# Rare-Earth-Element Compositions of Cenozoic Volcanic Rocks in the Southern Rocky Mountains and Adjacent Areas

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By PETER W. LIPMAN

Variations among REE analyses of Cenozoic volcanic rocks and associated intrusions are interpreted in terms of tectonic setting, age of activity, and local igneous sequence

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# Rare-Earth-Element Compositions of Cenozoic Volcanic Rocks in the Southern Rocky Mountains and Adjacent Areas

*By* Peter W. Lipman


## Abstract

Variations among about 180 rare-earth-element (REE) analyses of Cenozoic volcanic rocks and associated intrusions from the southern Rocky Mountain region are interpreted in terms of tectonic setting, age of activity, and local igneous sequence. Major igneous areas sampled include: several Oligocene caldera clusters within the San Juan volcanic field, Oligocene intrusive rocks of the Abajo Mountains, Miocene intrusive rocks of the Spanish Peaks center, Oligocene-Miocene volcanic rocks and cogenetic batholithic granitic rocks of the Latir volcanic field and associated Questa caldera, Miocene and Pliocene rocks of the Taos Plateau volcanic field within the Rio Grande rift zone and adjacent basaltic rocks on the east and west flanks of the rift zone, and Pliocene rocks of the Mount Taylor volcanic field.

Oligocene and early Miocene dominantly intermediate-composition rocks that are interpreted as related to plate convergence show relatively high total REE, high light/heavy REE fractionation, and lack Eu anomalies. Total REE and light/heavy fractionation increase eastward as the igneous rocks become more potassic, which is interpreted as indirectly reflecting increasing depth to a paleosubduction zone. These changes are inferred to reflect increasing components of lithosphere, probably mainly lower crustal material, in magmas that evolved complexly. Miocene and younger dominantly basaltic suites, associated with regional extension within and adjacent to the Rio Grande rift zone, include nepheline-normative alkalic basalt and basanite, olivine tholeiite, and silicic alkalic basalt. These vary greatly in REE composition and are interpreted as primarily reflecting differing depths and degrees of partial melting in the mantle.

Intrusive and extrusive silicic rocks, associated both with the intermediate-composition convergence-related volcanic fields and with younger basaltic suites in more extensional environments, also vary sizably in REE compositions. Much of the observed REE range can occur within compositionally zoned single ash-flow sheets that record differentiation in their source magma chambers. Some granitic plutons that represent late-stage crystallization of subvolcanic magma chambers have REE compositions differing markedly from previously erupted cogenetic silicic volcanic rocks. Some silicic rocks have features interpreted as reflecting fractionation of the major phenocryst phases, and others have been variably contaminated by crustal materials. The largest REE variations, involving large decreases in light REE concentrations and development of large negative Eu anomalies, appear due to crystal fractionation involving small amounts of REE-rich accessory minerals and (or) liquid-state processes. Distinctive U-shaped REE patterns for some silicic rocks emplaced late in local igneous sequences, which are unlike most previously observed REE patterns, are probably due to crystal fractionation involving accessory sphene.


## INTRODUCTION

Systematic rare-earth (REE) and other minor-element data have been widely applied in problems of basalt petrogenesis but are still relatively sparse for volcanic rocks of intermediate and silicic compositions, especially from the voluminous Tertiary rocks of the Western United States. This paper summarizes results of about 180 REE analyses, all but 29 previously unpublished, for volcanic rocks and associated intrusions from several Tertiary volcanic fields in the southern Rocky Mountains and adjacent areas. The data are evaluated for evidence of regional contrasts in REE distributions as functions of tectonic setting, age of activity, and the local igneous sequence. This approach contrasts with the detailed modeling, based on crystal fractionation or other differentiation processes, that has been the focus of many previous REE studies. Attempts to develop fractionation models for the silicic rocks discussed here, involving only the major phenocryst phases, were not successful in accounting for the bulk of the REE variations; REE-rich accessory minerals are thought to be important. Nevertheless, important comparisons can result from examining a large body of data from regionally related suites of igneous rocks. REE data alone are rarely adequate to solve significant petrologic problems; field relations, geochronology, major-element compositions, and isotopic geochemistry provide additional constraints for most rocks discussed here.

The contrasting tectonic regimes examined include: (1) middle Tertiary subduction-related volcanism in the southern Rocky Mountains (Lipman and others, 1971;

Lipman, Doe, and others, 1978), followed by (2) regional extension associated with the Rio Grande rift (Lipman, 1969; Lipman, Bunker, and Bush, 1973). Analyzed materials include intermediate-composition lavas and associated more silicic differentiates that are thought related to mid-Tertiary subduction along the western margin of the American plate, as well as later Cenozoic fundamentally basaltic or bimodal basalt-rhyolite suites associated with extensional tectonism.

Most of the REE analyses were by instrumental neutron activation between 1975 and 1981 at the U.S. Geological Survey (Denver) under the supervision of H. T. Millard, Jr. and R. A. Zielinski. For some analyses REE were preconcentrated by J. S. Pallister, using the method of Zielinski (1975). Additional analyses for the Platoro caldera complex, the Abajo Mountain laccolith cluster, and the Spanish Peaks intrusive center were made in 1972–75 by H. R. Bowman, Ken Street, and Harold Wollenberg at the Lawrence Berkeley Laboratory, University of California. Because the samples were analyzed in two laboratories, and over a period of six years in one, small abundance variations may not be significant. All analytical data used in this report (table 1) have previously been available only in open-file format (Lipman and others, 1982); the present report was written in 1982. The REE values are plotted here in chondrite-normalized diagrams (values of Frey and others, 1968), mainly for convenience in showing numerous data in a familiar style. All data are plotted as reported; a few suspect values are queried on the figures. Volcanic rock nomenclature is as used by Lipman (1975).

## Acknowledgments

This regional study of REE compositions has been peripheral to more general analysis of the Cenozoic igneous history of the southern Rocky Mountains, which has engaged me intermittently for the past 15 years, and in which I have been fortunate to have had productive and provocative collaboration with geolgists too numerous to list, but including my U. S. Geological Survey colleagues T. A. Steven, R. L. Christiansen, S. Ludington, R. A. Zielinski, B. R. Doe, C. E. Hedge, H. H. Mehnert, and C. N. Naeser. My field study of the key Platoro and Lake City calderas was assisted in the summers of 1971–72 by David Johnston, who brought a special joy and remarkable perception to the study of volcanic rocks. Splits of samples, previously analyzed for major oxides, from the Abajo Mountains and Spanish Peaks were provided by I. J. Witkind and R. B. Johnson. Earlier versions of this report benefited from critical review by R. A. Zielinski, S. Ludington, and C. R. Bacon.

## REE FRACTIONATION IN SILICIC MAGMAS

Varying concentrations of REE in mafic magmas commonly have been interpreted as reflecting closed-system crystal-melt equilibrium in which distribution coefficients between major phenocryst phases and liquids are generally less than one, and most differentiation processes increase REE concentrations (Schnetzler and Philpotts, 1970; Kay and others, 1970; Frey and others, 1974; Arth, 1981). Additional processes may affect REE distributions in more silicic magmas. Accessory phenocrysts, that are rich in REE, may be significant in crystal fractionation (Buma and others, 1971; Hanson, 1978; Simmons and Hedge, 1978; Miller and Mittlefehld, 1982). Liquid-state fractionation may produce large compositional gradients independent of crystal-melt equilibria, at least in highly silicic magmas (Shaw and others, 1976; Hildreth, 1979, 1981; Mahood, 1981; Bacon and others, 1981). Rare-earth and other elements may also be selectively removed from magmas by volatile complexing and separation of vapor. Mixing of silicic with mafic magma, a process increasingly recognized as common in continental igneous suites (Eichelberger, 1978), may yield compositions differing from closed-system fractionation. Crustal contamination, which selectively introduces easily melted silicic components (mainly quartz and alkalic feldspar), might also dilute, and accordingly lower, REE concentrations in an initially more REE-rich mafic or intermediate-composition melt.

## MID-TERTIARY SUBDUCTION-RELATED ROCKS

Diverse Tertiary volcanic rocks in the Western United States, extending as far east as the southern Rocky Mountains, are now genons in an erally interpreted as related to low-angle subduction of various "Pacific" plates beneath North America (Lipman and others, 1971; Snyder and others, 1976; Cross and Pilgar, 1978; Lipman, 1980). These rocks are dominantly of intermediate compositions, with associated more silicic differentiates; basalts are sparse. The volcanics become more alkalic and silicic with increasing distance from the western edge of the American plate, interpreted as reflecting both increased depth to the subducted slab and increased assimilation of lower sialic crustal material. A voluminous example, relatively distant from the plate margin, is the Oligocene San Juan volcanic field in Colorado (fig. 1); new data from this area are compared in this report with data from other presumed subduction-related suites at varying distances from the plate margin. These include the Abajo laccolith cluster on the Colorado Plateau to the west, the Spanish Peaks intrusive complex at the east margin of the Rocky Mountains, and the 1980 deposits of Mount St. Helens, which are considered representative of active arc volcanism in

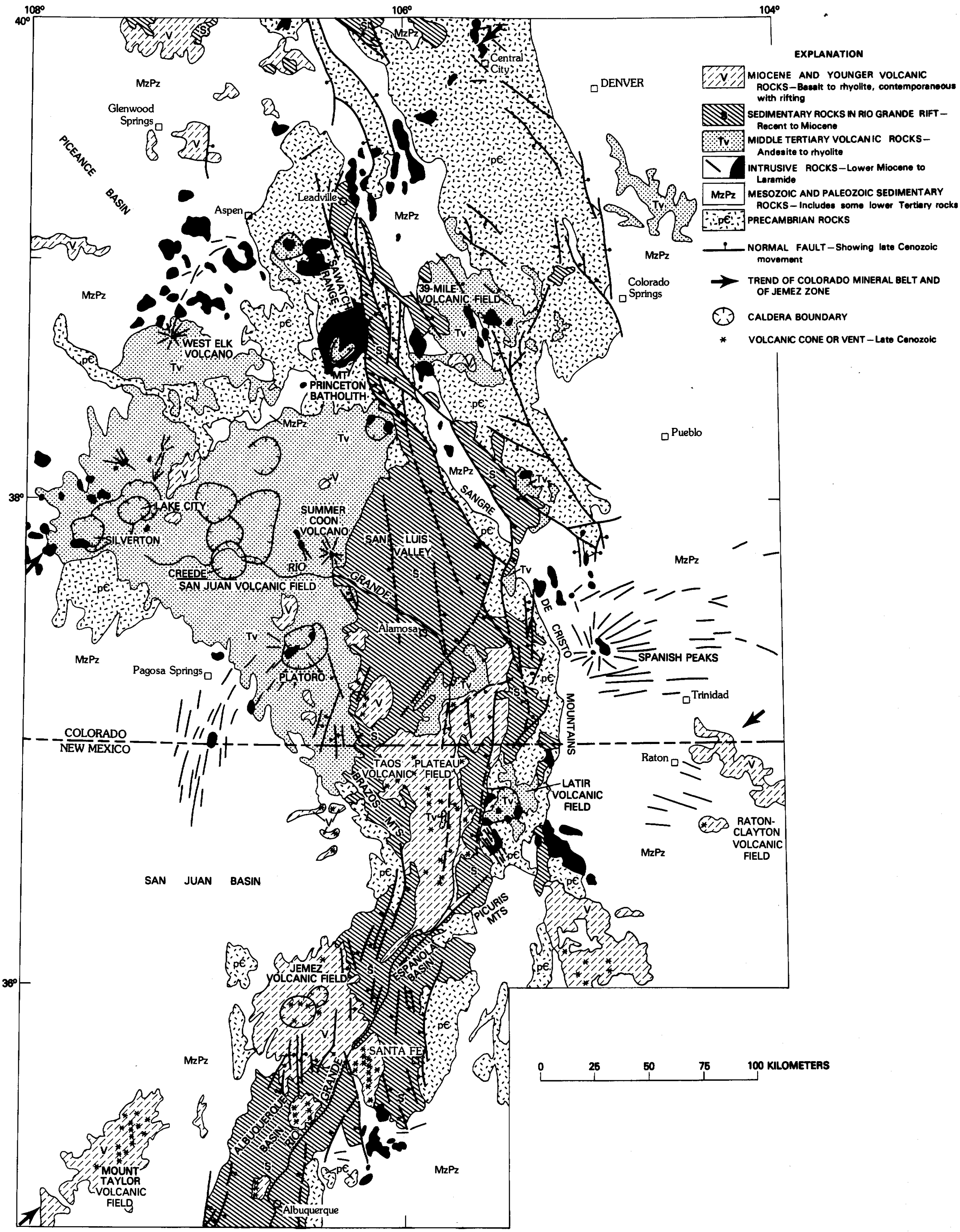


**Figure 1.** Map showing locations of volcanic fields in the southern Rocky Mountain region, for which REE data are reported in this report.

the Cascade Range. Comparisons also are made with published data for Tertiary volcanics from the Peruvian Andes—an incontestable continental-margin arc.

## San Juan Volcanic Field

Oligocene rocks of the San Juan field, southwestern Colorado (fig. 1) consist of dominantly intermediate-composition lavas and associated breccias erupted from central volcanoes, overlain by more silicic ash-flow sheets erupted from major calderas (Lipman and others, 1970; Steven and Lipman, 1976). The early intermediate rocks constitute at least two-thirds of the total volume of the field, and similar rocks continued to be emplaced as lavas and small intrusions during the subsequent pyroclastic stage. The entire Oligocene sequence is interpreted as recording the rise, emplacement, and consolidation of plutons that coalesced as a large composite batholith beneath the San Juan field, in which more differentiated cupolas erupted ash flows and then collapsed as calderas. The REE compositional variations among San Juan rocks are summarized here for a representative early intermediate volcano and for three major clusters of ash-flow calderas.

A detailed REE study of the Summer Coon volcano (Zielinski and Lipman, 1976), typical of the early intermediate sequence, shows chondrite-normalized patterns generally similar to many of the subsequently analyzed San Juan rocks (fig. 2). Andesitic rocks at Summer Coon have nearly linear trends, with pronounced light REE enrichment and no Eu anomaly that might indicate major feldspar fractionation. The more silicic rocks (rhyodacite to rhyolite) show slightly larger light REE concentrations, a crossover to lower Sm and heavy REE concentrations than in the andesites, and small Eu anomalies (fig. 2*A*). These variations are interpreted as largely reflecting generation of the intermediate-composition rocks by nonmodal partial melting of lower crustal material in which garnet was residual (Zielinski and Lipman, 1976); melting probably was ultimately caused by the rise of mantle-generated basaltic magma into the lower crust (Lipman, Doe, and others, 1978). The rhyolites, all relatively low in silica (72 percent maximum), were interpreted as resulting from fractional crystallization of andesitic magma, mainly involving feldspar and hornblende.

At the 29-m.y.-old Platoro caldera complex in the southeastern San Juan field (Lipman, 1975), variations in REE concentrations are smaller than at Summer Coon, except for a few late lava flows of small volume (fig. 3). As at Summer Coon, the precaldera intermediate lavas show pronounced light/heavy REE fractionation, although the limited REE variations do not correlate clearly with the sizeable variations in silica content (54–67 percent) or other differentiation indices. The REE trends are nearly linear to weakly concave upward. All but one

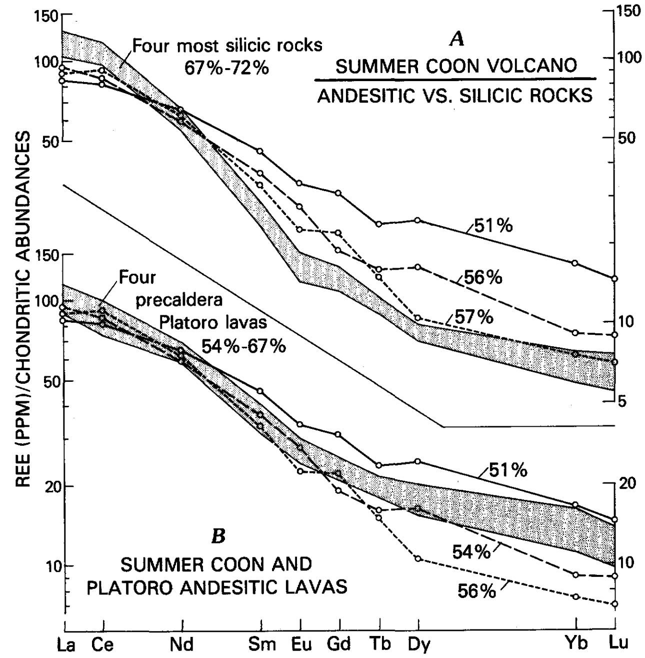


**Figure 2.** Chondrite-normalized REE compositions for rocks from the Summer Coon volcano, eastern San Juan Mountains. Numbers indicate whole-rock $SiO_2$ contents (calculated volatile-free). *A*, Andesitic and silicic volcanic rocks. Stippled area contains the four most silicic samples analyzed. Note crossover pattern for light and heavy REE elements between the two rock groups. From Zielinski and Lipman (1976, fig. 4). *B*, Andesitic Summer Coon rocks, compared to intermediate-composition precollapse lavas from the Platoro caldera area (stippled; see fig. 3). The two groups are similar and are considered representative of the early intermediate-composition rocks that volumetrically constitute the bulk of the San Juan volcanic field.

of the quartz latitic ash-flow tuffs that triggered caldera collapse are similar in REE compositions to the preceding intermediate-composition lavas, despite large ranges in major-element compositions (Fig. 3*A*); light REE are slightly higher in most of the tuffs. One volumetrically minor early tuff, the tuff of Rock Creek (Lipman, 1975, p. 14–16), is relatively REE-rich and characterized by a small negative Eu anomaly, probably due to feldspar fractionation. Postcollapse lavas and intrusions (fig. 3*B*, 3*C*), emplaced within about a million years of the ash-flow eruptions, are similar to the precaldera lavas, again despite large variations in silica content. Slightly increased light/heavy REE fractionation in the postcaldera lavas and intrusions causes weak crossover patterns with respect to precaldera rocks (fig. 3*B*, 3*C*), similar to those that are suggestive of crystal fractionation in Summer Coon rocks (fig. 2). The most silicic Oligocene lavas and intrusions are slightly lower in most REE concentrations than the preceding rocks, however, and this trend is continued by small volumes of younger silicic lavas, erupted near the caldera over the next 8 m.y. (fig 3*D*). In the late Platoro

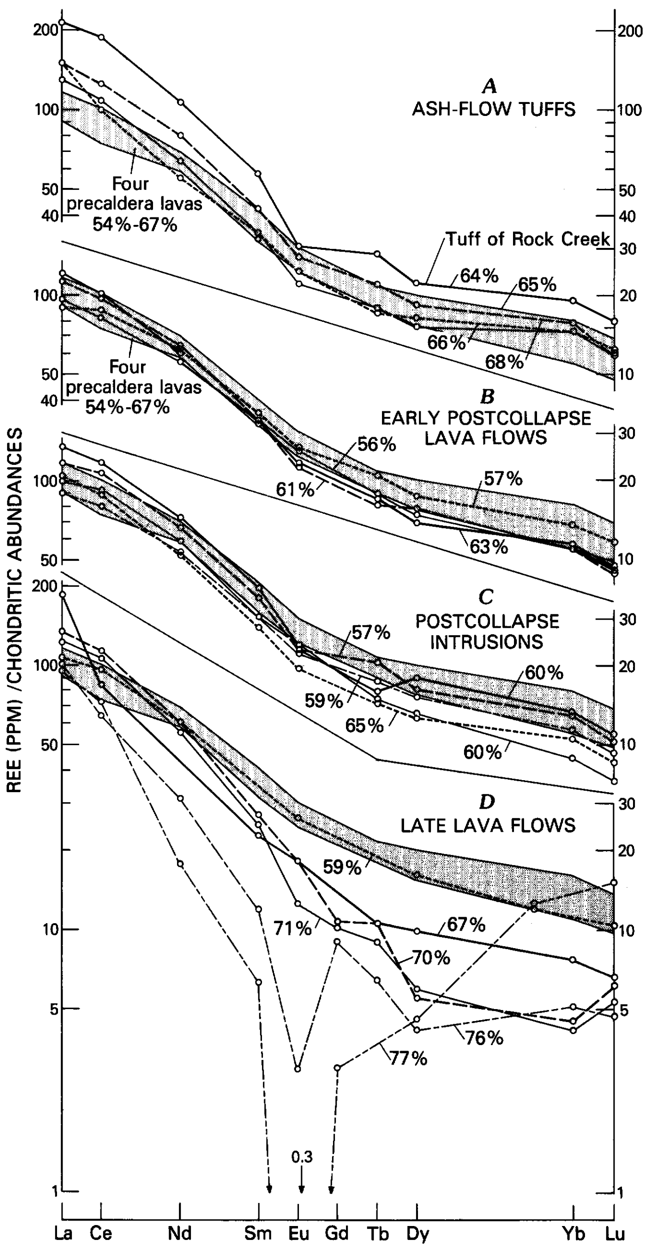


**Figure 3.** Chondrite-normalized REE compositions of volcanic rocks of the Platoro caldera complex, southeastern San Juan Mountains. Stippled area contains data for 4 precaldera lava flows (described in Lipman, 1975, table 2, nos. 1, 6–8) and is repeated in each diagram for reference. Numbers indicate $SiO_2$ contents (calculated volatile-free), from published analyses. *A*, Ash-flow tuffs (Lipman, 1975, table 4, nos. 1, 7, 14–15, 21). *B*, Early postcollapse lava flows (Lipman, 1975, table 9, nos. 1, 4, 6–7, 12). *C*, Postcollapse intrusions (Lipman, 1975, table 10 nos. 2, 4, 7, 9, 14). *D*, Late lava flows (Lipman, 1975, table 9, nos. 12, 17, 21, 22, and table 11, nos. 11–12.

flows, as silica increases, values of the middle REE decrease more than those of the light or heavy REE, tending to result in a U-shaped pattern that is rare among published REE data (but see Lipman, Rowley, and others, 1978; Izett, 1981, fig. 6). As discussed below, similar patterns recur elsewhere in the region among late-emplaced silicic volcanic and plutonic rocks.

In the central San Juan Mountains, at least seven compositionally diverse quartz latitic and rhyolitic ash-flow sheets were erupted from a cluster of calderas 28 to 26.5 m.y. ago (Steven and Lipman, 1976). These tuffs show complex REE compositions that are generally similar to those of rhyolitic rocks from the Summer Coon volcano (fig. 2*A*), just east of the caldera cluster. Light/heavy REE fractionation is slightly greater than for intermediate flows, with a crossover pattern in the middle REE for the tuffs versus the flows (fig. 4*A*), and the most silicic rhyolites (about 73 percent $SiO_2$) show small negative Eu anomalies. Two ash-flow sheets (fig. 4*B*, 4*C*: Carpenter Ridge and Mammoth Mountain Tuffs) are compositionally zoned from basal phenocryst-poor rhyolite upward into crystal-rich quartz latite, interpreted as reflecting compositionally zoned magmas in which rhyolite overlay quartz latite (Ratte and Steven, 1964; Lipman, 1975, p. 51–52). Rhyolitic portions of the sheets are similar to the quartz latites in REE contents but are characterized by negative Eu anomalies that may have resulted from feldspar fractionation (fig. 4*B*, 4*C*). Alternatively, development of the phenocryst-poor rhyolite may have marked the beginning of liquid-state fractionation in the source chamber (Hildreth, 1981). An especially mafic scoria block (61 percent $SiO_2$) from near the top of the Carpenter Ridge Tuff shows a positive Eu anomaly that may have been due to feldspar accumulation near walls or relatively deep within the source magma chamber. Postcollapse lavas within the Creede caldera, the youngest in the central cluster (Steven and Ratte, 1965), also vary from quartz latite to rhyolite, and their REE distributions show changes with major-element compositions similar to those of the ash-flow tuffs (fig. 4*D*). On the basis of the REE data, the silicic rocks of the central caldera cluster could primarily represent low-pressure differentiates from intermediate-composition magma, mainly by feldspar, hornblende, and possibly clinopyroxene fractionation (Zielinski and Lipman, 1976). Such an interpretation is compatible with other available petrologic data (Lipman, Doe, and others, 1978).

In the western San Juan Mountains, a cluster of five Oligocene calderas formed between about 28.5 and 27 m.y. ago (Ute Creek, Lost Lake, Uncompahgre, San Juan, Silverton), followed by development of the petrologically distinctive Lake City caldera at about 23 m.y. (Lipman, Steven, and others, 1973; Steven and Lipman, 1976). Limited REE data for ash-flow tuffs and postcollapse lavas from the older calderas are little different than those from the central and eastern San Juan field (fig. 5): the ash-flow tuffs have light/heavy fractionations similar to the postcollapse lavas, although both tend to be higher in light REE contents than Platoro rocks. The more silicic tuff (Sapinero Mesa) and both postcollapse lava flows

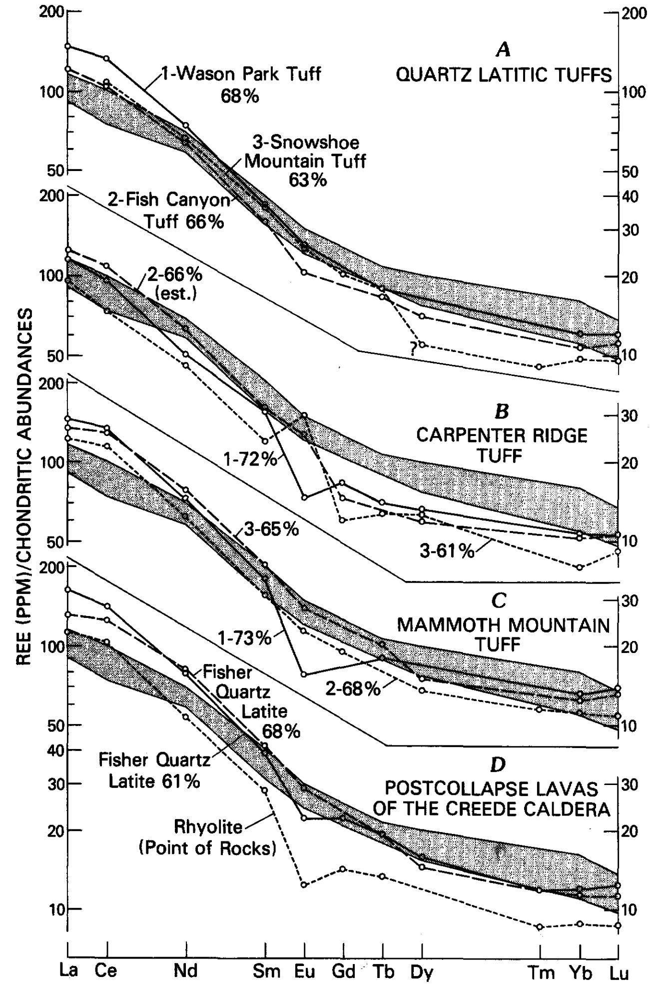


**Figure 4** Chondrite-normalized REE compositions of volcanic rocks from the central San Juan caldera cluster. Stippled areas are the field for precollapse lava flows of the Platoro caldera area (fig. 3). Reference numbers of samples are followed by whole-rock $SiO_2$ contents (calculated volatile-free), mostly from published analyses. *A*, Quartz latitic tuffs. Sample 1 is Wason Park Tuff (Ratte and Steven (1967, table 18, no. 7); sample 2 is Fish Canyon Tuff (Lipman (1975, table 6, no. 4); sample 3 is Snowshoe Mountain Tuff (Ratte and Steven, 1967, table 24, no. 1). *B*, Carpenter Ridge Tuff. Sample 1 is lower rhyolite, same locality as Lipman (1975, table 6, no. 17); sample 2 is upper quartz latite, same locality as Lipman (1975, table 6, no. 16); sample 3 is mafic scoria block in upper quartz latite (Lipman (1975, table 6, no. 15). *C*, Mammoth Mountain Tuff. Sample 1 is lower rhyolite (Ratte and Steven (1967, table 10, no. 2); sample 2 is upper quartz latite, collection of same locality as in Ratte and Steven (1967, table 10, no. 3); sample 3 is quartz latite (Ratte and Steven (1967, table 10, no. 4). *D*, Postcollapse lavas of the Creede caldera. Samples 1 and 2 from flows of Fisher Quartz Latite (Ratte and Steven, 1967, table 22, nos. 1–2); sample 3 is rhyolite at the Point-of-Rocks volcano, described by Steven and Ratte (1965).

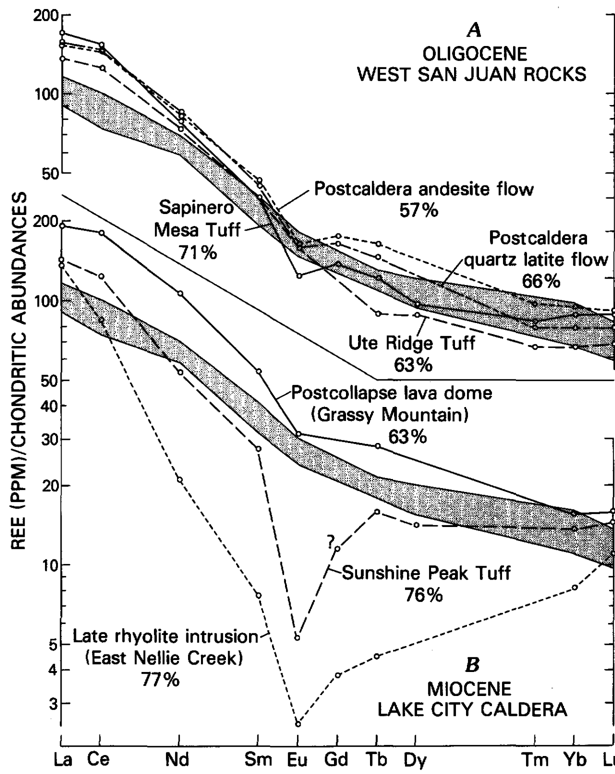


**Figure 5.** Chondrite-normalized REE compositions for rocks of the western San Juan caldera cluster. Stippled areas are the field for precollapse lava flows from the Platoro caldera area (fig. 3). Numbers indicate whole-rock $SiO_2$ contents, from unpublished analyses of the author. *A*, Oligocene tuffs and lavas of the Ute Creek, Uncompahgre, and San Juan calderas. *B*, Miocene rocks of the Lake City caldera area.

show small negative Eu anomalies, suggestive of feldspar fractionation (fig. 5*A*).

In contrast, the 23-m.y-old Miocene Sunshine Peak Tuff, a distinctive ash-flow sheet of alkali rhyolite erupted from Lake City caldera, is mostly more silicic than the Oligocene ash-flow sheets (Lipman, Steven, and others, 1973), although some late-erupted Sunshine Peak that ponded within Lake City caldera is low-silica rhyolite and records compositional zonation in the source chamber (Hon and others, 1983). Silicic Sunshine Peak Tuff is characterized by a large negative Eu anomaly and middle REE values below the field defined by the Oligocene rocks (fig. 5*B*). An intracaldera late lava dome (quartz latite of Grassy Mountain), indistinguishable in K-Ar age from the Sunshine Peak Tuff, has high REE contents and only a small Eu anomaly; it may have sampled a little-fractionated lower level of the magma chamber which erupted the ash-flow tuff. A silicic alkalic rhyolite about 5 m.y. younger than the caldera (East Nellie Creek intrusion), is characterized by strongly depleted middle REE contents (less than 10x chondrites), yielding a U-shaped pattern, similar to those of late rhyolites at Platoro (fig. 3*D*). The Lake City caldera and associated volcanic rocks have been interpreted as being related to, or transitional to, the regional bimodal basalt-rhyolite suite associated with initiation of extension in the southern Rocky Mountains (Lipman and others, 1970). The REE patterns for

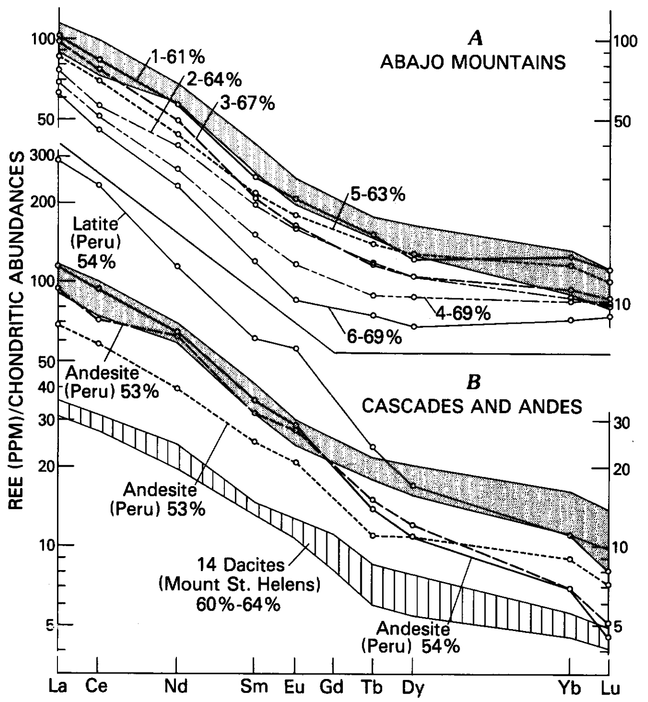


**Figure 6.** Chondrite-normalized REE compositions for Oligocene intrusive rocks of the Abajo Mountains, Utah, and comparisons with other continental-margin arc suites. Stippled areas are field for precollapse lava flows from the Platoro caldera area (fig. 3). Reference numbers of samples are followed by whole-rock $SiO_2$ contents (calculated volatile-free), from published analyses. *A*, Abajo Mountains, Utah. Samples 1-6 are from Witkind (1964, table 3, nos. 6-8, 10, 12, and 14, respectively). *B*, Cascades and Andes. REE analyses of eight Mount St. Helens dacites (vertical-lined area) are from samples described by Lipman and others (1981, table 1) and encompass compositional range (60-64 percent $SiO_2$) of 1980 eruptive products. Peruvian samples are from Noble and others (1975, table 2).

Lake City rocks, which contrast with the Oligocene trends of the San Juan field, are also typical of patterns defined by silicic units in other late Cenozoic basalt-rhyolite associations in the Western United States.

## Comparisons with Other Continental Volcanic Suites Associated with Plate Convergence

Dominantly intermediate-composition Tertiary volcanic rocks that are thought to be related to plate convergence along the western margin of the American plate vary widely in composition. Relatively low-K calcic suites are common in western areas, and highly alkalic rocks occur in the eastern cordillera; these variations have been interpreted as reflecting varying depth to a paleosubduction zone (Lipman and others, 1971; Coney and Reynolds, 1977), as well as varying interaction between the rising magmas and continental crust and lithosphere (Lipman, Doe, and others, 1978). Although published data are sparse, the regional major-element variations in subduction-related rocks are reflected in the REE data summarized here.

In comparison with the San Juan field, nearly contemporaneous igneous rocks of less potassic composition occur in scattered laccolithic clusters on the Colorado Plateau, west of the area of figure 1. Representative are the Abajo Mountains, Utah (Witkind, 1964), where hypabyssal intrusions of quartz diorite and granodiorite are about 28 m.y. old (Armstrong, 1969). These represent some of the most westerly Oligocene igneous activity in this sector of the southern cordillera, at a time apparently characterized by low-dip subduction (Coney and Reynolds, 1977; Lipman, 1980). Representative intrusive rocks from the Abajo Mountains (fig. 6*A*) have REE compositions that decrease fairly systematically as $SiO_2$ contents increase and are generally similar to those of intermediate San Juan rocks: the trends are weakly concave upward and lack Eu anomalies. Light/heavy REE fractionations are markedly lower (normalized La/Lu about 7 for Abajo samples, in comparison with ratios of 9-11 for most San Juan rocks). Light REE values for silicic Abajo samples are only 60-80 times chondritic abundances (fig. 6*A*), whereas many San Juan rocks have values 100-150 times chondrites (figs. 3-5); heavy REE values are similar for the two suites.

In these respects, the Abajo suite is transitional toward even lower-K and more calcic plate-margin arcs such as the Cascade Range. An interesting comparison is with dacitic lavas and tuffs from the 1980 eruption of Mount St. Helens, which have silica contents similar to those of the Abajo and San Juan suites (fig. 6*B*). The Mount St. Helens samples, like other Cascade volcanoes (Condie and Swenson, 1973), have REE contents lower than the Abajo Mountains suite, although the normalized light/heavy fractionation is similar (La/Lu about 7). In contrast, alkalic andesites of continental-margin arcs, such as the Peruvian Andes (Noble and others, 1975), have REE compositions much like those of the San Juan field, with large light REE concentrations and light/heavy REE ratios (fig. 6*B*).

To the east of the San Juan field, middle Tertiary igneous rocks along the margin of the High Plains are characterized by more alkalic compositions and correspondingly contrasting REE compositions. These contrasts are well illustrated by the Spanish Peaks intrusive complex (fig. 1; Knopf, 1936; Johnson, 1968; R. P. Smith, 1979). Potassium-argon and fission-track dates indicate that much of the igneous activity at the Spanish Peaks occurred 23-25 m.y. ago (Stormer, 1972b; R. P. Smith, 1979), near the end of major San Juan volcanism. Some would relate such activity to waning of mid-Tertiary subduction (Coney and Reynolds, 1977; Keith, 1978); alternatively, the Spanish Peaks rocks could be related to early

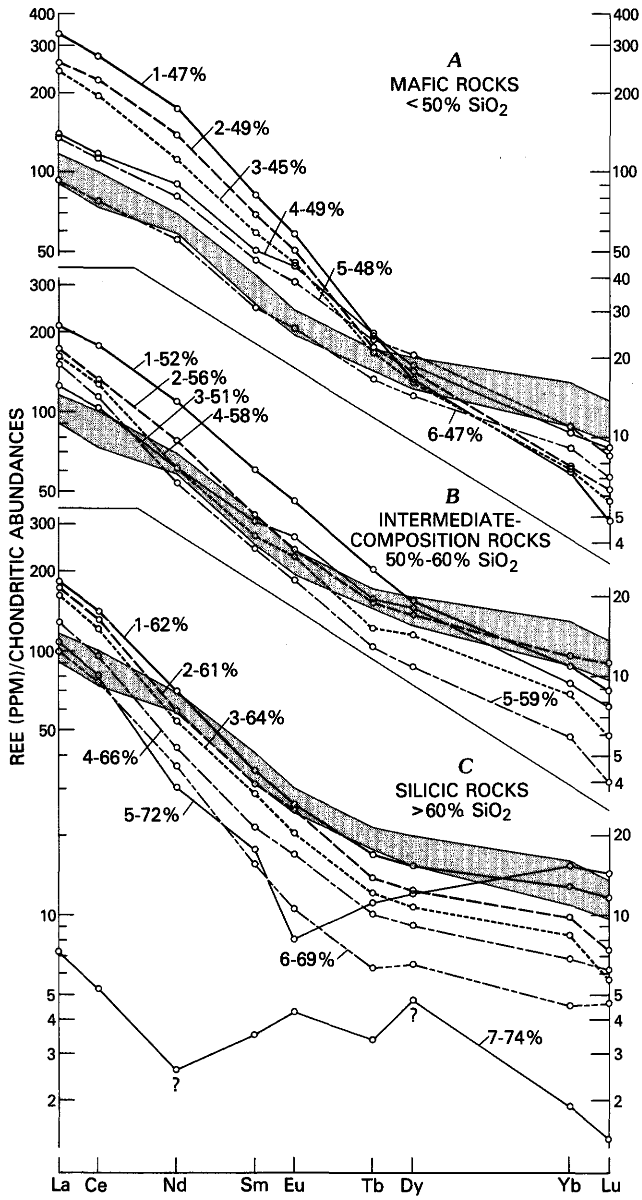


**Figure 7.** Chondrite-normalized REE compositions in rocks from the Spanish Peaks intrusive complex. Stippled areas are field for precollapse lava flows from the Platoro caldera (fig. 3). Reference numbers of samples are followed by whole-rock $SiO_2$ contents (calculated volatile-free). *A*, Mafic rocks (<50 percent $SiO_2$). Samples 1–6 are from Johnson (1968: table 10, no. 28; table 7, no. 97; table 19, no. 56; table 10, no. 137; table 13, no. 157; table 19, and no. 178, respectively). *B*, Intermediate-composition rocks (50–60 percent $SiO_2$). Samples 1–5 are from Johnson (1968: table 13, no. 155; table 10 , no. 150; table 10, no. 130; table 10, no. 108; and table 10, no. 132, respectively). *C*, Silicic rocks (greater than 60 percent $SiO_2$). Samples 1–7 are from Johnson (1968: table 7, no. 86; table 10, no. 113; table 10, no. 112; table 7, no. 87; table 1, East Spanish Peak stock; table 1, no. 78; and table 1, Mt. Mesitas, respectively).

extension along the Rio Grande rift. Either way, the Spanish Peaks are transitional rocks.

REE compositions vary substantially among Spanish Peaks rocks with limited major-element variations, especially the mafic rocks (fig. 7*A*); similar REE data have also been reported for the Spanish Peaks by Jahn and others (1979). Mafic rocks with the highest REE contents are the most fractionated ($La_N/Lu_N$ about 60), especially lamphrophyres characterized by high $K_2O$ and $P_2O_5$ and low $Al_2O_3$ and $Na_2O$ (fig. 7*A*, samples 1-3). Among the mafic rocks, the heavy REE tend to increase slightly as light REE decrease, resulting in a crossover pattern. The mafic rocks (fig. 7*A*) occur mainly as early east-west-trending dikes that are truncated by dikes radiating from the silicic central intrusions (R. P. Smith, 1979). Nevertheless, REE compositions of some early mafic rocks (fig. 7*A*, samples 4-6) differ only modestly from the later intermediate-composition intrusions (fig. 7*B*; 50-60 percent $SiO_2$). Both groups have nearly linear trends, high total REE contents, and more pronounced light/heavy REE fractionations than for intermediate rocks from the San Juan or Abajo Mountains. The extreme REE fractionation and the crossover pattern of REE distributions between lamphrophyric and other mafic rocks suggest varying degrees of melting in mantle materials in which garnet was a residual phase, as previously discussed for Summer Coon volcano (Zielinski and Lipman, 1976). All REE decrease with increasing silica in silicic rocks at Spanish Peaks (fig. 7*C*, except sample 5); this general feature of late Cenozoic silicic rocks in the region is discussed later. The most silicic rock (Fig. 7*C*, sample 7)—a granitic phase of the central intrusion—is the lowest in REE content, and the irregular chondrite-normalized pattern is probably due to analytical uncertainties at low concentrations.

## LATE CENOZOIC VOLCANISM ASSOCIATED WITH EXTENSIONAL TECTONICS

The regional transition, from dominantly intermediate-composition volcanism related to plate convergence and subduction, to basaltic or bimodal basalt-rhyolite volcanic suites associated with extensional tectonics began about 26 m.y. ago in the southern Rocky Mountains (Christiansen and Lipman, 1972; Chapin and Seager, 1975; Elston and Bornhorst, 1979; Eaton, 1979). The younger volcanic assemblage can be subdivided into: (1) an earlier transitional suite, containing abundant silicic alkalic rhyolite in association with alkalic basalt, basaltic andesite, and other intermediate-composition rocks, and (2) a later suite, in which basaltic rocks are more abundant and intermediate-composition and rhyolitic rocks are relatively sparse (Elston and Bornhorst, 1979; Lipman, 1980). The earlier suite appears to have erupted in an inter- or back-arc extensional environment while subduction-related volcanism continued farther west, whereas the younger suite seemingly represents volcanism associated with extension within the sector of the American plate adjacent to the growing oblique transform boundary with the Pacific plate. The transition between the two suites is also reflected by a change in orientation of regional principal stresses, from earlier normal faulting and dike emplacement along northwest trends to extension along nearly north-south trends later in the Cenozoic, both within the southern Rocky Mountains (Lipman, 1981) and throughout the U.S. Cordillera (Zoback and others, 1981; Eaton, 1979). The time of transition between the two suites is poorly constrained in the southern Rocky Mountains, at about 20–15 m.y. ago, due to the paucity of dateable volcanic rocks in this range.

Both suites are well represented in the southern Rocky Mountains, especially along and adjacent to the Rio Grande rift. Rocks of the Lake City caldera and the Spanish Peaks are in most respects representative of the transitional suite, although no major extensional deformation has been documented near Lake City, and the geometry of the Spanish Peak dikes indicates emplacement in a regional stress field different from that along the Rio Grande rift just to the west (Zoback and Zoback, 1980). An especially instructive transitional suite, discussed below, is the Latir field, near Questa, New Mexico, where igneous activity culminated 26–23 m.y. ago during intense extensional deformation within the early Miocene Rio Grande rift zone. Late Miocene and Pliocene basaltic fields, emplaced within and adjacent to the Rio Grande rift during extension along north-south trends, for which REE data are discussed, include the Taos Plateau field within the rift, basaltic rocks of the Raton-Clayton field on the High Plains to the east, similar rocks in the San Juan and Brazos (Tusas) Mountains to the west, and the Mount Taylor field in central New Mexico (fig. 1). These rocks also define the Jemez zone (Mayo, 1958), a northeast-trending zone of Pliocene volcanic centers that may reflect an underlying crustal flaw (Laughlin, 1976). These volcanic rocks also tend to show transverse petrologic variations, generally becoming more alkalic with distance from the Rio Grande rift (Lipman, 1969).

## Latir Volcanic Field

The Latir volcanic field, in northern New Mexico, consists of discontinuous downfaulted remnants of a dominantly intermediate-composition sequence of lava flows and breccias, overlain by an originally widespread ash-flow sheet of silicic alkalic rhyolite, erupted from the Questa caldera about 26 m.y. ago (Lipman, 1981, 1983). Associated with the caldera, and partially exposed by deep erosion and major uplift along bounding faults of the Rio Grande rift, is a composite batholith, ranging in composition from quartz monzonite to granite. The Questa caldera subsided into the originally structurally highest portion of the batholith, and the core of the caldera was resurgently uplifted by emplacement of late phases of the batholith. A cogenetic relation between the rocks of the Latir field and the batholith is demonstrated by geographic distribution of intrusive and extrusive rocks, isotopic age determinations, geophysical evidence for nearly confocal margins of batholith and caldera, relations between faulted volcanic rocks and structurally controlled intrusions, and paleomagnetic studies indicating deformation of the extrusive rocks while the batholith was still hot (Lipman, 1981; Hagstrum and others, 1982). Detailed petrologic studies of the volcanic and associated intrusive rocks are currently underway, but available REE data summarized here offer an opportunity to compare fractionation trends in a cogenetic suite of volcanic rocks with their more slowly solidified source magma chamber, as represented in its final form by the batholithic rocks of the Questa area.

Precaldera intermediate-composition rocks of the Latir volcanic field range from at least 35 to 26 m.y. old (Pilmore and others, 1973; H. H. Mehnert, written commun., 1983). Similar andesitic rocks, exposed along a horst within the Rio Grande rift 10 km west of Questa and interpreted as a structurally disrupted postcaldera remnant of the same volcanic field, overlie a local rhyolitic lava flow dated at 23–22 m.y. (Lipman and Mehnert, 1979, table 2, no. 13). Although somewhat variable in REE contents (fig. 8*A*), these rocks are similar to, and transitional between, intermediate-composition rocks from the San Juan and Spanish Peaks areas in total REE contents and light/heavy fractionations. Exceptionally REE-rich comenditic lava flows (fig. 8*A*, sample 6), that erupted just prior to formation of the Questa caldera, are also high in Y, Zr, Nb, U, and Th. They are thought to record buildup of relatively incompatible elements in the top of the magma chamber just prior to the culminating ash-flow eruptions.

The ash-flow tuff erupted from the Questa caldera is a major volcanic unit in the southern Rocky Mountains. The tuff flowed at least 45 km from its source, as indicated by small structurally preserved outliers, and accumulated to a thickness of 1–3 km within the caldera. It is a silicic peralkaline rhyolite, containing only quartz and alkali feldspar as abundant phenocrysts; most samples are somewhat altered and silicified as reflected by high and variable $SiO_2$ contents. Its REE composition is strikingly different from either the preceding intermediate-composition lavas or the granitic complex that crystallized after caldera collapse (fig. 8). The tuff is characterized by relatively small light/heavy REE fractionation, high heavy REE content (20–30x chondrites), and a large negative Eu anomaly. In comparison with the REE-rich comenditic lavas erupted just before caldera collapse (fig. 8*A*, sample 6), the ash-flow tuff is similar in heavy REE composition but much lower in light REE, aside from the Eu anomaly. The Questa ash-flow tuff is similar in many

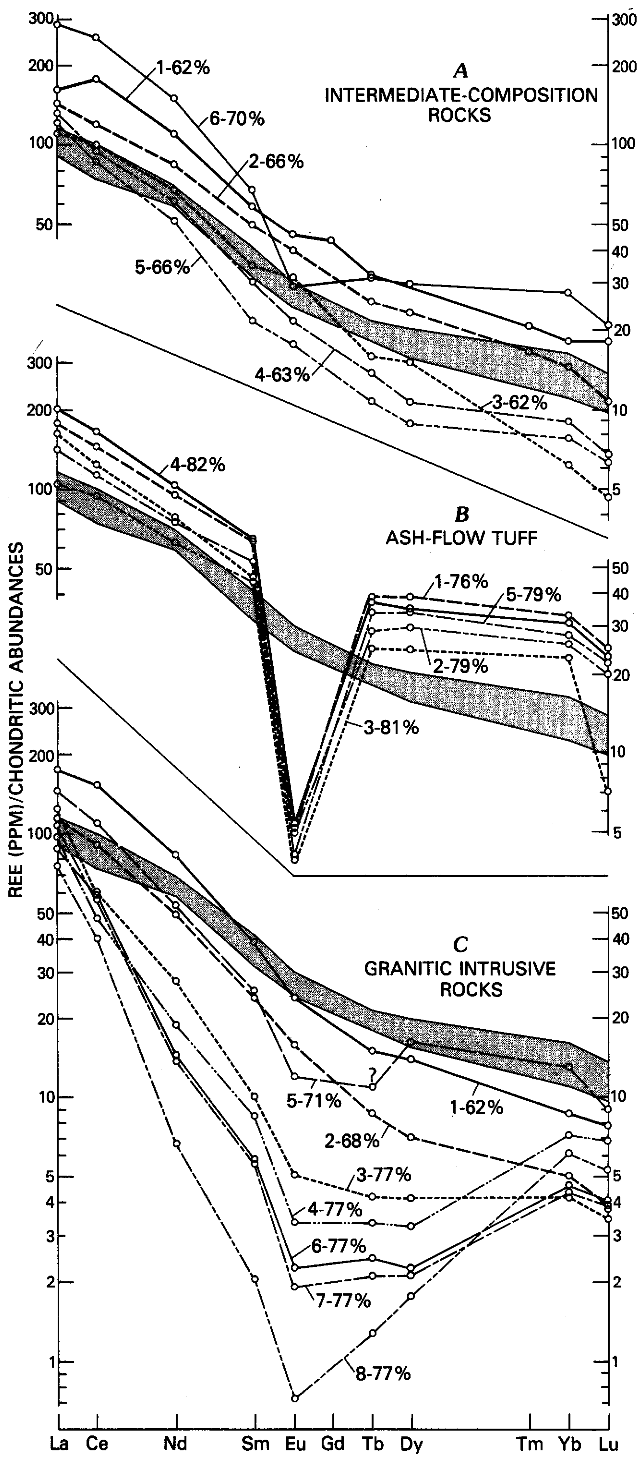


**Figure 8.** Chondrite-normalized REE compositions of rocks from the Latir volcanic field and the Questa caldera. Stippled areas are field for pre-collapse lava flows from the Platoro caldera area (fig. 3). Reference numbers of samples are followed by whole-rock $SiO_2$ contents (calculated volatile-free), mostly from unpublished analyses of the author. *A,* Intermediate-composition rocks. Sample 1 is andesite from intrarift horst, described by Lipman and Mehnert (1979, table 3, no. 17); samples 2, 4, and 5 are rhyodacite-quartz latite lava flows; sample 6 is a late precaldera comendite flow; and sample 3 is a dike rock from the Latir volcanic field. *B,* Ash-flow tuff of the Questa caldera. Samples 1–4 are from the outflow sheet north of the caldera, and sample 5 is from near Petaca, New Mexico, about 45 km west of Questa and west of the Rio Grande rift. *C,* Granitic intrusive rocks. Samples 1–3 are mafic quartz monzonite, typical quartz monzonite, and granitic upper phase of the Rio Hondo pluton, respectively; sample 4 is from the Moly Mine aplitic granite; samples 5–6 are typical granite and aplite from the Cabresto pluton; and samples 7–8 are typical granite and aplite from the Lucero Peak pluton.

respects to highly silicic igneous rocks such as the Pleistocene Bishop Tuff (Hildreth, 1979) and the Middle Proterozoic Redskin Granite (Ludington, 1981), which have chemical peculiarities that are difficult to explain by crystal-fractionation models and which have been interpreted as due to liquid-state fractionation (Hildreth, 1979, 1981). For example, the Questa ash-flow sheet shows (upward in section; downward in the source chamber) Zr increasing with decreasing Y (Lipman, 1983), elements that are highly concentrated in zircon (a phenocryst phase in the tuff) and accordingly would be expected to covary in crystal-fractionation mechanisms. The available REE data do not vary systematically with position in vertical section, perhaps because of obscuring effects of silicification and weak alteration.

In contrast with the Questa ash-flow tuff, REE compositions are markedly different in the bulk of the batholithic granitic rocks within and adjacent to the caldera (fig. 8*C*), even though they intrude the tuff, yield similar radiometric ages at 26–23 m.y., and are interpreted as representing remaining portions of the magma chamber from which the ash flows were erupted. Most of the caldera-related granitic rocks are metaluminous, but locally preserved volumetrically minor border phases of intracaldera resurgent granitic plutons that consist of petrologically distinctive peralkaline acmite-arfvedsonite granite provide a bridge to the composition of the ash-flow magma (Lipman, 1983). In contrast, the major quartz monzonite phases of the batholith have REE compositions similar to those of the intermediate-composition volcanic rocks (fig. 8*C*, no. 1, 2), and the more silicic phases have strongly depleted middle REE contents, whereas light and heavy REE show relatively small variations. These variations, which are similar to those noted for a few postcollapse rhyolites at both Platoro and Lake City calderas in the San Juan field, indicate that processes of REE fractionation in postcollapse magma chambers may be significantly different from those preceding the culminating ash-flow eruptions.

## Late Cenozoic Basaltic Rocks of the Rio Grande Rift

After about 20 m.y. ago, the volume of volcanism generally decreased in the southern Rocky Mountains, and the eruptions became increasingly basaltic. A Pliocene

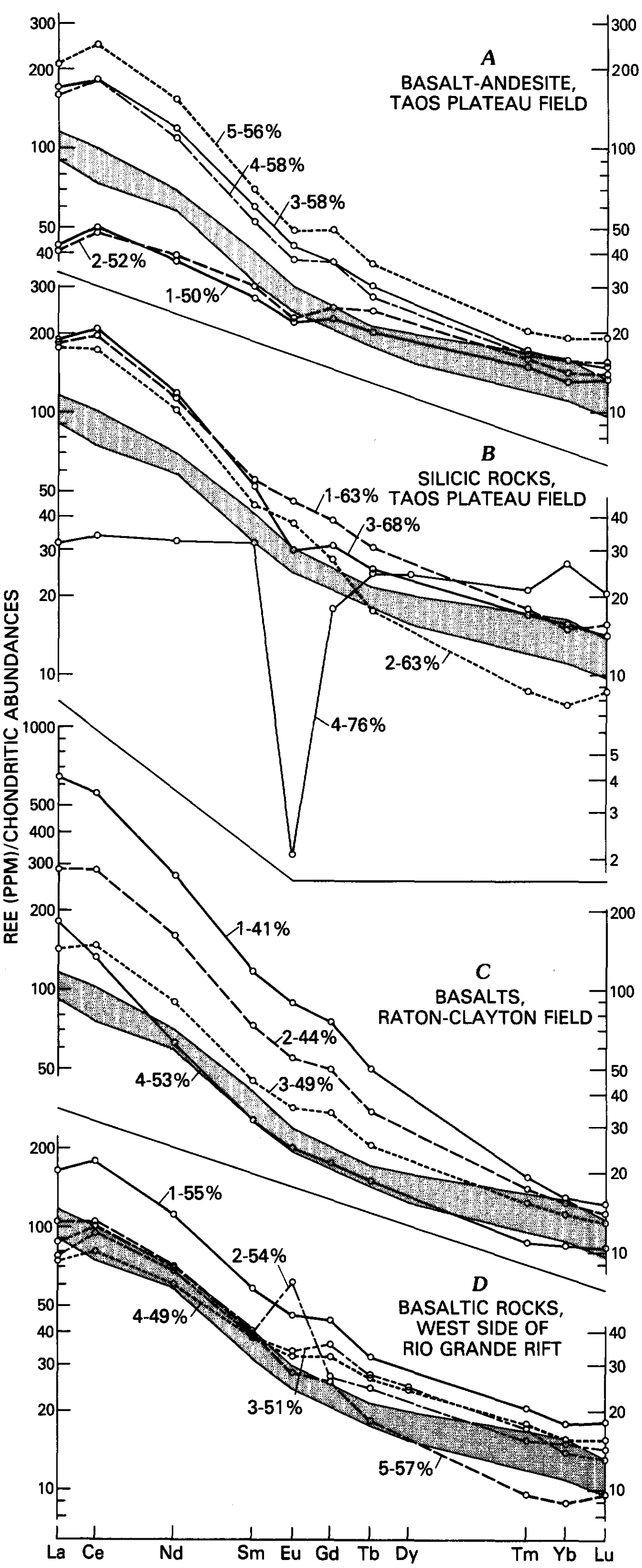


**Figure 9.** Chondrite-normalized REE compositions of upper Cenozoic basaltic rocks of the southern Rocky Mountains. Stippled pattern indicates field of intermediate-composition lava flows from the Platoro area (fig. 3). Reference numbers of samples are followed by whole-rock $SiO_2$ contents (calculated volatile-free). Unusually low La/Ce ratios for these rocks probably reflect an analytical problem. *A,* Basaltic to andesitic rocks of the Taos Plateau volcanic field. Samples 1 and 2 are tholeiitic Servilleta Basalt (major-element analyses are unpublished but see Lipman and Mehnert, 1975, table 3, nos. 1–2 for analyses of similar rocks). Sample 3 is a xenocrystic basaltic andesite (Lipman and Mehnert, 1979, table 3, no. 5); samples 4 and 5 are olivine andesites (Lipman and Mehnert, 1979, table 3, nos. 6, 8). *B,* Silicic rocks of the Taos Plateau volcanic field. Samples 1 and 2 are rhyodacites (Lipman and Mehnert, 1979, table 1, nos. 13, 11); sample 3 is a quartz latite (Lipman and Mehnert, 1979, table 1, no. 15); and sample 4 is a rhyolite obsidian (Lipman and Mehnert, 1979, table I, no. 16). *C,* Basaltic rocks of the Raton-Clayton field, northeastern New Mexico. Samples 1 and 2 are nepheline-normative Clayton Basalt; samples 3 and 4 are Capulin Basalt (Lipman and Mehnert, 1975, table 3, nos. 11–12, 15, 18, respectively). *D,* Basaltic rocks along the west side of the Rio Grande rift in southern Colorado and northern New Mexico. Samples 1 and 5 are xenocrystic basaltic andesites from the Tusas Mountains and southeastern San Juan Mountains, respectively (Lipman and Mehnert, 1975, table 3, no. 9; Doe and others, 1969, Appendix B, 66L–20); samples 2 and 3 are high- and low-K silicic-alkalic basalt, respectively, from the 5-m.y.-old Los Mogotes volcano at the southeastern margin of the San Juan field (Lipman, Doe, and others, 1978, table 6, nos. 32, 36); sample 4 is silicic alkalic Brazos Basalt from the Tusas Mountains (Lipman and Mehnert, 1975, table 3, no. 7).

peak of activity occurred about 4–2 m.y. ago, especially along the northeast-trending Jemez zone (fig. 1); scattered basaltic rocks that are 20–5 m.y. old are less voluminous and less well studied. This section considers Pliocene rocks of the Taos Plateau field within the Rio Grande rift, roughly contemporaneous basaltic rocks of the Raton-Clayton field on the High Plains, and similar basaltic rocks along the western side of the rift zone (fig. 1).

The Taos Plateau field, among the largest within the rift, contains a ranges from tholeiitic basalt to silicic rhyolite, mostly erupted about 4.5–2.0 m.y. ago (Lipman and Mehnert, 1979; Dungan and others, 1981). Volumes decrease fairly systematically from mafic (hundreds of cubic kilometers) to silicic (only a few cubic kilometeters) and volcanoes of differing composition occur in a crude concentric pattern, with vents for the predominant tholeiitic basalt central in the field. In contrast with most other basaltic rocks of the region, tholeiitic basalts of the Taos Plateau have relatively low light REE contents and light/heavy REE ratios (fig. 9*A*, samples 1–2); interestingly, these are similar to the source composition modeled for Oligocene San Juan rocks (Zielinski and Lipman, 1976). Basaltic andesite and andesite flows of the Taos Plateau have higher REE contents and light/heavy REE fractionations than the tholeiitic basalts (fig. 9*A*); they are higher in these respects than either the older intermediate-composition lavas flows from the San Juan field or most early-rift lavas of similar major-element composition in the Latir field to the east (fig. 8*A*) More silicic rocks of the Taos Plateau show decreasing REE contents, and an especially silicic rhyolite has much lower light REE, slightly higher heavy REE, and a large negative Eu anomaly (fig. 9*B*, sample 4). This rhyolite is even more

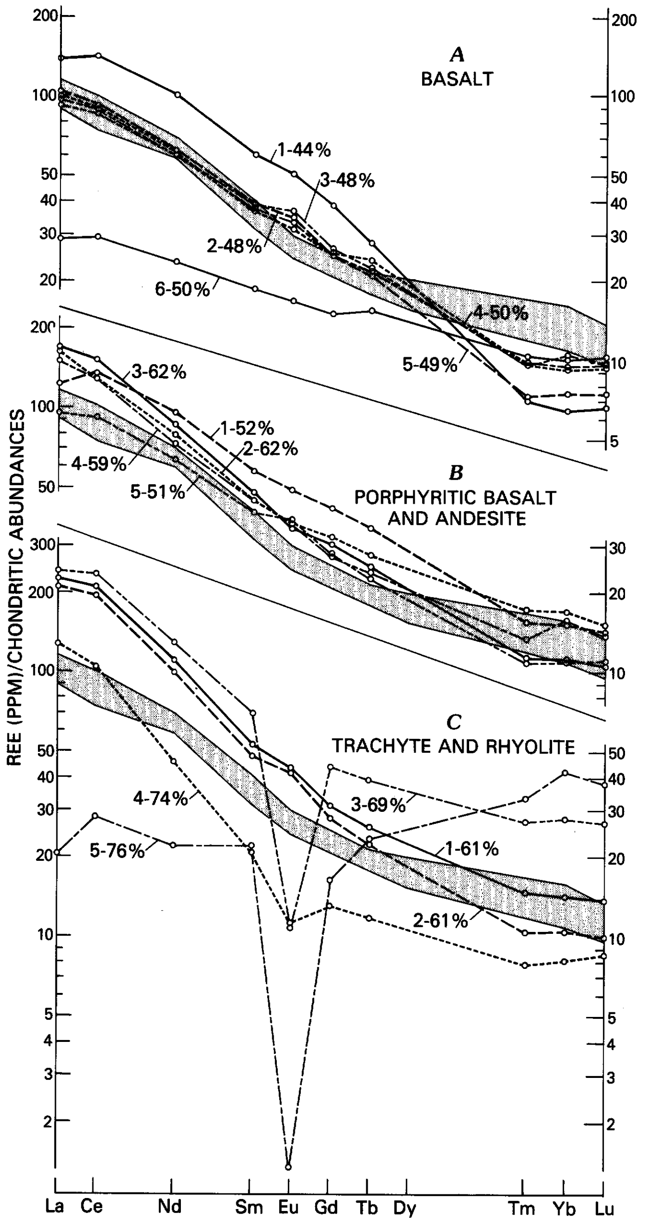


**Figure 10.** Chondrite-normalized REE compositions of rocks of the Mount Taylor volcanic field. Stippled areas are field of precollapse intermediate-composition lavas of the Platoro caldera area (fig. 3). Reference numbers of samples are followed by whole-rock $SiO_2$ contents (calculated on a volatile-free basis), from unpublished data of the author except where noted. *A,* Basalt flows, forming plateaus around the flanks of the Mount Taylor volcano. Sample 1 is an analcite basanite (Lipman and Moench, 1972, table 1, no. 2); sample 2 is a silicic alkalic basalt, and sample 3 is a similar basalt containing large augite phenocrysts, both from the southwest side of Mount Taylor; sample 4 is a silicic alkalic basalt from the southeast flank (Lipman and Moench, 1972, table 1, no. 10); sample 5 is a silicic alkalic basalt containing resorbed quartz and plagioclase xenocrysts, from the southwest side; and sample 6 is from a late tholeiitic flow (Lipman and Moench, 1972, table 1, no. 14). *B,* Porphyritic basalt and andesite flows from the Mount Taylor cone. Sample 1 is plagioclase basalt from the southeast flank (Lipman and Moench, 1972, table 1, no. 5); sample 2 is from the uppermost andesite flow on the northeast side of the volcano; sample 3 is from a biotite-rich andesite flow on the south flank; sample 4 is coarsely porphyritic andesite from the summit of Mount Taylor; and sample 5 is plagioclase basalt from the south flank. *C,* Trachyte and rhyolite flows. Sample 1 is from an early trachyte lava dome within the stratovolcano (Lipman and Mehnert, 1980, table 1, no. 1); sample 2 is from a trachyte dome from north of Mount Taylor (Lipman and Mehnert, 1980, table 1, no. 2); sample 3 is from the lower rhyolite dome within the Mount Taylor cone; sample 4 is from the upper rhyolite lava dome within the cone; and sample 5 is from a rhyolite dome on Grants Ridge, southwest of Mount Taylor (see Lipman and Mehnert, 1980, table 1, no. 5).

fractionated than tuff from the Questa caldera; it may record a similar differentiation mechanism, although volumetrically on smaller scale.

Late Cenozoic basaltic rocks of the Raton-Clayton field, east of the Rio Grande rift, include (in decreasing volume): silicic alkalic basalt (hawaiite), nepheline-normative alkalic basalt, and highly undersaturated basanite (Baldwin and Muehlberger, 1959; Stormer, 1972a). No studied Raton-Clayton rocks are as low in REE and other incompatible elements as the tholeiite of the Taos Plateau. Flows of silicic alkalic basalt, as young as about 10,000 years B.P. at Capulin Cone, are little different in REE compositions from otherwise similar basaltic rocks in the Taos Plateau field or elsewhere in the region (fig. 9*C*). Indeed, they would be difficult to distinguish, by REE abundance, from many early-rift and pre-rift intermediate-composition lavas already discussed.

In contrast, the mafic undersaturated basalts, a type not found widely elsewhere in the region, are strikingly enriched in light REE and have high light/heavy REE ratios, somewhat similar to some mafic dikes from the Spanish Peaks (fig. 7*A*). Older undersaturated basalts of similar major- and minor-element chemistry occur locally within the Rio Grande rift (Sun and Baldwin, 1958; Baldridge, 1979) and in the Latir field (Lipman, 1983).

Erosional remnants of a widespread former veneer of upper Cenozoic basaltic rocks, known as the Hinsdale Formation, are abundant along the western side of the Rio Grande rift in southern Colorado and northern New Mexico (Lipman and Mehnert, 1975). These are mostly silicic alkalic basalt and basaltic andesite, commonly containing resorbed xenocrysts of quartz and alkali feldspar and ranging in age from about 25 to 5 m.y.; tholeiite and nephelinic basalt are rare or absent. A cluster of petrographically similar basalts only about 0.25 m.y. old, the Brazos Basalt of Doney (1968), extend along the southern margin of the San Juan field in the Tusas Mountains of northern New Mexico. One silicic alkalic basalt from the 5-m.y.-old Los Mogotes volcano shows a conspicuous positive Eu anomaly, suggestive of feldspar accumulation (fig. 9*D*, sample 2). The few other REE analyses show moderate light/heavy fractionation little different from otherwise similar basaltic rocks in the Taos Plateau or Raton-Clayton fields.

## Mount Taylor Volcanic Field

Upper Cenozoic rocks of the Mount Taylor field cover about 1,000 km$^2$ in north-central New Mexico, along the Jemez zone near the southeast edge of the Colorado Plateau (fig. 1). Mount Taylor is a central stratovolcano ranging in composition ieldUpper Cenofrom alkali andesite to rhyolite (Hunt, 1938; Baker and Ridley, 1970); the central cone is surrounded by an eroded basalt-capped mesa consisting of flows erupted before, during, and after the growth of the central cone (Lipman and others, 1979; Lipman and Mehnert, 1980). Most of these flows are silicic alkalic basalt (hawaiite), but the total range is from basanite to trachyte (Lipman and Moench, 1972; Crumpler, 1980). Thus, the Mount Taylor field offers opportunites to compare minor-element fractionations among basalt-trachyte and basalt-andesite-rhyolite suites erupted in the cratonic environment of the Colorado Plateau, as well as comparisons with nearly contemporaneous volcanism on the Taos Plateau, in the extensional environment of the Rio Grande rift.

Basaltic flows on the mesas surrounding Mount Taylor vary from basanite to tholeiite, although the dominant type is silicic alkalic basalt, generally similar to the dominant late Cenozoic flows throughout the region (fig. 10*A*). All the Mount Taylor basalts are lower in REE contents, however, than the equivalent rock types in the southern Rocky Mountains. This is notable for the tholeiitic basalt, in comparison to petrographically similar Servilleta Basalt in the Taos Plateau (fig. 9*A*), and also for alkalic basalt and basanite, in comparison with similar rocks from the Raton-Clayton field (fig. 9*C*). Silicic-alkalic basalt from Mount Taylor tends to be similar in light REE but lower in heavy REE, in comparison with flows of similar age and major-element chemistry from the Rio Grande rift.

Andesitic rocks of the Mount Taylor cone have higher REE contents than silicic alkalic basalts of the adjacent mesas, with which they intergrade in major-element compositions (fig. 10*B*). These variations are parallel to those between silicic basalt and andesite in the Rio Grande rift (fig. 9*B*, 9*C*), although the Mount Taylor andesites, like the basalts, are characterized by lower REE contents than otherwise comparable rocks in the rift.

Silicic rocks of the Mount Taylor field include trachyte and biotite rhyolite. Trachyte domes occur both low within the Mount Taylor cone (Lipman and others, 1979) and interlayered with basaltic flows on mesas to the north (Crumpler, 1980). The trachyte has nearly linear REE compositions, with light REE distinctly higher than in the mesa-forming basalts with which it is associated (fig. 10*C*). It could have evolved from the basalt by fractionation of REE-poor phases such as olivine and pyroxene, but the lack of an Eu anomaly seemingly precludes significant feldspar fractionation. Lower Sr in the trachyte than in associated basalt flows (Lipman and others, 1982, table 1) is difficult to explain, however, without invoking feldspar fractionation.

In contrast, the rhyolite domes are characterized by negative Eu anomalies and concentrations of the other REE that vary from the highest to the lowest in the volcanic field. As in several areas already discussed, light REE contents of the rhyolites decrease as silica increases. The lower rhyolite dome within the cone (fig. 10*C*, sample 3) could have fractionated from andesite of Mount Taylor, involving removal of feldspar as a major phase. The upper rhyolite (fig. 10*C*, sample 4), although higher in silica, has a smaller Eu anomaly and is relatively low in the middle REE elements in comparison with Mount Taylor basalt, andesite, or trachyte. A satellitic high-silica rhyolite dome, at Grants Ridge on the southwest side of Mount Taylor (fig. 10*C*, sample 5), is poor in light REE, rich in heavy REE, has a large Eu anomaly, and compositionally resembles rhyolites elsewhere that are thought to have developed by liquid-state fractionation. Thus, REE data for even these few samples of silicic rocks from an isolated short-lived volcanic field suggest diverse mechanisms of fractionation.

# DISCUSSION

The REE data provide a fairly representative sampling of Cenozoic volcanic rocks from varied tectonic settings in the southern Rocky Mountains. For some areas, rocks ranging widely in major elements show only small REE variations (figs. 2–5, Oligocene San Juan volcanic field); elsewhere, large variations characterize igneous suites of limited major-element ranges from restricted areas (fig. 7*A*, mafic rocks of Spanish Peaks, or fig. 10*C*, silicic rocks from Mount Taylor). Generalizations based on only a few samples from such areas could be misleading. Especially interesting are (1) variations in composition with tectonic setting, regional distribution, and age; (2) contrasts in REE variations between cogenetic volcanic and plutonic rocks; (3) changing REE patterns as functions of major-element composition, especially for intermediate to silicic rocks; and (4) widely varying minor-element abundances among silicic rocks.

## Tectonic Setting, Distribution, and Age

Oligocene and lower Miocene igneous rocks of the southern Rocky Mountains, that have been interpreted as related to low-angle subduction beneath the American plate, are characterized by high REE content and pronounced light/heavy fractionation, in contrast with calcic continental-margin arc suites such as the Cascades (fig. 6*B*; Condie and Swenson, 1973) or the Aleutian Peninsula (Kay, 1978). In these respects, suites of the southern Rocky Mountains resemble relatively alkalic continental-margin arc suites such as Peru (fig. 6*B*; Noble and others, 1975) or Indonesia (Whitford and others, 1979). Regionally in the Western United States, as well as in other arc suites worldwide (Gill, 1981, fig. 5.12; Arth, 1981), REE content and light/heavy fractionation increase as volcanoes become more alkalic with increasing distance from the plate margin and inferred depth to the paleo-Benioff zone. Even within the southern Rocky Mountains, east-west compositional trends are evident, roughly perpendicular to the plate boundary (fig. 11). Relatively low-K quartz diorite and granodiorite of the Abajo Mountains intrusions have the lowest total REE contents and the lowest light/heavy fractionations (80–150 ppm REE; $La_N/Lu_N$ about 7, the same as Mount St. Helens), and the comparatively alkalic intermediate-composition rocks of the Spanish Peaks center are the highest (185–300 ppm REE; $La_N/Lu_N$=25–35). San Juan andesites are in between (140–175 ppm REE; $La_N/Lu_N$=9–11). Despite distances of as much as 1,000 km from the plate margin, the Oligocene intermediate suites in the southern Rocky Mountains fall within the spectrum of compositional variations defined by continental-margin arc volcanism.

The origin of such regional variations is controversial and may involve blends of melting of the descending oceanic crustal slab, melting in the overlying asthenospheric mantle wedge, and varying contributions from the lithospheric foundation of the arc volcanoes (Gill, 1981). In the southern Rocky Mountains, isotopic data provide evidence that, whatever the ultimate origin of the intermediate-composition magmas (presumably as mafic melts from near the interface between descending slab and aesthenospheric mantle), their initial chemical character has been obliterated by interactions with 1.7–1.5 b.y.-old cratonic lithosphere of the American plate (Lipman, Doe, and others, 1978). In particular, the isotopic data indicate a major contribution from granulite-facies lower crust, probably as a result of partial melting and assimilation by rising mafic magma from the mantle.

Later Cenozoic volcanic rocks that are associated with extensional tectonics in the southern Rocky Mountains have more diverse REE compositions than the preceding subduction-related suites. Highly alkalic basaltic rocks typically show high REE contents and large light/heavy fractionations, as in the Raton-Clayton field east of the Rio Grande rift and the Mount Taylor field to the west (figs. 9*C*, 10*A*). Tholeiitic basalts on the Taos Plateau and at Mount Taylor have lower light REE contents and light/heavy fractionations than any Oligocene volcanic rocks (figs. 9*A*, 10*A*). Silicic alkalic basalt, the most voluminous late Cenozoic type in the region, is transitional in REE composition between the tholeiitic and alkalic basalts. Its REE composition is also nearly

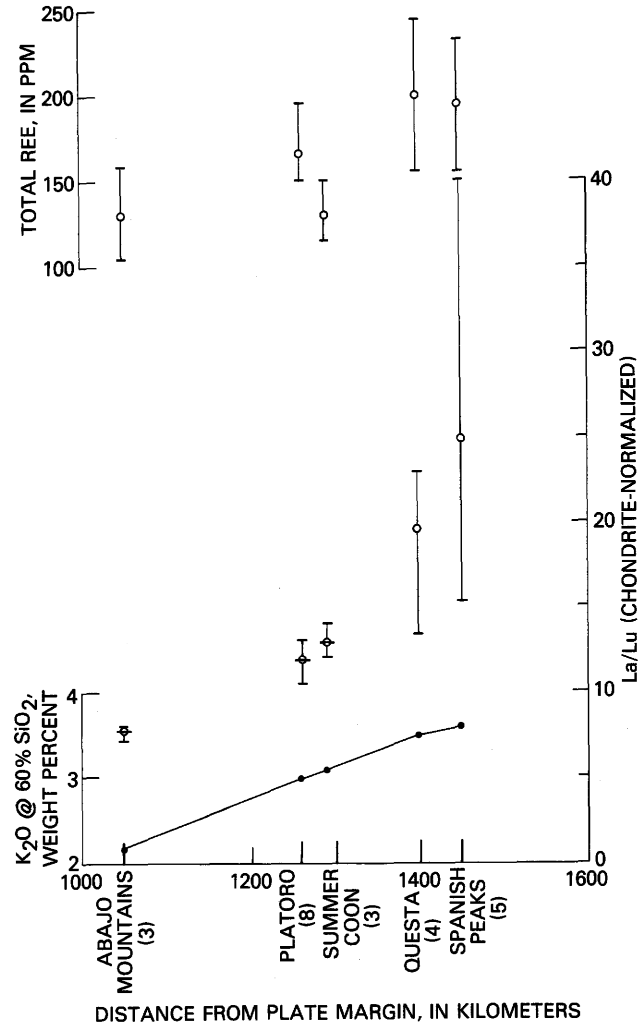


**Figure 11.** Compositional variations of middle Tertiary intermediate-composition volcanic suites as function of distance from western margin of the American plate, measured in a N. 60° E. direction. Northeastward increases in $K_2O$ values (solid dots), interpolated from $SiO_2$ variation diagrams, are inferred to indicate increasing depth to a paleosubduction zone (Lipman and others, 1971; Keith, 1978). Chondrite-normalized La/Lu ratios (circled crosses) and total REE content (circled dots) also tend to increase with distance from the plate margin; symbols indicate mean for each suite, and vertical line indicates range for all samples (number in parentheses).

the same as the intermediate-composition rocks of the preceding subduction-related volcanism (figs. 9*C*, 9*D*, 10*A*). Where late Cenozoic andesitic flows are voluminous, as at Mount Taylor and the Taos Plateau, they are enriched in REE in comparison with otherwise similar intermediate flows of the subduction-related suites (figs. 9*A*, 10*B*).

Other than the above, few systematic contrasts in REE composition are evident between the late Cenozoic volcanic suites related to extensional tectonics and the preceding dominantly intermediate suites, or regionally among the late Cenozoic volcanic fields as a function of distance from the Rio Grande rift or distance along the Jemez zone. In particular, the silicic alkalic basalts show no changes in REE composition that correlate with documented regional variations in U/K and Th/K ratios with distance from the rift zone (Lipman, Bunker, and Bush, 1973).

## Changing REE Patterns as a Function of Composition

Several general changes in REE distributions correlate with major-element composition. The large variations among different basaltic types—tholeiitic, silicic alkalic, and nepheline-normative—are similar to variations observed widely elsewhere and probably reflect differing depths and degrees of partial melting of mantle sources, modified by crystal fractionation and crustal assimilation (Lipman and Mehnert, 1979; Dungan and others, 1981).

Accordingly, tholeiitic basalts of the Taos Plateau and Mount Taylor may represent comparatively voluminous partial melting from shallow mantle depths. The other mafic lavas—all characterized by large light/heavy REE ratios—would result from smaller proportions of melting at depths where garnet or hornblende were residual phases. Nepheline-normative alkalic basalts and basanites, occurring mainly far east or west of the Rio Grande rift and characterized by the highest total REE contents and largest light/heavy fractionations, would represent the smallest degree of mantle melting (Kay and Gast, 1973). Low Mg numbers (less than 60) and other differentiation indices indicate that most of the basaltic lavas are not in chemical equilibrium with mantle olivine and that they underwent significant fractionation before eruption. As olivine is the main phenocryst in most of the basalts, olivine removal would have increased REE contents. In addition, isotopic data indicate contamination of some basaltic lavas by crustal material (Doe and others, 1969; Williams and Murthy, 1979). Effects of contamination on the REE compositions, although not well constrained, are probably small because typical crustal rocks of the region have REE compositions not markedly different from the dominant basalt types (Arth and Barker, 1976; Cullers and Koch, 1981). Lead isotopic analyses of basalts from the Taos Plateau and Mount Taylor define secondary isochrons of 1.7–1.5 b.y., the age of cratonization, suggesting that their sources were within lithospheric mantle of the American plate, rather than from upwelling of deeper asthenospheric mantle (Lipman, Doe, and others, 1978; Everson and Silver, 1978)

Andesite and rhyodacite from the Taos Plateau and Mount Taylor show high REE content, especially light REE (figs. 9*A*, 9*B*, 10*B*), in comparison with associated basalt. Other chemical data and phenocryst modes show that the intermediate lavas cannot have evolved from the associated basaltic rocks solely by low-pressure fractional crystallization (Lipman and Mehnert, 1979; Dungan and others, 1981); more likely, they represent mantle melts that have assimilated more lower crustal material than the basaltic rocks, as indicated especially for rhyodacite on the Taos Plateau by isotopic data (Williams and Murthy, 1979).

For intermediate-composition rocks, especially in the San Juan field, a crossover of REE patterns commonly occurs between light and heavy REE, with silicic andesite and rhyodacite showing larger light/heavy fractionations than associated mafic andesite. This pattern could be due to varying melting in a source in which garnet was residual (Zielinski and Lipman, 1976). On the basis of isotopic constraints, however, one-stage melting either in the mantle or in the lower crust seems unlikely. Rather, mafic melts from the mantle are thought to have interacted extensively with granulite-facies lower crust, to produce the compositions that reached the surface (Lipman, Doe, and others, 1978).

Other intermediate rocks decrease in all REE with increasing silica, especially rocks from the Abajo Mountains and the Spanish Peaks(figs. 6*A*, 7B*)*. In all the suites, regardless of tectonic setting, silicic rocks have low light REE (figs. 3*D*, 5*B*, 7*C*, 8*C*, 10*C*). Such variations are unlikely from differing degrees of primary melting because greater melting of mantle that could lower the REE contents would yield increasingly mafic magmas. The progressive decreases in REE with increasing silica may also reflect crystal fractionation of rhyodacite-quartz latite magmas in which important phases were hornblende and possibly clinopyroxene characterized by distribution coefficicents mostly greater than one (Arth, 1976; Zielinski and Lipman, 1976).

## REE Compositions of the Silicic Rocks

In contrast to the broadly uniform REE compositions of the intermediate lavas and intrusions in the southern Rocky Mountains, the associated silicic rocks are strikingly diverse in REE composition. Processes responsible for generation of silicic rhyolites and granites in subvolcanic magma chambers are less well understood than generally recognized (Hildreth, 1981). In upper parts of such magma chambers, temperature gradients may reach 100°C/km (Lipman, 1971; Hildreth, 1979). Such gradients must be accompanied by upward concentrations of volatiles that retard solidification of the cooler uppermost magma, which is typically phenocryst-poor. Meteoric water may enter the magma, indirectly by stoping of hydrothermally altered roof rocks (Taylor, 1980), or directly by convection-aided diffusion (Friedman and

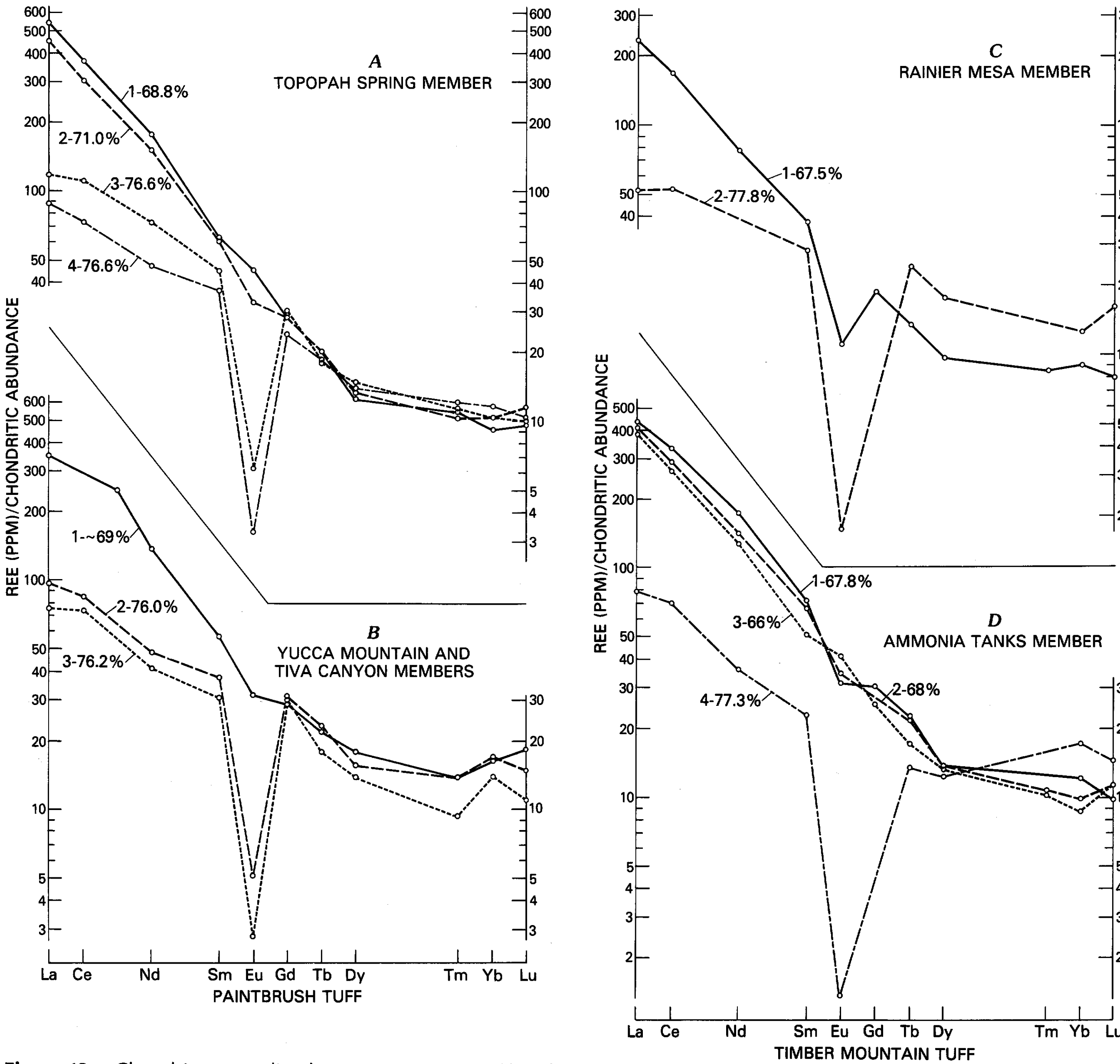


**Figure 12.** Chondrite normalized REE compositions of basal rhyolite and upper quartz latite of compositionally zoned ash-flow sheets of the Paintbrush and Timber Mountain Tuffs (Byers and others, 1976). Reference numbers of samples are followed by whole-rock $SiO_2$ contents (calculated volatile-free). *A*, Topopah Spring Member of the Paintbrush Tuff. Samples 1 and 2 are respectively bulk-rock and groundmass glass of the upper quartz latitic vitrophyre (Lipman, 1971, table 2, no. 4); samples 3 and 4 are groundmass glass from two rhyolitic pumice blocks (Lipman, 1971, table 2, nos. 1–2). *B*, Yucca Mountain and Tiva Canyon Members of the Paintbrush Tuff. Sample 1 is groundmass glass of the upper quartz latitic Tiva Canyon; sample 2 is glass from the basal rhyolitic Tiva Canyon; sample 3 is glass from basal Yucca Mountain (Lipman, 1971, table 2, nos. 13, 9, 7, respectively). *C*, Rainier Mesa Member of the Timber Mountain Tuff. Samples 1 and 2 are groundmass glasses from the upper quartz latite and basal rhyolite vitrophyres (Lipman, 1971, table 2, nos. 19, 17, respectively). *D*, Ammonia Tanks Member of the Timber Mountain Tuff. Samples 1 and 2 are groundmass glasses from pumice blocks of the upper quartz latite; sample 3 is a bulk sample, same pumice block as sample 2; sample 4 is groundmass glass from the basal rhyolite vitrophyre (Lipman, 1971, table 2, nos. 24, 25, 25, 23, respectively).

others, 1974); significant assimilation of wall rocks by some magmas is indicated by Sr and Pb isotopic relations (Lipman, Doe, and others, 1978; Hildreth, 1981).

The recurrence interval between major pyroclastic eruptions from high-level magma chambers is commonly on the order of a half million years (Smith, 1979; Hildreth, 1981); as a result, heat losses from large young magma chambers, as inferred beneath the Yellowstone and Long Valley calderas, are sufficient to cause solidification over a time span only 2-3 times longer (Lachenbruch and others, 1976; Eaton and others, 1975). Accordingly, new magma, probably basaltic, must be added recurrently to maintain the lifespan of recurrently active ash-flow magma systems (Smith and Shaw, 1975), and substantial crystallization will occur in their upper parts between most major pyroclastic eruptions.

Gravitational settling of phenocrysts in silicic magmas cannot account for the compositional gradients observed in many high-silica systems (Hildreth, 1979, 1981). Crystallization on walls of magma chambers, in conjunction with convective circulation of the residual liquid, probably accounts for the compositional zonations in some sequences (McBirney, 1980), as well as the concentric compositional zonations of many granitic plutons (Bateman and Chappell, 1979). In addition, processes of liquid fractionation may dominate upper portions of some differentiating silicic magma chambers (Hildreth, 1979, 1981; Mahood, 1981, Bacon and others, 1981; Ludington, 1981).

At present, the relative effects of crystal fractionation, liquid fractionation, and assimilation on REE compositions of silicic magmas are difficult to evaluate, but probably all contribute to the diverse REE compositions observed in the volcanic suites of the southern Rocky Mountains. The most compelling evidence for such processes in high-level magma chambers comes from ash-flow sheets in which compositional zonations in the magma chamber have been quenched and preserved in inverted order in the deposit. Lava flows that erupted before and after the pyroclastic eruptions provide additional useful data, but these may record temporal evolution of the magmatic compositions, as well as variations in existence at any time.

A key question is whether high-silica rhyolites, showing the distinctive REE patterns described in this report, overlie intermediate-composition magma in their source chambers, as implicit in most models (Lipman and others, 1967; R. L. Smith, 1979; Hildreth, 1979, 1981). Significantly, several ash-flow sheets (units of the Paintbrush and Timber Mountain Tuffs, Nevada), which record compositional gradients in single source magma chambers (Lipman and others, 1967; Byers and others, 1976), document changes from nearly linear REE patterns, such as observed for quartz latitic ash-flow tuffs and associated intermediate lava flows from the San Juan field, to Eu-depleted patterns characteristic of high-silica tuffs such as the Bishop Tuff (fig. 12). Analyzed samples of the Nevada tuffs are from basal and upper glass zones; transitional major-element compositions of intervening devitrified tuff indicate that gradations in REE compositions should also occur within these ash-flow sheets. The silicic phenocryst-poor basal rhyolite of each ash-flow sheet is characterized by a large negative Eu anomaly and by depleted light REE, in comparison with the crystal-rich upper quartz latite of the same unit. The rhyolites of the Timber Mountain units are enriched in heavy REE contents in comparison with the associated upper quartz latite; no systematic change is evident for the Paintbrush Tuff. All quartz latites show pronounced light/heavy fractionation, even greater than for many intermediate-composition rocks from the southern Rocky Mountains. The REE compositional changes within the Nevada ash-flow tuffs thus document transitions between the two types of REE patterns, only hinted at by data from compositionally zoned units in the southern Rocky Mountains. More detailed studies of intermediate compositions of the Paintbrush and Timber Mountain units might permit evaluation of the nature of the stratification in the source magma chamber and the relative roles of crystal fractionation and liquid-state differentiation.

In phenocryst-rich quartz latitic ash-flow tuffs of the San Juan Mountains (Figs. 3*A*, 4*A*), compositional variations are mostly small and explicable by physical fractionation of crystals and less dense shards during eruption and emplacement (Lipman, 1975, fig. 28). REE compositions of these quartz latites are typically within the range of intermediate-composition lava flows that were erupted from the same areas before and after caldera collapse (fig. 4*A*).

In contrast, several ash-flow sheets in the central and western San Juan caldera clusters, which consist mainly of phenocryst-poor low-silica rhyolite, are locally characterized by upward gradations into more phenocrystic and mafic tuffs (Figs. 4*B*, 4*C*). The rhyolitic bases of these sheets are little different in REE contents from either the preceding intermediate-composition lava flows of the region or from the more mafic upper parts of the same tuff unit, except for development of small negative Eu anomalies, despite ranges of about 10 percent $SiO_2$ in their zonations. Such Eu anomalies are conventionally interpreted as due to feldspar fractionation. Alternatively, they could be due at least in part to inception of liquid-state fractionation such as may have been dominant in more silicic ash-flow sheets such as the Bishop Tuff (Hildreth, 1979) or the Nevada units (fig. 12).

A similar problem arises in interpreting the REE data for the compositionally zoned Sunshine Peak Tuff, erupted from the Lake City caldera (fig. 5*B*), the rhyolitic part of which resembles the Bishop Tuff in both major oxides and REE. Both Bishop Tuff and Sunshine Peak Tuff are characterized by large negative Eu anomalies and low light/heavy fractionation ratios. Available data are inadequate to evaluate the origin of the REE patterns of the Sunshine Peak, other than to note its similarity to the Bishop Tuff; this unit is being studied in detail by Ken Hon and R. A. Zielinski of the U. S. Geological Survey.

Silicic rhyolite tuffs and flows, characterized by large negative Eu anomalies and small light/heavy REE fractionation, also occur as the main caldera-forming ash-flow sheet of the Latir volcanic field and as late lava domes on the Taos Plateau and at Mount Taylor (figs. 8*B*, 9*D*, 10*C*). Both lava domes have low phenocryst contents, and the tuff of the Questa caldera has trends of other distinctive elements, such as Y versus Zr, that resemble those in the Bishop Tuff, suggesting that liquid fractionation may have been significant. Yet another type of REE pattern, characterized by the distinctive U-shaped depletion of the middle REE, occurs in some late postcaldera silicic rhyolite flows and intrusions in the southern Rocky Mountains. The possible significance of these patterns is discussed in the following section.

## Contrasts Between Cogenetic Volcanic and Plutonic Rocks

REE data for the southern Rocky Mountains offer special opportunities to compare volcanic sequences with cogenetic intrusions, especially at the Platoro and Questa calderas. Such comparisons are intrinsically difficult and have rarely been convincing, because where volcanic sequences are well preserved, erosion typically has been insufficient to expose sizeable associated intrusions. In terranes of well-exposed shallow intrusive rocks, associated volcanic rocks are typically mostly eroded, widely altered and metamorphosed, and commonly too old to date with sufficient precision to evaluate the true plutonic equivalents. Such comparisons are important, however, because they potentially provide a basis for tracing the complete emplacement history of a silicic magma body. Compositionally zoned quenched pyroclastic units offer insight into the conditions within a subvolcanic magma chamber at one point in geologic time, and the interpretation of the evolution of such magma chambers can be extended somewhat by examining petrologic variations among volcanic units erupted before and after a culminating pyroclastic eruption (R. L. Smith, 1979). The later stages of emplacement and consolidation of silicic magma bodies probably are recorded only in the resulting subjacent intrusive complex, without voluminous surface volcanism, and these stages also commonly represent the important time of ore deposition.

In these respects, the Platoro and Questa caldera areas offer exceptional opportunities to examine the evolution of magmatic systems of contrasting style. At Platoro, postcollapse intrusions, although not extensive, range widely in major elements (56–66 percent $SiO_2$), yet vary only slightly in REE (fig. 3*C*), and are virtually coincident with compositions of precollapse and postcollapse lavas of similarly narrow REE ranges (fig. 3). Even deposits of the caldera-forming ash-flow eruptions plot within nearly the same limited REE field).

In the Questa area and Latir volcanic field, relatively young (26–23 m.y.) cogenetic volcanic and associated plutonic rocks are exceptionally preserved and exposed because of structural disruption and deep erosion along the margin of the Rio Grande rift. In contrast to the Platoro area, the precollapse lava flows, caldera-forming ash-flow deposits, and postcollapse intrusions show wide variations in both major- and minor-element composition. Concentrations of many incompatible minor elements peaked during the time of ash-flow eruptions, and the areally extensive suite of compositionally variable cogenetic intrusions that crystallized shortly after caldera collapse show compositional trends unlike those of the ash-flow tuff. Significantly, the major molybdenum and minor base- and precious-metal mineralization of the area (Clark and Reed, 1972) is associated with highly fractionated rocks of the late plutonic stage that are low in elements such as the REE, Zr, Nb, Y, and Rb/Sr, rather than with earlier ash-flow magmas that possessed the peak enrichments of these elements. The oscillations in minor-element contents of the Questa magma chamber are, in many respects, similar to those documented for Nb in the Valles magmatic system (R. L. Smith, 1979, fig. 8).

The U-shaped REE patterns of the Questa granitic rocks are in striking contrast to most published REE patterns of silicic alkalic rhyolites and granite, which typically are similar to the welded tuff of the Questa caldera (Hildreth, 1979; Izett, 1981; Bacon, 1981; Cullers and Koch, 1981). The cause of such middle-REE depletions in the postcaldera granitic rocks can be due neither to crystal fractionation of the major mineral phases of these rocks nor to the type of liquid fractionation inferred for silicic alkalic rhyolites. An attractive possibility is fractionation by REE-rich accessory minerals. New partition coefficients for sphene (and apatite and hornblende) from the quartz latitic Fish Canyon Tuff of the San Juan field (table 2) show strong preferences of sphene for the middle REE, with concentrations of some elements greater than 150 times the groundmass composition. REE abundances in sphene separated from a quartz monzonite from the Questa area (table 3) are about half as great but in similar proportions to the Fish Canyon sphene. Variations in distribution coefficients as a function of magma composition (Arth, 1976; Mahood, 1981) are presently poorly known for sphene, but distribution coefficients from porphyritic intrusions as diverse as monzonite and phonolite in the southern Rocky Mountains (Simmons and Hedge, 1978) are similar to the Fish Canyon data. Based on these values, removal of a crystal assemblage containing about one-half a percent sphene could produce the middle-REE depletions observed in granitic rocks of the Questa area. Such a hypothesis is attractive because the more mafic (quartz monzonite) phases of the batholith locally contain more than one percent sphene, and $TiO_2$ content decreases from as much as 1.2 percent to 0.1 percent or less with increasing silica content of the granitic rocks.

Mass-balance calculations are only possible by making poorly constrained assumptions about relative proportions of highly fractionated and primitive portions of

**Table 2.** Phenocryst-groundmass REE compositionsand distibution coefficients of the Fish Canyon Tuff, San Juan field
[INA analyses by J. S. Pallister and R. J. Knight]

| | Abundances, ppm | | | | Mineral-groundmass distribution coefficents | | |
|---|---|---|---|---|---|---|---|
| Lab. No. | Groundmass D172341 | Hornblende D172338 | Apatite D172340 | Sphene D172339 | Hornblende | Apatite | Sphene |
| Ba | 1150. | 712. | — | | .62 | — | — |
| La | 40 | .86. | 898. | 2530. | 2.1 | 22. | 63. |
| Ce | 84. | 252. | 1590. | 8020. | 3.0 | 19. | 95. |
| Nd | 36. | 129. | 652. | 5080. | 3.5 | 18. | 140. |
| Sm | 6.0 | 23. | 136. | 773. | 3.8 | 23. | 128. |
| Eu | 1.4 | 4.4 | 11. | 175. | 3.1 | 7.8 | 124. |
| Gd | 3.7 | 16.5 | — | 568. | 4.3 | — | 153. |
| Tb | 0.79 | 3.3 | 8.2 | 116. | 4.2 | 10. | 147. |
| Dy | 4.3 | 12. | 24. | 53. | 2.9 | 5.8 | 12.6 |
| Tm | — | — | 3.0 | — | — | — | — |
| Yb | 2.2 | 10.9 | 20. | 258. | 5.0 | 9.1 | 117. |
| Lu | 0.38 | 1.7 | 3.0 | 32. | 4.5 | 7.9 | 84. |

**Table 3.** REE abundances, in ppm, of sphene from the quartz monzonite of Rio Hondo, Latir volcanic field, New Mexico
[INA analysis by R. J. Knight and H. T. Millard]

| REE | Abundances, ppm |
|---|---|
| La | 1960. |
| Ce | 3380. |
| Nd | 1300. |
| Sm | 234. |
| Eu | 60. |
| Tb | 37.7 |
| Dy | 1923. |
| Yb | 92.3 |
| Lu | 11.3 |

the magma chamber. If a 1:10 ratio is assumed, as seems reasonable from geometric relations between caldera-collapse dimensions and sizes of plutons (R. L. Smith, 1979), then middle REE depletion in the fractionated magma could increase these elements only about 10 percent in the primitive underlying magma, assuming efficient convective mixing. Thus, a large positive inflection in middle-REE patterns of the deeper rocks need not be expected; indeed, even the most sphene-rich mafic schlieren analyzed from the quartz monzonite (fig. 8*C*, sample 1) shows a slightly concave-upward chondrite-normalized pattern for the middle REE.

Significant questions remain, however, in interpreting the middle-REE depletions in the Questa granitic rocks. Analogous depletions were noted for postcollapse rhyolitic lava domes and intrusions at Platoro and Lake City in the San Juan field; similar REE patterns are known for the Pleistocene lava domes and associated tuffs of the Mineral Mountains, Utah (Lipman, Rowley, and others, 1978; Izett, 1981). All three occurrences represent late rhyolites at sites of extensive earlier Cenozoic igneous activity, and accordingly are somewhat analogous to the postcaldera Questa granites. If fractionation of sphene is significant, however, why do some sphene-bearing volcanic rocks not develop U-shaped REE patterns? For example, the four compositionally zoned ash-flow sheets of the Paintbrush and Timber Mountain Tuffs show nearly identical sequences of changing REE patterns with the progression from rhyolite to quartz latite (fig. 12), yet the upper ash-flow sheet of each formation (Tiva Canyon and Ammonia Tanks Members) are sphene-rich, whereas the lower sheets are not (Lipman, 1971). These REE patterns may reflect liquid-state fractionation (Hildreth, 1979, 1981) or the role of additional accessory REE-rich phases known to be present, such as allanite, chevkinite, and monazite. What controls the contrasting fractionation trends between these units, and the otherwise compositionally similar rocks associated with late postcaldera volcanism in the southern Rocky Mountains? Tentatively, I infer that the bulk of compositional gradients in high-level subvolcanic magma chambers, especially for major elements, is due to crystal-melt fractionation, and only in already highly silicic bodies that are characterized by strong thermal and volatile gradients can liquid-fractionation processes become significant. Depletion of the middle REE, which seemingly occurs only in dying magma chambers that have previously been devolatilized by major pyroclastic events, may be typical of extreme fractionation in highly silicic magmas when volatile-driven liquid-state fractionation is supressed due to prior loss of volatiles.

A final intriguing question raised by the U-shaped REE patterns of the Questa granitic rocks concerns the major associated Mo mineralization of the area. To my knowledge, REE data are not available for silicic alkalic rhyolites and granites associated with the other well known Mo deposits of the southern Rocky Mountains, such as at Climax and Henderson (White and others, 1981), but at both Platoro and Lake City, subeconomic Mo mineralization occurs in conjunction with post-collapse silicic activity, although specific relations with individual intrusions have not been established. Could this distinctive REE fractionation pattern be an earmark of granite molybenite systems?

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