanoes (34.7-31.1 m.y.) and are older than the Fish Canyon Tuff (27.8 m.y.). The only age relations among these rocks that can be told directly by superposition are those between the several members of the Treasure Mountain Tuff that are derived from the Platoro and Summitville calderas. K-Ar ages of the Treasure Mountain Tuff related to the Platoro and Summitville calderas appear older than those obtained from tuffs related to any of the calderas in the western San Juan Mountains, but present data do not permit interpretation of age relations between the Bonanza caldera and any of the other older calderas.

Both the Bonanza caldera and the Platoro and Summitville calderas formed within clusters of earlier andesitic stratovolcanoes, and they are on or just outside of the margin of the shallow batholith that gravity data suggest underlies the San Juan volcanic field (fig. 1) (Plouff and Pakiser, 1972). The Bonanza caldera is located near the northeast end of a narrow gravity low that extends east-northeast from the main anomaly; this caldera probably is localized above a satellitie pluton. The Platoro and Summitville calderas are outside the sharp gradient along the southeast side of the main gravity low, and thus are probably not above the near-surface part of the main batholith. Quite possibly these early calderas developed above local high-level magma chambers that formed in the roots of earlier volcanoes before the main batholith had risen to its present near-surface position.

PLATORO AND SUMMITVILLE CALDERAS

The Platoro and Summitville calderas in the southeastern part of the volcanic field (fig. 1) constitute a composite collapse structure about 20 km in diameter that formed as a result of recurring eruptions of ash flows of the Treasure Mountain Tuff (Lipman and Steven, 1970; Lipman, 1975a, b). The Platoro caldera and the nested younger Summitville caldera (fig. 2) formed within a cluster of six or seven intermediate-composition stratovolcanoes of the Conejos Formation. These central volcanoes had been extensively eroded and the intervening basins filled with the resultant detritus, producing a widespread low-relief surface. Ash-flow activity began 30-29 m.y. ago when at least 500 km^3 of phenocryst-rich quartz-latitic ash that now constitutes the La Jara Canyon Member of the Treasure Mountain Tuff was erupted from sources in the Summitville-Platoro region and spread 30-40 km in all directions (fig. 3). Caldera collapse began before these eruptions were complete, and the late ash flows forming the La Jara Canyon Member ponded within the collapsing caldera to a thickness of more than 800 m. Similar concurrent eruption and collapse characterized other large calderas in the San Juan Mountains, when the

TABLE 1.—*Ash-flow stratigraphy in the San Juan volcanic field*

Ash-flow unit	Estimated volume (km^3)	Dominant composition	Age (m.y.)	Related caldera
Sunshine Peak Tuff	100–500	Silicic rhyolite	22.5	Lake City.
Snowshoe Mountain Tuff	>500	Quartz latite	26.5(?)	Creede.
Cochetopa Park Tuff	<100	Zoned rhyolite to quartz latite.	>26.4 <26.7	Cochetopa Park.
Nelson Mountain Tuff	>500	....do	>26.4 <26.7	San Luis.
Rat Creek Tuff	<100	Rhyolite	>26.4 <26.7	Early stage San Luis.
Wason Park Tuff	100–500	....do	>26.4 <26.7	Unknown.
Mammoth Mountain Tuff	100–500	Zoned rhyolite to quartz latite.	26.7	Do.
Carpenter Ridge Tuff	>500	Rhyolite, locally zoned to quartz latite.	>26.7 <27.8	Bachelor.
Crystal Lake Tuff	25–100	Rhyolite	>26.7 <27.8	Silverton.
Fish Canyon Tuff	>3,000	Quartz latite	27.8	La Garita.
Masonic Park Tuff (upper member)	>500	....do	28.2	Mount Hope.
Sapinero Mesa Tuff	>1,000	Rhyolite	>27.8 <28.4	Uncompahgre and San Juan.
Dillon Mesa Tuff	25–100	....do	>27.8 <28.4	Uncompahgre(?).
Blue Mesa Tuff	100–500	....do	>27.8 28.4	Lost Lake(?).
Ute Ridge Tuff	>500	Quartz latite	28.4	Ute Creek.
Treasure Mountain Tuff:				
Ra Jadero Member	100–500	....do	>29.1 <29.8	Summitville
Ojito Creek Member	40–70	....do	>29.1 <29.8	Do.
La Jara Canyon Member	>500	....do	29.8	Platoro.
Bonanza Tuff	......	....do	>27.8	Bonanza.

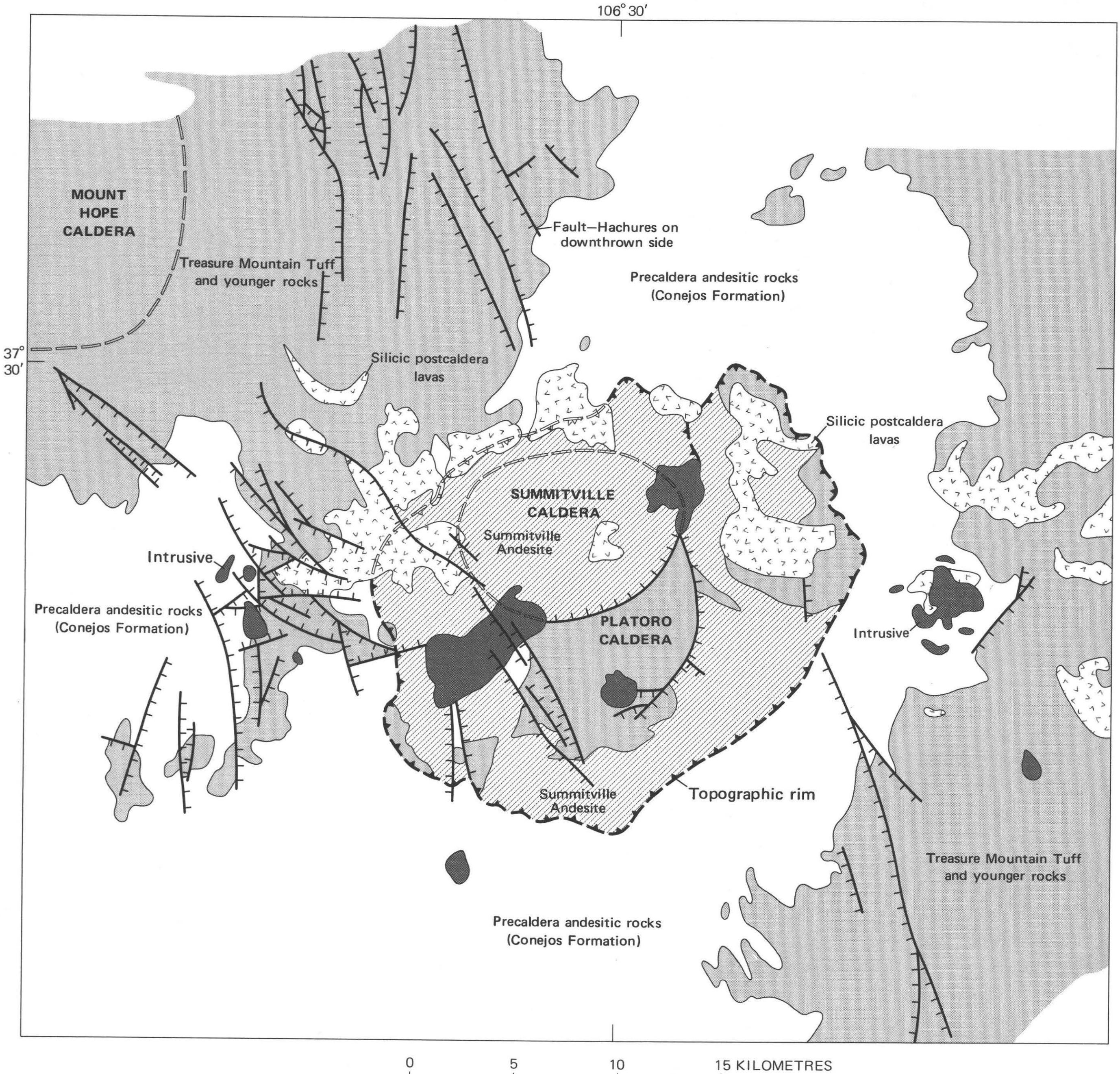

FIGURE 2.—Generalized geology of the Platoro and Summitville calderas. Control moderate to good where boundaries of calderas are shown by solid symbols; conjectural where shown by open symbols.

roofs of the magma chambers lost support before eruptions were completed.

The thick La Jara Canyon tuffs within the Platoro caldera are topographically and structurally high as a result of resurgent uplift shortly after collapse. Early resurgence is demonstrated by the presence in the core of the caldera of monolithologic talus breccias that were derived from the La Jara Canyon Member and that intertongue with lavas that filled the structural moat adjacent to the resurgent block. The resurgent core forms a nearly unbroken block that dips homoclinally to the southwest, in contrast with the fractured domical uplifts that characterize many other known resurgent calderas.

After resurgence was virtually complete, the marginal moat of the Platoro caldera was filled by as much as 1 km of dark andesitic lavas and interbedded volcaniclastic sedimentary rocks of the lower member of the Summitville Andesite. These andesitic lavas, in essence, represent

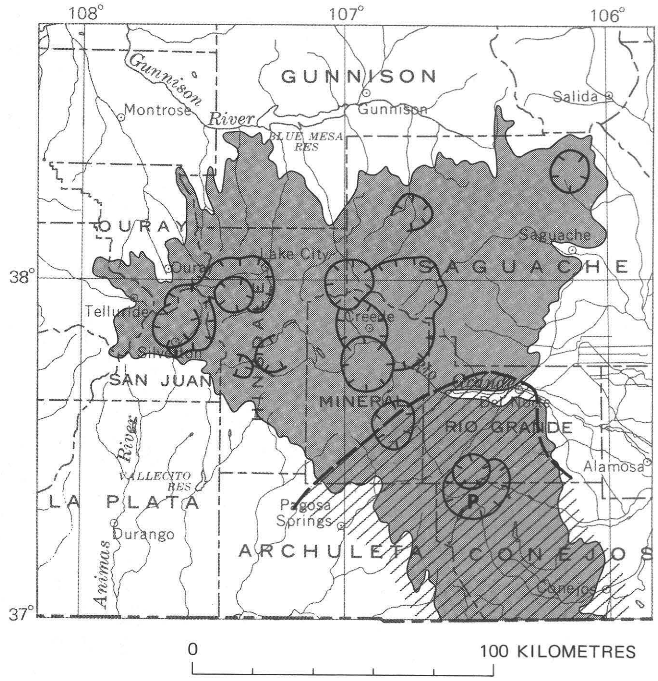

FIGURE 3.—Distribution of La Jara Canyon Member (diagonal lines) of Treasure Mountain Tuff in relation to Platoro caldera (P) and San Juan volcanic field (shaded). Base for figures 3, 4, 6–8, 10, 11, 15, 17–20, and 23–25 from U.S. Geological Survey, Colorado State map, 1:500,00, 1968.

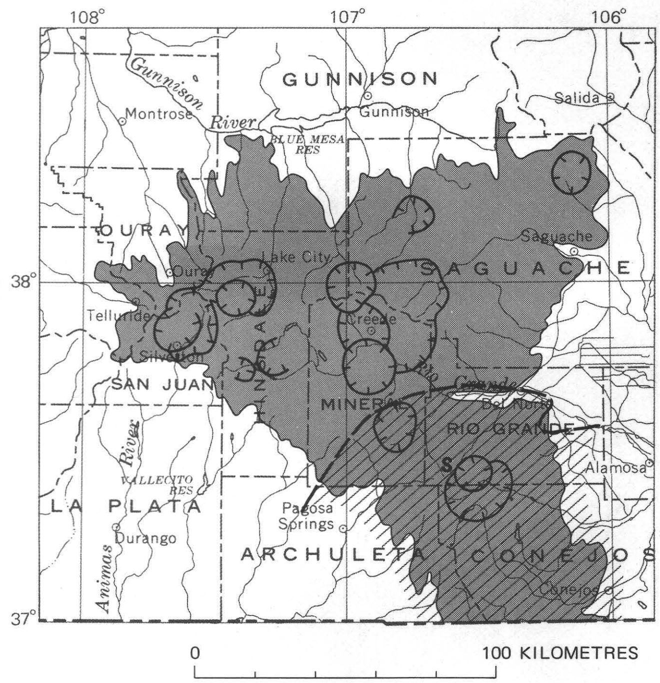

FIGURE 4.—Distribution of Ojito Creek and Ra Jadero Members (diagonal lines) of Treasure Mountain Tuff in relation to Summitville caldera (S) and San Juan volcanic field (shaded).

a continuation of the same type of volcanic activity that characterized the development of the Conejos Formation, with which they are readily confused in the field.

A younger collapse structure, the Summitville caldera, occupies the northern part of the Platoro caldera (fig. 2). This caldera apparently formed when ash-flows constituting the upper sheets of the Treasure Mountain Tuff, including the Ojito Creek and Ra Jadero Members, were erupted after the Platoro caldera moat was nearly filled by lavas of the lower member of the Summitville Andesite. The Ojito Creek and Ra Jadero tuffs (fig. 4) are nearly coextensive with those in the La Jara Canyon Member and their constituent ash must have been erupted from the same general area. Although the volumes of these upper two members are much less than that of the La Jara Canyon Member (table 1), they are large enough to suggest associated caldera collapse (Smith, 1960, fig. 3). In addition, the Summitville caldera is indicated by (1) a large-displacement (800+ m) arcuate fault marking the main ring-fracture fault on the southeast side of the caldera (fig. 2), (2) fragmentary exposures of the topographic wall, especially on the northeast side, and (3) the concentration of the products of late igneous activity and mineralization around the margins of the caldera. The caldera probably was not resurgent, but was filled by thick lavas of the upper member of the Summitville Andesite, and many key geologic relations are largely buried. In addition, extensive late intrusion and hydrothermal alteration further obscured relations.

Porphyritic rhyodacitic to rhyolitic lavas and genetically related dikes and granitic stocks were emplaced repeatedly around the margins of the Platoro and Summitville calderas during the interval between 29 and 20 m.y. ago, with dated events at 29.1, >26.7<27.8, 25.8, 22.8, and 20.2 m.y.; these shallow intrusions and associated rocks locally were hydrothermally altered and mineralized.

BONANZA CALDERA

A caldera in the vicinity of the old mining camp of Bonanza in the northeast part of the San Juan volcanic field has been postulated by Karig (1965), Mayhew (1969), Bruns (1971), Knepper and Marrs (1971, p. 261), and others.

The oldest rocks in the Bonanza area are andesitic to latitic flows and breccias of the Rawley Andesite and Hayden Peak Latite (Burbank, 1932; Mayhew, 1969) that form an interfingering assemblage. We interpret these rocks to be the near-source facies of one or more local volcanoes equivalent in age to the Conejos Formation near the Platoro area. These rocks are overlain by the Bonanza Tuff, a densely welded quartz-latitic ash-flow tuff that once formed a widespread sheet over much of the northeastern part of the San Juan volcanic field. Near Bonanza, remnants of this sheet must have been deeply faulted into the older andesitic pile, probably as a result of caldera subsidence. Younger andesitic flows and breccias cover at least some of the Bonanza Tuff that occurs within the subsided block (Knepper and Marrs, 1971, pl. 1).

Few generalizations can be made about the Bonanza caldera from available published data. However, we consider it significant that, as in the Platoro caldera complex, subsidence took place within an area of older intermediate-composition volcanoes and that post-subsidence lavas are predominantly andesitic in composition.

WESTERN SAN JUAN CALDERA COMPLEX

Six calderas in the western San Juan Mountains are located above the main western lobe of the gravity low that has been interpreted to represent a shallow batholith. The first five of these calderas, the Ute Creek, Lost Lake, San Juan, Uncompahgre, and Silverton, formed within the brief span of about 2 m.y., and the five related ash-flow deposits superficially resemble each other enough to have once been included within a single formation (the now-abandoned Gilpin Peak Tuff of Luedke and Burbank, 1963).

Of these five calderas, only the Ute Creek caldera is not clearly within the gravity low, but instead is located at the sharp gradient along the south side of the gravity low (fig. 1). This structure may have formed above a local magma chamber that either was too deep or, after ash-flow eruptions, did not retain enough relatively light silicic differentiate at its top to be detected by gravity measurements. The other four early calderas are well within the area of the gravity low, and, of these, three are closely clustered and have overlapping cycles of development. These cycles are believed to represent high-level magmatism and volcanic eruption related to the main upward movement of magma in this western part of the batholith.

The last subsidence structure, the Lake City caldera, formed about 5 m.y. after the earlier calderas subsided, and the associated ash-flow tuff contrasts markedly in composition and appearance with the earlier ash-flow tuffs. During the 5-m.y. interval, the main batholith is believed to have congealed sufficiently for a petrologically distinct batch of magma to penetrate to shallow depths and still retain its compositional identity.

UTE CREEK CALDERA

The southern margin of the caldera that formed during eruption of the Ute Ridge Tuff is exposed for about 3 km along the canyon of Ute Creek (figs. 5 and 6). Elsewhere, the eastern and northern topographic wall of the caldera can be located closely at only two places, one near the mouth of Ute Creek and the other along the south side of Pole Creek Mountain, near the eastern end of the mountain. The downdropped block within these limits may have subsided as a trapdoor that has no ring-fracture zone along its west side.

Along Ute Creek, intracaldera Ute Ridge Tuff, more than 300 m thick, is juxtaposed against Precambrian melasyenite and quartzite and an older unnamed crystal-poor ash-flow tuff of Tertiary age, whereas an outflow layer of the Ute Ridge Tuff is only about 130 m thick and extends out over an irregular surface cut on the older rocks. The probable, caldera-boundary fault between the thick section of Ute Ridge Tuff and the adjacent rocks is occupied by a quartz monzonite intrusive (fig. 5); another similar intrusive cuts the thick section of Ute Ridge Tuff north of lower Ute Creek.

In the vicinity of Ute Creek, a younger ash-flow sheet, the Blue Mesa Tuff, unconformably overlies the Ute Ridge Tuff, quartz monzonite intrusives, and Precambrian rocks. A chilled vitrophyre at the base of the Blue Mesa is in contact with all these older rocks, and north of Ute Creek a thin lens of andesite occurs locally along the unconformity. Development of the structural discordance between the thick section of Ute Ridge Tuff and the juxtaposed older rocks thus closely accords in time with eruption of the Ute Ridge Tuff, and seems most easily accounted for by caldera subsidence related to that eruption. Subsidence concurrent with eruption is indicated by the thick section of Ute Ridge Tuff within the downdropped block, in contrast with the relatively thin outflow sheet. Although we saw no evidence for post-subsidence resurgence, two quartz monzonite intrusive bodies along and near the southern margin apparently were emplaced late in the Ute Creek caldera cycle.

The topographic caldera wall along the east side of the downdropped block is closely controlled near the mouth of Ute Creek, where the top of a buried hill of older andesitic volcanic breccias (San Juan Formation) is exposed a few hundred metres east of the thick section of Ute Ridge Tuff that lies within the caldera. Several kilometres northwest, across the Rio Grande, another buried hill of andesitic breccias of the San Juan Formation is exposed along the south side of Pole Creek Mountain. The Ute Ridge and Blue Mesa Tuffs wedge out against this hill, which may represent a remnant of the northeast caldera wall.

Thick Ute Ridge Tuff is excellently exposed along the Rio Grande inside the west-facing semicircular arc described by the intrusive-filled fault along Ute Creek and the two buried hills of andesite breccia. The rude layers representing the many successive ash flows in the Ute Ridge Tuff dip about 5° east as part of a much later regional tilting that affected the whole western San Juan area, but otherwise are undeformed westward from the arcuate wall for 12-15 km. The tops of at least two buried hills of Precambrian crystalline rocks extending well up into the Ute Ridge Tuff are exposed along the Rio Grande 3-9.5 km west of the arcuate wall.

These incompletely exposed relations suggest that the

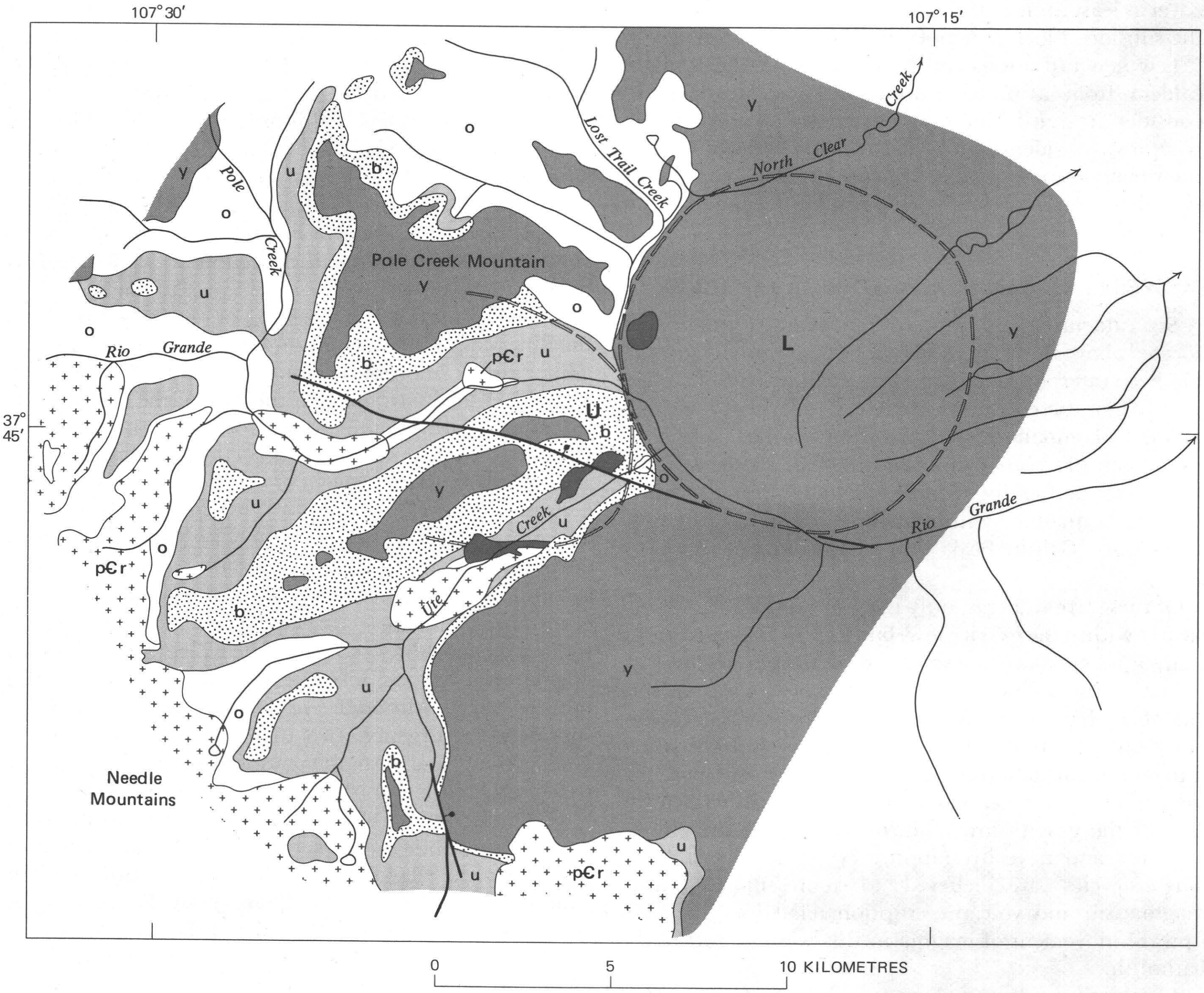

FIGURE 5.—Geologic map of Ute Creek (U) and Lost Lake (L) calderas. pЄr, Precambrian rocks; o, precaldera volcanic rocks; u, Ute Ridge Tuff; b, Blue Mesa Tuff; y, postcaldera volcanic rocks; black, intrusive rocks. Open rectangles indicate approximate boundaries of postulated buried calderas.

source of the Ute Ridge Tuff was in a hilly area cut on older Precambrian rocks and Tertiary andesitic rocks, and that the pyroclastic eruptions caused concurrent subsidence of a trapdoor block that was faulted along the south, east, and north but probably only downwarped on the west. The fragmentary structural and topographic wall exposed in places along Ute Creek and Pole Creek Mountain reflects the abrupt boundaries of subsidence in these directions, whereas the downwarped(?) western margin is obscured by the relatively flat lying upper part of the Ute Ridge Tuff exposed along the Rio Grande.

LOST LAKE CALDERA (BURIED)

A distinctive arcuate drainage pattern along the upper Rio Grande (fig. 5) reflects a buried caldera related to eruption of the ash composing the Blue Mesa Tuff. All rocks in this area dip regionally about 5° east and northeast; eastward across the arcuate drainage pattern, however, the dips increase to 10°-15° and then flatten again to form an arcuate monocline. Fracturing related to this monocline provided a zone of weakness later etched out by stream erosion. The monocline involves the Dillon Mesa and Sapinero Mesa Tuffs and younger units in this area, and reflects minor late subsidence around the western periphery of an older buried caldera.

The western margin of the largely buried Lost Lake caldera closely follows the arcuate monocline. The wall of the caldera is closely controlled near the mouth of Ute Creek, where a hill of older andesitic mudflow breccia protrudes up into the ash-flow section and represents a

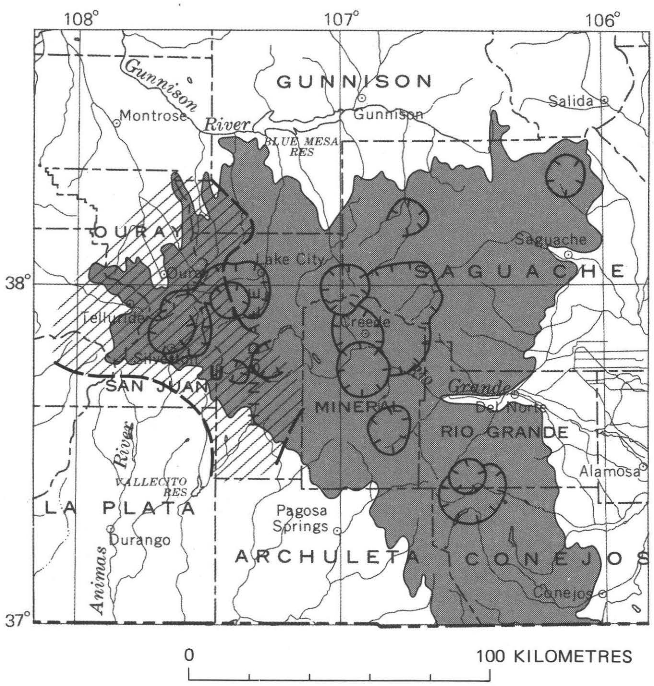

FIGURE 6.—Distribution of Ute Ridge Tuff (diagonal lines) in relation to Ute Creek caldera (U) and San Juan volcanic field (shaded).

wedge-shaped septum between the Ute Creek and Lost Lake calderas (fig. 5). Farther north, the northwestern wall of the Lost Lake caldera follows Lost Trail Creek for about 5 km; this segment of the caldera is marked, on the west side of the creek, by early, intermediate-composition andesitic rocks in the wall of the caldera and, on the east side, by caldera-filling rocks. No constraints are known on the east side of the caldera, however, and the projected margin (fig. 5) is drawn simply to close out the eastern side of a circular area that conforms to the arcuate monocline and drainage pattern to the west. The Lost Lake caldera, like several others in the San Juan volcanic field, possibly may have subsided as a trapdoor block with an incomplete ring-fracture zone and hinged eastern margin.

The oldest rocks exposed within the Lost Lakes caldera are the nearly identical Dillon Mesa and Sapinero Mesa Tuffs. These rocks form the lower parts of prominent cliffs along the Rio Grande, and are best exposed along the north side of the river opposite the mouth of Ute Creek. At this locality, the lower cliffs consist of Dillon Mesa Tuff; the upper 150 m of this unit is well exposed but, as the base is everywhere below the level of the river, its total thickness is not known—although it probably greatly exceeds the 0-100 m of Dillon Mesa Tuff exposed on Pole Creek Mountain west of the caldera. The overlying Sapinero Mesa Tuff, which forms the upper cliffs, is about 130 m thick, about the same as it is on Pole Creek Mountain. Evidently the Dillon Mesa ponded within and passively filled the caldera, and the succeeding Sapinero Mesa Tuff was deposited across it without appreciable thickening.

The Lost Lake caldera cuts off the Ute Ridge Tuff (fig. 5), and in turn was largely filled by the Dillon Mesa Tuff. These stratigraphic relations limit the time of caldera subsidence to the period during which the ash of the Blue Mesa Tuff was erupted. Of all the major ash-flow sheets in the upper Rio Grande area, only the Blue Mesa Tuff lacks an exposed source. The Blue Mesa is a widespread sheet (fig. 7) that pinches out against Precambrian rocks in the Needle Mountains on the south, extends westward to the eroded edge of the volcanic rocks near Telluride, and wedges out to the north against older volcanic rocks north of the Gunnison River, more than 80 km north of the upper Rio Grande area. To the east, the Blue Mesa Tuff is covered by younger rocks and its distribution is unknown (Steven, Lipman, Hail, and others, 1974). The Blue Mesa Tuff and older rocks are sufficiently well exposed north and west of the upper Rio Grande area that a caldera source can be eliminated in most of these areas. The source therefore most likely lies within the covered part of the sheet—and thus in the Lost Lake caldera.

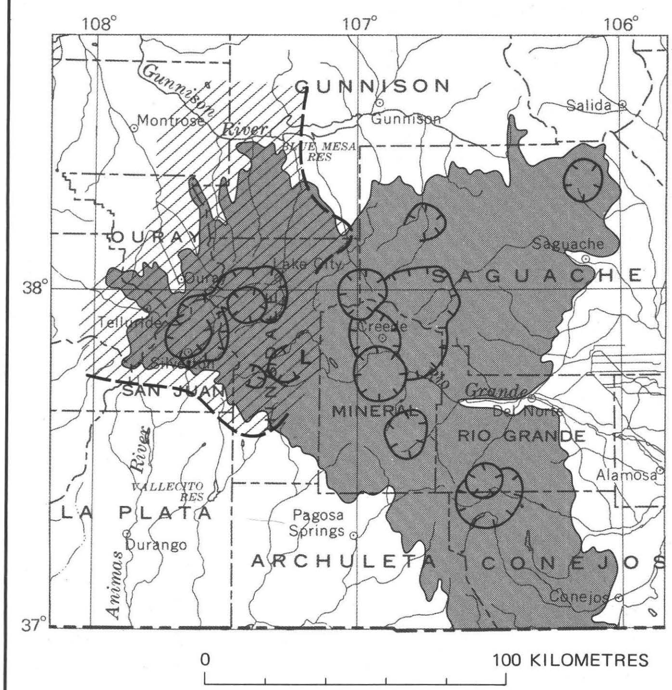

FIGURE 7.—Distribution of Blue Mesa Tuff (diagonal lines) in relation to Lost Lake caldera (L) and San Juan volcanic field (shaded).

The Blue Mesa Tuff is a uniform-textured, moderately phenocryst poor, densely welded ash-flow tuff over most of its exposed extent. In the upper Rio Grande area, however, the phenocrysts are larger and more abundant than elsewhere, and the unit is weakly compositionally zoned, becoming more mafic upward. A rhyodacitic lava flow also occurs locally between the Blue Mesa and the overlying Dillon Mesa Tuff on the north side of Pole Creek Mountain and just west of the arcuate monocline; this is the only known locality of lava-flow activity at this horizon. These areally restricted variations suggest a nearby source for the Blue Mesa Tuff.

No evidence was seen for resurgent doming of the Lost Lake caldera after subsidence. However, only the upper parts of the caldera fill can be seen, and the oldest rocks exposed are along the margins of the caldera, where the effects of resurgence would have been minimal. Thus, a low dome could exist a depth and not be reflected by the younger rocks that cover the caldera area.

SAN JUAN, UNCOMPAHGRE, AND SILVERTON CALDERAS

The geologic history of the caldera complex in the western San Juan Mountains has recently been reinterpreted by Lipman, Steven, Luedke, and Burbank (1973), and the discussion here is taken largely from them. The western San Juan Mountains were the site of a cluster of intermediate-composition central-vent volcanoes in early Oligocene time, 35-30 m.y. ago. The near-source facies of these volcanoes consists of complex accumulations of lavas, breccias, and pyroclastic debris, which pass laterally into coalescing volcaniclastic aprons consisting predominantly of mudflow breccias and, at the margins, of conglomeratic and other stream-worked debris. The clustered volcanoes formed part of the great field of early intermediate-composition volcanic rocks that covered much of the southern Rocky Mountains in early Oligocene time (Lipman and others, 1970; Steven and Epis, 1968; Steven, 1975).

Ash-flow sheets from nearby sources at the Ute Creek and Lost Lake calderas covered the lower flanks and coalescing outflow aprons of these volcanoes, and wedged out against highlands built up around the central vents.

UNCOMPAHGRE AND SAN JUAN COLLAPSES

The volcanic cycles that led to the development of the San Juan, Uncompahgre, and Silverton calderas probably began when the relatively small volume of material constituting the Dillon Mesa Tuff (table 1; fig. 8) was erupted shortly before 28 m.y. ago. No direct evidence can be marshalled to tie this eruption with any specific increment of subsidence, but the unit seems to be radially distributed around the area of the Uncompahgre caldera, and is thickest and most densely welded near the margins of this possible source area. Renewed eruptions of similar rhyolitic ash-flow tuff material about 28 m.y. ago led to widespread emplacement of the Sapinero Mesa Tuff, and to simultaneous collapse of the Uncompahgre and San Juan calderas (fig. 9).

The Sapinero Mesa Tuff spread widely (fig. 10) from its source area at these calderas, and had an estimated volume in excess of 1,000 km³. It has been traced northeastward for more than 90 km, northward 65-70 km, and southeastward 40-45 km. Apparently it wedged out southward against the older highland of Precambrian rocks in the Needle Mountains. The western flank of the volcanic pile has been removed by erosion, and the original extent of the Sapinero Mesa Tuff in this direction is not known. Outflow Sapinero Mesa Tuff is generally less than 100 m thick, whereas the intracaldera Eureka Member is at least 700 m thick in places and the base is only locally exposed. This disparity in thickness between outflow and intracaldera facies is common among the San Juan calderas, and is interpreted to indicate subsidence concurrent with eruption; the intracaldera accumulation is generally somewhat younger than most of the outflow sheet.

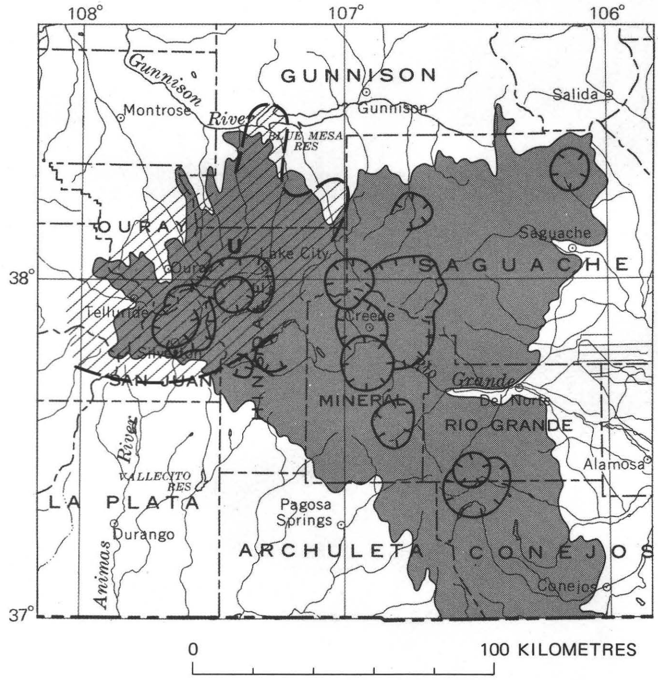

FIGURE 8.—Distribution of Dillon Mesa Tuff (diagonal lines) in relation to Uncompahgre caldera (U) and San Juan volcanic field (shaded).

Approximate contemporaneity of subsidence of the Uncompahgre caldera and eruption of the Sapinero Mesa Tuff can be demonstrated convincingly on the basis of geologic evidence (Lipman and others, 1973), and similar general relations of intracaldera and outflow accumulations of Sapinero Mesa Tuff for the San Juan caldera imply a similar timing. Subsidence of the two calderas was accompanied by widespread landsliding and avalanching of the steep caldera walls, and abundant debris from these sources is interleaved marginally with the intracaldera ash-flow accumulations (Eureka Member) in both calderas. By this process the topographic walls of the two calderas actually merged locally to form a single depression with a distorted dumbbell shape: the two main subsided blocks were joined across a low divide when the septum between them largely caved away (fig. 9).

The simultaneous development of adjacent but separate

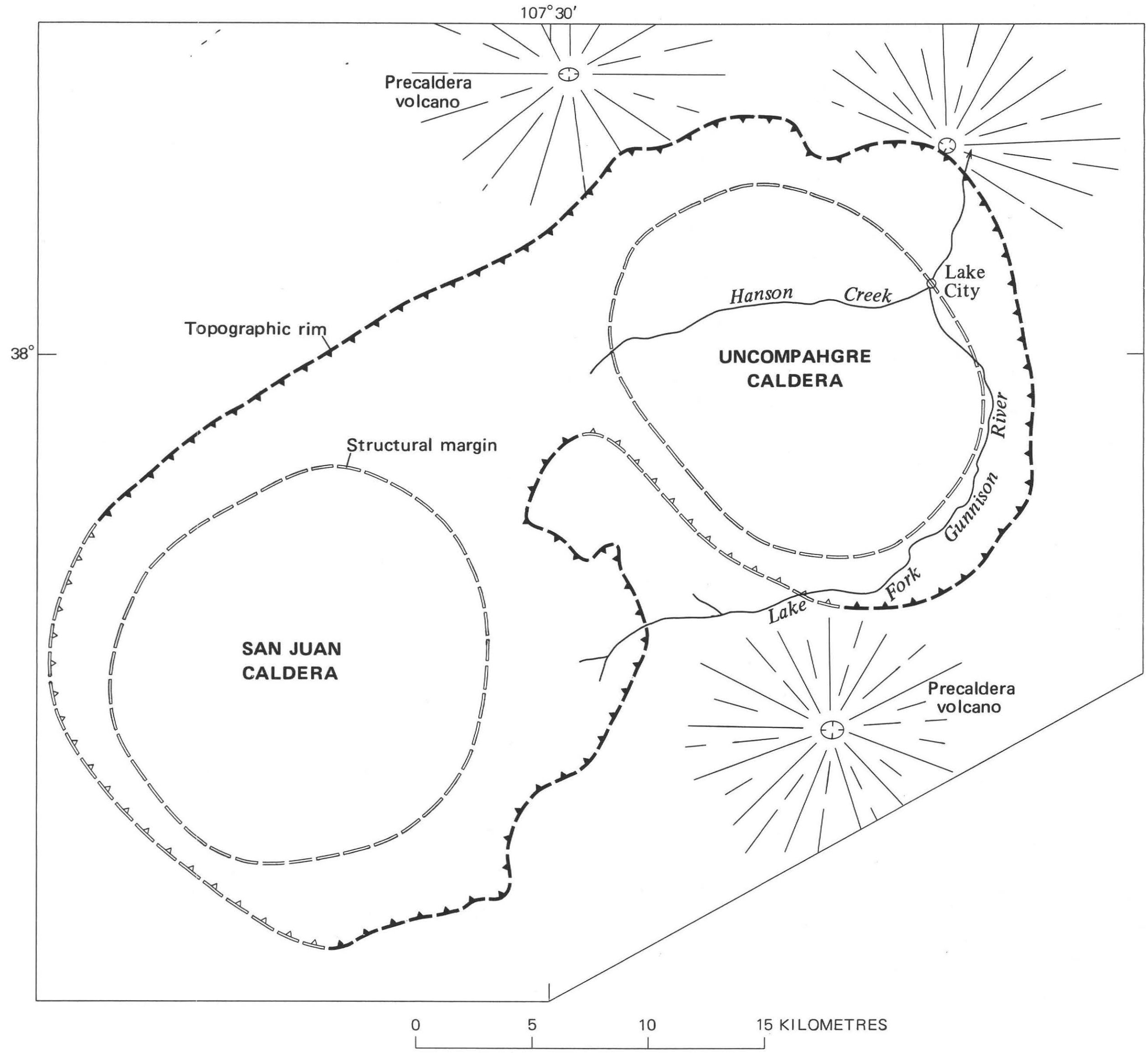

FIGURE 9.—Sketch map of the western San Juan caldera complex after subsidence related to eruption of the Sapinero Mesa Tuff. Control moderate to good where boundaries are shown by solid symbols; conjectural where shown by open symbols.

calderas was followed by merged later stages of the local caldera cycles. The calderas were resurgently domed together over an extended period of time, while the depressions were being filled with lavas and sediments from local sources and with ash-flow tuffs from concurrently developing calderas to the east. Renewed ash-flow eruptions forming the Crystal Lake Tuff during this period of resurgence and caldera filling led to subsidence of a local trapdoor block, the Silverton caldera, nested within the older San Juan caldera. These generally concurrent developments will be discussed separately in the following paragraphs, although the events are closely related and are manifestations of the same basic volcanic processes.

POSTCOLLAPSE LAVAS AND SEDIMENTS

The first postsubsidence eruptions within the San Juan and Uncompahgre calderas were mostly of viscous, coarsely porphyritic lavas of predominantly rhyodacitic and quartz-latitic composition. These heaped up in the vicinity of their vents to form prominent local domes and thick flows, surrounded by lower areas where pyroclastic and reworked debris accumulated as bedded tuffs and volcaniclastic sediments. Some of these lower areas apparently were the sites of local ponds in which finely stratified deposits formed. This assemblage of thick porphyritic flows and associated bedded deposits is best displayed within the San Juan caldera, where it has been called the Burns Formation. It can be recognized as a

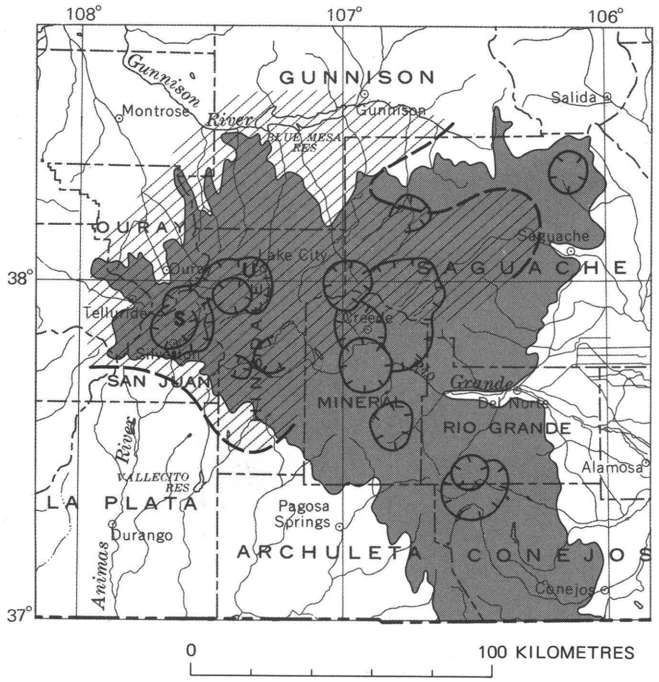

FIGURE 10.—Distribution of Sapinero Mesa Tuff (diagonal lines) in relation to San Juan (S) and Uncompahgre (U) calderas and San Juan volcanic field (shaded).

distinctive assemblage across the low divide into the northwest part of the Uncompahgre caldera; eastward, sedimentary rocks predominate and there are only minor porphyritic lavas.

The lavas filling the depression changed in composition upward to dark fine-grained andesite flows. These lavas were appreciably more fluid than the viscous porphyries of the Burns Formation, and the resulting flows are thinner and more widespread. Sedimentation in low areas continued, and the resulting bedded rocks are indistinguishable from many of those in the underlying Burns Formation. Local volcanic activity diminished later in the period of infilling, and volcaniclastic sedimentary rocks compose the upper layers of fill. The sequence of predominant andesitic flows grading upward into predominant sedimentary beds is best displayed in northeastern parts of the San Juan caldera, where the flows were originally called the pyroxene andesite unit and the overlying bedded rocks the Henson Tuff (Cross and others, 1905, 1907). Later, Luedke and Burbank (1963) combined both of these units into a redefined Henson Formation. Across the north side of the Uncompahgre caldera, the proportion of andesite flows to sedimentary rocks decreases eastward, and in the northeast part of the Uncompahgre caldera, the whole section generally equivalent to the Burns and Henson Formations consists largely of similar-appearing sedimentary rocks.

Rocks equivalent to the caldera-filling Burns and Henson Formations are found outside the calderas only on the southeast side, where andesitic flows and breccias overlie the Sapinero Mesa Tuff and underlie younger ash-flow units derived from sources to the east.

INTRACALDERA ASH-FLOW TUFFS

The Burns and Henson rocks forming the bulk of the fill in the San Juan and Uncompahgre calderas are overlain by a sequence of ash-flow tuffs, mostly from caldera sources in the central San Juan Mountains, interlayered with locally derived sedimentary and volcanic rocks. The basal unit of this upper sequence is the Fish Canyon Tuff, derived from the La Garita caldera source area about 27.8 m.y. ago. Overlying ash-flow units consist in sequence of the Crystal Lake Tuff (derived from the Silverton caldera), the Carpenter Ridge Tuff (from the Bachelor caldera), Wason Park Tuff (caldera source not identified), and Nelson Mountain Tuff (from the San Luis caldera). Locally derived sediments closely similar to those in the Henson and Burns Formations separate all these ash-flow units at one place or another, and locally derived lavas of generally intermediate composition intervene between the Crystal Lake and Carpenter Ridge Tuffs, the Carpenter Ridge and Nelson Mountain Tuffs, and overlie the Nelson Mountain Tuff within and adjacent to the Uncompahgre caldera.

SILVERTON COLLAPSE

Eruption of the Crystal Lake Tuff (fig. 11) during the period of caldera filling resulted in trapdoor subsidence of the Silverton caldera within the older San Juan caldera (fig. 12). A block 15 km across, consisting in its upper parts of thick sections of Burns and Henson lavas and sediments, was displaced more than 600 m downward along its southern margin, whereas a sharp monocline cut by a deeply infaulted graben marks its northeastern margin. Even in the present deeply dissected topography, the core of the trapdoor block stands nearly as high as the ash-flow deposits in the adjacent terrain, suggesting that no great thickness of Crystal Lake Tuff could ever have existed there. This suggestion accords with relations noted at other lesser calderas in the San Juan volcanic field related to small- to moderate-volume ash flow eruptions, where subsidence usually followed eruption and in places did not form complete ring-fracture zones.

RESURGENT DOMING

Resurgence of the San Juan, Uncompahgre, and Silverton calderas differed in several important aspects from resurgence at many of the other calderas in the San Juan volcanic field. Although it apparently began shortly after subsidence, uplift of the volcanic source areas probably continued for more than a million years through the period of infilling by locally derived lavas and sediments and by ash-flow tuffs from extraneous sources. As uplift continued rhyolitic magma regenerated beneath the San Juan caldera and erupted catastrophically as the ash-flows of the Crystal Lake Tuff, with related sub-

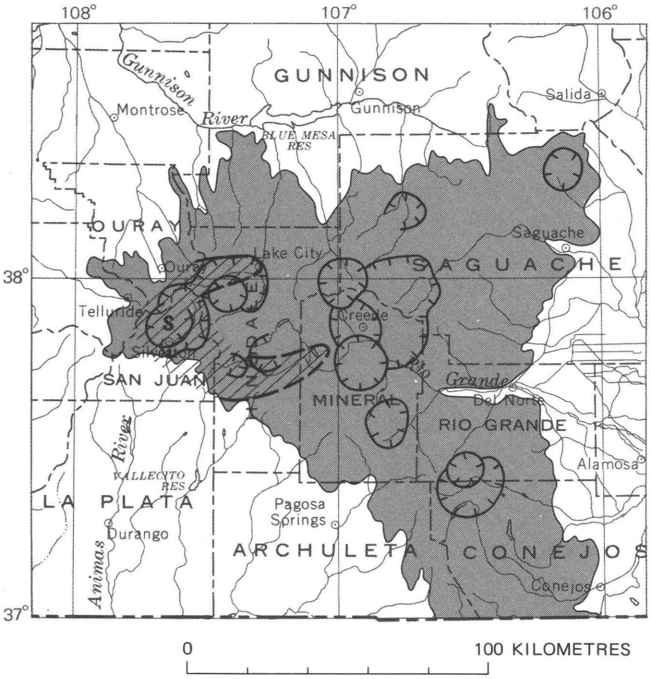

FIGURE 11.—Distribution of Crystal Lake Tuff (diagonal lines) in relation to Silverton caldera (S) and San Juan volcanic field (shaded).

sidence of the Silverton caldera. Structures that formed during this later subsidence appear to merge with some of the structures formed by uplift and seem to have developed concurrently.

Early resurgence is indicated by local angular unconformities between slightly tilted and eroded welded tuffs in the intracaldera Eureka Member of the Sapinero Mesa Tuff and overlying intermediate-composition lavas in the Burns Formation, as first noted by Luedke and Burbank (1968, p. 183). The extent of this early resurgence cannot be determined from the sparse evidence now available. Later magmatic uplift is indicated by the broad doming of the whole area of the San Juan and Uncompahgre calderas that affected the younger caldera fill as well. This broad uplift apparently was episodic, inasmuch as the ash-flow units overlying the Burns and Henson Formations appear to have been confined to a moat area around at least the eastern and northern margins of the uplifted core of older rocks, and yet in turn were tilted by further uplift of the core.

Longitudinal distention fractures along the crest of the broad domal uplift formed the deeply infaulted Eureka graben, which extends northeastward from the San Juan caldera into the uncollapsed septum between the San Juan and Uncompahgre calderas, where it is cut off abruptly by the much younger Lake City caldera. This graben offsets the caldera-filling Burns and Henson Formations as much as 0.5 km along the major faults, and, in places, graben faults cut small remnants of the younger Crystal Lake Tuff.

At it's southwest end, the trend of the Eureka graben changes sharply, turning from northeast to northwest and giving the downfaulted area the distinctive bootlike shape shown in figure 12 (Burbank, 1951; Burbank and Luedke, 1969). The intersection of the northeast-trending Sunnyside fault and northwest-trending Ross Basin fault at the instep of the boot is intensely mineralized and is the site of the highly productive Sunnyside mine. This area has been studied in detail by many geologists and is well illustrated on a geologic map by Burbank and Luedke (1969, pl. 2). The fractures and veins pass smoothly around a sharp right-angle bend, and seem to have formed concurrently. To the northwest, as shown in the same illustration, several important veins and faults begin at the footwall of the Ross Basin fault as northeast-trending fractures generally parallel to the leg of the boot, but after several kilometres they swing sharply east and southeast to parallel the instep of the boot. This change in direction would again seem to require coexistent distentional stresses related to both major trends of the Eureka graben.

Whereas the northeast-trending fractures are along the crest of the broad dome of the simultaneously uplifted San Juan and Uncompahgre calderas, the northwest-trending fractures that define the foot of the boot are within the monoclinal hinge area along the north side of the younger Silverton caldera. The northwest-trending fractures thus appear to represent distentional fractures related to trapdoor subsidence of this block. Thus, in order for these different fault systems to have merged so completely, eruption of the Crystal Lake Tuff and subsidence of the Silverton caldera must have been concurrent with a major episode of uplift of the older calderas. Later or continued uplift of the broad dome is suggested by several minor northeast-trending faults that cut the foot of the Eureka graben boot (Burbank and Luedke, 1969, pl. 2).

Except for its having been formed during the period of general uplift, the Silverton caldera itself shows no evidence of being resurgently domed. Development of the spectacular radial and other intricate vein and dike patterns just outside the northwest and southeast margins of the Silverton caldera (Burbank, 1941; Varnes, 1963) may have resulted from this special stress environment. No other San Juan caldera has similar intricate patterns of fracture-related structures.

LAKE CITY CALDERA

After about a 4-m.y. period of greatly reduced volcanic activity in the western San Juan Mountains, ash-flow eruptions that produced the Sunshine Peak Tuff began about 22.5 m.y. ago in the Lake City area (Lipman and others, 1973; Mehnert and others, 1973a). Outflow Sunshine Peak Tuff must have been deposited widely in the region, although only small erosional remnants have survived. Concurrently with these eruptions, an elliptical block about 12 by 15 km across, nested within the southern

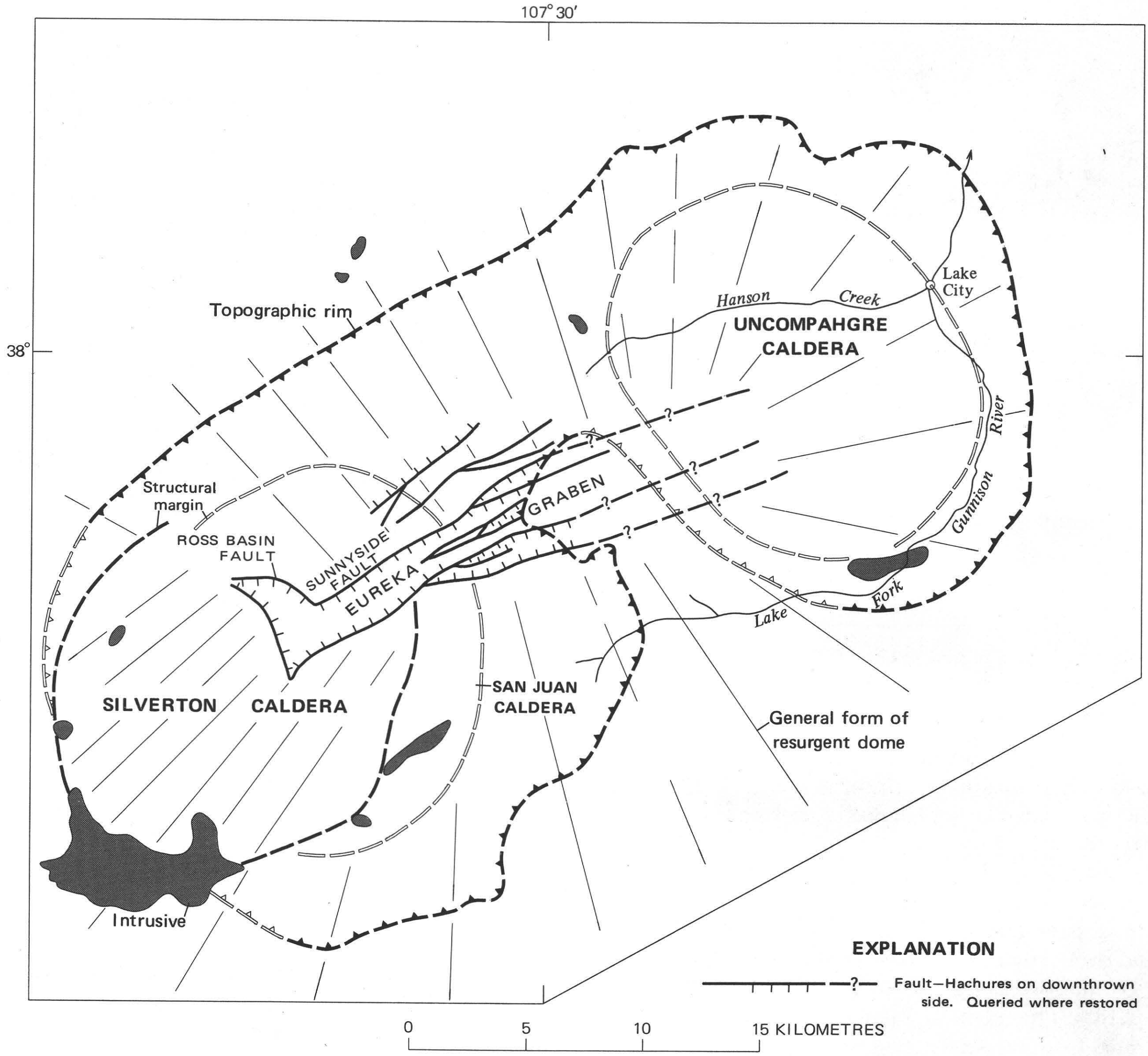

FIGURE 12.—Sketch map of the western San Juan caldera complex after subsidence of the Silverton caldera and general resurgence. Control moderate to good where boundaries are shown by solid symbols; conjectural where shown by open symbols.

part of the older Uncompahgre caldera, subsided to form the Lake City caldera (fig. 13). The last-erupted part of the Sunshine Peak accumulated to a thickness of as much as 1 km within the concurrently subsiding caldera, and great landslide avalanches caved off the caldera wall, spread across the caldera floor, and intertongued with the accumulating ash flows.

The ring fault along which this collapse occurred is continuously exposed for about 300° of arc around the caldera; it is nearly everywhere a single fault, typically marked by only a metre or so of gouge and minor hydrothermally altered rock. It is exposed over topographic relief of as much as 600 m, and is everywhere steep, dipping inward from 75° to nearly vertical.

Shortly after the ash-flow eruptions ceased, lava flows and domes of viscous silicic quartz latite, fed largely from vents along the ring fault, accumulated around the margins of the caldera floor. These lavas tend to overlie the Sunshine Peak Tuff conformably and dip quite steeply in places. They probably largely predate resurgent doming, although the effects of doming on them are difficult to distinguish reliably from primary dips of the flows. An east-northeast-trending line of rhyolite intrusives was emplaced in the moat area of the older Uncompahgre caldera, north of the Lake City caldera. These rocks are closely similar in composition to the Sunshine Peak Tuff, but apparently were emplaced somewhat more recently, with one intrusive yielding a K-Ar age of about 18 m.y. (H. H. Mehnert, written commun., 1974).

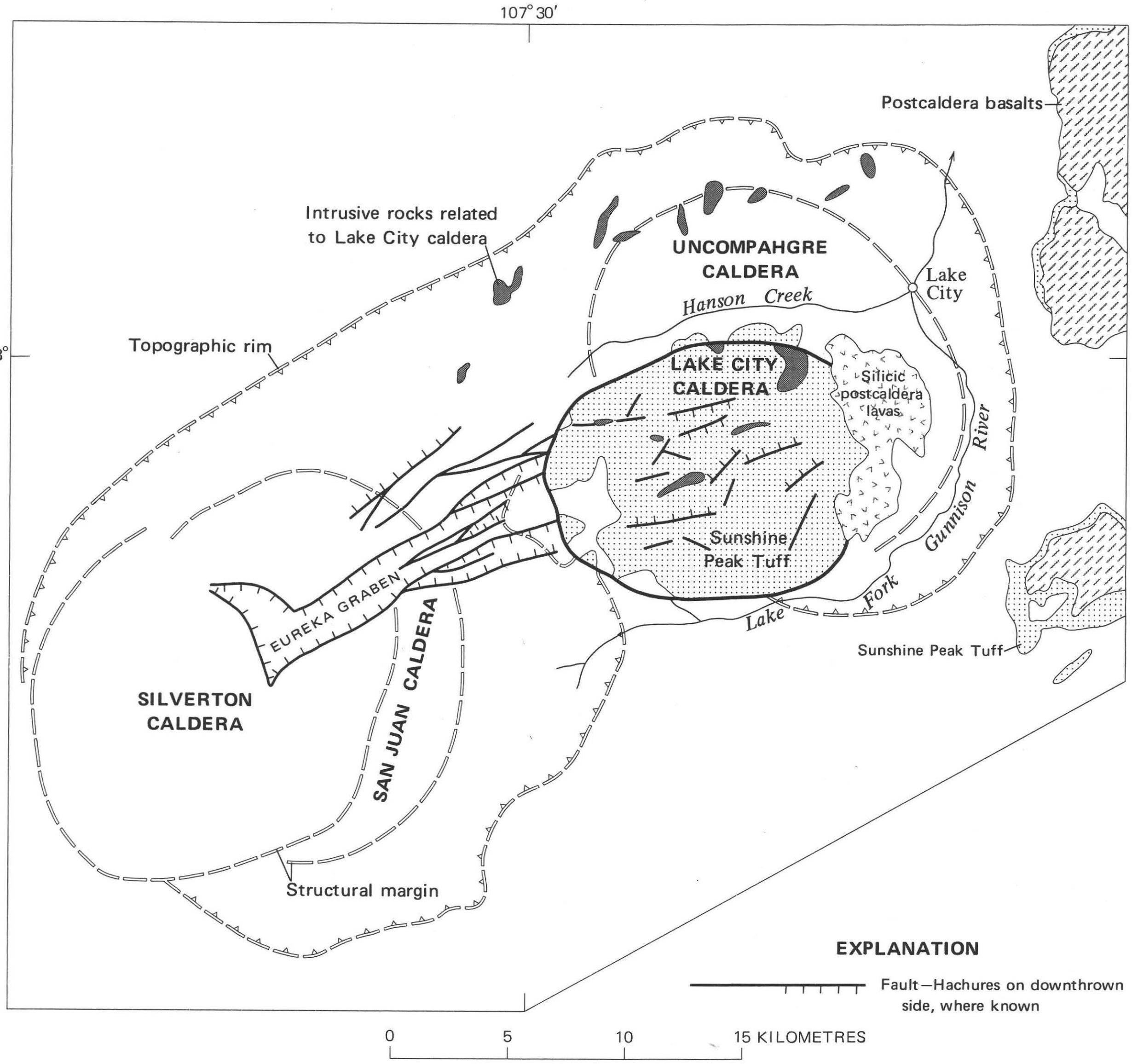

FIGURE 13.—Generalized geology of the western San Juan caldera complex showing distribution of rocks related to the Lake City caldera.

Resurgence of the Lake City caldera produced a simple dome characterized by outward dips of 20°-25° on its flanks and a northeast-trending apical graben over its distended crest. The trend of this graben reflects reactivation of the trends of the earlier Eureka graben system, which was related to resurgence of the Uncompahgre and San Juan calderas. Most of the mapped faults of the Lake City resurgent structure have relatively small displacements—10-50 m—and some seem to be little more than cracks that localized weak hydrothermal alteration. Chaotic caldera-collapse breccias are widely exposed below the intracaldera tuffs on the southwest side of the Lake City caldera, and the resurgence appears to have been somewhat asymmetrical, with maximum uplift in this area. Resurgence resulted from upward movement of magma which crystallized as a shallow stock of granite porphyry.

Gently dipping upper contacts of the granite porphyry are exposed at the bottoms of several deep erosional valleys within the core of the Lake City caldera, and the most intensely altered rock within the resurgent dome occurs around margins of the granite porphyry. Parts of the northern ring fault are occupied by a short, thick, discontinuous ring dike, which broadens and becomes coarser grained downward. The top of the granite porphyry is within 1 km of the top of the Sunshine Peak Tuff indicating crystallization at very shallow depths beneath the resurgent dome.

Most of the original topographic wall of the Lake City caldera has been eroded, and only a few small remnants are preserved southwest of Lake City. The present valleys of Henson Creek and the upper Lake Fork of the Gunnison River, which define a striking elliptical drainage pattern just outside the structural boundary of the Lake City caldera, are not directly controlled by any major fault structures. They more likely developed in debris that accumulated in a low topographic moat along the margin of the resurgent dome of the Lake City caldera outside the limits of the subsided block, and were subsequently superimposed onto older rocks of the caldera wall.

CENTRAL SAN JUAN CALDERA COMPLEX

The central San Juan caldera complex developed above the eastern part of the gravity anomaly (fig. 1) between 28.2 and 26.5 m.y. ago. Within this brief span of less than 2 m.y., eight major ash-flow sheets were erupted, at least seven calderas formed, and numerous local volcanic rock units accumulated. These caldera cycles thus had an average duration of only about a quarter of a million years, and in at least one case, the cycles of two nearby calderas overlapped in time.

We believe that these intense pyroclastic eruptions and resulting caldera subsidences marked the culmination of upward movement of magma to form the eastern part of the underlying batholith. As the roof above this segment of the batholith became progressively thinner, it was breached by numerous ash-flow eruptions of great magnitude, and related calderas subsided at the ash-flow source areas. The development of the numerous clustered and partly overlapping calderas that followed one another in rapid succession, and the common marked contrasts between lithologies—ranging from phenocryst-rich quartz latites to phenocryst-poor rhyolites—of successive ash-flow deposits, required rapid congealing of the upper parts of the local cupolas and equally rapid reestablishment of new cupolas and magmatic differentiation within them. The pyroclastic eruptions and caldera subsidences apparently ceased when the upper part of the batholith congealed to a thickness sufficient to contain the magmatic pressures.

MOUNT HOPE CALDERA

The Mount Hope caldera (fig. 14) is almost completely buried by younger rocks, primarily the Fish Canyon Tuff, but fragmentary evidence suggests that it was the source of two phenocryst-rich quartz latite ash-flow sheets of the Masonic Park Tuff. The lower sheet has been recognized only within 10-15 km of the caldera, but the upper sheet (fig. 15) extends 30 km west of the caldera, to the margin of the San Luis Valley 50 km east, and into New Mexico 75 km southeast (Steven, Lipman, Hail, and others, 1974).

The topographic wall along the north margin of the Mount Hope caldera is exposed for about 6 km. This wall cuts sharply across the lower ash-flow sheet of the Masonic Park Tuff, andesitic flows and breccias of the Sheep Mountain Andesite, thick quartz latite flows of the volcanics of Leopard Creek, and the upper ash-flow sheet of the Masonic Park Tuff. Total relief along the exposed section of this wall is about 500 m. The caldera is filled with Fish Canyon Tuff that is at least 1.4 km thick and extends over adjacent rocks on the south, east, and northeast sides of the caldera. Adjacent to the caldera, the Fish Canyon Tuff generally rests directly on the upper sheet of the Masonic Park Tuff.

The exposed segment of the topographic wall indicates that the caldera subsided after the ash flows forming the widespread upper sheet of Masonic Park Tuff were erupted (28.2 m.y. ago), and the basin formed by subsidence was in turn filled passively by the next succeeding major ash-flow sheet, the Fish Canyon Tuff (27.8 m.y. old). In addition to these stratigraphic constraints on the age of the caldera, other evidence, as follows, indicates that the Masonic Park Tuff was derived from a source within the Mount Hope caldera: (1) the position of the caldera well within the Masonic Park ash-flow sheet (fig. 15) and adjacent to the thickest sections of this formation; (2) intertonguing of the Masonic Park Tuff with andesite lavas of the Sheep Mountain Andesite and with other locally derived lavas near the rim of the Mount Hope caldera; and (3) the presence near the south and southwest edges of the caldera of bedded welded tuffs at the base of the upper ash-flow sheet of the Masonic Park that are believed to represent agglutinated ash fall, a depositional process only likely close to the eruptive source (Lipman, 1975a, fig. 26).

An earlier complex history of eruptions from the same general source is indicated by scattered exposures northwest and west of the Mount Hope caldera and in the highly faulted area southwest of the caldera (fig. 14). In these areas, the several individual ash flows within the composite older ash-flow sheet of Masonic Park Tuff intertongue with dark andesite flows and breccias of the Sheep Mountain Andesite that apparently formed a number of local volcanoes near the western margin of the later Mount Hope caldera. Just northwest of the Mount Hope caldera, the intertongued assemblage of Masonic Park Tuff and Sheep Mountain Andesite is overlain by thick coarsely porphyritic quartz latite lavas (volcanics of Leopard Creek), and these in turn are overlain by the thick upper sheet of Masonic Park Tuff (Steven and Lipman, 1973).

We interpret these relations to indicate early concurrent eruptions of quartz latitic ash flows of Masonic Park Tuff and andesitic lavas and breccias from local Sheep Mountain volcanoes. The ash-flow eruptions were apparently of small volume, and it is not known whether they were accompanied by caldera subsidence. Viscous quartz-latitic lavas forming a thick local assemblage (volcanics of Leopard Creek) were erupted along the

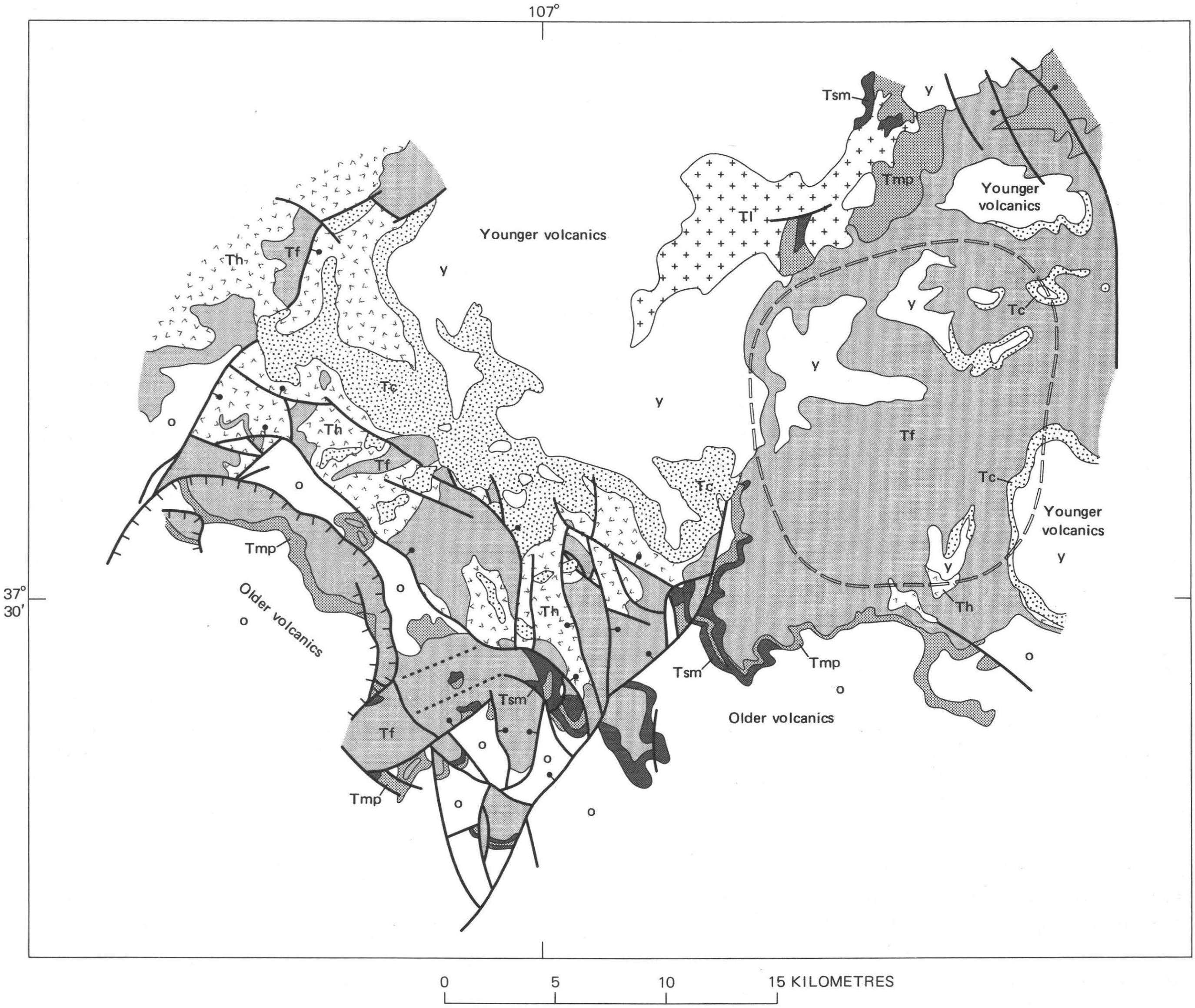

FIGURE 14.—Generalized geology of the Mount Hope caldera and adjacent areas. o, precaldera (older) volcanic rocks; Tmp, Masonic Park Tuff; Tsm, Sheep Mountain Andesite; Tf, Fish Canyon Tuff; Th,, Huerto Formation; Tl, volcanics of Leopard Creek; Tc, Carpenter Ridge Tuff; y, volcanic rocks younger than Carpenter Ridge Tuff. Open rectangles outline the buried caldera. Heavy lines indicate faults; bar and ball or hachures on downthrown sides; dotted where buried.

northwest side of the postulated source area following accumulation of the older Masonic Park ash-flow tuffs and Sheep Mountain andesitic flows and breccias. Renewed eruptions of quartz-latitic ash flows identical in composition and appearance to the older sheet of Masonic Park Tuff spread great volumes of tuff in all directions from the source area, thereby forming the widespread upper sheet of Masonic Park Tuff and resulting in subsidence of the Mount Hope caldera.

The Mount Hope caldera was not resurgently domed immediately after subsidence to any discernible extent; the Fish Canyon Tuff filled a hole more than 1.4 km deep and the floor of the fill is not exposed. Later broad uplift of the caldera area is indicated by the progressive overlap of younger ash-flow units onto the eastern side of the caldera fill (fig. 14). This uplift apparently was more a trapdoor uplift than a dome, with the western side preferentially uplifted. This later uplift probably was roughly concurrent with major faulting west and southwest of the Mount Hope caldera that will be discussed later. The Mount Hope caldera forms a type generally transitional between the earlier and later calderas of the San Juan field. Mount Hope is like the earlier calderas in its associated andesitic volcanism and the quartz-latitic composition of

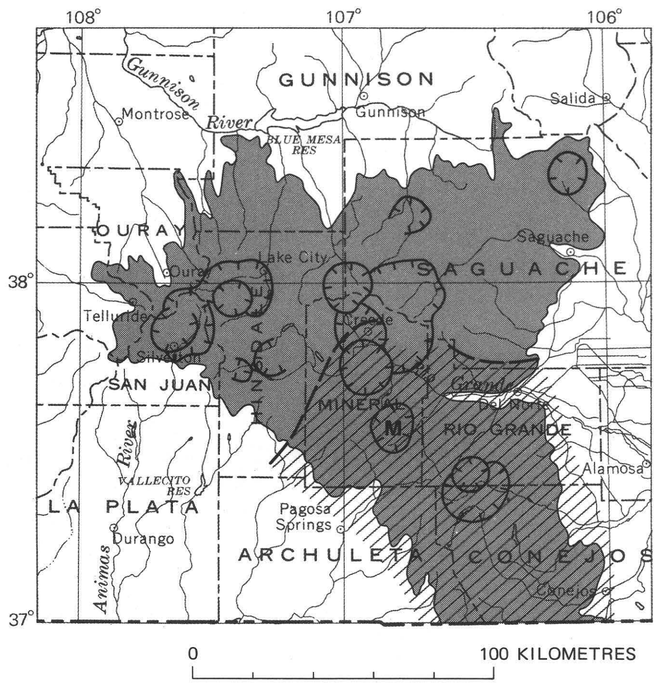

FIGURE 15.—Distribution of the upper member of Masonic Park Tuff (diagonal lines) in relation to Mount Hope caldera (M) and San Juan volcanic field (shaded).

the erupted tuffs; yet this caldera is well within the main gravity anomaly (fig. 1) and is associated with more silicic lava flows, as represented by the volcanics of Leopard Creek.

LA GARITA CALDERA

The La Garita caldera (fig. 16), the largest in the San Juan volcanic field, ranks among the great calderas in the world. The original topographic basin was at least 40 km across from north to south, and the subsided block within this basin appears to have been nearly 30 km across. The original east-west diameter of the caldera was somewhat less, but the precise dimensions cannot be established because the western part of the La Garita caldera has since been destroyed by later caldera subsidences.

The La Garita caldera is located near the center of the San Juan volcanic field, above the east-central part of the triangular-shaped batholith indicated by gravity data (fig. 1). Subsidence took place 27.8 m.y. ago (Lipman and others, 1970, p. 2340), in response to eruption of more than 3,000 km^3 of the phenocryst-rich quartz-latitic ash of the Fish Canyon Tuff (fig. 17). This unit spread over an area of more than 15,000 km^2; it is 30-200 m thick over wide areas and accumulated to a thickness of more than 1.4 km within the concurrently subsiding caldera.

Whereas many of the older San Juan calderas formed near clusters of earlier andesitic volcanoes (the Bonanza, Platoro-Summitville, San Juan, Uncompahgre, and Mount Hope calderas), any such relationship is more difficult to determine for the La Garita caldera because of its size. The intrusive core of an older volcano is exposed along the eastern wall of the La Garita caldera, and other volcanic centers are near the east, west, and north sides of the caldera, but exposures are inadequate to indicate whether these volcanoes were concentrated near the caldera.

A more important localizing factor may have been the position of the La Garita caldera with respect to the underlying batholith. The caldera occupies much of the roof above the broadest part of the batholith indicated by the gravity anomaly (fig. 1); this part of the roof was repeatedly disrupted by ash-flow eruptions and caldera subsidences throughout the less than 2 m.y. that remained of the period of intermediate to silicic volcanic activity. The recurrent volcanic activity and related subsidences here must have reflected equally active high-level magmatism throughout the eastern part of the batholith.

Little can be reconstructed of the early development of the La Garita caldera. The floor of the caldera is nowhere exposed, and the eastern and northern margins that survived later caldera subsidences are marked by a structural moat deeply filled with younger volcanic deposits. Little air-fall ash occurs below the outflow sheet, so premonitory eruptions seem to have been minor. In addition, no compositional zoning was noted anywhere in the outflow sheet of Fish Canyon Tuff, and the basal rocks seem indistinguishable from those elsewhere in the unit. Apparently, large volumes of ash were erupted quite suddenly from a major chamber containing relatively homogeneous phenocryst-rich quartz-latitic magma.

The disparity in thickness between the intracaldera (more than 1.4 km thick) and outflow parts (generally less than 200 m thick) of the Fish Canyon Tuff requires subsidence concurrent with eruption. Compaction foliation and rude layering, marked in places by less-welded partings, are virtually parallel throughout the caldera fill, and indicate that block subsidence was concurrent with filling.

Little igneous activity or sedimentation seems to have occurred immediately after subsidence, and the first demonstrable event was broad resurgent doming of the core. The crest of the dome was relatively flat over an area at least 5 km across, and the preserved eastern and northeastern flanks dip 5°-15° radially outward from the crest. Minor tensional faults separate flat from inclined segments of the core, and also separate inclined segments that dip in different directions. Maximum relief from the northeast moat to the crest of the dome was more than 1.4 km. The western and southwestern flanks of the resurgent dome have since caved into younger calderas, and have been covered by younger volcanic units.

Most of the moat is deeply filled by younger volcanic rocks, or has been destroyed by younger caldera subsidences. The lower fill, along the northeast side of the caldera, consists of Carpenter Ridge Tuff, in places showing evidence of having accumulated in shallow water. Minor tuffaceous sedimentary rocks exposed locally in this area probably represent deposition by small streams or in local ponds.

No late ring-fracture igneous activity is evident along the eastern or northern sides of the La Garita caldera, but the major rhyolite dome along Miners Creek, partly exposed in a deep canyon 6 km west of Creede (Steven and Ratté, 1965), is older than the Carpenter Ridge Tuff, and may have erupted through the western ring-fracture zone of the La Garita caldera.

The eastern wall of the La Garita caldera apparently stood especially high, and most subsequent units from the central San Juan caldera complex were trapped against it. Elsewhere, the younger ash flows overtopped the La Garita caldera rim and spread widely. This high part of the caldera wall marks the truncated end of a line of major older andesitic volcanoes that extended west-northwest from the Summer Coon center 10 km north of Del Norte (Lipman, 1968), through the Baughman Creek and upper La Garita Creek centers, to the Sky City center exposed in the eastern topographic wall of the caldera (fig. 16). These volcanoes were deeply eroded prior to eruption of the Fish Canyon Tuff, but protruded through all but the youngest subsequent ash-flow units.

BACHELOR CALDERA

The Bachelor caldera, the source of rhyolite ash flows that formed the widespread Carpenter Ridge Tuff (fig. 18), collapsed along the west margin of the La Garita caldera (fig. 16). The age of the Carpenter Ridge Tuff and of the Bachelor caldera is bracketed by K-Ar ages of 27.8 m.y. for the older Fish Canyon Tuff and 26.7 m.y. for the younger Mammoth Mountain Tuff.

The outflow Fish Canyon and Carpenter Ridge Tuffs are separated by andesite flows and breccias of the Huerto Formation that formed a series of volcanoes near the present edge of volcanic rocks south and southwest of the Bachelor caldera. After eruption of the andesites, the area southwest of the Mount Hope caldera (fig. 14) was intricately downfaulted toward the caldera complex, as described later. During the Huerto eruptions and later faulting, magma accumulated in a newly developed high-level chamber beneath the west side of the La Garita caldera, and differentiated to a silicic phenocryst-poor rhyolite which erupted to form the Carpenter Ridge Tuff. Southeast of the caldera, the Carpenter Ridge is locally compositionally zoned from rhyolite upward into quartz latite.

Eruption of the Carpenter Ridge Tuff was accompanied by subsidence of an oval-shaped caldera about 15 by 25 km across. Tuff more than 1.5 km thick accumulated within the subsiding caldera, whereas the outflow sheet generally is less than 400 m thick. As in other calderas in the San Juan Mountains, these relations are believed to indicate subsidence concurrent with eruption.

The floor and eastern wall of the Bachelor caldera are exposed locally northeast of Creede. In this area, a rough fault-block topography marked by tectonically shattered rocks, fault scarps, and talus breccia developed on the older rocks (Steven and Ratté, 1965, p. 17). These fault blocks underlie the Bachelor caldera fill and form the eastern caldera wall, where they mark the progressive breaking down of the resurgent core of the La Garita caldera toward the younger subsidence feature to the west. In part these fault blocks may represent inward sliding of the Bachelor caldera wall toward the main ring-fracture zone during Carpenter Ridge eruptions.

Similar relations on the west side of the caldera may be represented by the intertonguing of Shallow Creek Quartz Latite with the intracaldera Bachelor Mountain Member of the Carpenter Ridge Tuff, as described by Steven and Ratté (1965, p. 23). This intertonguing was mapped in the early 1950's before any of the calderas in the central San Juan Mountains had been recognized. In retrospect it seems plausible that the layers of Shallow Creek Quartz Latite within the Bachelor caldera fill may instead be avalanche and landslide breccia derived from a major quartz latite dome (fig. 8) that formed the nearby over-steepened caldera wall, a relationship which has been found in many other intracaldera fills in the San Juan Mountains. This suggestion needs to be checked in the field.

Three small ash flows resembling Fish Canyon Tuff appear to intertongue with the intracaldera Bachelor Mountain Member of the Carpenter Ridge Tuff on the east side of the Bachelor caldera (Steven and Ratté, 1965, p. 18). These relations, if valid, indicate that neighboring cupolas on the underlying batholith were sufficently locally restricted to permit contrasting magmas to coexist locally and earlier magma types to persist while the Carpenter Ridge rhyolite was differentiating.

The core of the Bachelor caldera was resurgently domed shortly after subsidence, and a fragmented cross section of the dome can be seen in the north wall of the younger Creede caldera. The top of the Carpenter Ridge Tuff is more than 700 m higher at the crest of the dome than it is near the eastern and western ring-fracture zones. Tensional fractures that formed during doming dropped local blocks nearly 500 m near the crest of the uplift, and longitudinal normal faults, including the ancestral Amethyst fault in the Creede mining district (Steven and Ratté, 1965, p. 55-56), extended north-northwest down the axis of the uplift. These faults marked the initial fracturing of an area that was recurrently broken during later volcanic episodes, and was widely mineralized at the time when the ores of the Creede mining district were deposited.

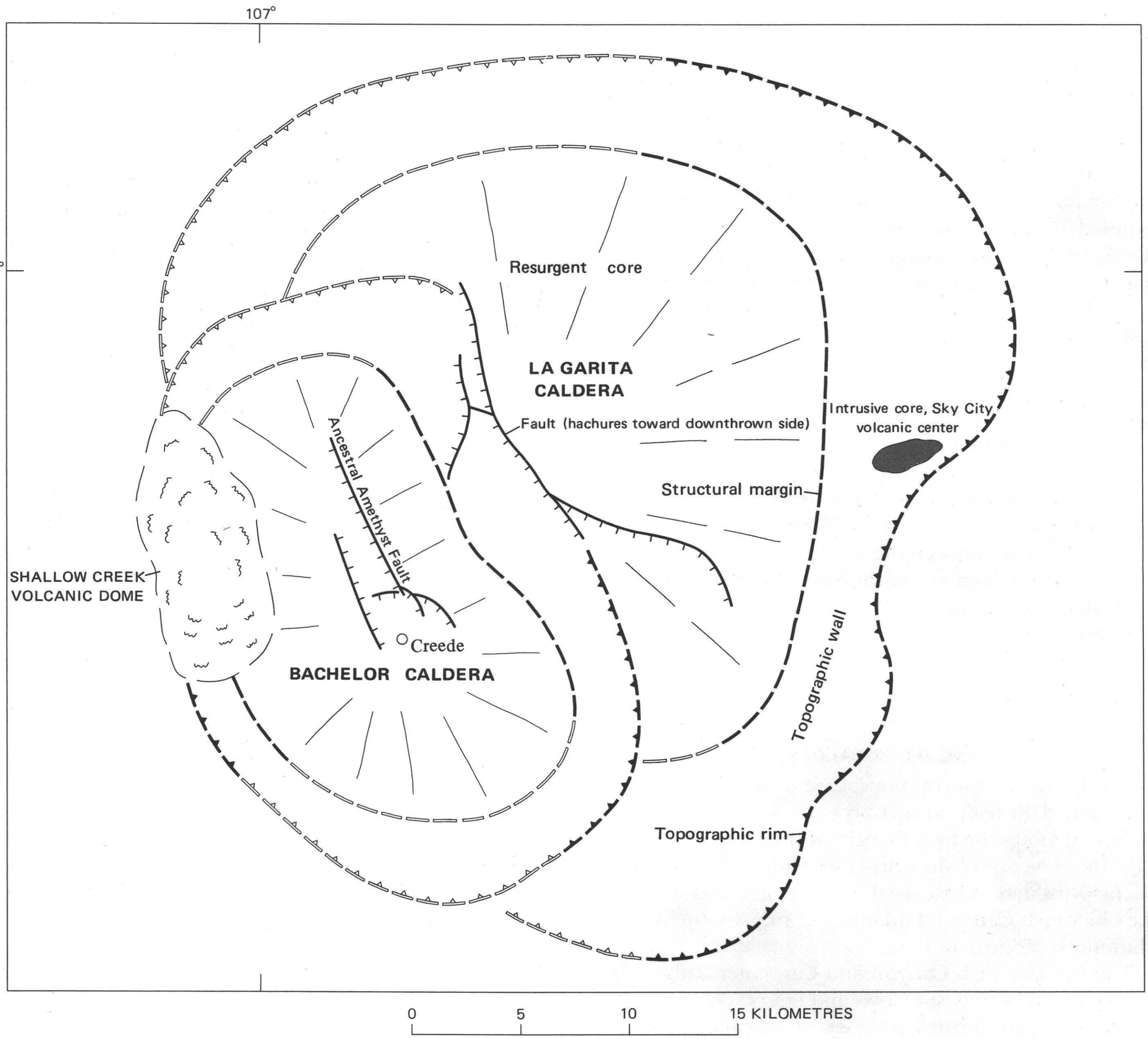

FIGURE 16.—Restored Bachelor and La Garita calderas. Control moderate to good where boundaries are shown by solid symbols; conjectural where shown by open symbols.

Small plugs of rhyolite cut the intracaldera tuffs near the center of the Bachelor caldera. These plugs are most abundant in the rocks that are cut by tensional faults and that were pervasively brecciated during resurgent doming. Evidence is ambiguous, but the rhyolite plugs may have been emplaced before brecciation and, thus, prior to resurgence. No postresurgence igneous activity related to the Bachelor caldera cycle has been recognized.

The shattered intracaldera Bachelor Mountain Member of the Carpenter Ridge Tuff on the resurgent dome was altered during the waning stages of the Bachelor caldera cycle. The shattered tuff was intensely silicified and largely healed to a massive rock. The K_2O content of the silicified rock increased markedly from about 5 percent to as much as 11 percent (Ratté and Steven, 1967, p. H13); this increase is reflected by abundant very fine grained orthoclase in the matrix. In the northern part of the Bachelor caldera, the intracaldera tuffs were variably bleached and altered, and disseminated pyrite was erratically introduced. No significant economic mineral deposits related to the Bachelor caldera cycle are known, however.

MAMMOTH MOUNTAIN(?) CALDERA

Indirect evidence suggests that subsidence took place during eruption of the Mammoth Mountain Tuff, but the

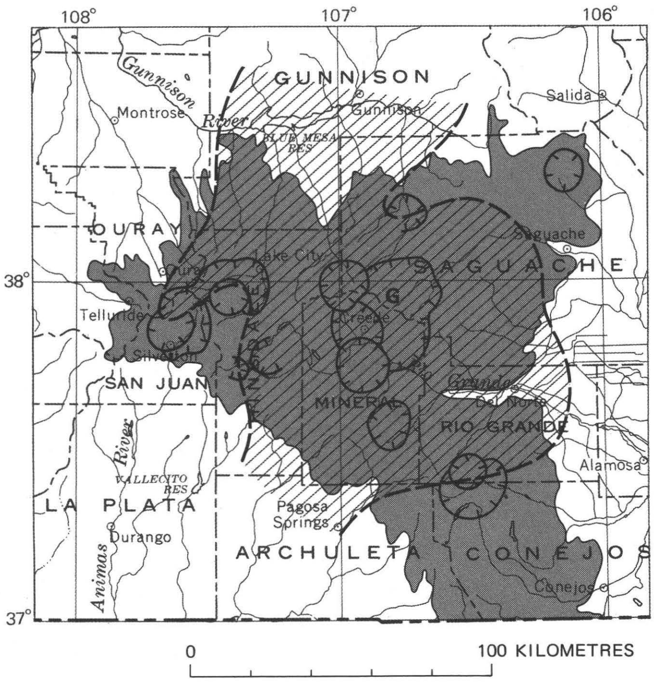

FIGURE 17.—Distribution of the Fish Canyon Tuff (diagonal lines) in relation to La Garita caldera (G) and San Juan volcanic field (shaded).

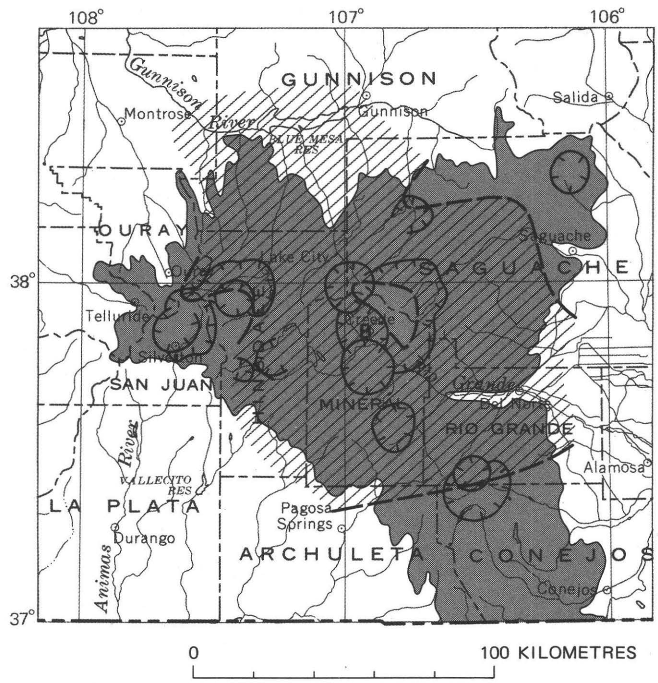

FIGURE 18.—Distribution of Carpenter Ridge Tuff (diagonal lines) in relation to Bachelor caldera (B) and San Juan volcanic field (shaded).

postulated caldera has been largely destroyed by the younger Creede caldera and covered by younger rocks.

The Mammoth Mountain eruptive cycle began with local episodic pyroclastic eruptions that formed a sequence originally called Farmers Creek Rhyolite by Steven and Ratté (1964, 1965) and Ratté and Steven (1967); subsequent regional work has indicated that these rocks were primarily local products of premonitory eruptions in the Mammoth Mountain cycle (Steven, Lipman, Hail, and others, 1974; Steven and Ratté, 1973) that were deposited just northeast of the postulated source beneath the younger Creede caldera. The early episodic pyroclastic eruptions progressed into a pulsating, nearly continuous, ash-flow eruption that flooded (fig. 19) the lower parts of the rough topography left by subsidence and resurgence of the La Garita and Bachelor calderas (fig. 1). Most of these Mammoth Mountain ash flows welded into coherent, dense tuff that shows obscure compound cooling (Ratté and Steven, 1967, p. H18-H33).

The Mammoth Mountain Tuff accumulated to a thickness of more than 500 m in the moat of the resurgent Bachelor caldera, where it is strongly zoned from phenocryst-poor rhyolite at the base to phenocryst-rich quartz latite at the top (Ratté and Steven, 1964, 1967). The Mammoth Mountain Tuff wedges out against and is absent over the top of the resurgent core of the Bachelor caldera, and was contained on the northeast and southwest by the outer topographic wall of the caldera. A 300- to 400-m-thick sheet of densely welded quartz latite tuff of the Mammoth Mountain Tuff extends southeast from the postulated source within the subsequently formed Creede caldera to the southeast topographic wall of the La Garita caldera where it wedges out abruptly. Remnants of crystal-rich Mammoth Mountain Tuff 5-20 m thick are preserved near the Continental Divide 35-40 km south of Creede, indicating that the unit spread widely in this direction over the smooth top of Carpenter Ridge Tuff.

Near the postulated source, the products of the Mammoth Mountain eruptive cycle show structural relations that may indicate nearby caldera subsidence related to the ash-flow eruptions. The rudely layered rocks at the base of the section—the Farmers Creek Tuff (Farmers Creek Rhyolite of Steven and Ratté, 1965)—and most of the overlying phenocryst-poor tuff are inclined 10°-15° NE. The dip of this compaction foliation flattens in the younger quartz-latitic rocks; the change in dip is about coincident with the change in lithology and takes place within a vertical span of about 50 m. This change in dip is interpreted to reflect structural disturbance during Mammoth Mountain eruptions, a structural disturbance perhaps related to caldera collapse at the source vents.

Most of any Mammoth Mountain caldera that may have existed was destroyed by the younger Creede caldera. The size or shape of the postulated caldera is unknown, except that it must be within the topographic wall of the Creede caldera, which exposes pre-Mammoth Mountain rocks on its northern, eastern, and southwestern segments. Numerous viscous quartz-latitic lava flows that probably

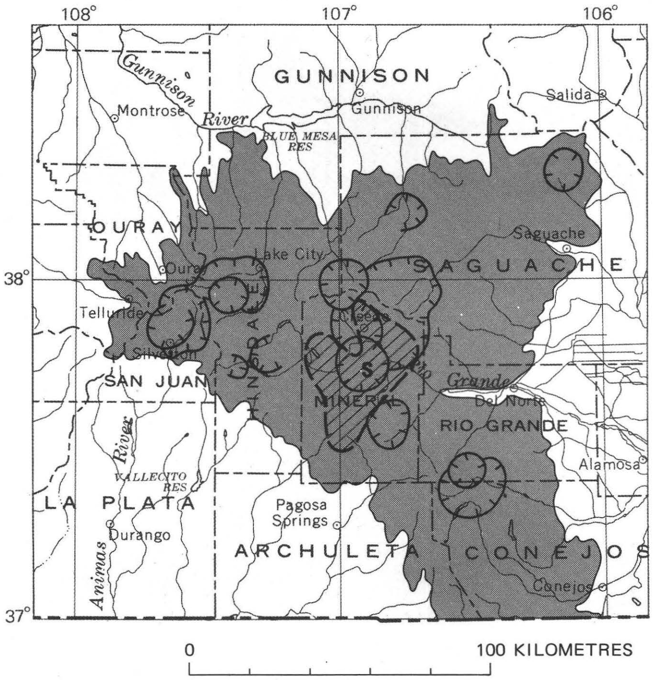

FIGURE 19.—Distribution of Mammoth Mountain Tuff (diagonal lines) in relation to probable source area (S) and San Juan volcanic field (shaded).

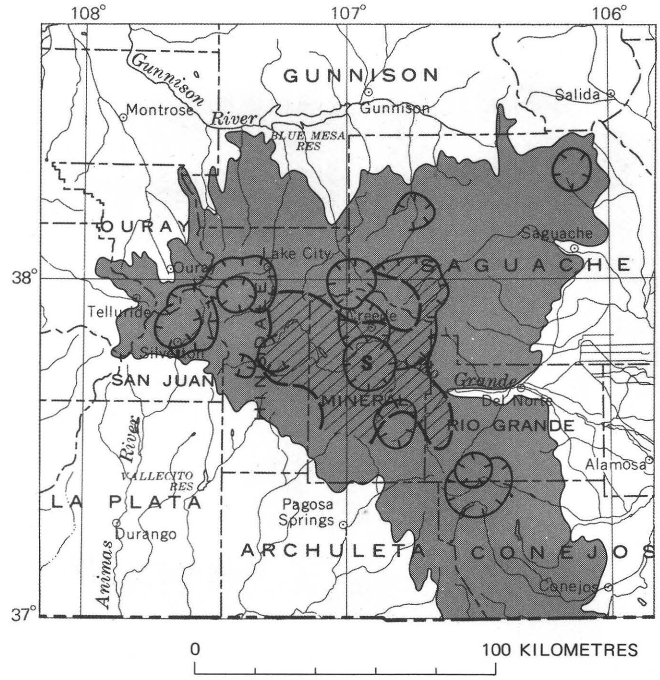

FIGURE 20.—Distribution of Wason Park Tuff (diagonal lines) in relation to probable source area (S) and San Juan volcanic field (shaded).

accumulated near their own vents overlie the Mammoth Mountain Tuff east and northeast of the Creede caldera and may represent the outer parts of flows and domes erupted marginally around the postulated Mammoth Mountain caldera.

SOURCE OF THE WASON PARK TUFF

The Wason Park Tuff is a simple cooling unit of rhyolitic ash-flow tuff that spread widely over the central San Juan volcanic field (fig. 20) and seems centered on the younger Creede caldera (fig. 1). North of the Creede caldera, the Wason Park fills the upper parts of the same rough topography that confined the Mammoth Mountain Tuff. It is largely confined to the moats around the resurgent La Garita and Bachelor calderas where it rests on thick tongues of Mammoth Mountain Tuff, and it thins or wedges out laterally against the resurgent cores or topographic walls of these calderas. To the west, south, and southeast, however, the Wason Park Tuff spread widely as a thin sheet on top of older ash-flow sheets.

The Wason Park Tuff has a volume greater than 100 km^3 (Ratté and Steven, 1967, p. H34) and is sufficiently voluminous that subsidence should have resulted at the source (Smith, 1960, fig. 3), but no caldera structure is exposed within the area covered by the sheet. The only area large enough for subsidence related to Wason Park Tuff is under the younger Creede caldera, which is near the center of the area of distribution of the thickest and most densely welded Wason Park Tuff. White pumice blocks characteristic of the Wason Park Tuff are larger near the Creede caldera than in the distal parts of the sheet (Ratté and Steven, 1967, fig. 16), and may indicate proximity to source. A local lava flow closely similar in lithology to the densely welded Wason Park Tuff underlies the Wason Park along the northeast rim of the Creede caldera (Ratté and Steven, 1967, fig. 15*B*), again suggesting a nearby source.

SAN LUIS AND COCHETOPA PARK CALDERAS

Although completely separate subsidence structures, the San Luis and Cochetopa Park calderas (figs. 21 and 22) are so intertwined in evolution that they are considered together. Furthermore, the San Luis caldera appears to be a compound structure consisting of two overlapping subsided blocks that formed in sequence during separate periods of ash-flow eruptions.

Stratigraphic uncertainties preclude confident interpretation of the evolution of these calderas. The history of past usages of the Rat Creek, Nelson Mountain, and Cochetopa Park as rock-stratigraphic units chronicles the confusion that has stemmed from attempts to correlate virtually identical rock types from area to area; nearly every report dealing with these units that has been published since 1964 treats them differently. This report continues this confusing practice because none of the previous usages permits reconstruction of a coherent history of evolution of the calderas.

In its type locality in the Creede mining district (Steven and Ratté, 1964, 1965), the Rat Creek Tuff consists largely of soft white nonwelded to slightly welded zeolitized tuff,

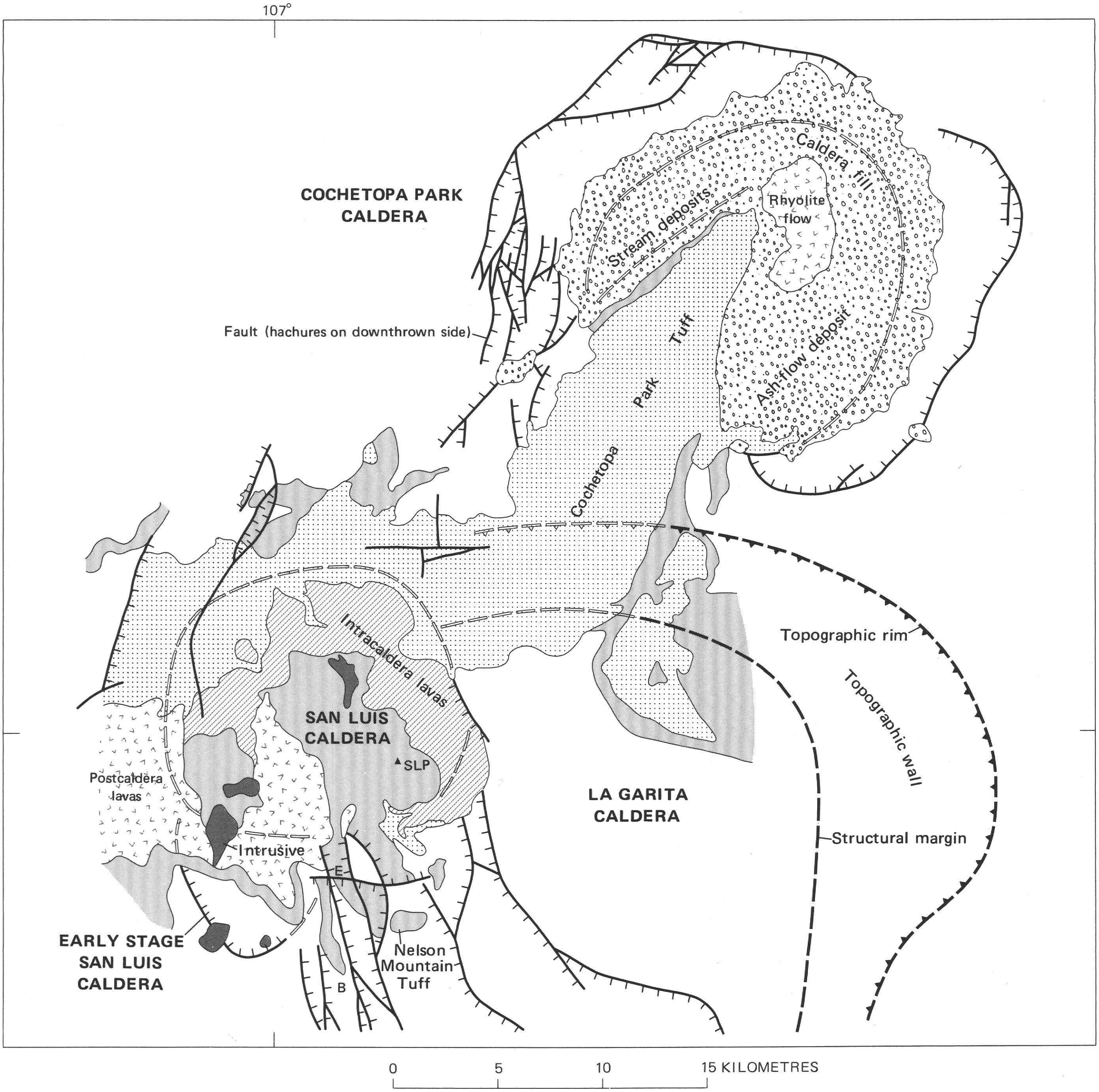

FIGURE 21.—Generalized geology of the San Luis and Cochetopa Park calderas in relation to remnants of the Bachelor (B) and La Garita calderas. Control moderate to good where boundaries are shown by solid symbols; conjectural where shown by open symbols. E, general area of the Equity mine; SLP, San Luis Peak.

with a ledge of densely welded tuff 10-30 m thick just above the middle. The Rat Creek is overlain by Nelson Mountain Tuff, a densely welded quartz latite containing 15-30 percent phenocrysts. Steven and Ratté (1965, p. 37) included in the Nelson Mountain the large mass of propylitized densely welded tuff (the Equity Quartz Latite as used by Emmons and Larsen, 1923) that fills the lower part of the San Luis caldera, although they could not prove physical continuity.

After extensive regional mapping in the central and northern San Juan Mountains, Steven, Lipman, and Olson (1974, p. A80) concluded that the densely welded rocks in the San Luis caldera were probably the intracaldera equivalent of the Rat Creek Tuff, and called them the Equity Member of that formation. Overlying densely welded tuffs on the north and northeast sides of the caldera were correlated with the lithologically identical Nelson Mountain Tuff at its type locality. These overlying welded

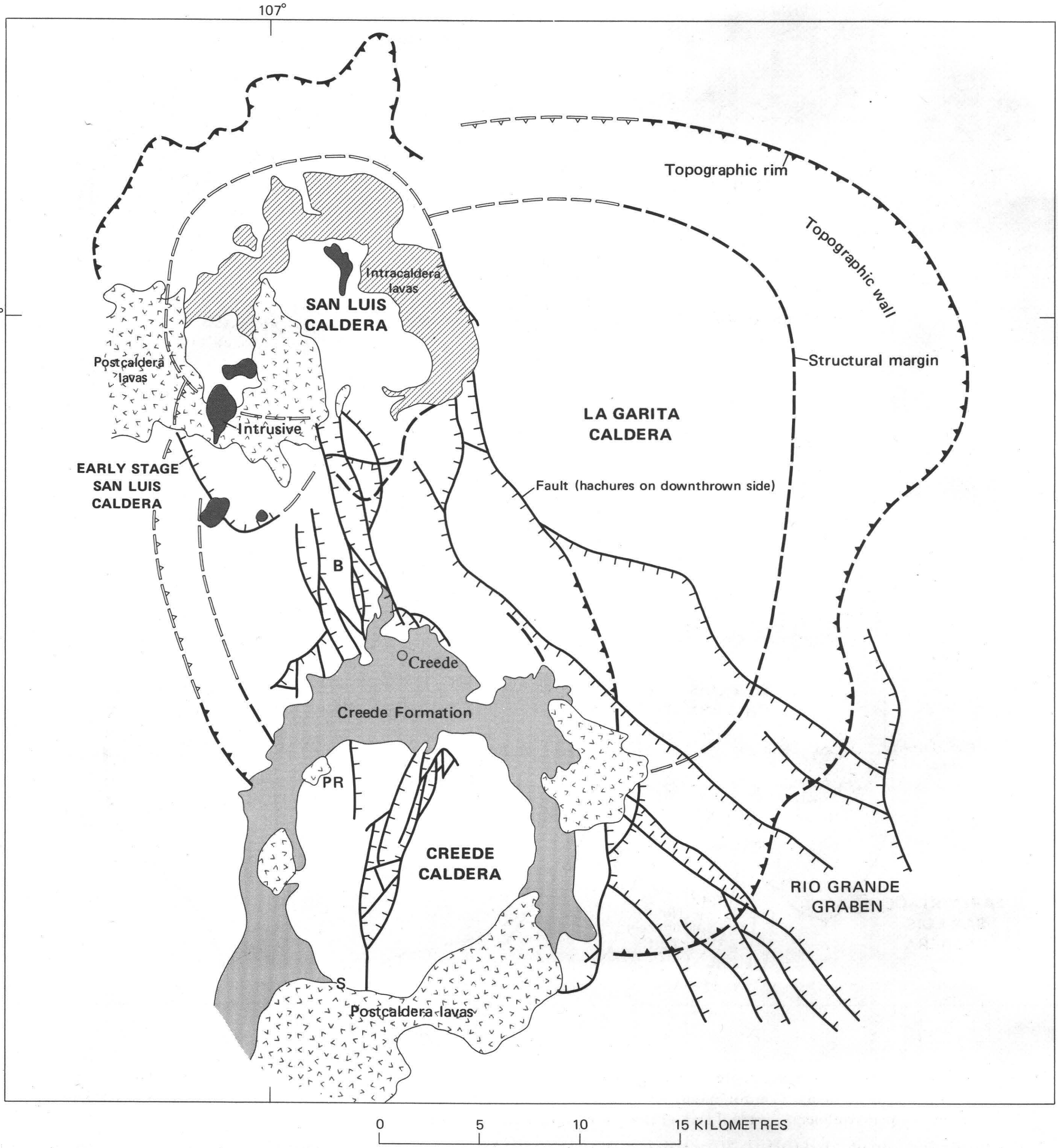

FIGURE 22.—Generalized geology of the Creede and San Luis calderas in relation to remnants of the Bachelor (B) and La Garita calderas. Control moderate to good where boundaries are shown by solid symbols; conjectural where shown by open symbols. PR, Point of Rocks volcano; S, Spar City.

tuffs extend into their apparent source area in the Cochetopa Park caldera to the northeast. Younger post-subsidence tuffs filling the Cochetopa Park caldera were called the Cochetopa Park Member of the Nelson Mountain Tuff.

Continued work in the northwestern San Juan Mountains has shown that something is wrong with this interpretation of the stratigraphic assemblage. Major densely welded ash-flow tuffs in the Lake City area (40 km northwest of Creede) almost certainly are equivalent to the

Nelson Mountain Tuff at its type locality in the Creede mining district, but details of distribution and volume make it highly unlikely that they were derived from the Cochetopa Park caldera. This forces the following tentative conclusions:

1. The correlation of Nelson Mountain Tuff in its type locality in the Creede district with lithologically identical tuffs northeast of the San Luis caldera probably is wrong.
2. The original correlation of Nelson Mountain Tuff with the densely welded (Equity) tuffs in the San Luis caldera by Steven and Ratté (1964, 1965) probably is correct. The Equity Member is therefore removed from the Rat Creek Tuff and assigned to the Nelson Mountain Tuff.
3. The densely welded tuffs north and northeast of the San Luis caldera, apparently derived from the Cochetopa Park caldera, constitute a separate unit younger than the Rat Creek and Nelson Mountain Tuffs. We therefore remove the Cochetopa Park Member from the Nelson Mountain Tuff and raise it to formational rank as the Cochetopa Park Tuff.

The interpretations that follow assume that these tentative conclusions are generally correct, but repeated examinations of critical field relations and petrographic studies have failed to develop the firm criteria for distinguishing these units that will be required for confident evaluation of our evolutionary model.

COMPOUND SUBSIDENCE OF THE SAN LUIS CALDERA

As currently (1975) understood, the Rat Creek Tuff appears to be a relatively low volume assemblage of poorly welded rhyolitic ash-flow tuffs confined largely to the vicinity of the Creede mining district (Steven and Ratté, 1965). Several factors imply a nearby source: (1) at least one local volcano of Rat Creek age is well exposed in the heart of the Creede district (Steven and Ratté, 1965, p. 35); (2) a local ledge of densely welded tuff occurs just above the middle of the Rat Creek Tuff within the Creede district; and (3) a small subsidence structure (caldera) of Rat Creek age is located along the northwest side of the Creede district. This last structure, described below, is here considered an early stage in the development of the compound San Luis caldera (fig. 21).

The regional sheet of Rat Creek Tuff ranges widely in thickness because of rough underlying topography. It is 150-200 m thick through the central part of the Creede district, but to the northeast it wedges out completely against an eroded fault scarp cutting the resurgent core of the La Garita caldera. North of the Creede district, the Rat Creek is cut off by the topographic wall of the main San Luis caldera.

In the early stage of the San Luis caldera along Miners Creek northwest of the Creede district (fig. 21), soft zeolitized tuffs that are physically continuous with type Rat Creek Tuff fill a partly exposed subsidence structure that has a steep arcuate fault along the south and southwest sides. To the north and northeast, this caldera is largely covered by younger rocks and relations are almost totally obscured; the map pattern (figs. 21 and 22) implies that the northern part of the caldera caved into the main San Luis caldera which developed shortly afterward.

Soft tuffs of the Rat Creek accumulated to a thickness of more than 350 m within the early caldera and are at least twice as thick as nearby correlative outflow tuffs. The intracaldera tuffs are flat lying and show no evidence of resurgence. The faulted margin is largely obscured by massive landslides, but it can be estimated to within a few metres along one gully where it appears to be very steep. Elsewhere the fault is indicated by juxtaposition of thick intracaldera Rat Creek Tuff and flat-lying older rocks in the wall. Two intrusives were emplaced along or near the faulted margin. One is a major neck, more than 1 km across, that clearly occupies the fault; the other forms a low knob, 500 m across, completely surrounded by landslide debris.

Several features indicate a Rat Creek age for the early caldera. The wall outside the faulted margin includes rocks as young as Wason Park Tuff, which is the next oldest ash-flow unit in the San Juan Mountains, and locally may include the overlying andesite of Bristol Head which is directly beneath the Rat Creek Tuff just east of the early caldera. The local ledge of densely welded tuff in the upper part of outflow Rat Creek Tuff extends westward to the vicinity of the early caldera, but is nowhere found within the caldera, although the area of its projected position is well exposed. However, the caldera margin, whose development probably accounts for this discordance, is covered by surficial debris and younger lavas. The caldera fill is overlain by typical Nelson Mountain Tuff that extends from its type locality westward across the area of the early San Luis caldera. The Nelson Mountain forms an unbroken rim across the trend of the older faulted caldera margin without any change in thickness or evidence of deformation.

The main San Luis caldera (figs. 21, 22, and 23) is now thought to have subsided concurrently with eruption of the Nelson Mountain Tuff, and at least 1.5 km of phenocryst-rich quartz latite accumulated within the subsiding basin, whereas the outflow sheet nearby is only about 300 m thick. This thick mass of intracaldera ash welded into a dense, nearly homogeneous rock with only a few local less-welded partings. Later propyllitic alteration further homogenized the rock and obscured partings. The base of the intracaldera Nelson Mountain Tuff is exposed locally within the north-central part of the caldera core

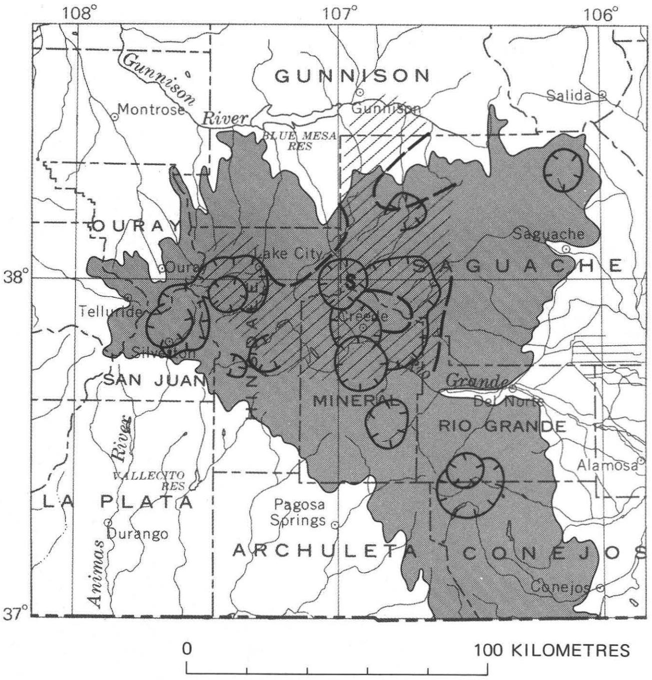

FIGURE 23.—Distribution of Nelson Mountain Tuff (diagonal lines) in relation to San Luis caldera (S) and San Juan volcanic field (shaded).

where densely welded quartz latite directly overlies a local hill, probably a volcanic dome, of older rhyolite. Some probable Carpenter Ridge Tuff is exposed on the north flank of this hill, but its relations with the adjacent rhyolite are obscure. No soft tuff representative of Rat Creek ash flows is exposed on this buried hill, but the lower parts of the caldera floor where such tuff deposits might more reasonably be expected are nowhere exposed.

Subsidence of the main San Luis caldera produced a broad basin nearly 15 km across. Intermediate to silicic lavas and breccias of the volcanics of Stewart Peak accumulated within the northern and eastern parts of this basin, and were locally accompanied by deposits of stream and lake sediments (figs. 21 and 22). Most intracaldera lavas around the eastern side of the caldera are rhyodacite and quartz latite, but perlitic rhyolite flows are abundant along the north margin. All known dike and neck feeders for the intracaldera lavas are within the caldera core. The eastern margin of the caldera block again subsided locally during eruption of the intracaldera lavas, as indicated by a fault with at least 500 m of throw that places the lower part of the volcanics of Stewart Peak within the caldera against older Fish Canyon Tuff in the wall. The fault passes under unbroken Cochetopa Park Tuff to the north, and ledges of this younger unit representing successive ash flows both to the north and south intertongue with younger lavas on the Stewart Peak sequence, providing an upper age limit for the renewed subsidence.

SUBSIDENCE OF THE COCHETOPA PARK CALDERA

Ash flows of the Cochetopa Park Tuff that were deposited in the San Luis caldera area (fig. 1) during accumulation of the intracaldera volcanics of Stewart Peak had their source in the Cochetopa Park area, some 30 km northeast. Minor phenocryst-poor rhyolite ash accumulated near the source, but the eruptions soon changed to crystal-rich quartz latite that is seemingly identical with the Nelson Mountain Tuff. The Cochetopa Park ash flows followed the nearly filled moat around the northern side of the La Garita caldera (fig. 1) and inter-tongued with the volcanics of Stewart Peak within the San Luis caldera (fig. 24).

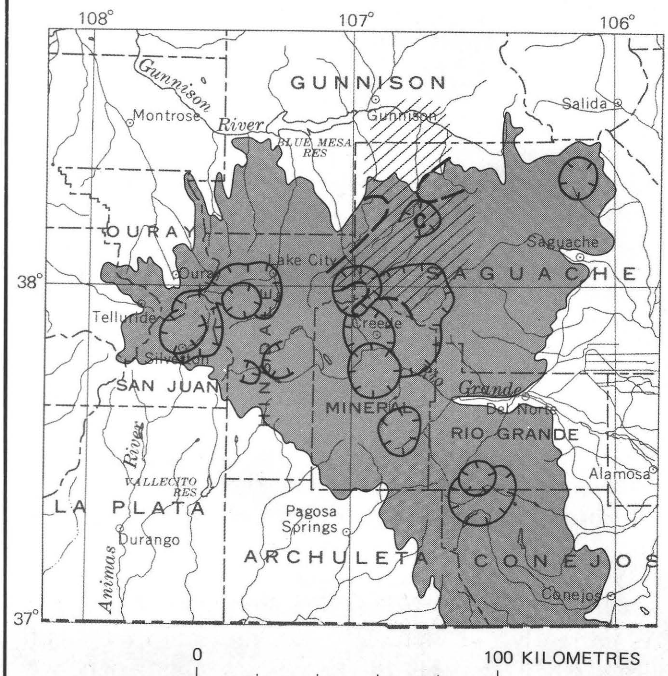

FIGURE 24.—Distribution of the Cochetopa Park Tuff (diagonal lines) in relation to Cochetopa Park caldera (C) and San Juan volcanic field (shaded).

In contrast with the larger San Juan calderas, where subsidence occurred concurrently with ash-flow eruptions, the Cochetopa Park caldera collapsed after major eruptions had ceased, as indicated by lack of thickening of the intracaldera tuff. In further contrast with the larger calderas, the Cochetopa Park caldera did not form a complete circular structure, but subsided as a trapdoor bounded by a horseshoe-shaped fault. The southwestern margin did not fracture, but merely bent downward and tilted eastward. A trough, probably representing a graben, formed along the northwest side of the caldera core, and a tilted, northeast-trending ridge of Cochetopa Park Tuff dipping 5°-10° E. extended beyond the middle of the caldera (fig. 21). An inner ring-fracture zone can be postulated to account for major subsidence (fig. 21).

Maximum displacement on the northeastern side of the trapdoor is 700-800 m, as judged from the height of the topographic wall in this direction.

After the inner trapdoor block had subsided, or perhaps concurrently with subsidence, the walls of the caldera slumped inward along arcuate faults that nearly surround the downfaulted parts of the caldera. The breakaway zone near the hingeline of the trapdoor on the west side of the caldera is a splintered area of many faults and jumbled relations between blocks. Elsewhere, the slumped blocks are bounded by curved, linking faults that are concave toward the subsided trapdoor. Locally along the northeast side, no slumping took place.

Minor pyroclastic eruptions after subsidence of the Cochetopa Park caldera deposited local moderately to densely welded ash-flow tuffs near the hingeline and thick nonwelded pumiceous ash-flow tuff within the caldera east of the medial ridge (fig. 21). The trough (graben?) northwest of the medial ridge was filled with sandy tuffaceous stream deposits and a few layers of air-fall tuff. The two facies merge in the northeastern part of the caldera about on trend with the medial ridge. Layering in the tuffaceous caldera fill is flat and shows no resurgence of the caldera core. In places the caldera fill covers arcuate faults of the outer slumped zone and provides an upper limit on the age of that faulting.

A thick rhyolite flow with a prominent black vitrophyre at its base was erupted through the caldera fill about on trend with the medial ridge, and eroded remnants still persist as the feature called Cochetopa Dome.

RESURGENCE OF THE SAN LUIS CALDERA

Whereas minor resurgence of the San Luis caldera may have preceded or accompanied eruption of the intracaldera volcanics of Stewart Peak, most resurgence took place later. Densely welded layers of the Cochetopa Park Tuff, representing many successive ash flows from the Cochetopa Park caldera, intertongue with the upper volcanics of Stewart Peak and are involved in this resurgent uplift. North of the caldera, the Cochetopa Park Tuff is inclined less than 10° in various directions, but near the caldera margin the layers are bent up along a curving hingeline and dip 20°-25° radially outward from the resurgent core. In part, this hingeline is marked by a fault with little displacement and the change in dip is sharp; elsewhere no fault is apparent and the change in dip is less abrupt. South of the caldera, resurgence is locally marked by an abrupt change in dip from flat layers of Nelson Mountain Tuff outside the caldera to layers dipping 15° or so southward off the dome within the caldera. Near the Equity mine in the northern part of the Creede district, however, local resurgence uplifted a triangular block, 1.5-3 km on a side, nearly a kilometre (Steven and Ratté, 1965).

This resurgence was somewhat asymmetrical to the San Luis caldera. The small remnant of the early subsided block along the southwest side of the caldera is not domed, and evidence of resurgence is apparently limited to the main caldera and to an area extending about a kilometre beyond the eastern and northeastern structural margin of the caldera. The edge of resurgent uplift on the north side of the San Luis caldera is just inside the outer topographic wall, and possibly is outside the buried structural margin.

The minimum structural relief caused by resurgence is a little less than a kilometre, as indicated by the elevation difference between the top of flat-lying Nelson Mountain Tuff outside the caldera and the top of San Luis Peak within the caldera. On the north side of the caldera, this difference is about 1.4 km, whereas on the south side it is about 0.7 km; as discussed later, this contrast reflects tilting caused by late general uplift of the roof of the batholith that underlies the central part of the San Juan volcanic field.

POSTCALDERA LAVAS

Resurgence of the San Luis caldera was followed by development of a line of volcanoes that extends westward from the caldera about 14 km. The eastern part of these postcaldera volcanic rocks, as shown in figures 21 and 22, consists of coarsely porphyritic lavas and breccias (the quartz latite of Baldy Cinco) that were erupted from many local vents, some within the western part of the San Luis caldera. Over most of their extent, these lavas and breccias rest on flat ledges of densely welded Nelson Mountain Tuff or Cochetopa Park Tuff, but on the east they abut and wedge out against tilted volcanics of Stewart Peak and Nelson Mountain Tuff in the resurgent core of the San Luis caldera. Apparently most of the western third of the caldera was once covered by these rocks. Lavas of similar age and composition (quartz latite of Rambouillet Park) (Steven, 1967) extend farther southwest, toward the southeast margin of the Uncompahgre caldera.

CREEDE CALDERA

The Creede caldera (fig. 22) formed in response to eruption of the Snowshoe Mountain Tuff about 26.5 m.y. ago and is the youngest subsidence structure in the central San Juan caldera complex. Its form is clearly reflected in the modern landscape. (See frontispiece, Ratté and Steven, 1967, for a color panorama of the Creede caldera.) The excellently preserved topographic form of this structure has resulted primarily from burial of all but the higher parts of the resurgent core by stream and lake sediments of the upper Oligocene Creede Formation that were not removed by erosion until late Cenozoic time (Steven, 1968, p. 114). Development of the Creede caldera was considered in detail by Steven and Ratté (1965, p. 58-62), and Smith and Bailey (1968, p. 625-626) used it as one of their seven examples of typical resurgent cauldrons.

The Creede caldera subsidence was localized along the southwest margin of the La Garita caldera (fig. 22); it obliterated the south part of the Bachelor caldera and the larger part of any calderas related to eruptions of the Mammoth Mountain and Wason Park Tuffs.

Initial eruptions of the phenocryst-rich quartz latite forming the Snowshoe Mountain Tuff spread a thin, poorly welded sheet over the flat surfaces of earlier ash-flow tuffs in adjacent areas (fig. 25). Subsidence began shortly thereafter and proceeded concurrently with eruption. More than 1.4 km, and perhaps more than 2 km, of nearly uniform crystal-rich ash accumulated within the subsiding basin; most of this is densely welded, but a few partings are less welded.

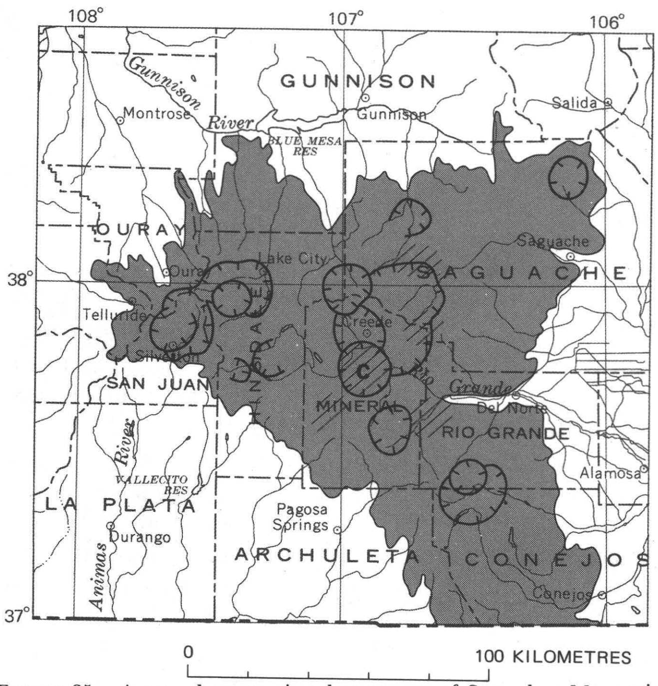

FIGURE 25.—Areas where erosional remnants of Snowshoe Mountain Tuff are preserved (diagonal lines) in relation to Creede caldera (C) and San Juan volcanic field (shaded).

Tongues of talus and rockfall breccia (Steven and Ratté, 1965, p. 42) extend into at least the upper 700 m of the intracaldera Snowshoe Mountain Tuff along the western side of the caldera, and probably are present but unexposed elsewhere within the intracaldera tuffs. These breccias clearly indicate subsidence concurrent with accumulation of the Snowshoe Mountain Tuff, and demonstrate that the developing caldera wall exposed rocks as old as Wason Park Tuff at least episodically during subsidence. The successive rude layering and compaction foliation in the Snowshoe Mountain Tuff are virtually parallel, and indicate that the core of the caldera sank as a coherent mass, rather than in piecemeal blocks.

Final subsidence left a basin 12–15 km across, with steep walls rising 1–1.4 km above the flat floor. These walls were unstable, and great masses fell off to form tongues of rockfall breccia that extended over the caldera floor. The northeast wall of the caldera, where densely welded Mammoth Mountain and Wason Park Tuffs overlie soft tuffs, was particularly susceptible to avalanching, and a broad crescent-shaped scallop, 8 km wide and 3 km deep, developed in the outer wall. Breccias derived from the northeast wall of the caldera (Steven and Ratté, 1965, p. 42-43) have been identified more than halfway across the caldera, 8-10 km from their source.

The core of the Creede caldera was strongly domed after subsidence, and the center of the dome was uplifted more than 1.5 km above the structural moat left around the periphery. The eastern part of the uplift is a simple half dome with the layers of Snowshoe Mountain Tuff dipping radially outward 25°-45°. A deep north-trending graben extends across the center of the uplift; displacement is minor near the north and south ends of the graben, but exceeds 700 m near the center of the dome. Internal structure of the graben is complex (Steven and Ratté, 1965, pl. 1), but its general form is a fractured keystone block across the distended top of the resurgent dome. The west part of the resurgent core was less regularly uplifted; the northern flank was tilted northwest and broken by faulting and the western flank was tilted generally westward and was progressively more uplifted toward the south.

A small dome of autobrecciated rhyolite (Point of Rocks volcano) formed along the west side of the Creede caldera at some time just preceding, during, or immediately after resurgent doming. Pebbles of similar rhyolite have been found in some avalanche breccias caught in jumbled fault blocks along the keystone graben, suggesting that this volcano may have formed before resurgence. On the other hand, the eruption may have followed resurgent uplift, inasmuch as a local exposure shows the feeding neck to be nearly vertical where it cuts across strongly inclined layers of Snowshoe Mountain Tuff.

Resurgence of the Creede caldera was followed by eruption of flows and domes of Fisher Quartz Latite at places around the periphery and by deposition elsewhere of the stream and lake sediments and travertine of the Creede Formation. Closely accordant K-Ar age determinations of Fisher lavas indicate that this stage in the Creede caldera cycle took place about 26.4 m.y. ago. Most of the postcaldera lavas were erupted from centers northeast and south of the caldera. Ash-flow deposits in the concurrently deposited Creede Formation are most abundant toward the south, indicating that Fisher centers in this direction supplied much of the ash that elsewhere was reworked into the predominant stream-and lake-sediment facies. Travertine in the Creede Formation was deposited widely around the periphery of the caldera; consideration of the timing of deposition and of carbon isotope ratios led

Steven and Friedman (1968, p. B32-B33) to conclude that the carbonate was derived from underlying sedimentary carbonate units by resurgent magma rising into the roots of the Creede caldera. The Creede Formation is presently exposed over a vertical range of more than 700 m; the bottom of the basin of deposition is not exposed and the top of the formation is eroded. The original thickness of the formation was more than a kilometre and was possibly as much as 1.4 km.

The final major stage in structural disruption that has been recognized in the vicinity of the Creede caldera was strong local faulting accompanied by mineralization in the Creede mining district adjacent to the north margin of the caldera (Steven and Ratté, 1965) and in the Spar City mining district along the south margin of the caldera (Steven, 1964). Steven (1972) and Steven and Eaton (1975) have interpreted the faulting and mineralization in the Creede district to have resulted from local intrusion of a stock into the roots of a preexisting broken zone. This intrusion may have been the terminal stage of the Creede caldera cycle or, more probably, may have been a later unrelated event, inasmuch as K-Ar age determinations on adularia from the OH vein in the Creede district indicate that mineralization took place there about 24.6 m.y. ago (M. A. Lanphere, P. M. Bethke, P. B. Barton, written commun., 1973), nearly 2 m.y. after caldera subsidence.

LATE GENERAL MAGMATIC UPLIFT

A broad zone extending from the Platoro caldera complex northwest through the central San Juan caldera complex was broken by normal faults late in the period of caldera development. Faults that developed at this time extend along the crest of the eastern part of the gravity low (fig. 1); these faults are thought to reflect uplift and distention related to a general buoyant rise of the whole eastern part of the batholith, where evidence for concurrent magmatism is strong.

Faulting took place in two general segments—the Rio Grande graben (figs. 1 and 22) extending southeast from the central caldera complex, and the Clear Creek graben (fig. 1) extending tangentially northwest from the caldera complex. Some faults in the Rio Grande graben were recurrently active, particularly near the northwest end, where we recognized several increments of displacement related to the progressive breakdown of the southwestern half of the La Garita caldera. Recurrent movement is also evident at the southeast end of the graben system, where Miocene basalts of the Hinsdale Formation are locally involved. The main graben faulting, which integrated some of the earlier faults into a regional pattern, took place during the Creede caldera cycle. Many of the faults cut Nelson Mountain Tuff and are in turn overlapped by unbroken Fisher Quartz Latite that was erupted late in the Creede caldera cycle. The northwest-trending faults are generally parallel to the trend of the underlying batholith. This same part of the batholith was the source of repeated ash-flow eruptions and caldera subsidences during and just before graben development, indicating high-level activity in the underlying magma chamber. Some Rio Grande graben faults terminate to the southeast against a north-trending fault that closely parallels the eastern margin of the gravity low—again implying a close relationship between the faulting and distention of the roof above an active segment of the batholith.

As shown on figure 1, the Clear Creek graben (Steven, 1967) extends tangentially northwest from the southwest side of the central San Juan caldera complex. Its trend is parallel to the southwest side of the gravity low in the south-central part of the volcanic field. Where the graben extends across the gravity low toward the north, it separates an area of then-recent ash-flow eruptions and caldera subsidences to the east from an area of older ash-flow eruptions and caldera subsidences to the west. The graben reflects distention of the roof of the batholith, and it also marks relative uplift of the area to the east (Steven, 1967), toward the area of concurrently active magmatism. To the north, faulting changes from a graben to a west-facing normal fault and then to a northwest-facing monocline that bends around the northwest side of the San Luis caldera and dies out as it approaches the margin of the gravity low. As discussed earlier, the Nelson Mountain Tuff is about 0.7 km higher to the south of the San Luis caldera than it is to the north—a discordance believed to measure some of the late general uplift of the area above the batholith.

The Clear Creek graben began to develop during the closing stages of the San Luis caldera cycle, and may have been about concurrent with the Creede caldera cycle. The west-facing normal fault at the north end of the graben already existed when the quartz latite of Baldy Cinco was erupted, inasmuch as lavas of this unit poured over and covered a scarp related to the fault. Relations are ambiguous near the Creede caldera at the southeast end of the graben, where widespread glacial till obscures much of the bedrock. We saw no evidence that the graben existed when the Creede Formation was being deposited, yet none of the faults can be demonstrated to cut the Creede Formation. At least one fault on trend with the Clear Creek graben cuts Fisher Quartz Latite flows in the Spar City mining district on the south side of the Creede caldera, but this might reflect late reactivation of an earlier fault.

The Rio Grande and Clear Creek grabens are thus believed to reflect general distention and minor buoyant uplift of the eastern part of the batholith, where intense ash-flow activity and caldera subsidence demonstrated concurrent high-level magmatism in the underlying batholith. The faulting dies out southeastward and northwestward as it approaches the margins of the related gravity low, and no related graben faults of this age are present in the western part of the gravity low where ash-flow eruptions and caldera subsidences are older. However, the intricate pattern of veins and small faults that radiate outward from the Silverton caldera may reflect analogous broad uplift during waning stages of volcanism in that area.

BLOCK-FAULTED AREA

An area west and southwest of the Mount Hope caldera is also broken by faults that were recurrently active during the period of caldera formation. This structurally somewhat anomalous area seems localized where the south margin of the gravity low, and presumably of the subvolcanic batholith (fig. 1), extends southwest across a thick wedge of Paleozoic-Mesozoic sedimentary rocks marking the northern extension of the San Juan Basin (fig. 1). The faults have the general pattern of a short ladder (fig. 14), with two northeast-trending faults bounding an area cut into narrow blocks by irregularly northwest trending steep faults. Several periods of movement can be discerned.

The oldest faulting followed deposition of the intertongued Masonic Park welded tuffs and Sheep Mountain andesitic lavas, and preceded deposition of the Fish Canyon Tuff. A later period of faulting is indicated in the eastern part of the highly faulted area, where andesitic breccias and minor flows in the Huerto Formation thin abruptly from more than 1,500 m to about 70 m thick eastward across a buried scarp on the Fish Canyon Tuff. This scarp probably marks a local fault that was active between deposition of the Fish Canyon Tuff and the Huerto Formation.

The main faulting followed eruption of the andesitic lavas and breccias of the Huerto Formation. The ladder-shaped pattern of faults formed at this time and the general result was to depress the area toward the caldera area to the north. These faults are superimposed on the steep gravity gradient along the south side of the underlying batholith (fig. 1), and the general effect of the faulting was to warp a local segment of the roof downward toward the batholith across its southwestern margin. This faulting did not coincide with any particular ash-flow eruption, but rather followed accumulation of episodically erupted andesitic lavas and breccias at a number of local volcanic centers. The movement thus probably resulted from magmatic movements within the batholith and distention along its south margin. This distention may have been in part localized by the relatively incompetent prevolcanic sedimentary sequence in this area.

Many of the faults that formed during the main post-Huerto faulting were reactivated later, after the Carpenter Ridge Tuff accumulated. In places, this reactivated movement was in the same direction as the earlier movement, and in other places, the direction of displacement was reversed. Most of the post-Carpenter Ridge faulting appears to have reflected minor readjustments in the already broken roof of the batholith.

The youngest faults within this area reflect shallow gravity sliding of the south flank of the volcanic pile out over underlying Cretaceous shales. Fracturing took place along crescentic faults facing southward toward the edge of the volcanic plateau (fig. 14). The rocks enclosed within these faults were dropped downward toward the south, and tilted northward 30° or more by concurrent rotation. These faults are related to the present erosional scarp along the south side of the volcanic plateau, and are not directly related to the older faults that resulted from magmatic movement during late Oligocene volcanic activity.

DISCUSSION

DEVELOPMENT OF THE BATHOLITH

Calderas and related subsidence structures in the San Juan volcanic field are situated within a marked negative gravity anomaly that is believed to reflect an underlying shallow batholith. Successive ash-flow eruptions and caldera collapses in the volcanic pile above this batholith probably mark the local culminations of upward movement of magma: when the roof of an individual chamber became so thin that it failed, voluminous ash was erupted rapidly and a caldera collapsed into the partly evacuated magma chamber. Resurgent upward movement of magma domed many of the calderas and caused extrusion of lavas along the earlier formed structures. High-level magmatism, as manifested by volcanic eruptions and related structural adjustments, diminished at each center as the underlying cupola crystallized.

Using this model, we can trace the development of the high-level batholith beneath the San Juan volcanic field from the histories of the successive calderas. The early calderas are widely scattered and are either on the margins of the gravity low or on outward projections from it. Most of these early calderas developed within clusters of older andesitic stratovolcanoes, and the postsubsidence eruptions were commonly of intermediate lavas similar to the older andesites. We interpret these calderas to have developed above isolated high-level cupolas of magma that developed in the roots of older volcanoes before the main body of the batholith rose to its present position. The upper parts of these cupolas differentiated to quartz latite and low-silica rhyolite, which formed the ash-flow tuffs associated with the early calderas, but the quantity of silicic material was limited, and the postsubsidence lavas were from the underlying relatively undifferentiated andesitic magma.

The later calderas and associated structures are above the main body of the batholith as indicated by gravity data. At least 12 separate calderas formed within about 3 m.y. This intense activity is believed to reflect the rise of the batholith in two main high-level segments corresponding to the two main caldera complexes. The segment beneath the western San Juan Mountains rose to shallow depths about a million years before the central San Juan segment, but high-level magmatic activity in each segment overlapped in time.

The top of the batholithic mass of magma was extensively differentiated—to phenocryst-poor rhyolite in the upper parts of local cupolas, and to large volumes of phenocryst-rich quartz latite beneath. Ash-flow eruptions in the western San Juan Mountains depleted the more silicic differentiates in the upper parts of the magma chambers, and the postsubsidence lavas were more mafic intermediate-composition rocks from progressively greater depths in the chambers. In the central San Juans, however, even the largest ash-flow eruptions did not exhaust the differentiated material in the underlying chambers, and the postsubsidence lavas that were erupted around the calderas are typically porphyritic quartz latites which are related in composition to the associated ash flow tuffs. Local andesitic volcanoes not closely associated with the calderas tapped deeper, little-differentiated parts of the batholith throughout the period of ash-flow eruptions and caldera subsidences.

The Lake City caldera in the western part of the San Juan volcanic field, which is related to eruptions of the petrologically distinct alkali rhyolite of the Sunshine Peak Tuff, collapsed about 4 m.y. later than the youngest major eruptions of andesitic and derivative rocks from the central and western parts of the San Juan volcanic field. This late caldera is believed to have formed above a later high-level magma chamber unrelated to the earlier segments of the batholith.

These interpretations suggest some time limitations on the magmatic life span of a shallow, composite batholith 100 km across. After about 5 m.y. (during the period from 35 to 30 m.y. ago) of intensive eruption of andesitic lavas from many scattered centers, local magma chambers 10-30 km across had risen to shallow depths beneath some of the larger volcano clusters, and had differentiated sufficiently to supply large-volume eruptions of silicic ash. Within the next 4 m.y. (30-26 m.y.) the batholith evolved from this collection of scattered chambers to a broad shallow mass of extensively differentiated magma, and then to virtual dormancy. Within another 4 m.y. (26-22 m.y.), the lower part of the batholith had congealed sufficiently to permit a younger, petrologically distinctive body of magma to work its way up to similar shallow depths, while still retaining its compositional identity.

RELATION OF ASH-FLOW ERUPTIONS AND CALDERA SUBSIDENCE

An essentially one-to-one relationship exists between major eruptions of ash flows and subsidence of calderas in the San Juan volcanic field. Unresolved is the volume of ash required to make this maxim operative. Most of the ash-flow sheets we have mapped have either very small (<10 km^3) or moderate (100-500 km^3) to large (>500 km^3) volumes; caldera subsidence is known or suspected to have been associated with all the moderate-volume sheets and invariably accompanied the large-volume sheets. Several of the calderas associated with moderate-volume ash-flow sheets did not form complete circular collapse structures, but subsided as trapdoors hinged on one side. Such calderas generally were not resurgently domed after subsidence. Calderas associated with large-volume sheets, on the other hand, generally are complete subcircular structures, and commonly were resurgently domed after collapse.

All large-volume ash-flow units are much thicker within the calderas, typically by an order of magnitude, than in the surrounding outflow areas. This relationship is most easily explained by subsidence concurrent with eruption. Many of the large-volume units are compositionally zoned from early rhyolite to later quartz latite. In most, the rhyolite is confined to the base of the outflow sheet, commonly near the source, and the exposed intracaldera tuff is entirely quartz latite. This suggests that by the time ash-flow eruptions had removed sufficent magma to cause collapse, the rhyolitic material at the top of the chamber was usually exhausted. Alternatively, initiation of collapse may have disrupted the vent systems and caused tapping of deeper, less differentiated parts of the magma chamber. No generalization can be made concerning the beginning of subsidence relative to composition of the ash being erupted, however, as the relative volumes of rhyolitic versus quartz-latitic ash vary widely from one sheet to another. At the extremes, no rhyolite at all has been found at the base of the Fish Canyon Tuff, which forms the largest sheet in the San Juan field, whereas rhyolite dominates in both the outflow and intracaldera facies of the large-volume Sapinero Mesa and Carpenter Ridge Tuffs.

DIFFERENTIATION IN LOCAL CUPOLAS

Evidence for independent differentiation at separate volcanic source areas supports the idea that the successive calderas developed above local cupolas that projected above the general top of the batholith. This postulate is inherent in our interpretation of the development of the widely scattered early calderas, but appears valid for the clustered calderas in the western and central San Juan complexes as well.

In the western San Juan caldera complex, contrasting phenocryst-rich quartz-latitic Ute Ridge Tuff and phenocryst-poor rhyolitic Blue Mesa Tuff were erupted sequentially from calderas only a few kilometres apart, and individual magma chambers with separate differentiation seem required. The later series of eruptions of rhyolitic Dillon Mesa and Sapinero Mesa Tuffs, progressively more mafic lavas and breccias of the Burns and Henson Formations, and rhyolitic Crystal Lake Tuff, all from within the confines of the San Juan-Uncompahgre-Silverton caldera cluster, chronicle the sequence of depletion of the differentiated magma at the top of one major cupola, establishment of another cupola, further differentiation, and, finally, renewed eruptions of regenerated rhyolite. Inasmuch as only about 2 m.y. intervened between eruptions of the Ute Ridge and Crystal Lake Tuffs, these sequential high-level magmatic processes must have progressed rapidly.

The major La Garita caldera in the central San Juan Mountains occupied much of the roof of the eastern segment of the batholith. The associated ash flows show virtually no evidence of compositional zoning; evidently, little highly silicic material had accumulated at the top of the broad magma chamber that supplied the enormous quantities of ash for the Fish Canyon Tuff. The magma chambers that developed successively along the west side of the La Garita caldera, however, were strongly differentiated. Rhyolite is a major constituent in the Carpenter Ridge, Mammoth Mountain, and Wason Park Tuffs, which followed in succession from closely associated source areas. Each of these units has distinctive phenocryst characteristics requiring separate development, and the first two are strongly compositionally zoned upward from phenocryst-poor rhyolite to phenocryst-rich quartz latite. All three of these units evidently developed under conditions that permitted local differentiation within sequentially formed restricted chambers.

The later Rat Creek, Nelson Mountain, Cochetopa Park, and Snowshoe Mountain Tuffs are from more widely scattered centers, for which local cupolas can readily be postulated. Except for the rhyolitic Rat Creek Tuff, these units are mostly composed of closely similar phenocryst-rich quartz latite, although the Cochetopa Park Tuff has some rhyolitic ash at its base. The overlap in time of the areally separate San Luis and Cochetopa Park caldera cycles also indicates concurrently developing, separated cupolas containing individually differentiated batches of magma.

Considering the number of calderas that developed sequentially within the approximately 4 m.y. of ash-flow activity above the San Juan batholith, differentiation must have been relatively rapid to generate silicic magma at the tops of the individual cupolas. This is particularly true for the succession of Fish Canyon, Carpenter Ridge, Mammoth Mountain, and Wason Park Tuffs, where the related calderas and source areas apparently overlap and the individual high-level magma chambers had to develop and differentiate in sequence.

RESURGENCE

Two broad types of magmatic uplift and general uplift related to calderas in the San Juan volcanic field have been recognized—in one, the uplift was closely confined to the caldera and the immediately adjacent area and occurred soon after collapse; in the other, however, broader uplift involved major segments of the roof of the batholith and occurred over an extended period. These two types of magmatic uplift merge and are, in places, difficult to distinguish.

Virtually none of the smaller calderas in the San Juan volcanic field show evidence of resurgent doming after subsidence. Fairly clear-cut relations indicating no resurgent doming are found at the Summitville, Ute Creek, Silverton, and Cochetopa Park calderas, as well as at the buried or postulated Lost Lake, Mammoth Mountain, and Wason Park calderas. Of these, the Silverton, Cochetopa Park, and probably the Ute Creek calderas subsided as trapdoor blocks with horseshoe-shaped incomplete ring-fracture zones interrupted by monoclinal hinges on one side; the buried Lost Lake caldera possibly may have subsided in a similar manner. The Summitville caldera is deeply buried by a fill of andesite flows, and the postulated Mammoth Mountain and Wasson Park calderas were largely or completely destroyed by younger subsidences.

Most major San Juan calderas were resurgently domed shortly after subsidence. The Platoro, La Garita, Bachelor, San Luis, Creede, and Lake City calderas display such doming particularly well, and the Bonanza caldera may belong to this group. These are the typical resurgent cauldrons so well described by Smith and Bailey (1968), in which uplift was a definite stage in the caldera cycle (stage V) and was closely confined to the collapsed block and a narrow belt around the margin. Uplift clearly seems to have resulted from the rise of a central pluton beneath the subsided block, and often was accompanied by escape of magma along the marginal ring-fracture zones. The uplifted blocks within these calderas range from nearly symmetrical domes cut by tensional fractures (the Creede, Lake City, San Luis, and probably La Garita and Bachelor calderas) to tilted trapdoor blocks (the Platoro caldera).

Less well defined is the long-continued uplift of the area of the western San Juan caldera complex. Although some typical resurgence—in the sense described by Smith and Bailey (1968)—of both the San Juan and Uncompahgre calderas may have taken place, the main uplift was of long duration and involved an oval-shaped area that included both calderas. It began shortly after collapse of the San Juan and Uncompahgre calderas, continued through filling by locally derived lavas and sediments of the Burns and Henson Formations, eruption of the Crystal Lake tuff and resultant subsidence of the Silverton caldera, and further filling by ash flows from intracaldera sources in the central San Juan Mountains. Quite possibly the total period of recurrent uplift spanned a million or more years. This long-continued activity may have resulted in part from general buoyant uplift by the major magma chamber that underlay the whole western caldera complex.

Another example of late general uplift is the Mount Hope caldera. We saw no evidence for postcollapse resurgence, and the succeeding Fish Canyon Tuff appears to have passively filled a deep depression. After filling, however, the whole area of the caldera was broadly upwarped, and so several of the overlying ash-flow sheets wedged out laterally against a low dome in the caldera area. Again, slight buoyant uplift above either a persisting cupola of magma, or a later renewed incursion of magma, would account for the relations seen. This type of uplift, and to a lesser extent that displayed in the Uncompahgre and San Juan calderas in the western part of the volcanic field, seems transitional to the broad buoyant uplift that affected the whole eastern part of the shallow batholith, as described in the section on "Late magmatic uplift."

MINERALIZATION

Only about a third of the calderas in the San Juan volcanic field are significantly mineralized (Steven, Luedke, and others, 1974). These calderas all had complex postsubsidence histories involving recurrent intrusion and extrusion of magma along the ring-fracture zones and related grabens. Some mineralization may have taken place during terminal stages of the associated caldera cycle, but the association of mineralization with a given caldera cycle generally seems tenuous, and the caldera seems principally to have provided fractures that guided later igneous intrusion and hydrothermal activity.

The Creede mining district occupies a radial graben on the north side of the Creede caldera. Faulting began during resurgence of the Bachelor caldera, and was reactivated several times later during the volcanic history of the area. The last faulting took place either late in the Creede caldera development cycle or shortly thereafter, when a generally equidimensional area 5-6 km across just outside the Creede caldera wall was broken, probably by intrusion of a stock at depth (Steven and Eaton, 1975). Important silver, lead, zinc, copper, and gold ores were deposited widely in fractures in the heart of the broken area (Steven and Ratté, 1965). The Creede caldera subsided about 26.5 m.y. ago, whereas the ores were deposited about 24.6 m.y. ago (M. A. Lanphere, P. M. Bethke, and P. B. Barton, written commun., 1973). These dates are perhaps too widely separated for the mineralization to be considered a terminal phase of the Creede caldera cycle of development and should, instead, be considered a later, unrelated event.

Mineralization around the nested Platoro and Summitville calderas is even less closely tied to the caldera cycles. The calderas formed 29-30 m.y. ago in response to the repeated ash-flow eruptions of the Treasure Mountain Tuff (Lipman and Steven, 1970; Lipman, 1975a). The ring-fracture zones of these calderas were the sites of repeated igneous intrusion that began shortly after caldera subsidence and continued to about 20 m.y. ago. Significant mineral deposits seem to be concentrated where ring fractures of the Summitville and Platoro caldera complex intersect a regional northwest-trending fault zone (fig. 1) in the Summitville, Stunner, and Platoro mining districts. Other mineralized areas in or near this complex, at Crater Creek, Jasper, and Cat Creek, are also localized by caldera-margin faulting and igneous activity. The ores at Summitville have been dated by K-Ar methods as 22.4 m.y. old (Mehnert, Lipman, and Steven, 1973b), and thus are much too young to be tied to the main caldera cycles.

The western San Juan Mountains have a complex history of mineralization with several distinct periods of ore deposition extending over an interval of about 15 m.y. in late Tertiary time (Lipman and others, 1976). In the Lake City area, scattered mineral deposits, currently of limited economic significance, occur in the intrusive cores of intermediate-composition stratovolcanoes that were active between 35 and 30 m.y. ago, before any of the ash-flow eruptions that resulted in caldera collapses. Significant vein and disseminated mineralization occurred within northern parts of the Uncompahgre caldera after it collapsed about 28 m.y. ago, but before collapse of the Lake City caldera during eruption of the Sunshine Peak Tuff 22.5 m.y. ago. This timing is indicated by mineralized areas cut off by the younger subsidence and fragments of mineralized rock in landslide debris within adjacent parts of the Lake City caldera fill. Additional vein and disseminated mineralization occurs within and adjacent to the Lake City caldera, and is therefore younger than 22.5 m.y. old.

Major veins that follow faults of the Eureka graben (fig. 13) between the Lake City and Silverton calderas seem also to have formed after collapse of the Lake City caldera, although the graben faults existed as pre-Lake City structures. Later mineralization seems indicated by the following field relations: (1) We saw no altered rocks or vein fragments in landslide breccias within the Lake City caldera adjacent to the Eureka graben, although veins and mineralized rocks along graben faults extend to the structural margin of the caldera. (2) At Engineer Pass on the northwest side of the Eureka graben, silicic quartz porphyry intrusions that cut the Sunshine Peak Tuff, which was erupted from Lake City caldera, occur at the junction of a hydrothermally altered breccia pipe with associated mineralized veins and have yielded K-Ar and fission-track ages of 15-22 m.y. (H. H. Mehnert and C. N. Naeser, written commun., 1974). These silicic quartz porphyry intrusives, which form a well-defined northeast-trending belt extending about 40 km from northwest of

Silverton to north of Lake City, range from quartz latite to silicic rhyolite and granite. They are petrologically distinct from dated intrusions of the main cycle of ash flows and caldera collapse, which occurred at about 28 m.y., but they have close petrographic affinities to magmas of the 22.5-m.y. Lake City cycle.

In the productive Red Mountain district, on the west side of the Silverton caldera, intense alteration and breccia-pipe mineralization are similarly associated with silicic quartz-porphyry intrusions that have been dated at 22-23 m.y. (H. H. Mehnert and C. N. Naeser, written commun., 1974), suggesting that mineralization in this area is young and genetically unrelated to the Silverton caldera cycle. The ages of the major vein systems southeast and northwest of the Silverton caldera are less certain, but at least some of the major veins southeast of Silverton cut quartz-porphyry intrusions similar to those in the Engineer Pass and Red Mountain areas, and replacement ores associated with the rich veins on the northwest side of the Silverton caldera have yielded adularia K-Ar ages of 11-17 m.y. (F. S. Fisher and H. H. Mehnert, written commun., 1974). Thus, much—perhaps all—of the productive mineralization structurally associated with the Silverton caldera appears to have occurred at least 6–10 m.y. later than formation of the caldera 28 m.y. ago. The caldera appears to have acted mainly as a structural control, with some mineralization genetically associated with quartz-porphyry intrusions that are petrologically distinct from volcanic rocks erupted during the caldera-forming process.

The primary function of calderas in mineralization thus appears to be the preparation of zones of weakness in the roofs of major magma-chambers. If conditions at depth are favorable, some of these zones are the sites of recurrent igneous intrusion and extrusion, locally accompanied by hydrothermal activity and mineralization. Whether this activity is the terminal stage of a specific caldera cycle, or is later and generally independent, seems accidental at our present incomplete state of knowledge.

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