Petrologic evolution of the San Juan volcanic field, southwestern Colorado: Pb and Sr isotope evidence

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ABSTRACT

Two distinct suites of igneous rocks occur within the San Juan volcanic field: an Oligocene suite of predominantly intermediate-composition lavas and breccias, with associated silicic differentiates erupted mainly as ash-flow tuffs, and a Miocene-Pliocene bimodal suite of silicic rhyolites and mafic alkalic lavas.

The Oligocene volcanism, probably related to subduction along the western margin of the American plate, has chemical and isotopic characteristics indicative of complex interactions with Precambrian cratonic lithosphere. It also appears to record the rise, differentiation, and crystallization of a large composite batholith beneath the San Juan field. The earliest intermediate-composition lavas and breccias have major- and minor-element compositional patterns indicative of high-pressure fractionation and are relatively nonradiogenic in both Pb and Sr, suggesting significant interaction with lower crust of the American plate. The more silicic ash-flow tuffs show compositional evidence of low-pressure fractional crystallization and are more radiogenic in Pb and Sr — features thought to indicate significant shallow residency for the magmas and interaction with upper crust. Especially radiogenic Pb-isotope compositions of some of these rocks may reflect interactions between the magmas and convecting meteoric water rich in leached Pb, a process thought to have been even more important in forming associated hydrothermal ore deposits. Ore leads tend to be more radiogenic than associated rock leads.

Many of the Miocene-Pliocene basaltic lavas seem to be mantle-derived lavas, similar to those of oceanic islands, but some anomalous xenocrystic basaltic andesites, containing relatively nonradiogenic lead, may have been slightly contaminated by lower crustal components. Rhyolitic lavas and intrusions of the bimodal suite are also nonradiogenic in Pb and Sr, in comparison with the Oligocene rhyolites, and do not appear to have interacted with Precambrian upper crust, probably because they erupted largely through the subvolcanic batholith. The Miocene-Pliocene rhyolites are best interpreted as partial melts of lower crust, with the thermal energy to initiate magma generation provided by concurrent basaltic volcanism.

INTRODUCTION

The Oligocene San Juan volcanic field, southwestern Colorado (Fig. 1), consists largely of intermediate-composition lavas and volcaniclastic rocks, with associated more silicic ash-flow tuffs (Lipman and others, 1970; Steven and others, 1974). The origin of such voluminous intermediate-composition volcanic accumulations in continental interiors has become an important petrologic problem, because many andesitic terranes are most reasonably interpreted in terms of subduction-related processes along plate-tectonic boundaries. This paper presents new Pb and Sr isotopic data that, along with recent geological, geophysical, and geochemical studies, are used to trace the evolution of middle and late Tertiary magmatism in the San Juan field.

The Oligocene magmas were calc-alkalic and appear initially to have been generated deep in the mantle, perhaps related to a complex subduction system. The initial magmas were probably mafic, but during their rise to the surface, they evolved chemically and isotopically by interaction with lithospheric mantle and sialic crust. Miocene-Pliocene magmas constitute a bimodal suite of rhyolite and basalt erupted in an extensional tectonic environment. The basalts are thought to represent magma of upper-mantle origin, and the associated rhyolites may be partial melts of lower crust, related to thermal effects of emplacement of the basaltic magmas.

VOLCANIC HISTORY

The nature of middle and late Tertiary volcanism was rather similar throughout the southern Rocky Mountains, and the San Juan field represents the largest erosional remnant of a formerly much more extensive composite volcanic field (Steven, 1975). In the San Juan area, intensive volcanism during Oligocene time was concentrated approximately along the crest of the northwest-trending Brazos-Uncompahgre uplift (Kelley, 1957), which developed in Late Cretaceous–early Tertiary time (Laramide). This area was also the locus in part of early Tertiary volcanism about 65 to 70 m.y. ago (Dickinson and others, 1968).

Mid-Tertiary activity began in the San Juan field with eruption of voluminous intermediate-composition lavas and breccias (Table 1) from widely scattered central volcanoes between about 35 and 30 m.y. ago. This early suite represents about two-thirds of the volume of Oligocene activity in the San Juan area, and perhaps even more in other parts of the southern Rocky Mountains. As the central volcanoes grew, aprons of mudflow and other volcaniclastic debris from them accumulated in the intervening basins, eventually to produce a composite volcanic pile. The San Juan segment of the larger field covered more than 40,000 km^2 and averaged about 1 km thick.

Some early volcanoes in the San Juans are fairly uniform in composition, consisting of alkali andesite or rhyodacite with SiO$_2$ contents of 55% to 65%, but others — such as the Summer Coon center (Lipman, 1968; Mertzman, 1971; Zielinski and Lipman, 1976) — erupted quartz latite and low-silica rhyolite late in their history. Silicic rocks also tend to be more abundant high in the early volcanic pile. Histograms of SiO$_2$ contents of about 450 available analyzed samples from the San Juan volcanic field (Fig. 2) illustrate these compositional variations, although the plotted analyses do not provide a completely valid sample of volumes (atypical rocks are over-represented).

Beginning about 30 m.y. ago, pyroclastic eruptions of ash-flow tuff became dominant in the San Juan field, and between about 30 and 26.5 m.y. ago at least 16 major ash-flow sheets (Table 1) poured out to form a great welded-tuff plateau overlying the early

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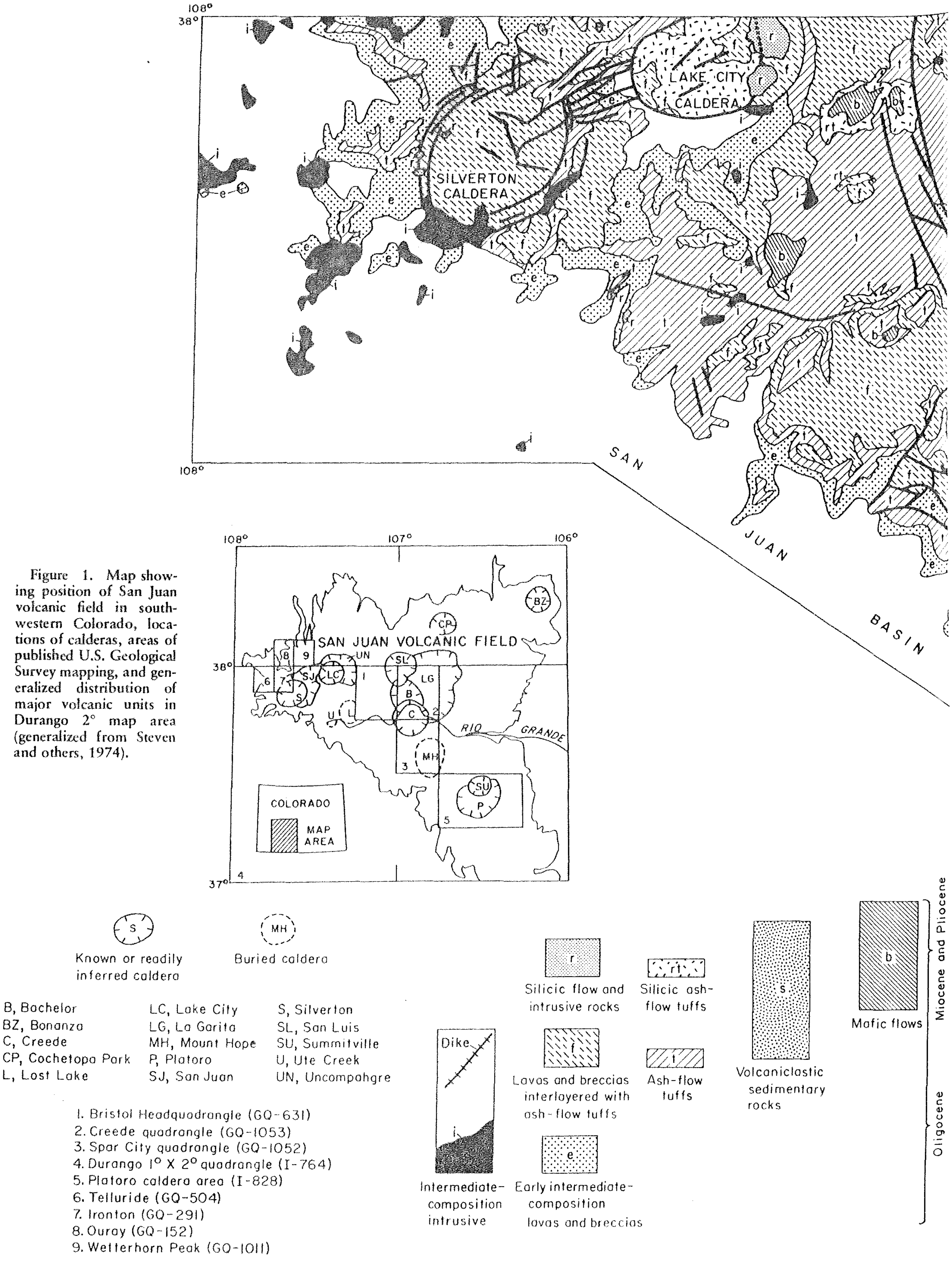

Figure 1. Map showing position of San Juan volcanic field in southwestern Colorado, locations of calderas, areas of published U.S. Geological Survey mapping, and generalized distribution of major volcanic units in Durango 2° map area (generalized from Steven and others, 1974).

Figure 1. *(Continued).*

intermediate-composition rocks. The ash-flow sheets were generally coextensive with the early lavas and breccias, but they were only about half as voluminous. Some individual ash-flow sheets were very large, covering as much as 15,000 km^2 and having initial volumes as great as 3,000 km^3. They were erupted from areally restricted sources marked by at least 15 large calderas (Fig. 1).

In a crude way, the size of a caldera is proportional to the volume of its associated ash-flow sheet, with the largest caldera (La Garita) being the source of the most voluminous ash-flow sheet (Fish Canyon Tuff). Most of the larger ash-flow sheets accumulated to much greater thickness within their associated calderas — commonly by an order of magnitude — than on the surrounding volcanic plateau. This stratigraphic relation indicates that caldera collapse typically began during the eruption of ash-flow tuff, with late-erupted ash flows largely ponding within the subsiding caldera (Steven and Lipman, 1976). The cores of many calderas were resurgently domed after collapse, following a typical caldera cycle (Smith and Bailey, 1968), and postcollapse eruptions of lava and accumulations of volcaniclastic sedimentary rocks filled the low moat between resurgent dome and caldera wall.

Three major groups of prominent calderas provide a convenient basis for subsequent discussions: (1) the southeastern Platoro caldera complex, (2) a central group in which the Creede and several other calderas are nested within the large La Garita caldera, and (3) a western group including the well-known Silverton and Lake City calderas (Fig. 1).

The ash-flow tuffs are more silicic than the early intermediate-composition rocks, varying from quartz latite to low-silica rhyolite (Fig. 2), but several features indicate that these tuffs may represent the more fractionated upper parts of bodies of intermediate-composition magma. Some ash-flow sheets are compositionally zoned, becoming more mafic upward (Ratté and Steven, 1964; Lipman, 1975, p. 49–53; Steven and Lipman, 1976). This change indicates eruption from vertically zoned magma chambers in which rhyolite overlay quartz latite and suggests the presence of even more mafic magma at depth. Individual sheets, such as the Carpenter Ridge and the Mammoth Mountain (Table 1), are zoned over a compositional range as great as that of the entire group of ash-flow sheets. The most mafic, last-erupted parts of these zoned ash-flow sheets approach the compositional peak for the preceding intermediate-composition lavas and breccias (Fig. 2). Inference of more mafic magma at depth is also supported by the continued minor eruption of andesitic to rhyodacitic lavas concurrently with the more silicic ash flows.

TABLE 1. GENERALIZED TERTIARY VOLCANIC STRATIGRAPHY OF SAN JUAN MOUNTAINS, COLORADO

Late basalts and rhyolites

Basalt of Servilleta Formation (3.6 to 4.5 m.y.)
Hinsdale Formation
  Basalt (4.7 to 26.4 m.y.)
  Rhyolite (4.8 to 22.4 m.y.)
Sunshine Peak Tuff (ash-flow sheet of Lake City caldera, 22.5 m.y.)

Main ash-flow tuffs

Snowshoe Mountain Tuff (>26.4 m.y.)
Nelson Mountain Tuff
Rat Creek Tuff
Watson Park Tuff
Mammoth Mountain Tuff (26.7 m.y.)
Carpenter Ridge Tuff
Fish Canyon Tuff (27.8 m.y.)
Masonic Park Tuff (28.2 m.y.)
Sapinero Mesa Tuff
Dillon Mesa Tuff
Blue Mesa Tuff
Tuff of Ute Ridge (28.4 m.y.)
Treasure Mountain Tuff
  Ra Jadero Member
  Ojito Creek Member
  La Jara Canyon Member (29.8 m.y.)
Tuff of Rock Creek

Lavas and related rocks erupted concurrently with ash-flow tuffs

Local andesitic–quartz latitic flows and breccias that intertongue with ash-flow sequence in and near their source calderas. Fisher Quartz Latite (26.4 m.y.) overlies main ash-flow sequence

Early intermediate-composition lavas and breccias

Andesitic–quartz latitic rocks of the Conejos Formation and related units (31.1 to 34.7 m.y.)

Note: Modified from Lipman and others (1970).

These later intermediate-composition lavas and related rocks are generally similar in petrology to the early lavas and breccias. Most of them accumulated within and marginal to the calderas, although a few large stratovolcanoes of these rocks grew on the ash-flow plateau beyond the calderas within the volcanic field. Such intermediate-composition lavas occur locally between almost every ash-flow sheet.

Some older calderas, notably in the southeastern and western caldera clusters, were flooded by intermediate-composition lavas soon after collapse. At the Platoro and San Juan–Uncompahgre calderas, the postcollapse fill progresses from rhyodacite or quartz latite, similar to the last-erupted ash-flow tuffs, to more mafic andesitic types. This variation may reflect tapping of progressively deeper, less differentiated parts of the same magma chambers that earlier produced the ash-flow tuffs. Subsequently, however, the compositional trend tended to reverse, and the postcollapse lavas progressed toward more silicic types, suggesting renewed differentiation or progressive change in the conditions of magma generation at depth.

The younger calderas, especially in the central San Juan cluster, have only minor associated andesite, and the postcollapse lavas form viscous domes of silicic rhyodacite and quartz latite within the calderas and around their rims. Examples are the flows of Fisher Quartz Latite around the Creede caldera (Steven and others, 1974).

Small stocks and dikes mark the eroded vents for many of the lava flows that accumulated contemporaneously with the ash-flow sequence. Although not separated from intrusions that predate the ash-flow sequence in Figure 1, most of the intrusions shown were emplaced during the ash-flow eruptions. These intrusions also tend to have intermediate compositions (Fig. 2), especially the larger stocks, which are mostly monzonite or granodiorite porphyry.

About 25 m.y. ago, late in Oligocene time, volcanic activity in the San Juan field changed from the association of intermediate-composition lavas and related more silicic rocks, just described, to widespread eruptions of basaltic lavas and local rhyolitic flows and tuffs. This bimodal assemblage, representative of the "fundamentally basaltic volcanism" that has been recognized widely in the western United States for late Cenozoic time (Christiansen and Lipman, 1972), seems largely unrelated genetically to the Oligocene activity in the San Juan field. Basaltic lavas, mostly silicic alkalic types 26 to 4 m.y. old (Lipman and Mehnert, 1975), formed a widespread thin veneer over much of the Oligocene San Juan volcanic plateau. Contemporaneous silicic rocks accumulated mainly near the Lake City caldera, which formed as a result of eruption of the rhyolitic Sunshine Peak Tuff about 22.5 m.y. ago, and in the southeastern San Juan Mountains around the north margin of the older Summitville caldera. These Miocene rhyolites differ petrologically from Oligocene silicic rocks of the field in that they are more silicic and alkalic, with abundant phenocrysts of quartz and sodic sanidine but little or plagioclase.

MAJOR-ELEMENT COMPOSITIONS

Major-element compositions of the Oligocene rocks of the San Juan volcanic field tend to define a single variation series ranging from mafic to silicic. Analyses from the whole field are too numerous to plot clearly on a single diagram, but compositional variations of rocks from the Platoro caldera area (Fig. 3) are representative. In general, if the SiO_2 content of a rock is known, the other elements can be estimated fairly reliably. Some scatter in the variation diagrams reflects significant differences among units, as noted below, but much of the variation is due to slight postdepositional alteration.

Gross compositional differences, as between the early intermediate-composition lavas and the ash-flow sheets, are readily evident (Figs. 2, 3). No consistent differences in major-element compositions reflect geographic distribution, and lavas and intrusions of different age or volcanic setting overlap in composition. However, the Oligocene ash-flow sheets vary subtly between two types, which are especially evident among ash-flow sheets related to the central La Garita–Creede caldera complex. Silicic tuffs, especially compositionally zoned sheets that contain relatively large proportions of rhyolite relative to quartz latite, tend to have distinctly higher K_2O and Al_2O_3, slightly higher Na_2O, distinctly lower total iron, and slightly lower CaO and MgO at any given SiO_2 content, in comparison with the dominantly quartz latitic ash-flow sheets. Similar differences, although less pronounced, also are present among ash-flow sheets from the western and southeastern caldera complexes.

These two contrasting compositional fields, defined by the central San Juan ash-flow sheets, are well shown on an Ab-Or-Q diagram (Fig. 4) that constitutes the "simple granite system" of Tuttle and Bowen (1958). Although compositions of the San Juan rocks vary in too complex a manner to interpret quantitatively, the different fields qualitatively may reflect crystal-liquid fractionation under differing pressures. A "low-pressure" field, converging on the quartz-feldspar cotectic at 500 b water pressure or less, is defined by analyses of the Carpenter Ridge, Mammoth Mountain, and Wason Park Tuffs, whereas a more diffuse "high-pressure" field is defined by compositions of the Fish Canyon, Rat Creek, Nelson Mountain, and Snowshoe Mountain Tuffs.

An observation consistent with this interpretation of pressure

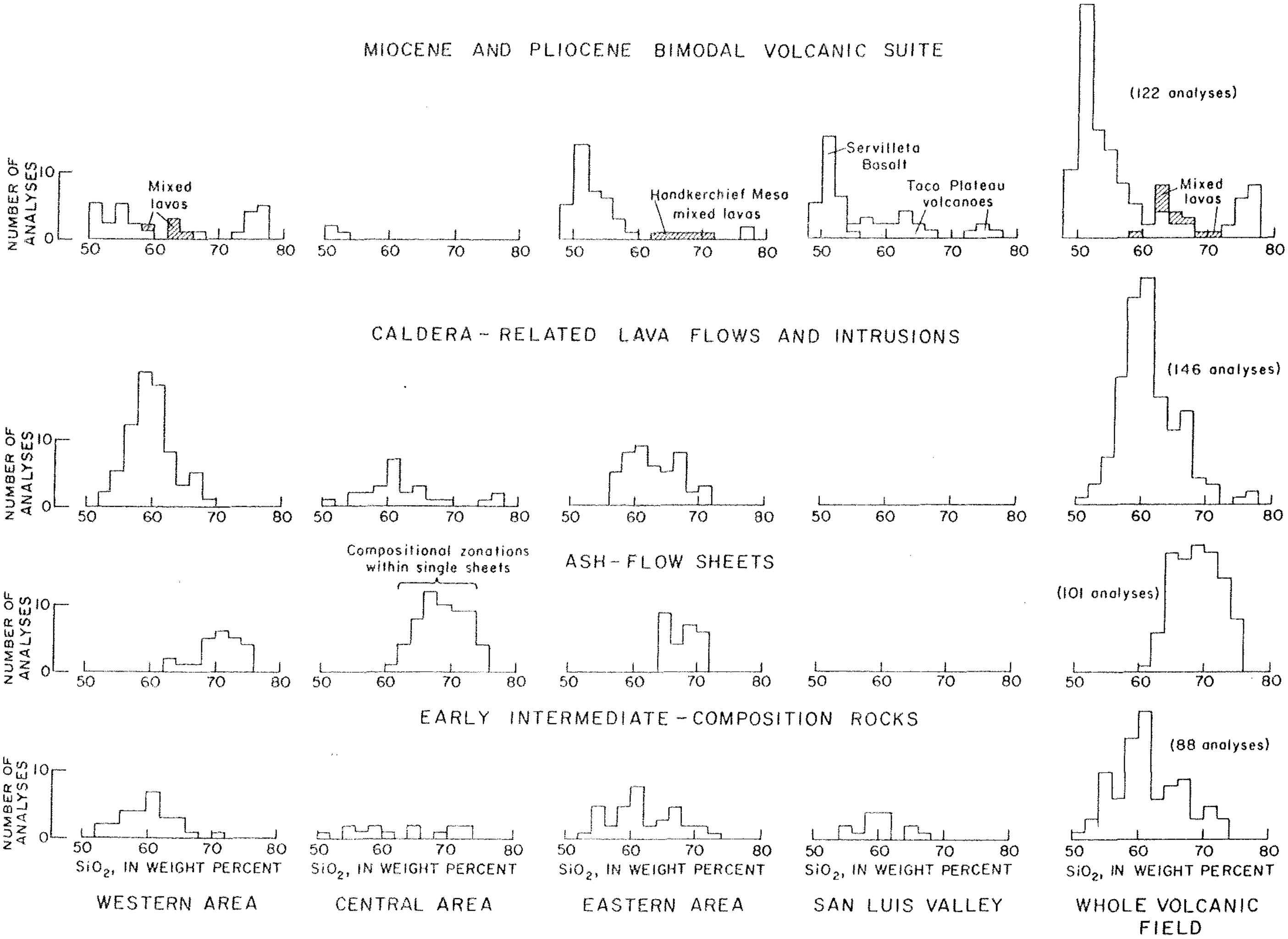

Figure 2. Histograms of SiO_2 contents for major groups of Tertiary igneous rocks in San Juan Mountains. Histogram interval is 2% SiO_2. Analyses are from sources cited by Lipman and others (1970, Fig. 2), Lipman (1975, and unpub. data), and Lipman and Mehnert (1975). All 1975 chemical analyses are plotted, except for a group of 64 from Summer Coon volcano (Mertzman, 1971), which have been omitted because they represent density of sampling far in excess of any comparable area elsewhere in volcanic field.

dependence is the presence of resorbed quartz phenocrysts in tuffs of the "high-pressure" group. These tuffs, all dominantly quartz latites showing no isotopic evidence of contamination, have SiO_2 contents too low for quartz to have crystallized at the relatively shallow depths of a subcaldera environment, and the quartz crystals must be high-pressure phenocrysts that crystallized at greater depth and were partly resorbed later in the evolution of the magmas. A similar multistage interpretation of analogous features of some Arizona ash-flow tuffs has been documented by Stuckless and O'Neil (1973).

Nearly all the Oligocene lava flows and intrusions plot with the "high-pressure" groups, including even the most silicic components of compositionally diverse volcanic suites such as those from the Summer Coon center. This suggests that much of the compositional

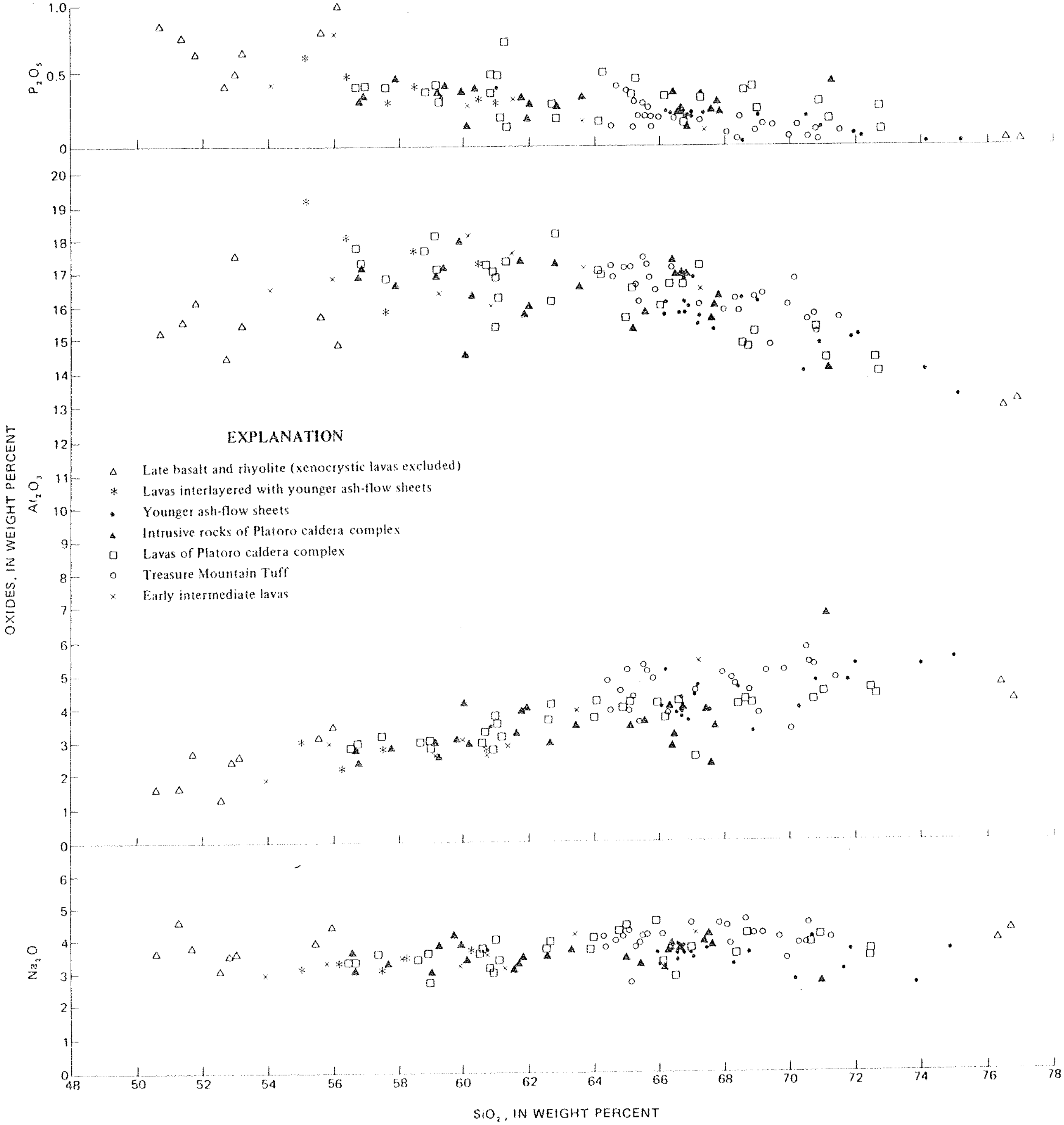

Figure 3. SiO_2 variation diagrams for major igneous units of Platoro caldera complex, southeastern San Juan Mountains (from Lipman, 1975).

variation orginated at depth, perhaps at the site of magma generation or early during migration to upper crustal levels, rather than by fractional crystallization in shallow subvolcanic magma reservoirs.

The interpretation of contrasting high- and low-pressure fractionation trends among the San Juan rocks is also supported by minor-element data, especially by rare-earth element analyses (Zielinski and Lipman, 1976), and unpub. data). All the intermediate-composition rocks and also the "high-pressure" ash-flow sheets show steep chondrite-normalized rare-earth element abundance patterns without europium anomalies. Both these features are indicative of fractionation in the upper mantle or deep in the crust where plagioclase was not a stable phase and equilibration was with a garnet-rich residuum (Zielinski and Lipman, 1976). In contrast, the ash-flow tuffs showing "low-pressure" major-element trends have sizable negative europium anomalies, indicating that

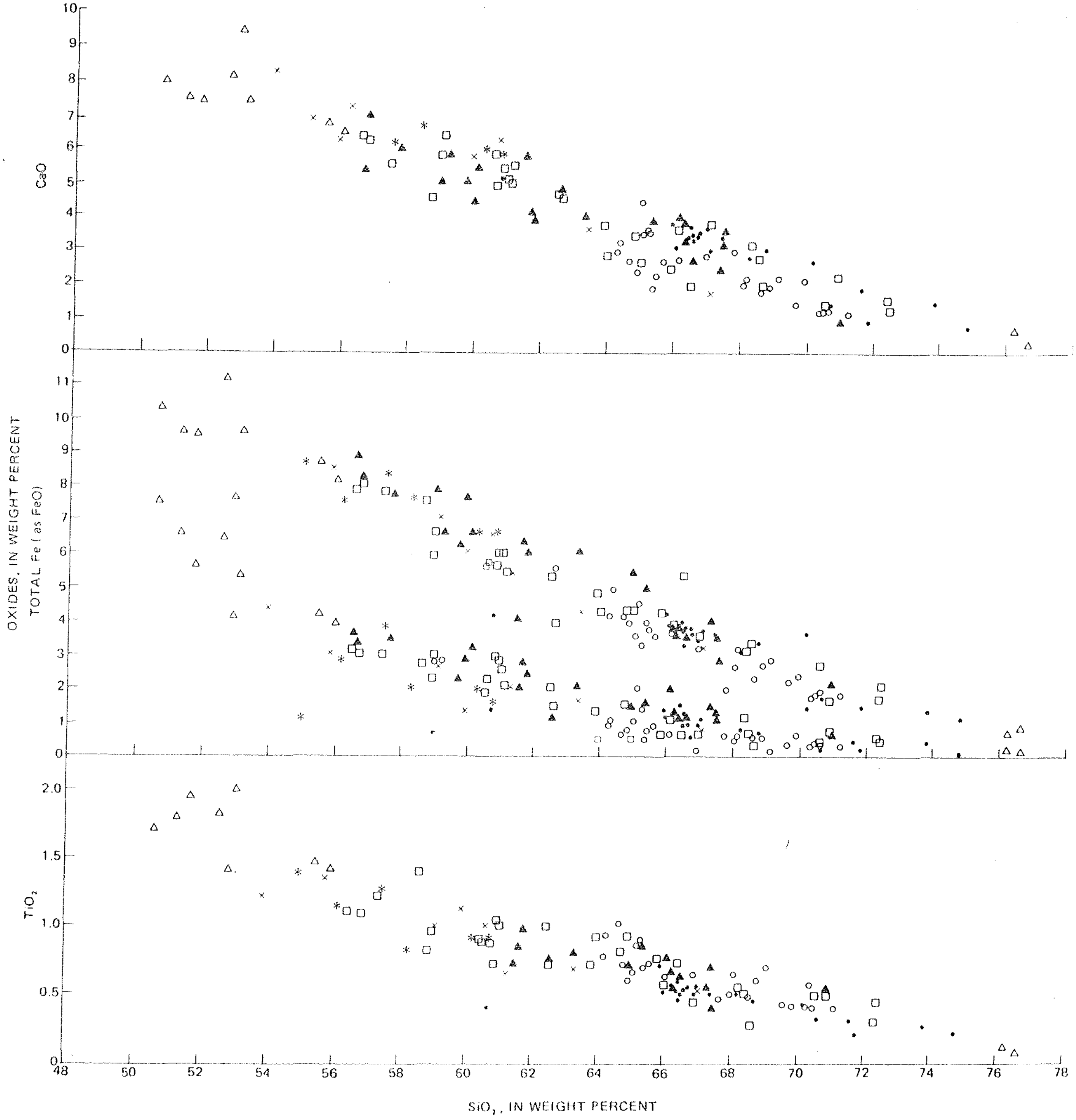

Figure 3. *(Continued).*

these rocks underwent significant fractionation of feldspar at relatively shallow depths.

Pb ISOTOPE DATA

Pb isotope compositions of the San Juan volcanic rocks and associated ores (Tables 2, 3, 4) vary widely and suggest complex interactions between the magmas and the old continental lithosphere that underlies the southern Rocky Mountains.

Analytical Methods

Pb analyses of San Juan rocks began in 1962, and the precision and accuracy of measurements have improved significantly since then. Early data were obtained by the PbS-NH_4NO_3surface-emission technique and, later, by this technique augmented by sample-size control, which improved reproducibility by about a factor of two (Doe and others, 1967). In this paper we do not distinguish between these two techniques and consider analytical precision (2σ) for both to be 0.54% for $^{206}Pb/^{204}Pb$, 0.90% for $^{207}Pb/^{204}Pb$, and 1.1% for $^{208}Pb/^{204}Pb$. In 1970 we adopted the silica-gel "emitter" technique (Chernyshev and Shanin, 1967; Tatsumoto and others, 1972), in which the uncertainties (2σ) were reduced to 0.075% for $^{206}Pb/^{204}Pb$, 0.11% for $^{207}Pb/^{204}Pb$, and 0.15% for $^{208}Pb/^{204}Pb$. All data are corrected to absolute ratios through the use of Tilton's gravimetric standard, NBS SRM 981, and BCR-1 basalt reference sample.

A small systematic discrepancy of about 0.1% to 0.2% in $^{207}Pb/^{204}Pb$ values remains between the PbS-NH_4NO_3 and silica-gel data (see Fig. 8). Because the silica-gel values are more reproducible and because corrections to absolute ratios are only about one-fourth those from the earlier method, we have reanalyzed most key samples and utilize the older data mainly in arguments involving $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$, where sensitivity is less important.

Pb, U, and Th concentrations were determined by isotope dilution (Doe and others, 1967), with an analytical uncertainty of ± 3%. These elements were separated by various combinations of conventional coprecipitation, resincolumn purification, dithizone extraction, and electrodeposition. All blanks were less than 1% of the analyzed concentration.

Corrections for Pb generated by decay of U and Th since the sample formed are negligable for feldspars and small for most whole rocks. The age-corrected compositions for whole-rock samples (Tables 2, 3, 4) are only approximate because of possible modification of minor-element contents, especially U/Pb ratios, by ground-water leaching. Only one sample (Table 3, no. 25) has an age correction large enough to be significant in the figures.

Only one sample has been analyzed for most San Juan units. Because Pb compositions vary significantly within some igneous bodies, such as individual plutons of the Boulder batholith, Montana (Doe and others, 1968), we evaluated isotopic uniformity of several San Juan units. Comparisons were made of intracaldera and outflow parts of single ash-flow sheets (Table 3, nos. 15, 16, 29, 30) and also of the differentiated rhyolitic base and quartz latitic top of one ash-flow unit (Table 3, nos. 18, 19). For each ash-flow sheet the paired samples are identical in isotopic composition within analytical precision. Phenocryst and groundmass K-feldspars from a single lava flow (Table 3, no. 13) also have the same isotopic compositions. Rocks ranging in composition from basaltic andesite to rhyolite from the differentiated Summer Coon volcanic center

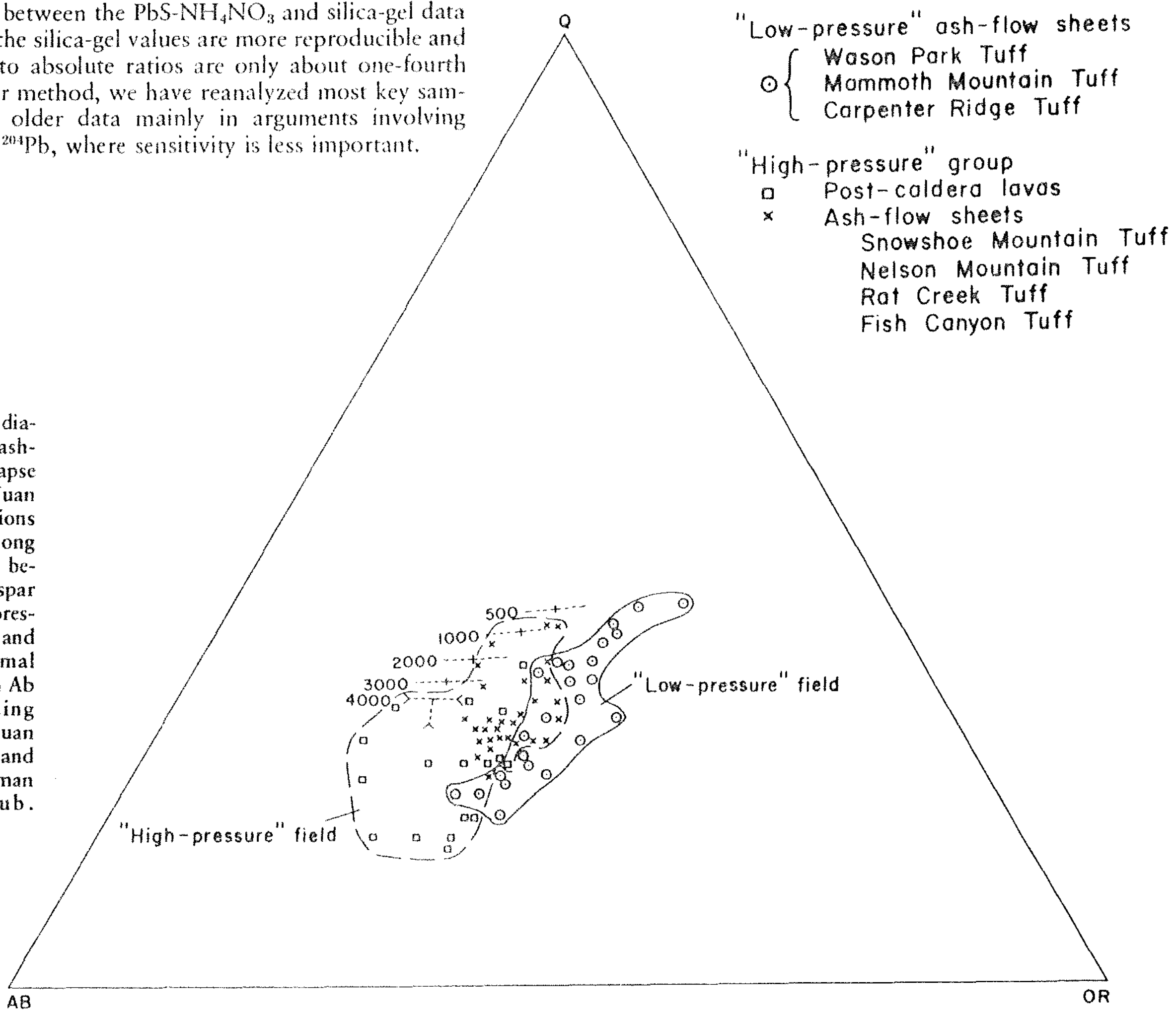

Figure 4. Ab-Or-Q diagram for Oligocene ash-flow sheets and postcollapse lavas of central San Juan caldera complex. Positions of thermal minima along isobaric boundary lines between quartz and feldspar fields at various water pressures are from Tuttle and Bowen (1958). Thermal minima shift away from Ab corner with decreasing water pressure. San Juan analyses are from Ratté and Steven (1967) and Lipman (1975), and (unpub. analyses).

(Table 2, nos. 4, 5, 6) have nearly the same Pb isotopic composition.[1] Only when comparisons are made between separate flows from a generally similar volcanic environment, such as the postcollapse lavas of the Platoro caldera (Table 3, nos. 10, 11) or of the Creede caldera (Table 3, nos. 20, 21) are there differences in isotopic composition comparable to those observed in single plutons of the Boulder batholith.

Compositional Range

Forty U-Th-Pb isotope analyses of whole rocks and mineral separates are available from the San Juan field (Tables 2, 3, 4).[2] A few of these have been published previously (Doe, 1967; Doe and others 1969a, 1969b), but most are new analyses, and some old samples have been reanalyzed by the more precise silica-gel method.

The compositional range for the Oligocene rocks is sizable, with ^{206}Pb/^{204}Pb varying from 17.3 to 18.9, and ^{208}Pb/^{204}Pb from 36.7 to 38.5. This wide range clearly requires a heterogeneous source or combination of sources for lead in the magmas and, by inference, for the magmas themselves. These values are generally typical of Cenozoic igneous rocks of the southern Rocky Mountain region, but they are somewhat lower in ^{207}Pb/^{204}Pb and distinctly lower in ^{208}Pb/^{204}Pb for a given ^{206}Pb/^{204}Pb (Fig. 5A) than igneous rocks from such areas in the northern Rocky Mountains as Yellowstone Park, the Absaroka Mountains, and the Boulder batholith (Doe and others, 1968; Peterman and others, 1970; Zartman, 1974).

Southern Rockies
i.e. more Pb^{204} in southern Rockies – either more silicic (lots of original Pb^{204}) or lots of $Pb^{207, 208}$ ⇒ older

All these Cenozoic igneous rocks are less radiogenic than most upper-crustal Precambrian rocks of North America (Fig. 5B, including Colorado samples; Appendix B [see footnote 2]). Precambrian rocks that are less radiogenic than the San Juan volcanic rocks are mostly granulites and related rocks, as well as quartz diorites and meta-andesites, that have low U/Pb and Th/Pb ratios Lambert and Heier, 1968; Doe and others, 1968). Accordingly, the Pb isotope ratios of these Precambrian rocks have increased only slightly since they formed.

The San Juan volcanics and all other igneous rocks from the Rocky Mountains are also less radiogenic than young igneous rocks along the western Cordilleran margin (Doe, 1967, 1968; Zartman, 1974). The contrast is especially striking for andesitic rocks of the Cascade Range (Fig. 5C). The San Juan volcanics are, somewhat surprisingly considering the different settings, not grossly different in isotopic composition from deep-ocean tholeiites (Fig. 5D) and volcanic rocks of a few intraplate oceanic islands,

TABLE 2. ANALYSES OF EARLY INTERMEDIATE-COMPOSITION VOLCANIC ROCKS, SAN JUAN VOLCANIC FIELD

Sample no.	Unit analyzed	Field no.*	Age† (m.y.)	SiO$_2$† (%)	Elemental contents (ppm) U	Th	Pb	Isotope ratios (atomic)# ^{206}Pb/^{204}Pb	^{207}Pb/^{204}Pb	^{208}Pb/^{204}Pb	Data source**
Southeastern San Juan Mountains											
1	Navaho Peak, rhyodacite flow	68L91P	32.4	~64	..	..	5.8	17.35	15.46	36.87	1
2	Conejos Peak, rhyodacite flow	67L129P	30–31	~63	..	..	..	18.15	15.53	37.57	1
3	Horseshoe Mountain, andesite flow, upper lava unit	65L138W††	~30	~60	2.3	8.0	12.6	17.83 (17.78)	15.48 (15.48)	37.37 (37.32)	1
East-central San Juan Mountains											
4	Summer Coon volcanic center, rhyodacite dike	65L297W††	34.7	64	1.71	4.76	18.4	17.34 (17.31)	15.45 (15.45)	36.90 (36.87)	1
5	Summer Coon, basalt dike	67L106W††	~33	51	0.55	2.39	7.45	17.34 (17.31)	15.42 (15.42)	36.94 (36.41)	1
6	Summer Coon, rhyolite dike	65L206AW††	32.1	72	1.22	7.31	25.6	17.47 (17.45)	15.43 (15.43)	36.86 (36.83)	2
7	Baughman Creek volcanic center, intrusive	DS66P	~33	~65	..	..	..	17.33	15.38	36.72	1
Northwestern San Juan Mountains											
8	Cimmarron Ridge, rhyodacite flow	RD336-68P	32.1	~64	..	..	5.7	17.74	15.51	37.33	1

* Letter ending field number designates type of sample analyzed: W = whole rock, K = K-feldspar, P = plagioclase.
† Sign ~ indicates that age or silica content is determined from different sample than used for lead isotope analyses.
\# Initial lead ratios for whole rocks given in parentheses.
** 1, This paper; 2, Doe and others (1969a).
†† Determined by silca-gel technique. All ratios normalized to absolute.

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[1] The Summer Coon rhyolite is about 0.75% higher in ^{206}Pb/^{204}Pb than the other two samples. Even this small difference could be due to post-emplacement radioactive decay of U, if significant uranium were lost in recent incipient weathering. Such U loss is typical of devitrified rhyolites (Rosholt and Noble, 1969) and seems likely for the Summer Coon rhyolite on the basis of its high Pb/U and Th/U ratios (Table 2, no. 6).

[2] Appendix A, locations and descriptions of analyzed samples, and Appendix B, selected element contents and Pb isotope ratios of Precambrian rocks of Colorado, GSA supplementary material 77-10, may be ordered from Documents Secretary, Geological Society of America, 3300 Penrose Place, Boulder, Colorado 80301.

TABLE 3. ANALYSES OF CALDERA-RELATED ROCKS, SAN JUAN VOLCANIC FIELD

Sample no.	Unit analyzed	Field no.*	Age† (m.y.)	SiO_2† (%)	Elemental contents (ppm)			Isotope ratios (atomic)§			Data source**
					U	Th	Pb	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	
Platoro caldera complex, southeastern San Juan Mountains											
9	Treasure Mountain Tuff, La Jara Canyon Member, main ash-flow sheet	65L132P	29.8	68	..	..	..	18.42	15.55	37.66	1
10	Summitville Andesite, lower member, postcollapse lava	67L125W††	~29.5	60	1.37	4.20	8.99	18.52 (18.48)	15.57 (15.57)	37.75 (37.71)	2
11	do.	67L126W††	~29.5	58	2.11	6.98	12.00	18.11 (18.06)	15.54 (15.54)	37.59 (37.54)	2
12	Rhyodacite of Park Creek, postcollapse lava	64D1W	~29	~62	..	..	..	18.11	15.48	37.47	1
13	Quartz latite of South Mountain, postcollapse lava	64D2MK§§	22.8	68	..	..	..	18.00	15.52	37.22	1
	do.	64D2K	22.8	68	..	..	..	17.97	15.51	37.28	1
	do.	64D2W	22.8	68	..	..	..	17.95	15.52	37.28	1
14	Rhyolite of Cropsy Mountain, postcollapse lava	64D3-1W	20.2	70	..	..	..	17.69	15.44	36.90	1
		64D3-2W	do.	do.	..	..	..	17.68	15.41	36.80	1
La Garita–Creede Caldera Complex, central San Juan Mountains											
15	La Garita caldera, Fish Canyon Tuff, outflow	Ds28K	27.8	67	..	..	..	18.38	15.50	37.46	1
16	La Garita caldera, Fish Canyon Tuff, La Garita Member, intracaldera tuff	S292BK	27.8	67	..	..	..	18.42	15.54	37.60	1
17	Bachelor Mountain caldera, Carpenter Ridge Tuff, Willow Creek unit	PBB178-59W††	~27.5	72	7.25	20.3	26.1	18.71 (18.63)	15.60 (15.60)	38.01 (37.95)	3
18	Creede caldera area, Mammoth Mountain Tuff, First Fork section, rhyolite vitrophyre	67L137AK	26.7	73	..	..	..	18.54	15.48	37.61	1
19	Same as 18, but quartz latite	67L137MK	26.7	67	..	..	..	18.59	15.54	37.75	1
20	Creede caldera, Fisher Quartz Latite, postcollapse lava	Ds10P	26.4	~64	..	..	13.1	18.43	15.52	37.65	1
		Ds10G††			5.45	15.65	27.5	18.55	15.60	37.89	1

21	Creede caldera, Fisher Quartz latite, Wagon Wheel Gap, postcollapse lava	PBB168B59W	26.4	65	..	..	..	(18.50) 18.29	(15.59) 15.49	(37.84) 37.40	3
Uncompahgre–San Juan–Silverton caldera complex, western San Juan Mountains											
22	Uncompahgre–San Juan caldera, Sapinero Mesa Tuff	68L42AP	28	72	..	..	14	18.78	15.60	38.45	1
23	Burns Formation, post-collapse quartz latite lava	73L52BP	28	65	0.20	0.51	10.4	18.78	15.60	38.46	1
24	Henson Formation, post-collapse andesite lava	73L44P	28	57	0.13	0.23	8.12	18.64	15.59	38.44	1
25	Silverton Caldera, Crystal Lake Tuff	72L43AG[††]	~27.5	71	9.46	31.3	32.7	18.87 (18.79)	15.64 (15.64)	38.46 (38.38)	1
26	Sultan Mountain stock, postcollapse quartz monzonite intrusive	46DV36K	25.5	64	..	..	..	18.76	15.60	38.28	1
27	National Belle plug, post-collapse quartz latite intrusive	NB-BIK	22.6	~65	0.11	0.23	32.4	18.71	15.61	38.38	1
28	Engineer Pass plug, post-collapse quartz latite intrusive	73L101K	15.4	~65	0.08	0.11	36.1	18.13	15.53	37.74	1
Lake City caldera, western San Juan Mountains											
29	Sunshine Peak Tuff, outflow tuff	Ds29AK	22.5	76	..	..	..	18.60	15.60	38.25	1
30	Sunshine Peak Tuff, Intra-caldera tuff	Ds445K	22.5	76	..	..	..	18.62	15.59	38.21	1
31	Nellie Creek plug, post-collapse rhyolite intrusive	72L47K	18.5	76	1.0	0.83	23.1	18.25	15.55	37.82	1

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[*] Letter ending field number designates type of sample analyzed: W = whole rock, K = K-feldspar, P = plagioclase, G = glass.

[†] Sign "~" indicates that age or silica content is determined from different sample than used for lead isotope analyses or is otherwise estimated by stratigraphic position, and so forth.

[#] Samples 9, 13 (64D2W), 17, 20(Ds10G), and 22–31 by silica-gel technique. All ratios normalized to absolute.

[**] 1, This paper; 2, Doe and others (1969a); 3, Doe (1967).

[††] Initial lead ratios for whole rocks given in parentheses.

[##] Megacryst (~3 cm in diameter).

TABLE 4. ANALYSES OF LATE BASALTS AND RHYOLITES OF HINSDALE FORMATION, SAN JUAN VOLCANIC FIELD

Sample no.	Unit analyzed	Field no.[*]	Age[†] (m.y.)	SiO$_2$[†] (%)	Elemental contents (ppm) U	Th	Pb	Isotope ratios (atomic)[#] ^{206}Pb/^{204}Pb	^{207}Pb/^{204}Pb	^{208}Pb/^{204}Pb	Data source[**]
32	Andesitic basalt of Beaver Creek	65L32W[††]	~23	52	1.67	5.85	11.1	18.84 (18.81)	15.58 (15.57)	38.03 (37.98)	2
33	Rhyolite of Beaver Creek, obsidian	65L161AW[††]	21.9	76	10.7	27.5	26.8	18.10 (18.02)	15.55 (15.55)	37.46 (37.39)	1
34	Basalt of Handkerchief Mesa	70L150AW[‡‡]	22–23	51	1.29	4.09	6.40	18.23 (18.18)	15.55 (15.55)	37.65 (37.60	1
35	Rhyolite of Handkerchief Mesa	70L151W[‡‡]	22–23	71	4.49	15.08	17.1	18.09 (18.03)	15.54 (15.54)	37.48 (37.42)	1
36	Basalt of La Jara Reservoir region, slightly xenocrystic	66L26W[‡‡]	26.8	52	0.76	2.96	5.4	17.89 (17.85)	15.47 (15.47)	37.36 (37.31)	2
37	Basalt of La Jara Reservoir region, primitive	65L120W[‡‡]	5	52	1.11	1.85	3.40	18.32 (18.30)	15.53 (15.53)	37.68 (37.67)	2
38	Basaltic andesite of La Jara Reservoir region, highly xenocrystic	66L20W[‡‡]	~17	57	2.14	6.15	8.04	17.83 (17.79)	15.43 (15.43)	37.01 (36.97)	2
					2.09	6.34	8.01	..	..	..	2
39	Same as 38, low density	66L109P	~17	~57	..	..	..	17.92	15.51	37.35	2
	medium density	66L109P	~17	~57	..	..	..	18.20	15.49	37.63	2
40	Basalt of Jarosa Mesa	Ds29BW[‡‡]	14	51	0.88	3.50	7.9	18.31 (18.29)	15.53 (15.53)	37.97 (37.95)	3

[*] Letter ending field number designates type of sample analyzed: W = whole rock, P = plagioclase.

[†] Sign ~ indicates age or silica content is determined from different sample than used for lead isotope analyses or is otherwise estimated by stratigraphic position, and so forth.

[#] Samples 32–35 and 37 by silica-gel technique. All ratios normalized to absolute.

[**] 1, this paper; 2, Doe and others (1969b); 3, Doe (1967).

[‡‡] Initial lead ratios for whole rocks given in parentheses.

such as Hawaii. Most oceanic-island alkalic volcanic rocks are distinctly more radiogenic, however (Oversby and Gast, 1970; Sun and Hanson, 1975).

Volcanogenic ores of the San Juan Mountains are highly variable, ranging from 17.7 to 21.1 in ^{206}Pb/^{204}Pb, but ore Pb in any area is similar to igneous host rocks or more radiogenic (Doe and others, 1977). The ore Pb data are discussed briefly in this paper, where pertinent to interpretation of the rock Pb data.

Time Variations within Subareas

Detailed consideration of the San Juan data indicates systematic variations in isotopic composition within the volcanic field, both with age and, to a lesser extent, with geographic distribution. In any area, the volcanic rocks tend to become more radiogenic with time, with peak values coinciding with ash-flow eruption and caldera collapse. Then isotopic compositions reverse, and postcaldera rocks become less radiogenic with time (Fig. 6). This effect is particularly marked when data from the Oligocene intermediate to silicic rocks and from the Miocene to Pliocene basalts and rhyolites are considered together. This seemingly significant temporal variation, which we informally call "the yo-yo effect," characterizes all the caldera sequences that span a time interval of a few million years or more and for which we have isotopic data.

In any area, the older lavas in early intermediate-composition accumulations are relatively nonradiogenic: for example, the rhyodacite from Navajo Peak in the southern part of the field, the rhyodacite from Cimarron Ridge in the northwestern part, or rocks of the Summer Coon center to the northeast (Fig. 6). All these are radiometrically dated samples, relatively low in the early intermediate-composition sequence, that approximate the beginning of volcanism (Lipman and others, 1970).

In the southeastern San Juan Mountains, intermediate-composition rocks high in the sequence that predates the ash-flow tuffs are transitional in Pb isotope composition between stratigraphically lower rocks of the early intermediate sequence and younger rocks of the Platoro caldera complex. The major ash-flow sheet erupted from the Platoro caldera, the La Jara Canyon Member of the Treasure Mountain Tuff, is the most radiogenic sample analyzed from the southeastern part of the field, and lava flows of the Summitville Andesite that filled the caldera shortly after it collapsed are about as radiogenic (Fig. 6, A). Lavas that were erupted intermittently around margins of the Platoro caldera complex, for almost 10 m.y. after the time of collapse, become progressively more silicic and less radiogenic with time, and the youngest flow — the rhyolite of Cropsy Mountain, erupted 20.2 m.y. ago — is almost as nonradiogenic as the oldest rocks of the area.

Galenas in the Platoro caldera area are similar to, or more radiogenic than, associated rocks in Pb isotope composition. Minor galena associated with the Summitville copper-gold deposit within the caldera complex has an isotopic composition similar to that of adjacent altered rock, from which the ore lead may have been leached (Doe and others, 1977). Galena from fault-controlled veins in the Crater Creek area, just west of the caldera area, is more radiogenic than any associated rock lead.

In the central part of the volcanic field, leads in the early intermediate-composition rocks of the Summer Coon and Baughman Creek centers are the least radiogenic in the entire San Juan field. The first major ash-flow sheet erupted from the central caldera complex, the compositionally uniform and seemingly little-fractionated Fish Canyon Tuff, is distinctly more radiogenic; the highly differentiated and compositionally zoned Carpenter Ridge and Mammoth Mountain Tuffs, erupted from calderas nested within the La Garita caldera, are even more radiogenic (Fig. 6, B). Postcollapse lavas of the Fisher Quartz Latite that accumulated in the Creede caldera are slightly less radiogenic than the Carpenter Ridge and Mammoth Mountain Tuffs but do not differ significantly from the Fish Canyon Tuff, which they resemble petrographically. No extended history of postcollapse volcanism has been recognized in the central caldera complex, and thus, in contrast with the southeastern Platoro caldera complex, there is only a hint of a shift toward young nonradiogenic rock leads late in the evolution of this part of the volcanic field.

Galenas in the major lead-silver deposits of the Creede district, along graben faults just outside the Creede caldera, were deposited about 1 m.y. later than the lavas that postdate formation of the caldera (Steven and Eaton, 1975) and are more radiogenic than any rocks of the central caldera complex. Galenas associated with intrusive cores of the Summer Coon and Baughman Creek center are even more radiogenic, in striking contrast to the nonradiogenic nature of the associated igneous rocks (Fig. 6, B).

Isotopic variations in the western San Juan field define a pattern generally similar to that in the central and eastern areas, although interpretation is complicated by a more intricate volcanic history for this area. The least radiogenic Pb is from rhyodacite at Cimarron Ridge, an early flow that underlies the ash-flow sequence north of the caldera complex. The two analyzed Oligocene ash-flow sheets, the Sapinero Mesa and Crystal Lake Tuffs, that erupted from the San Juan–Uncompahgre and Silverton calderas, respectively (Lipman and others, 1973b), have similar isotopic compositions — the most radiogenic in the volcanic field. Lavas of the Burns and Henson Formations that filled the Uncompahgre and San Juan calderas soon after collapse are similar in isotopic composition to the ash-flow tuffs. Quartz monzonite of the Sultan Mountain stock, emplaced along the ring-fracture zone of the Silverton caldera with 1 to 2 m.y. after collapse (Lipman and others, 1970), is only slightly less radiogenic than the Crystal Lake Tuff erupted from this caldera, but younger postcollapse intrusions in the Silverton caldera area, at the National Belle mine and at Engineer Pass, are progressively less radiogenic. Again, these younger, less radiogenic rocks were emplaced during the period of bimodal basalt-rhyolite eruptions in Miocene time, and their genesis may have been different from the older intermediate to silicic rocks.

Although they are part of a separate caldera cycle related in age and rock type to the bimodal basalt-rhyolite suites, rocks of the Lake City caldera nested within the western caldera complex plot along the same isotopic trends as the older rocks. The 22.5-m.y.-old Sunshine Peak Tuff (Mehnert and others, 1973b), erupted from this caldera, is less radiogenic than any caldera-related rocks of the Uncompahgre–San Juan–Silverton cluster. In addition, the 18.5-m.y.-old rhyolite plug at Nellie Creek, which is part of a postcollapse belt of silicic intrusions around the north side of the Lake City caldera, is even less radiogenic (Fig. 6, C). Thus, the rocks of the western San Juan calderas show a reversal in pattern of isotopic compositions very similar to that observed for the Platoro caldera complex, whether the late Lake City caldera is included in the trend or is considered as a separate cycle.

The major Pb-bearing ore deposits in the western San Juan Mountains vary widely in isotopic composition, from 18.3 to 19.1 in $^{206}Pb/^{204}Pb$. This range is greater than that of rocks of the associated calderas. Although interpretation is complicated by uncertainties about ages, most major mineral deposits probably have Pb isotope compositions similar to or slightly more radiogenic than contemporaneous associated igneous rocks (Doe and others, 1977).

Geographic Variations among Oligocene Rocks

In addition to the sizable temporal isotopic variations within various subareas of the volcanic field (yo-yo effect), Pb compositions appear to vary slightly with location in the field at any stage in the volcanic cycle. In general, for any rock assemblage of similar age, slightly more radiogenic leads occur in the western part of the field. Thus, the rhyodacite from Cimarron Ridge (Table 2, no. 8), in the northwestern part of the field is slightly more radiogenic than any of the early intermediate-composition samples farther east (Table 2, nos. 1–7). The two analyzed Oligocene ash-flow sheets from the western caldera complex (Table 3, nos. 22, 25) are more radiogenic in Pb than any tuffs from the central or eastern caldera complexes (Table 3, nos. 9, 15–19), and the postcollapse lavas and intrusions also show a rough increase in radiogenic Pb to the west (Table 3). These differences, especially in $^{208}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$, probably reflect important lateral compositional variations in the source region of the magmas.

Miocene-Pliocene Rocks

Seven samples of Miocene-Pliocene basaltic lavas of the Hinsdale Formation have widely varying Pb isotope compositions (Table 4; Fig. 7). Three typical olivine basalt samples cluster closely, however, with $^{206}Pb/^{204}Pb$ ratios of 18.2 to 18.3 (Table 4, nos. 34, 37, 40). One exceptionally radiogenic basaltic andesite (Table 4, no. 32), with a $^{206}Pb/^{204}Pb$ ratio of 18.84, is atypical in other respects, such as containing abundant euhedral plagioclase phenocrysts. It may be highly contaminated by radiogenic upper crustal Pb, as also suggested by a very high Pb content (11 ppm) for its SiO_2 content.

Three basaltic samples that contain xenocrysts of quartz and sodic feldspar (Table 4, nos. 36, 38, 39) are less radiogenic than the nonxenocrystic basalts and may have been contaminated by nonradiogenic lower crust (Doe and others, 1969b). Alternative interpretation of the quartz and plagioclase "xenocrysts" as very high-pressure phenocrysts (Nicholls and others, 1971) seems less likely to us, because such "xenocrystic" lavas are rare in noncontinental environments. If the interpretation of high-pressure crystallization is valid, however, the "xenocrystic" San Juan lavas, which are relatively nonradiogenic, could reflect generation relatively deep in a compositionally zoned mantle in which U/Pb and Th/Pb ratios decrease with depth.

Some xenocrystic basaltic lavas in the San Juan field clearly resulted from incomplete mixing of mafic and silicic magmas prior to eruption (Lipman, 1975, p. 97–100); these mixed lavas are similar to those described for the Gardner River complex in the Yellowstone Park area, Wyoming (Wilcox, 1944). The mafic and silicic end members of a mixed lava complex at Handkerchief Mesa in the southeastern San Juan field have small but real differences in isotopic composition (Table 4, nos. 34, 35), indicating isotopically different sources (mantle versus lower crust?) for typical mafic and silicic rocks of the Hinsdale Formation.

Two silicic lavas of the Hinsdale Formation, from Beaver Creek and the Handkerchief Mesa mixed lava complex (Table 4, nos. 33, 35), are similar in isotopic composition and are intermediate in isotopic range between the xenocrystic basaltic andesites and olivine basalts in the San Juan field. They are also compositionally similar to the rhyolite of Nellie Creek, adjacent to the Lake City caldera in the western part of the volcanic field. This rhyolite, although previously discussed in terms of evolution of the Lake City caldera, could as readily be discussed as a Hinsdale rhyolite, as it is contemporaneous in age (18.5 m.y.) with the thick basalt sequence on Cannibal Plateau, just northeast of the caldera (Lipman and Mehnert, 1975).

No systematic relation is evident between isotopic composition and geographic location, as observed for the Oligocene rocks, but the present data are probably too few to evaluate such variations in the Miocene-Pliocene rocks.

Model Age Relations

A well-defined linear array characterizes most of the San Juan Pb data, whether for the Oligocene volcanic rocks, the Miocene-Pliocene volcanic rocks, or the ore leads (Fig. 8). This array does not follow the trends of a single-stage model of Pb compositional evolution. However, it can be interpreted readily in terms of a two-stage Pb evolution model, in which an event at some time in the past homogenized Pb isotopic compositions and established a range of U/Pb and Th/Pb ratios in the source region (Kanasewich, 1962; Doe and Stacey, 1974). Using only the precise silica-gel data, the array defines a secondary isochron for which the indicated age is 1.86 ± 0.11 b.y. (Table 5) — similar to that of most upper-crustal Precambrian basement rocks in the southern Rocky Mountains (Hedge and others, 1968). A few samples, including some Oligocene volcanic rocks from the Platoro caldera complex (Table 5) and especially galenas from the Creede, Baughman Creek, and Summer Coon mineralized areas (Doe and others, 1977) deviate slightly from this trend and make a better fit to a somewhat younger secondary isochron with an age of about 1.4 to 1.5 b.y. —the time of the other major Precambrian igneous event in the southern Rocky Mountains (Hedge and others, 1968). Precambrian rocks of both 1.8-b.y.-old and 1.45-b.y.-old types are exposed widely around the margins of the San Juan field (Bickford and others, 1968).

Secondary-isochron ages of Cenozoic volcanic leads also correlate with Precambrian crustal age in places where the chronology is different. Both the predominantly intermediate-composition Eocene volcanic rocks of the Absaroka Mountains, Wyoming, and the Pleistocene bimodal basalt-rhyolite assemblage of the Yellowstone Park area plot on a 2.8-b.y. secondary isochron — the approximate age of the Precambrian crust in the same region (Peterman and others, 1970). This correlation between isotopic composition and crustal age seems generally valid throughout the

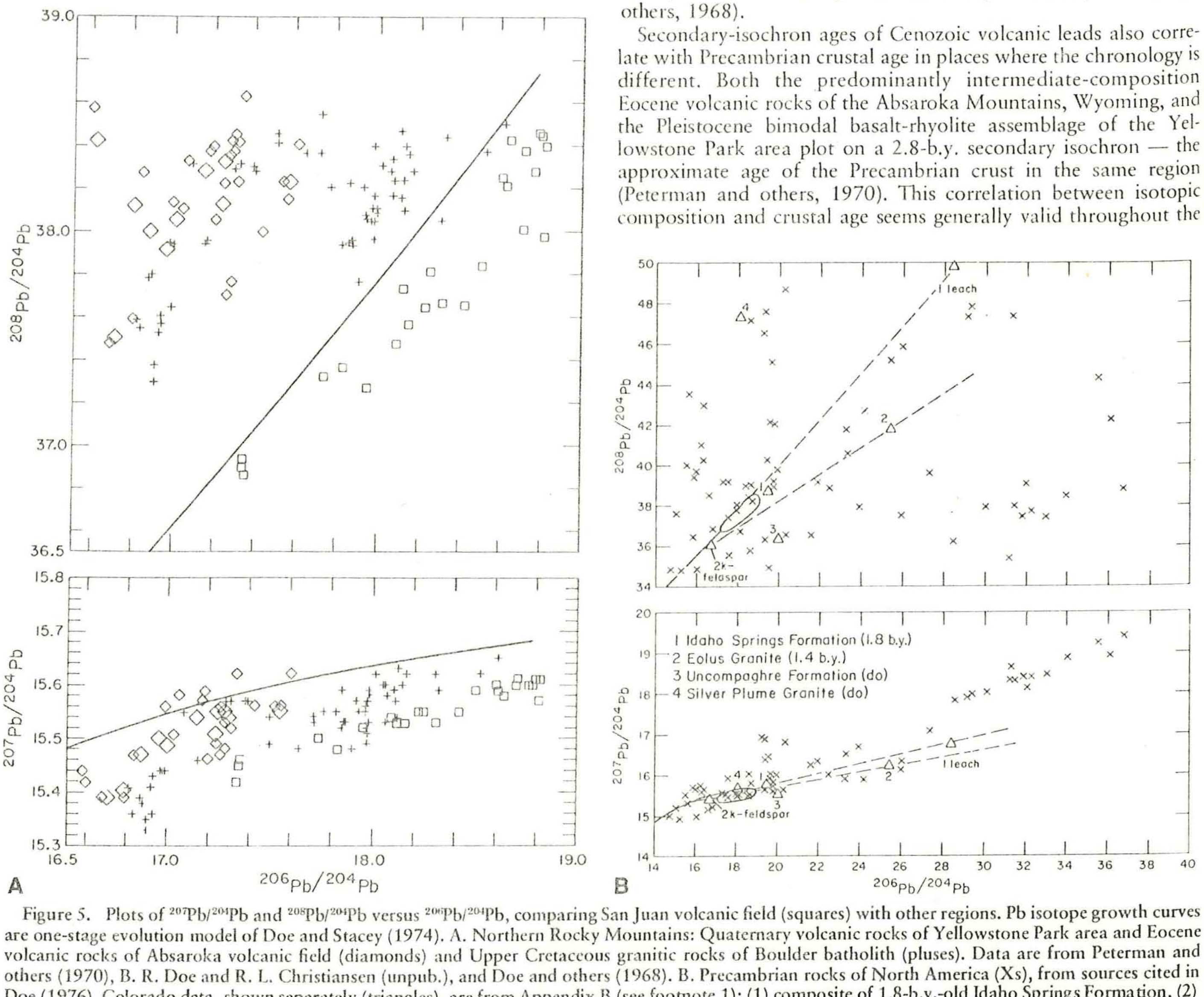

Figure 5. Plots of ^{207}Pb/^{204}Pb and ^{208}Pb/^{204}Pb versus ^{206}Pb/^{204}Pb, comparing San Juan volcanic field (squares) with other regions. Pb isotope growth curves are one-stage evolution model of Doe and Stacey (1974). A. Northern Rocky Mountains: Quaternary volcanic rocks of Yellowstone Park area and Eocene volcanic rocks of Absaroka volcanic field (diamonds) and Upper Cretaceous granitic rocks of Boulder batholith (pluses). Data are from Peterman and others (1970), B. R. Doe and R. L. Christiansen (unpub.), and Doe and others (1968). B. Precambrian rocks of North America (Xs), from sources cited in Doe (1976). Colorado data, shown separately (triangles), are from Appendix B (see footnote 1): (1) composite of 1.8-b.y.-old Idaho Springs Formation, (2) 1.45-b.y.-old Eolus Granite, (3) 1.45-b.y.-old granite from Uncompahgre uplift, and (4) 1.45-b.y.-old Silver Plume Granite. Upper dashed line connects analyses of rock and leach solution for Idaho Springs Formation; lower dashed line connects whole-rock and K-feldspar analyses for Eolus Granite. Elliptical outlines = Tertiary rocks, San Juan volcanic field; Xs = Precambrian rocks, North America; triangles = Colorado only.

western United States (Zartman, 1974). It suggests that the volcanic leads obtained their dominant isotopic character from a lithospheric plate that developed diverse U/Pb and Th/Pb ratios during stabilization of continental crust, with little subsequent modification. This isotopic character of such Tertiary volcanogenic leads was not necessarily derived from interaction with upper crustal rocks. A similar pattern could be generated by lead from the lower sialic crust or, particularly for the basalts, from the immediately underlying lithospheric mantle that apparently has been attached to the continental crust and little modified since it formed.

Sr ISOTOPE DATA

Isotopic compositions and related data for 39 middle to late Tertiary volcanic rocks from the San Juan field are summarized in Table 6; many of the samples are the same as those analyzed for Pb (Tables 2, 3, 4).

Analytical Techniques

Sr isotope composition was measured on a 6-in. 60°-sector Nier-type mass spectrometer using a triple rhenium filament mode of ionization. Data was recorded digitally and reduced by computer; the measured $^{87}Sr/^{86}Sr$ of Eimer and Amend standard $SrCO_3$ was 0.7080. From numerous earlier replicate analyses made on the same mass spectrometer, the analytical precision at the 95% confidence level is estimated at about ±0.0002. The assigned precision values include uncertainties introduced by errors in the determination of the Rb/Sr ratios and ages of the specimens. Rb and Sr contents were determined by x-ray fluorescence, with an uncertainty of ±5% to 10% for both elements.

Discussion

Sr isotope variations among San Juan rocks are relatively small, both compared to the wide Pb isotope variations and to other carefully studied Cenozoic volcanic fields in the western United States. In the Oligocene San Juan rocks the observed variation in initial Sr ratios is 0.7048 to 0.7075. In contrast, several other well-studied volcanic areas in the western United States are characterized by lower values for mafic rocks and more radiogenic compositions for silicic units. $^{87}Sr/^{86}Sr$ ratios in the range 0.710 to 0.715 occur widely in Cenozoic rhyolites from southwestern Nevada (Noble and Hedge, 1969), north-central Nevada and Utah (Hedge and Noble, 1971), and the Yellowstone Park area (Doe and others, 1970).

For the San Juan field, six analyses of typical Oligocene early intermediate-composition rocks cluster at 0.7054 ± 0.0002 —within the range of analytical precision (Table 6, nos. 1–6).

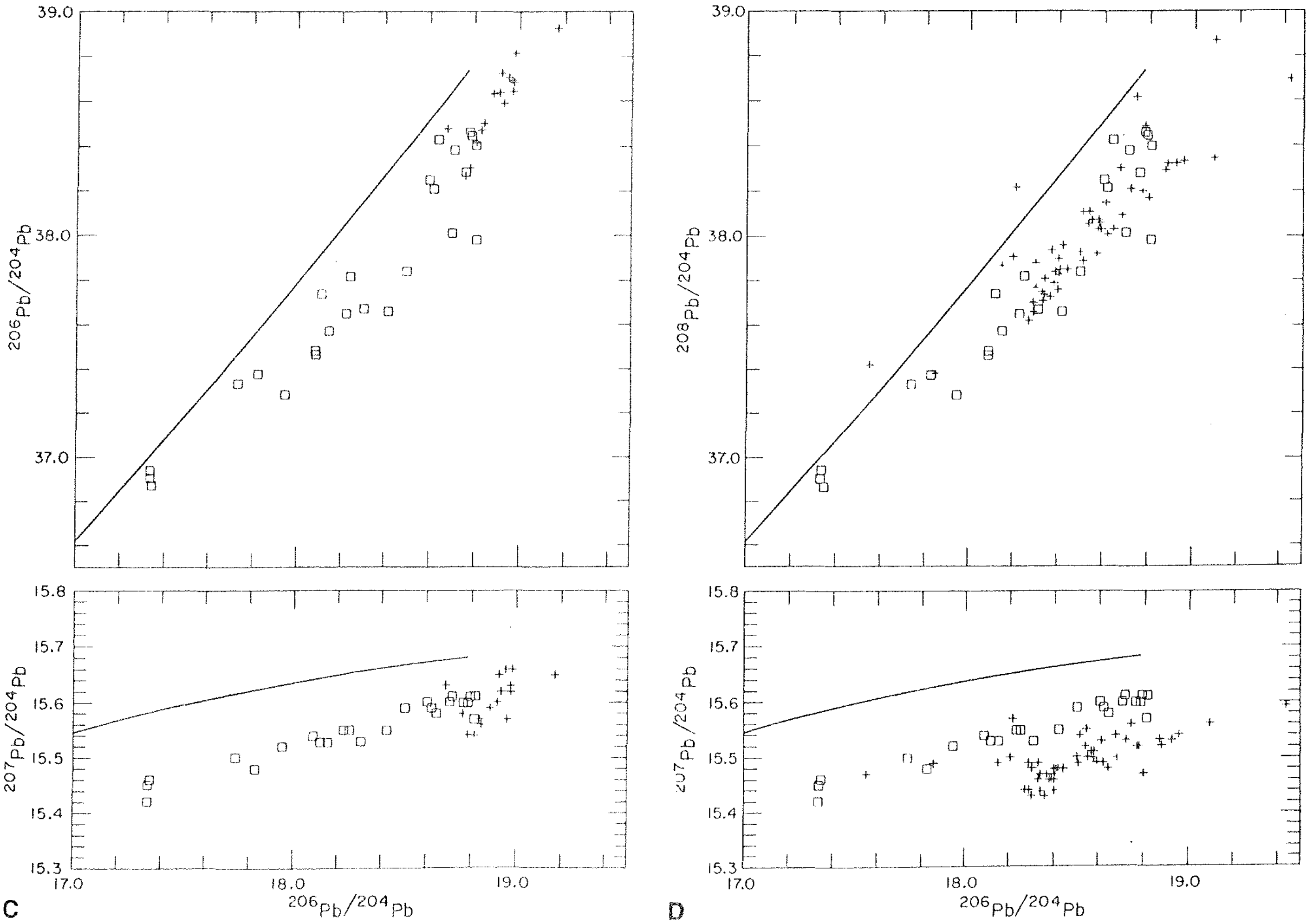

Figure 5. (*Continued*). C. Volcanic rocks of South Cascade area (pluses): Data from Church and Tilton (1973). D. Deep-ocean tholeiites and related rocks of the Pacific basin (pluses). Data from sources cited in Doe and Zartman (1977, Fig. 4).

These relatively nonradiogenic values preclude significant involvement of upper crust in generation of these rocks, but are consistent with a source in the lower crust or lithospheric mantle, as inferred also from the Pb isotope data. One sample from this group is somewhat more radiogenic (0.7059 to 0.7060; Table 6, no. 7), but this sample also yielded discordant K-Ar ages on phenocryst separates (biotite, 32 m.y.; hornblende, 40 m.y.; plagioclase, 80 m.y.), indicating isotopic disequilibrium suggestive of addition of crustal radiogenic argon and strontium.

The silicic ash-flow tuffs tend to be more radiogenic than the intermediate-composition rocks, and the Miocene-Pliocene basaltic lavas tend to be less radiogenic, resulting in a positive correlation between radiogenic Sr and SiO_2 contents (Fig. 9, A). This correlation is especially good within geographic subareas, such as the Platoro or La Garita–Creede caldera complexes. The most radiogenic ash-flow tuffs are those that plot in the "low-pressure" group in terms of major-element compositions (Carpenter Ridge and Mammoth Mountain Tuffs).

Isotopic variations of Sr are largely independent of those of Pb. About half of the observed $^{206}Pb/^{204}Pb$ range (17.3 to 18.2) occurs within the early intermediate-composition group with Sr compositions of 0.7054 ± 0.0002 (Fig. 10). The silicic ash-flow tuffs of the "low-pressure" group are very radiogenic in both Pb and Sr (Fig. 10), but otherwise, the correlation between SiO_2 and isotopic composition is poorer for Pb than for Sr (Fig. 9, B).

The limited Sr data for Miocene and Pliocene basalts of the Hinsdale Formation plot in two groups (Fig. 9 A). Four scattered samples from the main area of the volcanic field are all close to 0.7050, only slightly less radiogenic than andesites erupted both before and after the ash-flow sheets in Oligocene time. Eight Sr analyses from the 5-m.y.-old Los Mogotes volcano at the southeast edge of the volcanic field, on the margin of the San Luis Valley sector of the Rio Grande rift (Fig. 1), are distinctly less radiogenic (0.7037 to 0.7048).

The San Juan volcanic rocks are more radiogenic than island-arc andesitic suites or than calcic continental-margin andesitic arcs such as the Cascades (Peterman and others, 1970). The San Juan suite is isotopically similar to more alkalic andesites from continental margins such as the northern Chilean Andes (Pichler and Zeil, 1972; Noble and others, 1975; C. E. Hedge, unpub. data).

PETROLOGIC EVOLUTION

Two related problems in the petrologic evolution of the San Juan field are the environment of initial magma generation beneath it and modifications to the magmas during their rise toward the surface.

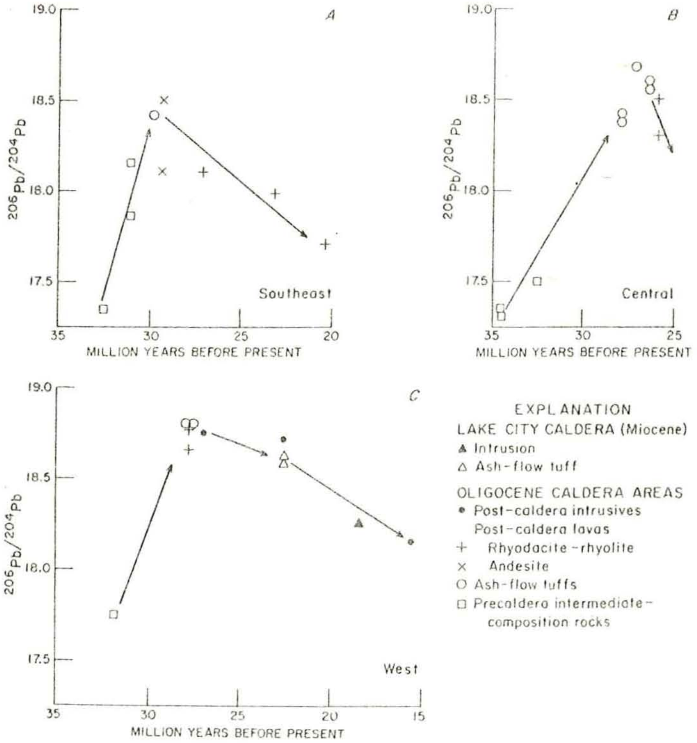

Figure 6. Variations in $^{206}Pb/^{204}Pb$ of volcanic rocks as function of time in subareas of San Juan volcanic field. A, Southeastern San Juan Mountains and Platoro caldera complex; B, central San Juan Mountains; C, western San Juan Mountains.

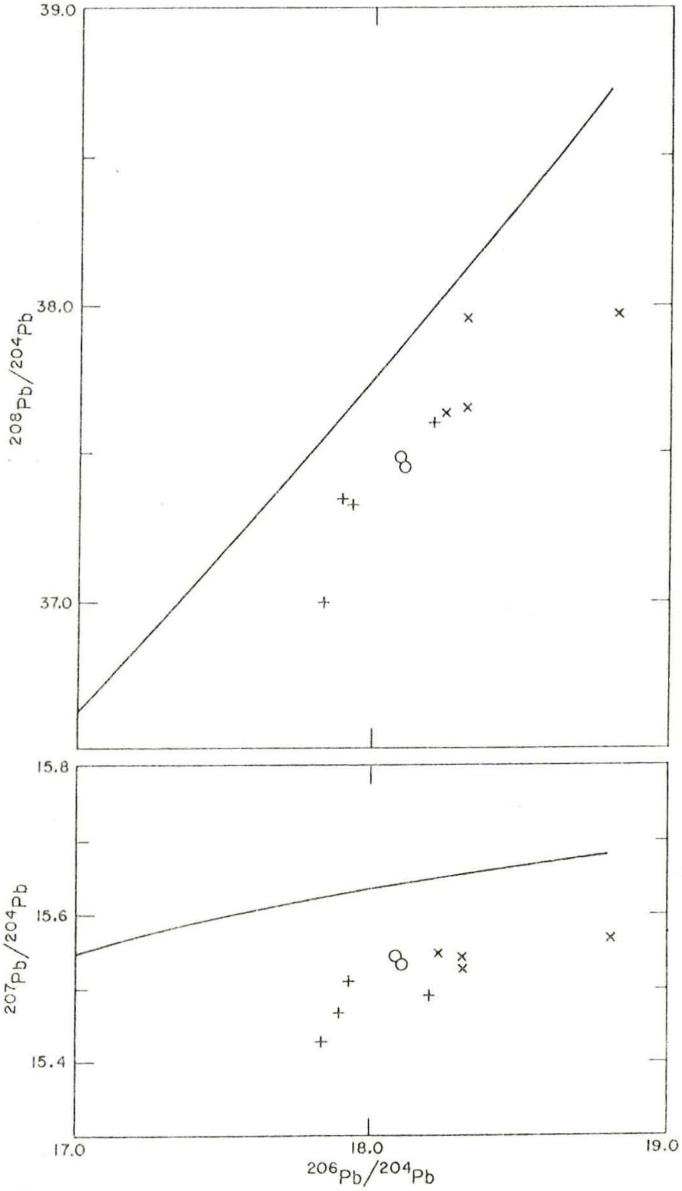

Figure 7. Pb isotope compositions of Miocene and Pliocene basaltic and rhyolitic lavas of Hinsdale Formation. Pb isotope growth curves are same as in Figure 5. Xs = alkalic olivine basalt; pluses = xenocrystic basaltic andesite; circles = rhyolite.

The Oligocene activity in the San Juan field is fundamentally andesitic, including the voluminous associated silicic rocks, and the genesis of all these rocks requires interpretation in terms of the general origin of andesitic suites. Especially significant is the predominance of intermediate compositions during accumulation of the first two-thirds of the Oligocene field (35 to 30 m.y. ago). The more silicic ash-flow tuffs, erupted 30 to 26.5 m.y. ago, are interpreted as genetically related differentiates that accumulated high in a differentiating intermediate-composition batholith, as indicated by compositional zonations within individual ash-flow sheets and by continued availability of more mafic magmas in the form of lavas and intrusions throughout the period of ash-flow eruptions.

Despite the generally simple history of San Juan volcanism in Oligocene time, the petrologic and isotopic relations preclude any one-stage model for generating magmas at some level in the crust or mantle that then rise unmodified to the surface. Sizable bodies of magma probably rarely rise long distances without undergoing some compositional modification (O'Hara, 1965). The Pb and Sr data reflect significant interactions between the evolving San Juan magmas and upper crustal rocks, and they point to a major lower crustal component in the intermediate-composition magmas. These magmas were probably initially generated deep in the mantle, perhaps related to subduction at the western margin of the American plate (Lipman and others, 1971, 1972).

One consequence of a subduction model for the San Juan magmas is the potential for especially complex crust and upper mantle structure and composition that would complicate petrogenetic interpretations. At the time of Oligocene magma generation the compositional and structural zones beneath the San Juan field presumably would have included (1) 1.4- to 1.8-m.y.-old sialic upper crust that is relatively radiogenic both in Pb and Sr, (2) more mafic lower crust of probable less radiogenic isotopic character, (3) lithospheric mantle of the American plate, from about 50- to 100-km depth between the Moho and the top of the low-velocity zone, that presumably has been little chemically modified since formation of the craton, (4) asthenospheric mantle, below about 100-km depth, of relatively world-wide compositional homogeneity (because of slow convective or counter-flow mixing), and (5) a subducted plate descending slowly to the east through the asthenosphere to a depth of several hundred kilometres. This proposed subducted plate would have consisted of oceanic crust and mantle lithosphere generated at the East Pacific Rise and subjected to little-understood processes and interactions with asthenosphere beneath the American plate for 10 to 20 m.y. before arriving at a position beneath the San Juan field.

Early Intermediate-Composition Magmas

The processes and depths of initial generation of the Oligocene intermediate-composition magmas are difficult to decipher. We favor a complex subduction model (Lipman and others, 1971, 1972), in which the magmas were initially generated in the descending oceanic plate or in the overlying asthenospheric mantle. At first, such magmas would have been relatively mafic, similar to primitive early basalt and andesite of island arcs (Jakeš and White, 1972), but they would have evolved greatly by interaction with country rocks and by crystal fractionation during their rise several hundred kilometres to the surface. Whether the San Juan magmas were initially generated by such subduction-related processes within the asthenosphere or by some other little-understood mechanism, the geochemical record of their interaction with lithosphere of the American plate — especially lower crust — is clear from both Pb and Sr isotope data.

The relatively nonradiogenic Sr isotope compositions of the early San Juan magmas preclude significant *upper* crustal contribution. Also, the rare-earth element patterns indicate equilibration with a feldspar-poor garnet-rich residuum that could be stable only in the lower crust or deeper (Zielinski and Lipman, 1976). In contrast, major interaction between mantle-derived magma and *lower* crustal rocks seems virtually required by the geochemical data, and for the intermediate-composition magmas the lower crust appears to have been the level of the last major equilibrium. For these magmas, involvement of old crust is indicated by (1) the secondary-isochron Pb ages — the same as those of the crust, (2) Sr isotope compositions that are somewhat radiogenic in comparison with oceanic basalt and island-arc suites but compatible with mafic 1.8-b.y.-old lithosphere, and (3) the presence of voluminous associated silicic calc-alkalic volcanic rocks — an assemblage absent from oceanic areas.

The Pb isotope variations from local areas define secondary isochrons that reflect both the 1.8- and the 1.4-b.y.-ago events recognized in the exposed Precambrian rocks. These isochrons are roughly similar to the apparent isochron of about 1.6 b.y. observed

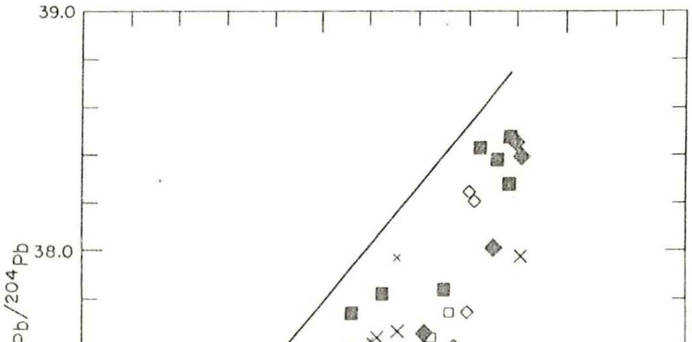

Figure 8. Lead evolution diagram for rocks of San Juan volcanic field, showing secondary-isochron interpretation. Solid lines are single-stage evolution curves for "best model-lead ages" of Doe and Stacey (1974). Dashed line on ^{207}Pb/^{204}Pb plot, derived from more precise silica-gel data only (larger symbols), is apparent secondary isochron of slope 0.112 ± 0.007 equivalent to source age of 1.86 ± 0.11 b.y. Smaller symbols represent analyses by older PbS-NH$_4$NO$_3$ technique. Triangles = early intermediate-composition rocks; diamonds = ash-flow tuffs; squares = caldera-related lavas and intrusions; Xs = late basalts and rhyolites.

in oceanic basalts derived from the shallow suboceanic aesthenosphere (Tatsumoto, 1966; Ulrych, 1967), but this similarity is probably coincidental because the ^{207}Pb/^{204}Pb ratios of the San Juan rocks are higher (Fig. 5D). Elsewhere in western North America, Pb isotope compositions of young igneous rocks commonly reflect age of the crust, including volcanic rocks resting on the older 2.8-b.y. basement in the northern Rocky Mountains (Peterman and others, 1970; Zartman, 1974).

The nonradiogenic Pb isotope compositions of early intermediate-composition rocks of the San Juan field require that the 1.8-b.y.-old source terrane had low U/Pb, Th/Pb, and Th/U ratios for at least this time interval. For example, a source ^{238}U/^{204}Pb ratio of only 5.3 to 8.9 would satisfy the observed ^{206}Pb/^{204}Pb ratios of the intermediate-composition rocks; this contrasts with values of 9.6 to 9.7 calculated for sources of modern arc andesites (Doe and Stacy, 1974). As the observed ^{238}U/^{204}Pb ratios of San Juan intermediate-composition rocks (9.6 to 12.5) are typical (50th percentile for andesitic rocks is 10: Doe, 1970), even the intermediate-composition San Juan magmas must have differentiated slightly relative to their source (U/Pb and Th/Pb ratios increase with differentiation).

The San Juan rocks plot below the single-stage evolution curve for ^{208}Pb/^{204}Pb (Fig. 8), requiring a low Th/U ratio in the source terrane. This feature is unusual for continental igneous rocks and ore deposits (Doe and Zartman, 1977) and suggests a relatively mafic source. Upper-crustal continental rocks typically yield calculated

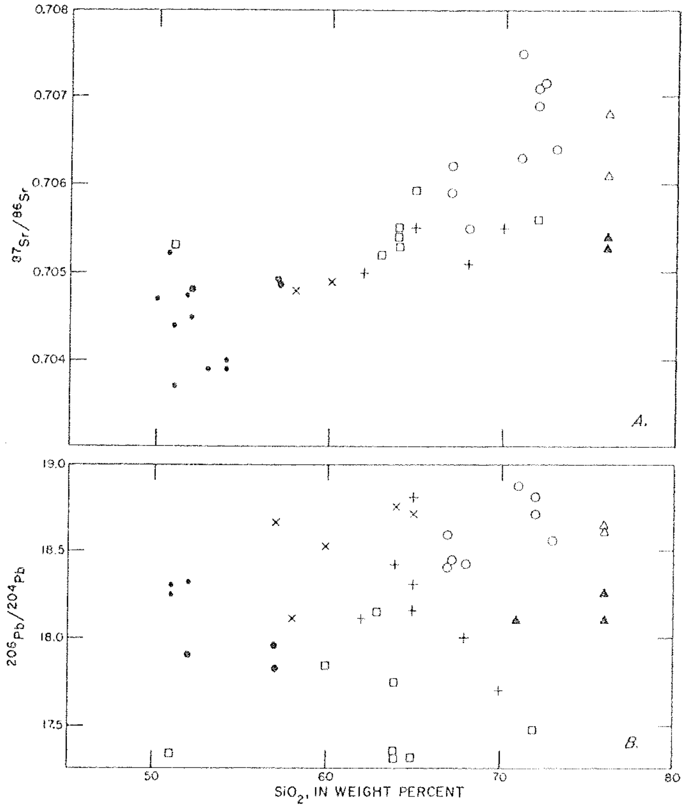

Figure 9. Relations between isotope composition and bulk-rock SiO$_2$ contents of volcanic rocks of San Juan field. A, Strontium isotope composition versus SiO$_2$; B, lead isotope composition versus SiO$_2$.

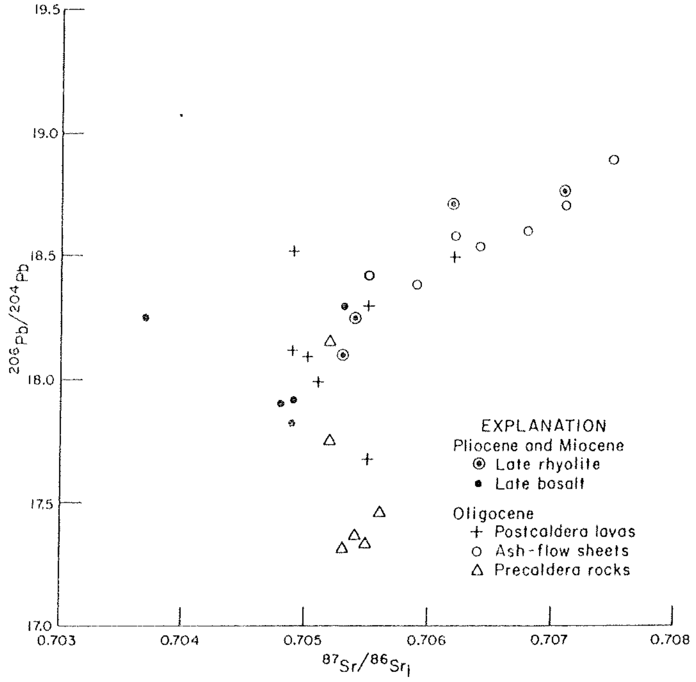

Figure 10. Relations between isotopic compositions of lead and strontium, volcanic rocks of San Juan field.

TABLE 5. Pb ISOTOPE SECONDARY-ISOCHRON REGRESSIONS, CALCULATED AGES, AND CALCULATED Th/U RATIOS FOR SOURCES OF VOLCANIC ROCKS OF SAN JUAN FIELD

Area	Regression*		"Age"	"Th/U"	No.
	^{207}Pb/^{204}Pb vs. ^{206}Pb/^{204}Pb	^{208}Pb/^{204}Pb vs. ^{206}Pb/^{204}Pb	(b.y.)		of samples
All	0.112 (±0.007)	0.913 (±0.025)	1.86 (±0.11)	3.1 (±0.1)	20
Southeastern	0.088 (±0.029)	0.759 (±0.094)	1.40 (±0.50)	2.6 (±0.3)	5
Central	0.120 (±0.021)	0.796 (±0.067)	1.97 (±0.25)	2.7 (±0.2)	4
Western	0.105 (±0.021)	1.060 (±0.069)	1.71 (±0.32)	3.6 (±0.3)	11
Early intermediate, all	0.107 (±0.03)	0.883 (±0.100)	1.78 (±0.35)	3.0 (±0.4)	6

Note: Silica-gel analyses only.

* Calculated using least-squares method of York (1969). "Th/U" calculation is insensitive to age; 1 b.y. is used arbitrarily. Uncertainties are 1 σ.

TABLE 6. Sr AND Rb CONTENTS AND Sr ISOTOPE COMPOSITIONS OF ROCKS OF SAN JUAN VOLCANIC FIELD, COLORADO

Sample no.	Unit analyzed	Field[*] no.	Age[†] (m.y.)	SiO_2[†] (%)	Element contents (ppm)		$^{87}Sr/^{86}Sr$		Data[‡] source
					Rb	Sr	Observed	Initial	
	Early intermediate-composition rocks								
1	Navajo Peak, rhyodacite flow	68L-91P	32.4	~64	0.4	1,910	0.7054	0.7054	1
2	Conejos Peak, rhyodacite flow	67L-129P	30–31	~63	..	..	0.7052	..	1
3	Summer Coon Center, rhyodacite dike	65L-267W	34.7	64	84	810	0.7055	0.7055	2
4	Summer Coon Center, Basalt dike	67L-106W	~33	51	29	710	0.7053	0.7053	2
5	Summer Coon Center, rhyolite dike	65L-206AW	32.1	72	99	370	0.7059	0.7056	2
6	Cimarron Ridge, rhyodacite flow	RD336-68P	32.1	~64	0.5	2,030	0.7052	0.7052	1
7	Cimarron Ridge, rhyodacite breccia	RD1877H	~32	~65	..	..	0.7059	..	1
	Cimarron Ridge, rhyodacite breccia	RD1877P	~32	~65	..	..	0.7060	..	1
	Caldera-related rocks								
Platoro caldera complex									
8	Treasure Mountain Tuff, La Jara Canyon Member	65L-132P	29.8	68	2.2	1,340	0.7055	0.7055	1
9	Summitville Andesite, lower member	67L-125W	~29.5	60	82	770	0.7049	0.7049	2
10	Summitville Andesite, lower member	67L-126W	~29.5	58	77	820	0.7048	0.7048	2
11	Rhyodacite of Park Creek	64D1W	~29	~62	71	676	0.7051	0.7050	1
12	Quartz latite of South Mountain	64D2K	22.8	68	192	984	0.7052	0.7051	1
13	Rhyolite of Cropsy Mountain	64D3W	20.2	70	100	527	0.7056	0.7055	1
La Garita–Creede caldera complex									
14	Fish Canyon Tuff	67L-37BP	27.8	67	2.6	1,050	0.7059	0.7059	1
15	Carpenter Ridge Tuff	PBB178-59K	~27.5	72	80	613	0.7072	0.7071	3
16	Carpenter Ridge Tuff	HM-C-11W	~27.5	~72	259	87.0	0.7102	0.7069	1
17	Mammoth Mountain Tuff, rhyolite	67L-137AP	26.7	73	..	..	0.7064	..	1
18	Mammoth Mountain Tuff, quartz latite	67L-137MP	26.7	67	..	..	0.7062	..	1
19	Wason Park Tuff	68L-43P	~26.5	71	56	1,180	0.7063	0.7063	1
20	Fisher Quartz Latite	DS10P	26.4	~64	..	..	0.7062		1
21	Fisher Quartz Latite	PBB168-59W	26.4	65	83	660	0.7056	0.7055	1
Uncompahgre–San Juan–Silverton caldera complex									
22	Sapinero Mesa Tuff	68L-42AP	~28	72	13.8	1,640	0.7071	0.7071	1
23	Crystal Lake Tuff	72L-43AP	~27.5	71	6.0	1,600	0.7075	0.7075	1
Lake City Caldera									
24	Sunshine Peak Tuff	72L-12K	22.5	76	145	40.5	0.7101	0.7068	1
25	Sunshine Peak Tuff	DS445K	22.5	76	132	157	0.7069	0.7061	1
26	Nellie Creek plug	72L-47K	18.5	76	281	112	0.7073	0.7054	1
	Late basaltic and rhyolitic rocks of the Hinsdale Formation								
27	Xenocrystic basalt, southeast area	66L-26W	26.8	52	18.6	612	0.7048	0.7048	4
28	Xenocrystic basaltic andesite, southeast area	66L-20W	~17	57	58.1	570	0.7049	0.7049	4
29	Xenocrystic basaltic andesite, southeast area	66L-109P	~17	~57	..	..	0.7049		4
30	Basalt, Jarosa Mesa	DS29W	14	51	46.3	1,030	0.7053	0.7053	4
31	Basalt, Los Mogotes	65L-120W	5	51	20.4	1,040	0.7037	0.7037	4
32	Basalt, Los Mogotes	68L-134IW	5	54	223	983	0.7039	0.7039	1
33	Basalt, Los Mogotes	68L-134EW	5	54	23.6	1,370	0.7040	0.7040	1
34	Basalt, Los Mogotes	68L-134DW	5	~53	24.8	881	0.7039	0.7039	1
35	Basalt, Los Mogotes	68L-134CW	5	52	24.7	860	0.7045	0.7045	1
36	Basalt, Los Mogotes	68L-134BW	5	51	18.5	675	0.7044	0.7044	1
37	Basalt, Los Mogotes	67L-16	5	50	25.0	440	0.7047	0.7047	1
38	Diabase dike, Los Mogotes	67L-17A	5	52	22.2	472	0.7048	0.7048	1
39	Rhyolite, lava flow, Beaver Creek	69L-732K	22	76	147	54.7	0.7077	0.7053	1

[*] Letter at end of field number designates type of sample analyzed: W = whole rock, P = plagioclase, K = potassium feldspar, H = hornblende.

[†] Sign ~ indicates that age or SiO_2 content is determined from a different sample than used for Sr isotope analysis or is otherwise estimated by stratigraphic position, and so forth.

[‡] 1, This paper; 2, Doe and others (1969a); 3, Hedge (1966); 4, Doe and others (1969b).

Th/U ratios of about 4, but the calculated values for San Juan rocks are 2.6 to 3.6, increasing from east to west (Table 5). A Th/U ratio of about 3 is typical for mafic and intermediate-composition rocks, such as basalts and adesites (Doe, 1970), and may be a reasonable value for lower crustal materials that have been metamorphosed to grades as high as amphibolite facies. Granulite-facies metamorphism, however, would probably increase the Th/U ratios above 4 (Heier, 1973; Gray and Oversby, 1972).

The intermediate-composition San Juan rocks probably could have derived their compositional characteristics solely by partial melting of lower crustal materials. Abundant geophysical data document the generally mafic average compositions of the lower crust in western North America (Pakiser, 1963), compositions suitable for generating voluminous andesitic and more silicic melts by large-scale partial melting. The magnitude of mid-Tertiary volcanism in western North America, of which the San Juan field is representative (Lipman and others, 1972), implies such a large-scale thermal anomaly, however, that initiation of this activity within cratonic crust seems unlikely to us. The U- and Th-depleted nature of the lower crust under the Rocky Mountains, indicated by the Pb isotope data, and the resulting lowered contribution to heat flow from radioactive decay also suggest a subcrustal source for initial generation of the volcanic magmas.

Similarly, the Oligocene intermediate-composition magmas probably did not obtain their primary geochemical features from the lithospheric upper mantle that has been part of the American plate since crustal formation 1.8 b.y. ago. This conclusion is based on the isotopic dissimilarity between the Oligocene magmas and the Miocene-Pliocene basaltic rocks of the same region that likely were generated from this part of the mantle (Lipman and Mehnert, 1975). In comparison with the basaltic rocks, the Oligocene intermediate-composition rocks are slightly more radiogenic in Sr and less radiogenic in Pb (Fig. 9). Possibly, the Pb isotope compositions of the intermediate-composition magmas could be due to generation deeper in lithospheric mantle in which U/Pb and Th/Pb ratios decrease with depth, as implied by a high-pressure interpretation of the xenocrystic basaltic andesites (Nicholls and others, 1971). However, Rb/Sr would have to *increase* downward, somewhat improbably, to account for the slightly more radiogenic Sr in the Oligocene lavas and the xenocrystic basaltic rocks than in other late Cenozoic basalts of the region.

Subvolcanic Batholith

Evolution of the San Juan magmas shallower in the crust is more readily integrated with the surface volcanic history, and the rise of intermediate-composition magmas to shallow crustal levels marks the first stage in evolution of a large composite batholith beneath the volcanic field (Steven and Lipman, 1976).

Eruptions that formed the early volcanoes 35 to 30 m.y. ago

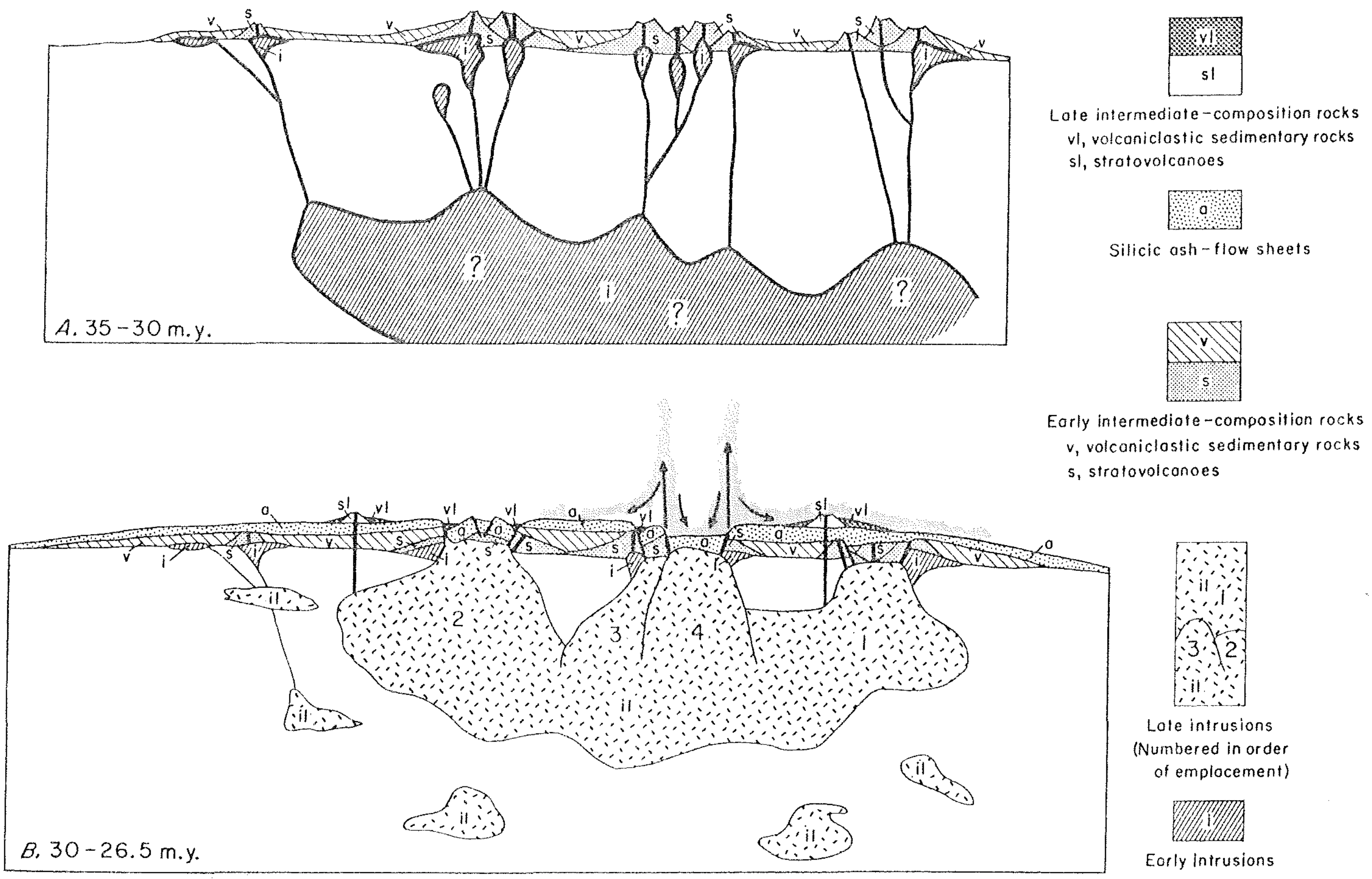

Figure 11. Schematic model for evolution of Oligocene subvolcanic batholith in San Juan Mountains. A. During time of early intermediate volcanoes. Clusters of intermediate-composition stratovolcanoes are surrounded by interfingering aprons of volcaniclastic debris. Small intrusions form at shallow levels in volcanic pile, but it is uncertain whether large high-level intrusive complex has developed by this time. B. During time of ash-flow eruptions and caldera formation. Eruption of complex sequence of ash flows and associated caldera collapses is triggered by accumulation at shallow depth of batholithic-size magma bodies of intermediate to silicic composition. Many of these shallow accumulations are localized within clusters of earlier stratovolcanoes. Some calderas are composite, with younger activity nested within older collapse structures, and many caldera collapses are followed by resurgent doming, indicating renewed upwelling of silicic magma.

were accompanied by emplacement of small isolated stocks high in the crust (Fig. 11 A). The isotopic and chemical data indicate that these bodies acquired their main characteristics in the lower crust or deeper, and only relatively minor modification occurred during final emplacement at shallow depth. Therefore, formation of the individual volcanoes and crystallization of their cogenetic stocks probably were relatively rapid. In parts of the field, the early volcanoes of intermediate composition are clustered, marking sites of concentrated accumulations of magma high in the crust. Within several of these clusters, sufficient magma eventually accumulated at shallow depth to permit formation of calderas (Lipman and others, 1973b; Lipman, 1975), and the petrologic characteristics of the younger Oligocene rocks reflect processes involving the shallow presence of large volumes of magma for prolonged intervals.

The area of the gravity anomaly, and by inference, that of the batholith, is roughly 50 by 100 km (Fig. 12); these dimensions are comparable to those of the Upper Cretaceous Boulder batholith of Montana (Klepper and others, 1971; Hamilton and Myers, 1974), which may represent a close analogue for the inferred batholith beneath the San Juan field. The Elkhorn Mountains volcanic field, cogenetic with the Boulder batholith (Hamilton and Myers, 1967; Tilling, 1974), also has close parallels with the San Juan field in terms of volcanic sequence, composition, and volume.[3]

Development of the Oligocene calderas in the San Juan field is believed to chronicle the emplacement of successive segments of this ascending batholith (Steven and Lipman, 1976). Early calderas in the eastern part of the field formed in areas of clustered andesitic volcanoes, just outside the main gravity low. These may reflect local high-level magma chambers that formed in the roots of the clusters before the main batholith rose to shallow depth.

The western caldera complex also formed within clustered earlier andesitic volcanoes, but it lies above the western part of the abtholith indicated by gravity data. Large volumes of "low-pressure" silicic differentiates were erupted as ash-flow tuffs. Five calderas

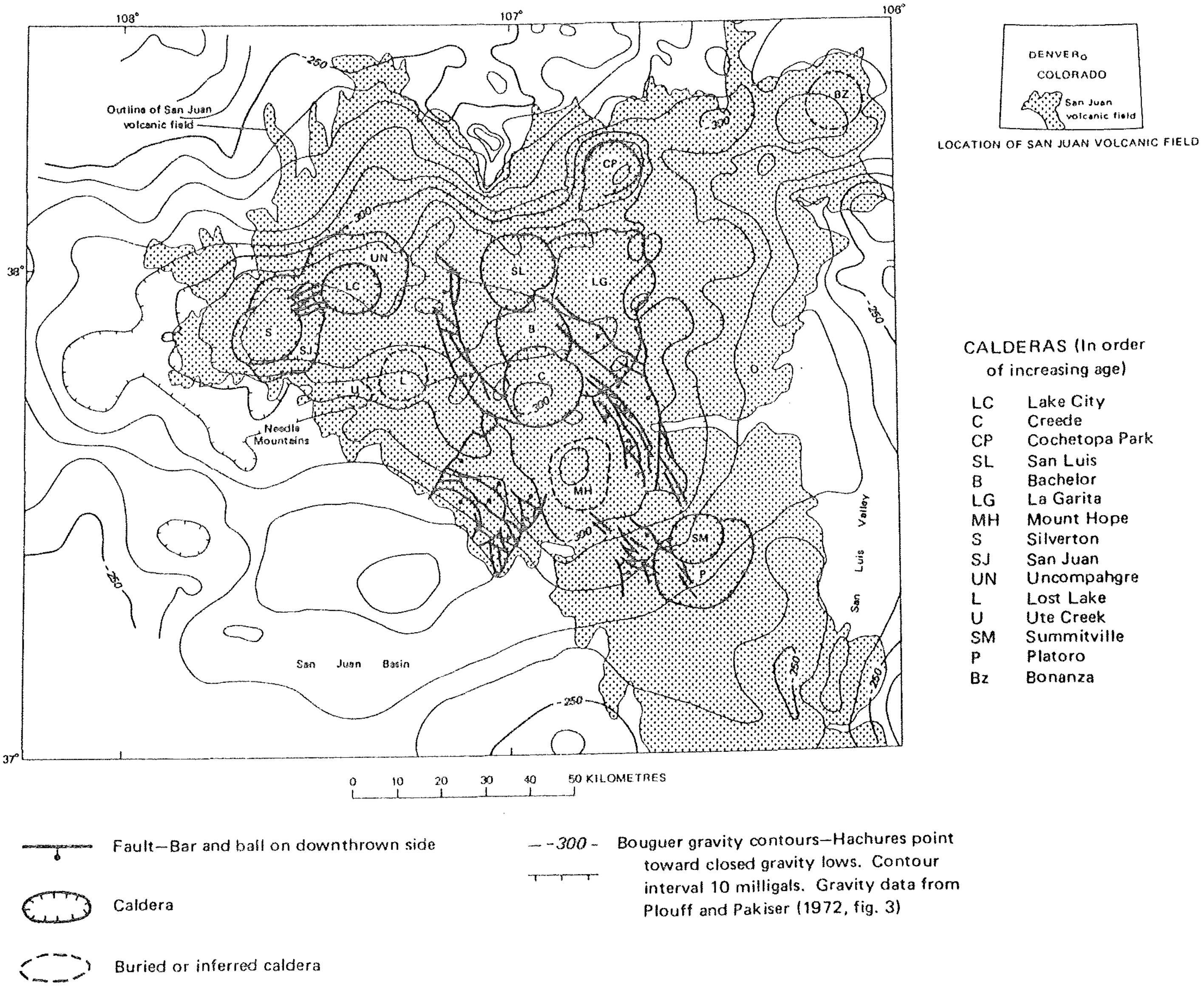

Figure 12. Calderas in San Juan volcanic field in relation to Bouguer gravity field.

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[3] The isotopic variations are also somewhat analogous, including a possible yo-yo effect. A major early intrusion, the Rader Creek pluton, is the least radiogenic part of the Boulder batholith, in both Pb and Sr. The mainstage Butte Quartz Monzonite and associated Elkhorn Mountains Volcanics are more radiogenic in both Pb and Sr. The late intrusions (Hells Canyon and Donald plutons) are again less radiogenic in Pb, but Sr remains radiogenic (Doe and others, 1968).

formed within 2 m.y. (29 to 27 m.y. ago), and contrasting lithologies of the related ash-flow sheets require sequential development of cupolas and of magmatic differentiation within them. Postsubsidence lavas, erupted after emplacement of the most voluminous sheets, were largely mafic quartz latite to andesite, indicating temporary exhaustion of silicic differentiates.

Development of the central caldera complex began about 28 m.y. ago, during the ash-flow eruptions and caldera collapses in the western San Juan field, and was largely complete by late Oligocene time, 26 m.y. ago. During this 2-m.y. span, eight major ash-flow sheets were erupted, and at least seven calderas formed. The calderas are above the main eastern segment of the gravity low and probably mark the culminating upward movement of magma in the batholith. Postsubsidence lavas are largely coarsely porphyritic quartz latites similar in composition to the associated ash-flow tuffs; apparently even the most voluminous ash-flow eruptions did not exhaust the silicic upper part of the batholith.

Caldera-Related Magmas

The petrology of the caldera-related rocks reflects their variable residence time and position in subcaldera environments. "Low-pressure" major-element compositional trends, inferred for some ash-flow sheets, are interpreted as having developed largely by crystal fractionation in the shallow subcaldera environment. These are also the only rocks for which rare-earth data indicate fractional crystallization involving feldspar, despite common feldspar phenocrysts in most of the intermediate-composition and more silicic rocks. In addition, these "low-pressure" rocks are the most radiogenic in both Pb and Sr, indicating that their bulk compositions may also reflect significant assimilation of upper crustal country rocks.

The positive correlation between SiO_2 and radiogenic Sr (Fig. 9, A) is readily interpreted in terms of interaction between the rising magmas and radiogenic crustal material. Sr content decreases with increasing SiO_2, so relatively minor crustal contamination could produce the observed enriched ^{87}Sr in the more silicic rocks (Hedge, 1966; Noble and Hedge, 1969). On a regional scale in the western United States, Sr isotope composition of young igneous rocks appears to reflect the distribution of old cratonic basement (Kistler and Peterman, 1973), in a manner somewhat analogous to the Pb data.

Even the more radiogenic Oligocene San Juan rocks cannot have been generated by partial melting solely of upper crustal materials, however, because these volcanic rocks are less radiogenic in both Pb and Sr than most crustal materials (Fig. 5B). Similar conclusions have been drawn virtually everywhere young igneous rocks resting on old sialic crust have been studied isotopically (Hurley and others, 1962b; Doe, 1967, 1968).

Probably, interactions between the evolving magmas and meteoric water also became significant at the subcaldera level. Oxygen isotope data (I. Friedman and P. W. Lipman, unpub. data) indicate that feldspar phenocrysts in intermediate-composition rocks, whether the rocks predate or postdate caldera formation have "normal" igneous oxygen isotope compositions ($\delta^{18}O = +7$ to $+8$). In contrast, the ash-flow sheets, especially those erupted later from compound caldera clusters, have feldspars with variably lighter $\delta^{18}O$ ($+6 \pm 1$). Similar isotopically light phenocrysts in late-stage silicic rocks of several young volcanic fields have been interpreted as reflecting interaction with isotopically light meteoric water in the magmatic environment (Friedman and others, 1974; Lipman and Friedman, 1975).

Interactions between cooling igneous rocks and meteoric water at shallow crustal levels have been documented for several intrusive areas within the San Juan field (Forester and Taylor, 1972; Taylor, 1974). These studies indicate that convecting cells of meteoric water circulate in proximity to intrusive bodies, propylitizing the volcanic piles and forming hydrothermal ore deposits. The evidence for these relations comes from postconsolidation deuteric effects under subsolidus conditions, whereas the oxygen-isotope variations observed in volcanic phenocrysts are inferred to have occurred at liquidus temperatures prior to eruption (Friedman and others, 1974).

The interaction of meteoric waters with magmas may also have been significant in modifying Pb isotope compositions in caldera-related volcanic rocks of the San Juan field. The Pb isotope compositions are most radiogenic at the time of caldera formation, with less radiogenic values from andesitic rocks that predate formation of the caldera rocks that postdate it, especially if they are much younger (Fig. 6). This relation is independent of composition (Fig. 9, B) and seems too striking to be fortuitous; it is interpreted as reflecting upper crustal lead mobilized in the subcaldera environment. The ore leads are similar to or more radiogenic than closely associated igneous rocks — spectacularly more radiogenic for the major Pb ores at Creede (Doe and others, 1977). We suggest that upper crustal Pb and meteoric water were both very mobile in the subcaldera environment. Failure of radiogenic Sr to vary sympathetically with Pb may indicate either that the Sr was less mobile than the Pb or that the concentration of Sr in the upper crustal rocks beneath the San Juan field was low relative to that in the magmas.

Miocene-Pliocene Rocks

The Miocene and Pliocene volcanic rocks of the San Juan field constitute a bimodal basalt-rhyolite suite, similar to those widespread in the western United States in late Cenozoic time (Christiansen and Lipman, 1972). Although there was little interruption in volcanic activity between the waning stages of the Oligocene batholith-related activity and the younger basalts and rhyolites, the two igneous suites appear related to contrasting igneous-tectonic environments: plate convergence and subduction before about 25 m.y. ago, and intraplate extension since that time.

The mafic rocks of the Miocene-Pliocene suite in the San Juan field are divisible into two types: silicic alkali-olivine basalts, and xenocrystic basaltic andesites. Both types occur widely in the western United States (Leeman and Rogers, 1970; Best and Brimhall, 1974; Lipman and Mehnert, 1975). In the San Juan region the silicic alkalic basalt can be regarded as relatively noncontaminated primitive products of partial melting within the lithospheric upper mantle of the American plate (Doe and others, 1969b). In contrast, the xenocrystic basaltic andesite is typically less radiogenic in Pb, perhaps owing to contamination by a nonradiogenic lower crust similar to that responsible for the relatively nonradiogenic character of the initially erupted middle Tertiary intermediate-composition rocks.

Rhyolites of the Miocene-Pliocene suite, including the voluminous Sunshine Peak Tuff erupted from the Lake City caldera 22.5 m.y. ago, are more silicic and alkalic than the Oligocene rhyolites, and they have higher Rb/Sr ratios. Accordingly, they should be sensitive to even small amounts of contamination by radiogenic crustal Sr. Yet these plot below the trend of the Oligocene silicic rocks (Fig. 9, A), a relation that indicates little interaction with upper crustal material. All the late rhyolites were erupted from vents within the Oligocene batholithic complex, as outlined by the gravity data, and the batholith may have shielded them from upper crustal contamination.

The Miocene-Pliocene rhyolites are also less radiogenic in Pb than most of the Oligocene rhyolites, fitting the downturn in the Pb isotope "yo-yo" trends (Fig. 6), and also indicating limited interaction with upper crust and suggesting a deeper source. Voluminous silicic rocks of this type do not occur where sialic crust is absent, as in the ocean basins, and we interpret them as partial melts from the lower sialic crust, with the thermal energy for melting probably provided by concurrent mantle-generated basaltic volcanism.

Thus, both the Oligocene intermediate-composition magmas and the late Cenozoic bimodal suite seem ultimately to have originated in the mantle with generation of mafic magma. For both types, more silicic material was mobilized by the mafic magma as it passed through the lower crust. In the Oligocene plate-convergent tectonic setting, the mafic and silicic components were well mixed before erupting as intermediate-composition lavas, but in the Miocene-Pliocene extensional tectonic setting the mafic and silicic melts rose separately to form a bimodal volcanic suite.

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