

REE Variations Across the Peninsular Ranges Batholith: Implications for Batholithic Petrogenesis and Crustal Growth in Magmatic Arcs

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(Received 22 September 1985; revised typescript accepted 3 July 1986)

ABSTRACT

Rare earth element (REE) patterns of plutonic rocks across the Cretaceous Peninsular Ranges batholith vary systematically west to east, transverse to its long axis and structural trends and generally parallel to asymmetries in petrologic, geochronologic and isotopic properties. The batholith can be divided into three distinct parallel longitudinal regions, each defined by distinct REE pattern types. An abrupt transition occurs between rocks with slightly fractionated REE patterns in the western (coastal) region and rocks with middle to heavy REE fractionated and depleted patterns in the central region. Further to the east a second transition to strongly light REE enriched rocks occurs. The slopes of the REE patterns within each of these regions are largely independent of rock type. The first REE transition is closely coupled to regional discontinuities in other parameters: elimination of negative Eu anomalies, an increase in Sr content, and a marked restriction in petrologic diversity. This transition occurs over a range of initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios and $\delta^{18}\text{O}$ values, but approximately correlates to a major shift in the emplacement style of the batholith from a stationary arc to a rapidly eastward-migrating (cratonward) arc.

The sense of the regionally consistent REE trends cannot be explained by crystallization, assimilation, combined crystallization–assimilation, or mixing processes. The consequences of assimilation and high-level differentiation are not observed generally, despite the sensitivity of the REE to these processes. Geochemical and petrological features argue that the partial melting of mafic source rocks in which plagioclase-rich (gabbroic) residual assemblages abruptly gave way laterally and downward to garnet-bearing (eclogitic) residual assemblages produced all the changes associated with the first REE transition. The change in residual assemblages from gabbroic to eclogitic was superimposed on source regions already zoned in light REE abundances, $^{87}\text{Sr}/^{86}\text{Sr}$ and ^{18}O . Temperature and pressure constraints on the source regions place them in a subcrustal location. The calcic nature of the batholith and the dominance of tonalite and low- K_2O granodiorite in all its regions argue that the source materials are broadly basaltic in composition. Experimental studies are consistent with the generation of the abundant tonalitic magmas by the partial melting of basalt under both low and high pressure conditions. Arc basalts such as those commonly erupted in modern island arcs and continental margins are inferred to have provided much of the source material and the heat. Additional high- ^{18}O components are needed in the more easterly source regions. These materials must be distributed so as to contribute equally to the range of magmas that occur in a given local region, and must preserve the calcic nature of batholithic sources. Altered basalts of ancient oceanic crust and possibly their associated metasediments, previously incorporated into the lithosphere beneath the continental margin during earlier cycles of subduction, most readily satisfy these constraints.

The REE geochemistry of the central and eastern regions of the batholith differs from that of oceanic island arcs in the presence of strongly heavy REE depleted and fractionated magmas. A model is proposed in which arc basalts accumulate beneath a crustal layer. Melting of accumulated material at low pressure produces magmas of the western region. Where thickening of the basaltic underplate is sufficient to form eclogitic assemblages, eclogite-derived magmas of the central and eastern region are

produced. The abrupt transition to eclogite-derived magmas that suggests a process driven by a density instability is responsible for their origin.

The Peninsular Ranges batholith appears to be representative of a major differentiation process in which mantle-derived basalt is remelted, contributing its more sialic fractions to the continental crust and leaving its mafic to ultramafic residues in the mantle. This process preserves the sialic character of the continental crust and may play a significant role in its growth and evolution. The batholith and the processes that produced it may be a more appropriate basis than immature oceanic island arcs on which to construct models of continental growth and evolution.

INTRODUCTION

Extensive tracts of Mesozoic plutonic and volcanic rocks are prominent geologic features of the Cordillera of western North America. Commonly arranged in elongate, arcuate batholithic belts parallel to past Cordilleran margins, these rocks are generally interpreted as the products of magmatic arcs formed during episodes of convergence between the North American plate and now-consumed oceanic plates to the west. Batholith-forming events contributed significantly to the growth of circum-Pacific North America during the Mesozoic. Investigations of how the batholithic rocks formed are fundamental to our understanding of the growth and evolution of the North American continent and of continental crust in general.

An important objective in the study of the Cordilleran batholiths is to establish how their characteristics are related to the tectonic environments in which they formed. The inference that the batholiths formed at convergent plate boundaries is based on the overall geological setting of the batholiths, the close temporal, spatial and chemical association of their plutonic and volcanic elements, the compositional similarities of these rocks to those in more modern magmatic arcs, and the similarities of geochemical asymmetries or gradients across batholithic belts and modern magmatic arcs. However, the nature of the processes and materials involved and how they have influenced the geometry, petrology, and geochemistry of the arc magmas is incompletely understood, even in modern arcs. For many of the Cordilleran batholiths, interpretation is further complicated in that they are composite belts produced by the superposition of several tectonically distinct episodes of plutonic emplacements. Particularly well documented examples are known in the Sierra Nevada and the Alaska-Aleutian Range, where distinct Jurassic and Cretaceous batholith belts are present and have differing geographic trends (e.g., Kistler *et al.*, 1971; Lanphere & Reed, 1973; Kistler, 1974). The superposition of the plutonic belts presumably resulted from a succession of changes in plate boundaries, orientations and relative plate motions during the Mesozoic, for which the earlier record can only be surmised.

A notable exception to this complexity is found in the Cretaceous Peninsular Ranges batholith of southern and Baja California. The Peninsular Ranges batholith was emplaced during a comparatively simple, continuous intrusive cycle with no recognized spatial overlap with older plutonic arcs in the peninsular region (Silver *et al.*, 1975, 1979). The relative structural and geochronological simplicity of the Peninsular Ranges offers an opportunity to examine the systematic petrological and geochemical characteristics of a plutonic belt closely analogous to modern magmatic arcs. Extensive early studies (e.g., Larsen, 1948) established the general petrographic nature of the Peninsular Ranges batholith, particularly in its northwestern sector. More recent investigations have revealed remarkable regularities of longitudinal trends and persistent regional asymmetries in geochronological, petrological, geochemical and isotopic characteristics over the northern 600–800 km of the batholith (e.g., Gastil, 1975; Silver *et al.*, 1975, 1979; Baird & Miesch, 1984). The asymmetries have gradients transverse to the structural axis of the batholith and therefore appear to bear some fundamental relationship to its origin. The extended exposure of the Peninsular Ranges

batholith and its broad transverse expanse invites a thorough investigation of how the transverse asymmetries are related to the formation and evolution of magmatic arcs.

The present study is focused on the rare earth element (REE) geochemistry of an extensive sampling of the major rock types of the northern batholith. The geochemistry of the REE provides a sensitive and powerful petrogenetic tool that, integrated with existing information on the batholith, is used to provide insights into the sources, generation and evolution of the batholithic magmas. A relevant companion study of REE distributions among minerals in a typical eastern granodiorite from the Peninsular Ranges (Gromet & Silver, 1983) has given important constraints on REE behavior during crystallization differentiation involving the major and accessory mineral assemblages found in the batholithic rocks. This information is used to identify the role of high-level differentiation processes in modifying the REE characteristics of the batholithic magmas, allowing the present study to address the contributions originating from more deeply seated processes and materials.

OVERVIEW OF CHARACTER AND SETTING OF THE BATHOLITH

General features

The Peninsular Ranges batholith of southern California and the peninsula of Baja California is one of the longest batholithic segments in the Cordilleran province (Fig. 1). Generally paralleling the Pacific coast for 1000 km from Los Angeles to central Baja California, the batholith is comprised of at least several hundred plutons. Cenozoic rifting to form the Gulf of California has separated the Peninsular Ranges from closely related plutonic and volcanic rocks to the east in the states of Sonora and Sinaloa, Mexico (e.g., Anderson & Silver, 1974; Silver *et al.*, 1975).

The plutons of the peninsular part of the batholith were emplaced into thick metavolcanic

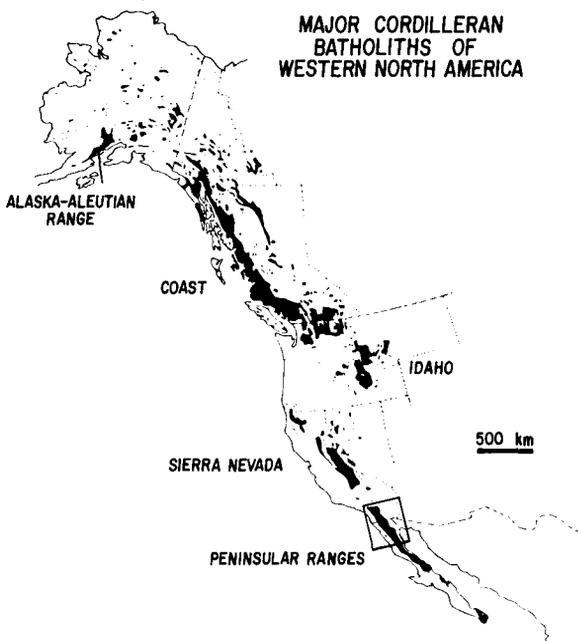


FIG. 1. The major segments of the Mesozoic Cordilleran batholiths of western North America. Substantial volumes of related Mesozoic plutonic rocks also occur east of the coastal belts but are not shown. The area of the northern Peninsular Ranges batholith as seen in Figs. 2 and 3 is outlined.

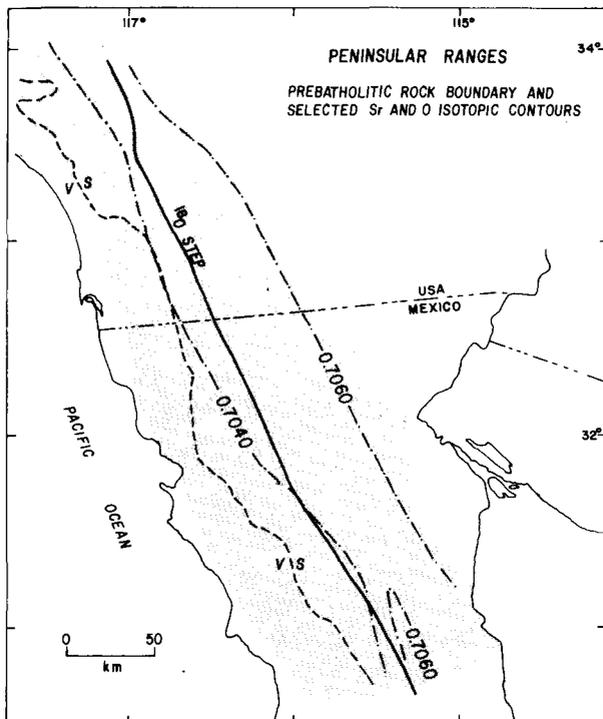


FIG. 2. Outline of approximate outcrop of batholithic rocks in the northern Peninsular Ranges. Dashed line separates regions in which the prebatholithic rocks are predominantly volcanic and volcanoclastic (v) from those in which they are predominantly sedimentary (s) (after Gastil *et al.*, 1975). Selected isopleths of initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (Silver *et al.*, in prep.) and the ^{18}O 'step' (Taylor & Silver, 1978) in batholithic rocks are shown.

and metasedimentary sequences of Mesozoic to Paleozoic age (Larsen, 1948; Silver *et al.*, 1963; Gastil *et al.*, 1975; Gastil & Miller, 1981; Hill, 1984). Volcanic and volcanoclastic rocks dominate the prebatholithic section along the western flanks of the Peninsular Ranges (Fig. 2). The volcanic rocks are in part coeval with batholithic emplacement and represent extrusive counterparts (Silver *et al.*, 1963). The age and basinal settings of metasedimentary rocks in the central and eastern Peninsular Ranges are more poorly understood. Greywackes, arkosic sandstones, and argillaceous rocks dominate in the central parts of the batholith with increasing proportions of quartz-rich sandstones and carbonates in the eastern ranges (Woodford & Harris, 1938; Silver *et al.* 1979; Todd & Shaw, 1979; Gastil, 1983). Some of the easternmost ranges are allochthonous with respect to the central part of the Peninsular Ranges, having been transported westward by post-batholithic thrusts (Silver, 1982). Older crystalline basement rocks have been sought but none has been identified.

Plutons are commonly a few kilometers to a few tens of kilometers in dimension, although internal intrusive units have only been well defined in a few detailed studies of specific bodies. Individual plutons range in lithology from gabbro (locally peridotitic) to granite. Tonalite and low- K_2O granodiorite (granodiorite with 5–10 per cent modal alkali feldspar) are the most common rock types (Larsen, 1948; Gastil *et al.*, 1975; Silver *et al.*, 1975, 1979; Gastil, 1983). Many plutons display only limited internal compositional variations, although detailed studies have revealed some zoning, heterogeneity or composite emplacement in some plutons (Duffield, 1968; Morton *et al.*, 1969; Murray, 1978; Todd & Shaw, 1979; Hill *et al.*, 1985), and gabbroic complexes are often highly differentiated (Miller, 1937;

Larsen, 1948; Walawender, 1976; Nishimori, 1976). The minerals plagioclase, quartz, hornblende, biotite and alkali feldspar make up all but a few per cent of most non-gabbroic rocks. Minor masses of peraluminous felsic rocks are found in and near some metasedimentary pendants and screens, and are inferred to reflect local assimilation or anatexis.

Regional asymmetries

Emplacement ages

Silver *et al.* (1975, 1979) have established a two-part space-time progression of plutonic emplacements across the batholith. Plutons were emplaced continuously over an interval of 130–105 Ma in the western half of the batholith, whereas a regular age-space progression from 105 Ma to 80 Ma with younging eastward characterizes the eastern half. That is, the batholith is a composite of an older western static magmatic arc and a younger eastern transgressive arc. Emplacements associated with the younger arc migrated eastward to intrude Precambrian crust in Sonora, Mexico (Anderson & Silver, 1974).

Petrological characteristics

Tonalites and low-K₂O granodiorites, the most common rock types in the batholith, display a limited range in modal and chemical composition and have several unifying characteristics. They are feldspathic, containing 50–60 per cent zoned andesine and 0–10 per cent alkali feldspar. Quartz contents are typically 15–25 per cent. Hornblende and biotite in variable proportions are the dominant mafic constituents together yielding color indices of 10–25 for most. Color indices for rocks from the central and eastern portions of the batholith tend to be somewhat lower than their counterparts to the west. Idiomorphic sphene is common in the more eastern lithologies.

Beyond the dominance of tonalite and low-K₂O granodiorite across the batholith, a considerable regional variability in the presence and relative proportions of other lithologies has been recognized (Larsen, 1948; Baird *et al.*, 1974; Gastil *et al.*, 1974; Silver *et al.*, 1979; Gastil, 1983). The western portion of the batholith is characterized by a diversity of lithologic types, with gabbro, quartz gabbro, diorite, and siliceous leucogranodiorites joining tonalite as common rock types. Quartz gabbro contains at least several per cent quartz and biotite and is transitional to diorite and tonalite. Gabbro with only traces or no free quartz (hereafter referred to as gabbro) is not transitional to the more felsic rocks, but some gabbros form internally differentiated complexes. Siliceous leucogranodiorite is abundant, forming large and apparently independent intrusive masses. In contrast, intermediate lithologies such as low-K₂O granodiorite are minor and gradational into tonalite.

This petrologically diverse western terrane gives way eastward to one with a much more restricted range of common lithologies. Gabbro is rare. Tonalite and low-K₂O granodiorite are commonly gradational and appear to constitute > 80 per cent of the intrusive mass of the region. Together, these rock types form some of the largest intrusive bodies in the batholith. The aggregate volume of exposed intrusive rock also increases sharply in this region. In the easternmost ranges of southern California and northern Baja California, tonalite appears to drop somewhat in abundance, being supplanted to some extent by low-K₂O granodiorite. Granodiorite and monzogranite form the other more common lithologies.

Isotopic and geochemical gradients

Rb–Sr isotopic studies of the northern 600 km of the batholith have revealed systematic geographic variations in initial ⁸⁷Sr/⁸⁶Sr ratios of whole rocks. Values rise from less than 0.7035 in the west to more than 0.7075 in the east, with two small but significant

reversals (Early & Silver, 1973, in prep.; Silver *et al.*, 1979). Initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios are largely independent of rock type. The trend of contours of equal initial ratios closely parallels the NNW emplacement and structural axis of the batholith (Fig. 2).

Sr concentrations in whole rocks also show a well-defined increase eastward across the batholith, with a second-order dependence on rock type (Silver & Early, 1977). Rb concentrations are highly dependent on rock type, but display only a slight increase across the batholith for a particular lithology. The behavior of K_2O is similar in this regard (Silver *et al.*, 1979), and can be contrasted to variations observed across many modern volcanic arcs (e.g., Jakes & White, 1972) and in the Sierra Nevada batholith (Bateman & Dodge, 1970).

Whole rock oxygen isotopic compositions are also zoned systematically across the batholith, and are nearly independent of rock type (Taylor & Silver, 1978; Silver *et al.*, 1979). Primary $\delta^{18}\text{O}$ values rise from +6 per mille on the west in a steep gradient to as much as +12 per mille (SMOW) on the east. There is a marked step (see Fig. 2) at or near the discontinuity in emplacement ages, and considerable regional irregularities develop east of the step. A similar step and irregularities have not been noted for Sr isotopic compositions, although there is a broad covariation in the isotopic compositions of Sr and O. Nd and Sr isotopic compositions of a profile of rocks from the northern Peninsular Ranges indicates that the isotopic composition of Nd becomes less radiogenic eastward and is generally negatively correlated to that of Sr (DePaolo, 1981). All the isotopic and geochemical gradients may be telescoped to some degree in the easternmost ranges due to post-emplacement west-directed thrusts.

REE IN BATHOLITHIC ROCKS

Sampling design

The selection of samples for this investigation was strongly influenced by the regional variations in age, petrological and geochemical characteristics summarized above. Many of the samples analyzed were collected as part of preceding and parallel studies by Silver and his coworkers, permitting direct comparison of REE characteristics with other properties in individual samples as well as with the regional gradients. To establish the patterns of regional variations in REE characteristics, significant emphasis was placed on sampling tonalitic intrusives throughout the batholith, thereby minimizing the contributions from petrological variations. The remainder of the sampling was directed toward the characterization of a spectrum of lithologies within each of the various regions of the batholith. This allowed REE variations among the different lithological types to be identified and compared to the regional variations, and provided some insight into the processes that gave rise to the petrological diversity. It is emphasized that sampling for these purposes was generally restricted to major intrusive units. For example, the minor anatectic and/or hybrid rocks found near some contacts with prebatholithic rocks were specifically avoided.

Results

REE concentrations for 56 whole rock samples, two prebatholithic metasedimentary rocks, three separate analyses of USGS rock standard BCR-1 and normalizing values are given in the Appendix. The locations of 56 whole rock samples analyzed for REE are shown in Fig. 3. Eight REE from Ce to Yb were analyzed by isotope dilution methods, providing a uniform characterization of the REE spectrum. Rock powders were spiked then subjected to extensive HF-HClO_4 attacks in open beakers. Bomb dissolutions performed on selected replicate samples reproduce the results reported here. Details of the sample preparation and isotope dilution mass spectrometric techniques employed are discussed in Gromet (1979).

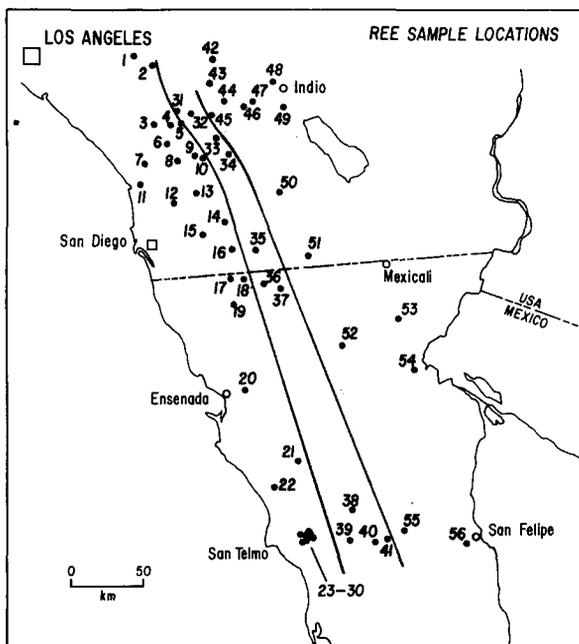


FIG. 3. Locations of analyzed samples in the Peninsular Ranges. Shaded area outlines approximate extent of batholithic exposures. Solid lines paralleling the length of the peninsula divide the batholith into western, central, and eastern REE regions.

REE concentrations for the chondrite Leedy (Masuda *et al.*, 1973), adjusted by a factor of 0.8 to bring them into approximate agreement with the chondrite average of Haskin *et al.* (1968), are used for normalizations.

The results are presented graphically in the form of chondrite-normalized REE patterns (Figs. 4 to 9). The REE characteristics of the rocks fall naturally into three principal REE fractionation pattern groups. The areal distribution of these three distinct groups bears a simple relationship to geographic position within the batholith, defining western, central and eastern REE regions (Fig. 3). These highly elongate regions parallel the NNW structure of the batholith. A fourth, subordinate group has been observed only in the extreme southwest of the sampling area, near the village of San Telmo, Baja California del Norte, Mexico. Gabbros are the only rocks whose REE patterns do not seem to share consistently in the general geographic groupings. They are discussed separately.

Regional patterns of REE variations

The foremost feature of the observed data is that the REE fractionations of the quartz-bearing rocks vary systematically and drastically across the Peninsular Ranges batholith, from nearly flat in the west to highly fractionated in the east. The variation is transverse to the long axis and structural trends, and generally parallel to other known asymmetries in petrologic, geochronologic, and various isotopic properties. Differences in the REE characteristics associated with variations in rock type within each region are small and secondary compared to the magnitude of geographically correlated trends.

The abundant tonalites, which commonly have similar mineral abundances and bulk major chemical compositions in all regions (see Appendix), illustrate the transverse variations. Western region tonalites and quartz gabbros (Fig. 4A) display remarkably similar

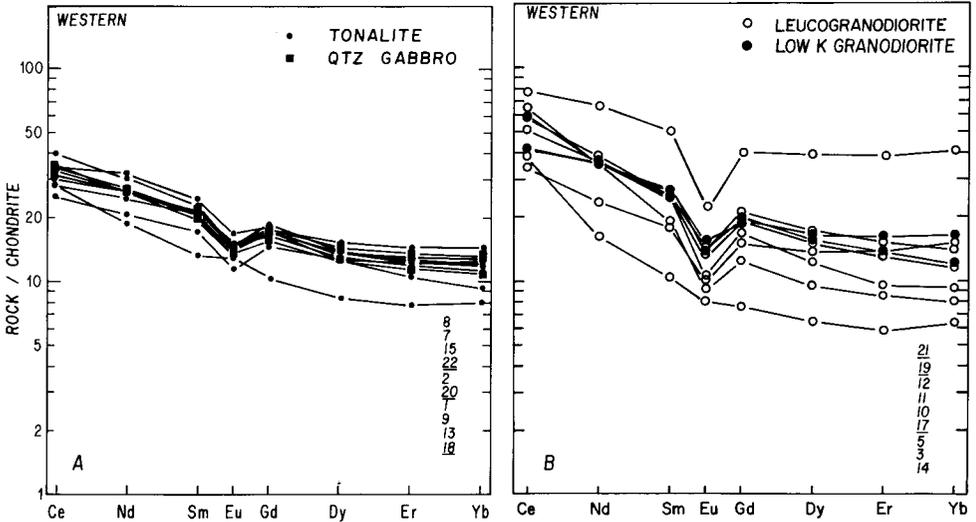


FIG. 4. (A) REE patterns of tonalites and quartz gabbros from the western region, exclusive of the San Telmo ring complex. In this and the following diagrams, sample numbers are listed in order of their relative Yb abundances and underlined numbers indicate samples from Baja California. (B) REE patterns of low- K_2O granodiorites and leucogranodiorites from the western region.

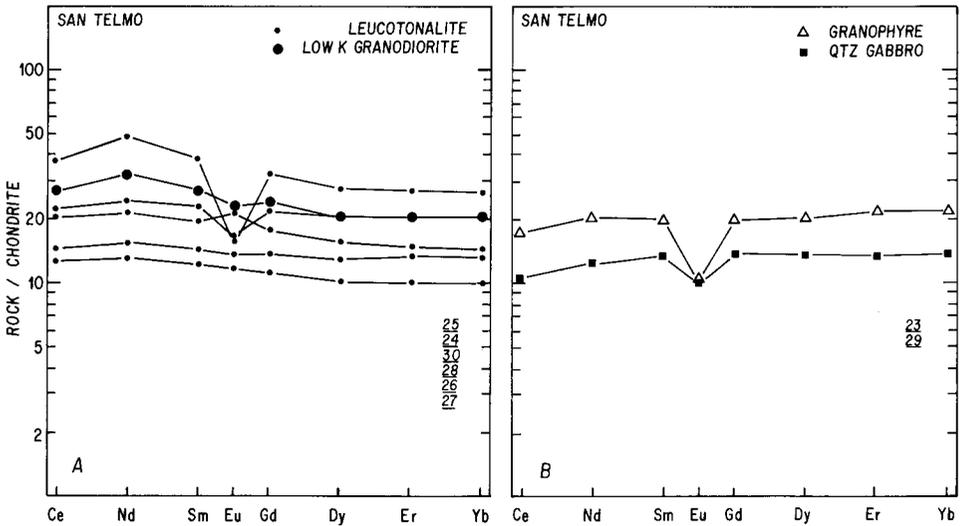


FIG. 5. (A) REE patterns of leucotonalites and a low- K_2O granodiorite from the San Telmo ring complex, Baja California. (B) REE patterns of a granophyre and quartz gabbro associated with the San Telmo ring complex.

REE pattern characteristics. All are near flat in the heavier REE with typically 10–15 times chondritic levels, and have a moderate relative enrichment in the light REE. All except one have a modest (15–20 per cent) negative Eu anomaly. The central region tonalites (Fig. 6) are similar in the light REE, but all have much lower heavy REE contents. The patterns are strongly fractionated in the middle to heavy REE and do not have negative Eu anomalies. The tonalites of the eastern region (Fig. 7A), with one exception, display consistent steep-sloped fractionation patterns with strong light REE enrichment (Ce > 50 times

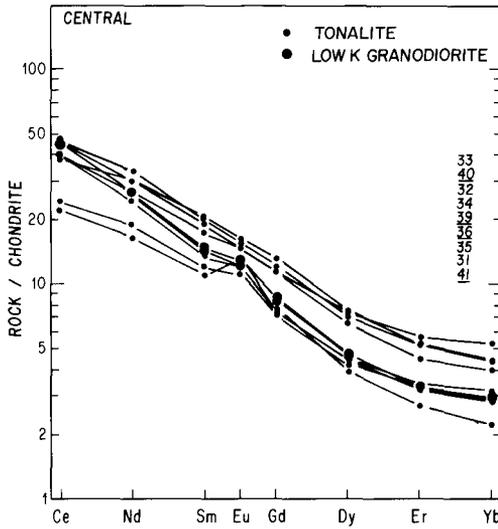


FIG. 6. REE patterns of tonalites and low-K₂O granodiorites from the central region.

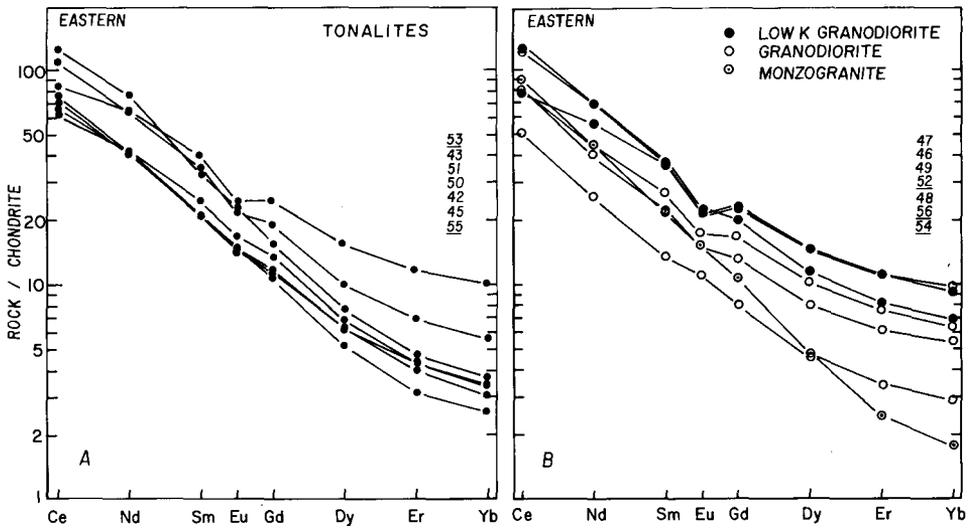


FIG. 7. (A) REE patterns of tonalites from the eastern region (sample 43 is on the borderline between tonalite and low-K₂O granodiorite). (B) REE patterns of low-K₂O granodiorites, granodiorites, and a monzogranite from the eastern region.

chondritic) and minor to negligible Eu anomalies. The principal difference between these rocks and those of the central region is the abundance and fractionation in the light REE. The tonalites thus display two separate and distinct major changes in their REE patterns from west to east. The first transition is a fractionation and depletion of the middle to heavy REE and disappearance of negative Eu anomalies. The second transition is to strong light REE enrichment. Figure 8 summarizes the regional REE variations in the tonalites.

For the portion of the batholith in southern California, a special effort was made to obtain samples close to the geographical boundary between the western and central REE regions. The purpose was to more precisely locate this boundary, and to determine whether it was a

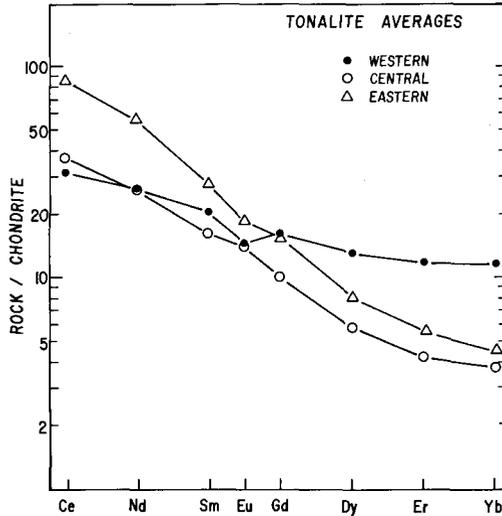


FIG. 8. REE patterns of averages of tonalite samples from each of the western, central, and eastern regions. All tonalites (seven from each region) were used to calculate the average.

sharp, discontinuous break or a smooth variation. The resulting higher density of samples in the vicinity of the boundary (see Fig. 3) yielded one tonalite (sample 13) with what might be considered marginally transitional REE properties. This rock has a slightly steeper slope in the heavier REE than other western tonalites, a larger Eu anomaly, and somewhat higher light REE contents. This rock is grouped with the western region tonalites, these differences being small compared to the more marked contrasts with central region rocks. The geographic distribution of samples restricts the possible occurrence of additional rocks with similar REE characteristics to a narrow and probably discontinuous zone between the western and central regions; both regions otherwise encompass broad areas over which rocks have nearly uniform REE characteristics. The transition between the western and central regions therefore appears to be abrupt. It is emphasized that the boundaries between the NNW-trending REE regions are neither defined nor controlled by the late Cenozoic NW-trending, right-lateral faults in the Peninsular Ranges.

In addition to systematic west to east REE variations, some variations along the axis of the batholith are apparent. The flat to light REE depleted patterns of the San Telmo complex in western Baja California (Fig. 5A, B) are distinctive and suggest the southward appearance of a fourth REE region or domain on the western margin. One other leucogranodiorite in Baja California (sample 21) may belong to this kindred. Similar REE patterns have not yet been recognized further to the north.

REE and petrographic variations within each REE region

One of the most surprising features of the data within each REE region is the absence of a consistent correlation between REE characteristics and bulk composition. For example, the samples of tonalites and quartz gabbros of the western REE region have a range in modal and chemical compositions ($Cl = 10-35$, plagioclase = An_{40-55} , $SiO_2 = 53-66$ per cent), and come from widely separated plutons emplaced over a period of 20 Ma. Yet all of these rocks save one display a striking uniformity in their REE pattern shapes and Eu anomalies (Fig. 4A). Absolute REE abundances in these rocks vary up to 50 per cent but do not correlate

with rock type. One exceptional tonalite (sample 18) has significantly lower REE abundances than other tonalites and a positive Eu anomaly, suggesting the possibility of cumulate enrichment in plagioclase. However, the mineral proportions and petrographic features of this rock are not notably different than other western tonalites.

The more felsic rocks of the western region (Fig. 4B) have the same overall REE pattern shape as the tonalites and quartz gabbros, but differ from them in having much more variable absolute abundances of the REE and larger negative Eu anomalies. One exceptional leucogranodiorite (sample 14) has lower REE contents and a less distinct Eu anomaly than petrographically similar rocks.

The large range in REE concentrations among the closely related rocks of the San Telmo ring complex bears little relation to rock type. Located 120 km SSE of Ensenada, Mexico at the extreme western limit of plutonic exposures in the batholith, the complex consists of a series of high-level ring intrusions of leucotonalite (grading to low- K_2O granodiorite) and minor granophyric leucogranodiorite emplaced into older quartz gabbro and prebatholithic volcanics (DePaolo *et al.*, 1975; Gromet & Silver, 1977). Compared to other rocks of the western REE region, the San Telmo rocks have more nearly flat, unfractionated REE patterns (Fig. 5A, B). A range of more than a factor of two in REE abundances and highly variable Eu anomalies characterize five leucotonalites and a low- K_2O granodiorite, but there are only slight deviations from parallelism in their REE patterns. The leucotonalite with the highest REE contents (sample 25) has the largest negative Eu anomaly of all the San Telmo rocks, even the granophyre. The magnitude and sign of Eu anomalies in the other leucotonalites, however, appear independent of REE concentrations, and the low- K_2O granodiorite is intermediate within the range of REE contents and Eu anomalies displayed by the leucotonalites. The older quartz gabbro has lower REE contents but a larger negative Eu anomaly than most of the leucotonalites.

In the central region, tonalites and low K_2O granodiorites span a range of a factor of approximately two in REE concentrations (Fig. 6). The tonalite REE patterns could be separated into a group with higher REE contents and no Eu anomalies, and a group with variably lower middle to heavy REE contents and small to moderate positive Eu anomalies. There are, however, no petrographic or bulk chemical features that appear to correlate with these differences in REE character. Two low- K_2O granodiorites (samples 35 and 36, both from the La Posta pluton (Miller, 1935), one of the largest intrusive units recognized in the batholith), have REE abundances within the range of the tonalites. In contrast to granodiorites of the western region, these granodiorites have positive Eu anomalies.

Eastern region tonalites and granodiorites occupy nearly identical ranges in REE contents (Fig. 7A, B), although the granodiorite REE patterns are slightly less fractionated than most of the tonalite patterns. Eu anomalies range from negligible to small and negative. One gneissic tonalite (sample 53) has distinctly higher heavy REE contents, resulting in a less steeply sloped pattern. Most of the variability in the REE patterns of the eastern rocks occurs within each rock type group, where rocks with the highest REE contents tend to have small negative Eu anomalies and rocks with lower REE contents tend to have smaller or no Eu anomalies. The single monzogranite (sample 54) is somewhat more steeply fractionated across the heavier REE than the granodiorites, more closely paralleling the tonalites.

The only compositional group of rocks for which we have data whose REE patterns do not show obvious regular regional variations are the gabbros. The REE patterns of these rocks are presented in groups based on their dominant mafic mineral, pyroxene or hornblende (Fig. 9A, B). If the few completed analyses of these rocks may be generalized, they always have low REE concentrations and positive Eu anomalies. The analyzed samples range from near critically silica saturated (sample 38) to strongly undersaturated (samples 6, 16, and 44), but

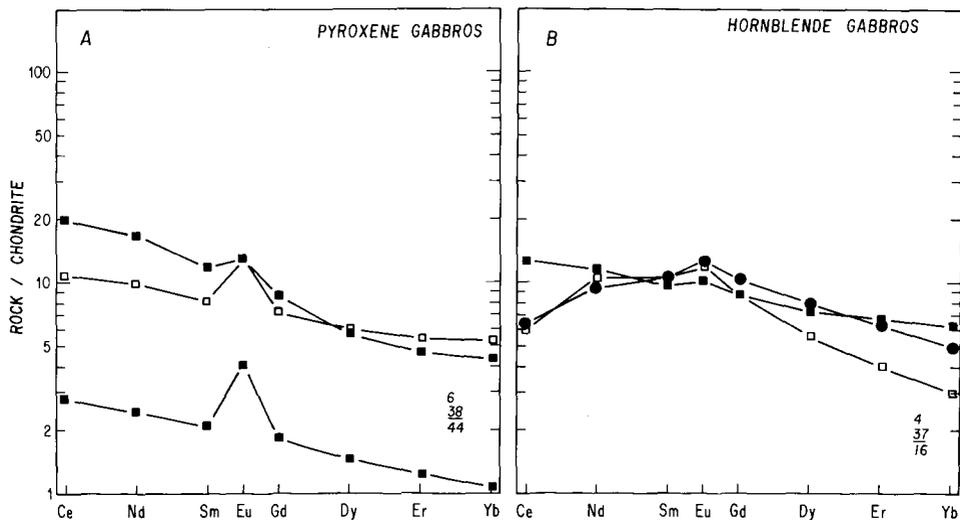


FIG. 9. (A) REE patterns of pyroxene gabbros from the western (sample 6), central (sample 38), and eastern (sample 44) regions. (B) REE patterns of hornblende gabbros from the western (samples 4 and 16), and central (sample 37) regions. Sample 16 is from the Los Pinos mafic complex (Walawender, 1976).

a correlation of this property with REE pattern type or major mafic phase is not apparent. Two of the hornblende gabbros have distinctive strongly concave-down REE patterns, as would be expected of hornblende cumulates, but the third does not. Several of the samples are from highly differentiated gabbroic complexes (samples 16, 38, 44). The potentially significant effects of various differentiation processes on the REE patterns of these rocks cannot be effectively addressed with the few analyses presented here, nor are the gabbros sampled in this study sufficient to completely characterize of the range of gabbros observed in the batholith (e.g., Miller, 1937; Creasey, 1946; Walawender, 1976). The results do establish, however, the distinctive nature of the REE characteristics of the gabbros relative to the more felsic rocks, including the quartz gabbros, and that the gabbros do not share in the regional trends so strongly developed in the quartz-bearing plutons of the batholith. These observations complement the broad petrographic and chemical distinctions already established for the gabbroic rocks of the batholith (Larsen, 1948; Baird *et al.*, 1979; Walawender & Smith, 1980; Baird & Miesch, 1984).

In review, few elements of consistency can be generally drawn between REE concentrations and fractionations and bulk compositional variations. Absolute REE abundances in rocks of each region are quite variable but appear largely independent of rock type. In the central and eastern regions, rocks with higher REE abundances generally tend toward slight negative Eu anomalies, but such rocks are not always the most felsic or differentiated. Only in the western region do the more felsic rocks commonly have larger negative Eu anomalies. A more extensive discussion of REE variations and their relation to differentiation processes is provided in a following section.

REE variations compared to regional gradients in other parameters

REE fractionations and petrologic patterns

Among the petrologic asymmetries noted across the batholith, the limitation of abundant gabbro, quartz gabbro, and siliceous leucogranodiorite to the western side of the batholith is

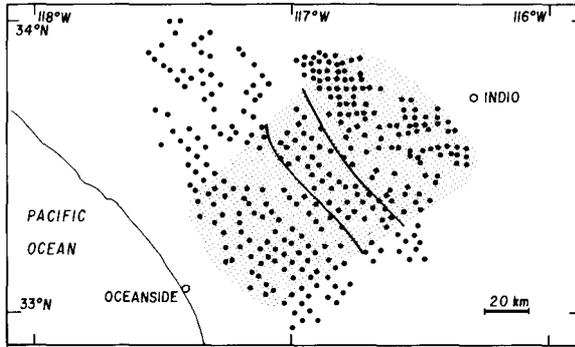


FIG. 10. Array of sample locations used in the chemical studies of Baird *et al.* (1974, 1979) in the northernmost Peninsular Ranges. Shaded region covers the area where the density of REE analysis allows the boundaries between REE regions (curved lines) to be well located. Only samples within the shaded area are considered in Fig. 11.

the most striking. In southern California, Larsen (1948) noted that the boundary between the part of the batholith in which these lithologies were abundant and the part in which they are not was about parallel to the long axis and structural trends of the batholith. This boundary appears to be fairly sharp, although not necessarily smooth. Gastil (1975) extended this observation to include the rest of the batholithic segment in Baja California. Silver *et al.* (1979) noted that this boundary also corresponds closely to the eastern limit of plutons emplaced more than 105 Ma ago.

During the course of this study, it became apparent that the boundary between the western and central regions—a boundary defined solely by a discontinuity in the REE characteristics of the rocks—occurred at about the same place. To pursue this possible correlation, an extensive study of the chemical composition of batholithic rocks in part of southern California by Baird *et al.* (1974, 1979) was consulted. The statistical sampling procedures employed in this work allows the chemical data to be used to obtain an estimate of the comparative proportions of the various lithologies in each REE region. As a convenient means of indexing the composition of the rocks with a single parameter, the Larsen differentiation index ($1/3 \text{ SiO}_2 + \text{K}_2\text{O} + \text{CaO} - \text{MgO} - \text{FeO}_{\text{total}}$) was chosen. The areal divisions obtained from the REE study have been superimposed upon the array of sample locations from the Baird *et al.* study, shown in Fig. 10. The area in which the density of REE analyses is highest is a 70 km wide, 125 km long traverse across southern California, from Oceanside to Indio (shaded pattern in the figure). Frequency histograms of Larsen indices were compiled for rocks from the areas of the three principal REE regions traversed in this profile (Fig. 11).

The histogram of Larsen indices for the plutonic rocks of the western region displays the broad range in bulk composition from calcic gabbro to leucogranite (from less than 50 per cent to greater than 75 per cent SiO_2), with three distinct modalities corresponding to gabbro, quartz gabbro and tonalite, and leucogranodiorite and adamellite. A distinct minimum is present between the tonalites (Larsen indices up to 14) and the siliceous leucogranodiorites (most with Larsen indices between 20 and 26). Larsen's petrographic studies and estimates of the areal abundances of the various lithologies (Larsen, 1948, p. 138) also indicate the paucity of rocks with compositions intermediate between tonalite and siliceous leucogranodiorite. Similar results were obtained by Silver *et al.* (1979) utilizing a different suite of chemical analyses derived for the northern 600 km of the batholith.

The compositional range of the central region is notably restricted. The distribution is unimodal with a strong maximum corresponding to the ubiquitous tonalites and subordinate

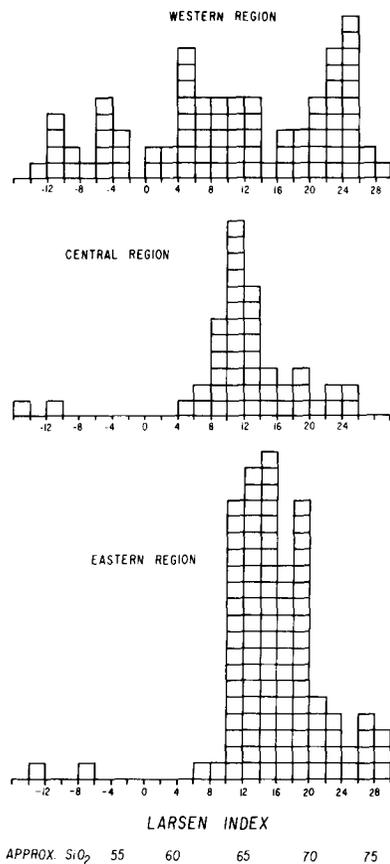


FIG. 11. Frequency histograms of Larsen indices ($1/3 \text{ SiO}_2 + \text{K}_2\text{O} - \text{CaO} - \text{MgO} - \text{FeO}_{\text{total}}$) for rocks from the Ree-defined western, central, and eastern regions in the northernmost Peninsular Ranges, calculated from the data of Baird *et al.* (1979).

low- K_2O granodiorites. Quartz gabbros are essentially absent. The form of the frequency distribution for the rocks of the eastern region is similar to that of the central region, but shifted to slightly higher Larsen indices. Tonalites and low- K_2O granodiorites are subequal in abundance, and a lesser but significant proportion of more siliceous and potassic lithologies are present. As in the central region, gabbros are rare.

The histograms indicate that a significant correlation exists between lithologic diversity and REE characteristics for the western and central regions. Information about rock distribution in San Diego County and in northern Baja California (e.g., Everhart, 1951; Gastil *et al.*, 1975; Todd & Shaw, 1979; Gastil, 1983) and our own observations (Silver *et al.*, 1979, in prep.) indicate the correlation extends to the southern limit of the study area. It appears that the factors that caused the lithologic and the REE distinctions between the western and central regions are related in some fundamental manner. The lithologic distinction between the central and eastern REE regions is less pronounced.

REE fractionation vs Sr concentration

To compare REE fractionation with Sr concentration graphically, a parameter corresponding to REE pattern slope is needed. Chondrite-normalized Sm/Dy ratio is chosen for

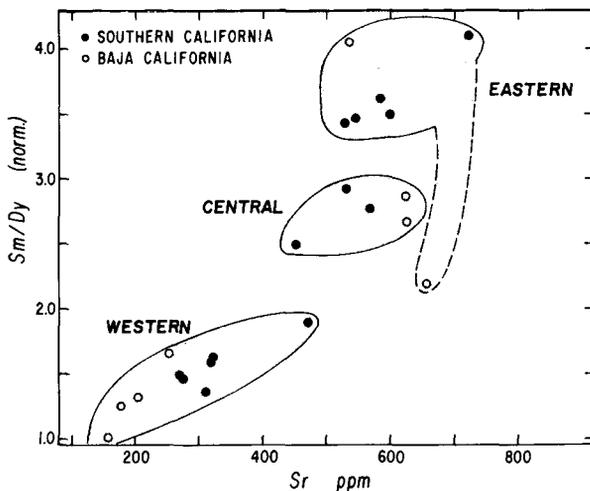


FIG. 12. Chondrite-normalized Sm/Dy ratio (a measure of REE pattern slope) vs. Sr concentration for tonalites and quartz gabbros. Samples are grouped by REE region. Western and central region rocks are fully resolved in Sm/Dy ratio and nearly resolved in Sr contents. Central and eastern region are resolved in Sm/Dy ratio save one anomalous tonalite (sample 53) but overlap extensively in Sr content. Sr concentrations from unpublished data of T. O. Early, L. P. Gromet, and L. T. Silver, and from Hill (1984).

this purpose because it reflects pattern slope near where most patterns cross. In Fig. 12, chondrite normalized Sm/Dy ratio is plotted against Sr concentration for all tonalite and quartz gabbro samples for which both REE and Sr have been determined by isotope dilution methods. Consideration has been limited to these lithologies as Sr concentration is somewhat dependent on lithology. REE fractionation and Sr concentration exhibit a good correlation on this plot, and a grouping by regions is observed. The quartz gabbros and tonalites of the western region have low Sm/Dy ratios and Sr contents. Tonalites of the central and eastern regions have higher values of both quantities.

A gap appears in the distribution of points between the western and central regions, even though there is no comparable geographic gap among the sample locations. In southern California there is actually a higher density of samples near the boundary as a result of efforts to study this transition. The existence of a gap indicates a distinct and abrupt change in REE characteristics and Sr concentrations between the western and central regions, which persists along the length of the batholith segment studied. The differences between the central and eastern groups, in terms of these parameters, are less pronounced; the tonalites from the eastern region plot at higher Sm/Dy ratio (save the one anomalous eastern tonalite), but there is a substantial overlap in Sr concentration with the tonalites from the central region.

REE fractionation vs. initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, $\delta^{18}\text{O}$, ϵ_{Nd} , and age

A plot of Sm/Dy ratio against $^{87}\text{Sr}/^{86}\text{Sr}$ initial ratio (Fig. 13) indicates a general correlation between these parameters. However, in contrast to the correlations observed between REE fractionations and Sr concentrations, there is a nearly complete overlap in the Sr isotopic compositions of the western and central REE region rocks, and the eastern region rocks appear isotopically distinct with more radiogenic compositions. Thus Sr isotopic composition and REE fractionation co-vary in a much different manner than do Sr concentration and REE fractionation. A corollary of this is that Sr isotopic composition and Sr concentration do not have a simple co-variation. A significant portion of the non-correspondence in the

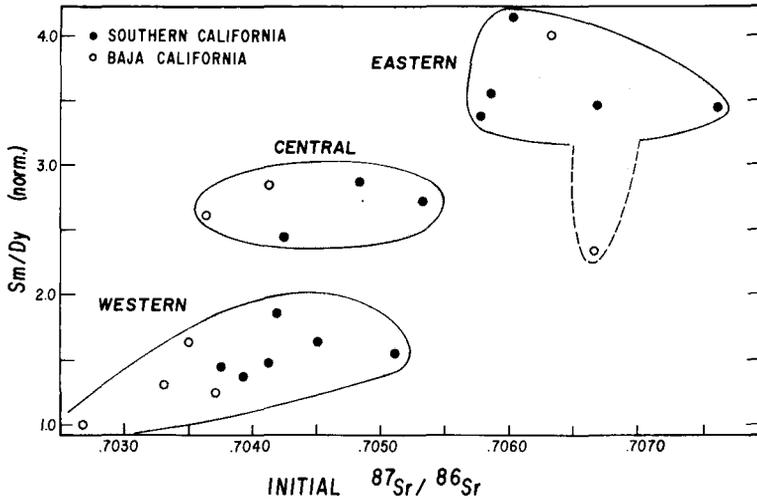


FIG. 13. Chondrite-normalized Sm/Dy ratio vs. initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio for tonalites and quartz gabbros. Western and central region rocks overlap extensively in initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio. Eastern region rocks have higher values. Sources of Sr isotopic data are the same as for Fig. 12.

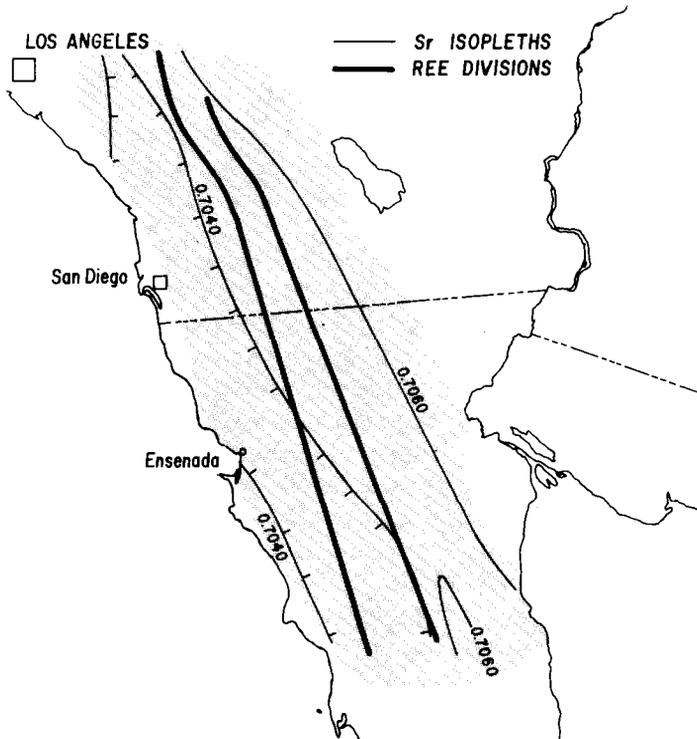


FIG. 14. REE-defined regions compared to the 0.7040 and 0.7060 initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio isopleths. The REE regions and the isopleths are parallel locally and both generally parallel the axis of the peninsula, but they diverge along the length of the peninsula.

regional variations of these properties can be seen to be due to differences in their trends along the axis of the batholith (Fig. 14). Isopleths of initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio and the boundaries between the REE-defined regions are locally parallel, but deviate substantially from complete parallelism over the region studied here.

An along-axis discrepancy also is observed in the correlation between REE fractionation and ^{18}O . The discontinuity of the variations of $\delta^{18}\text{O}$ of the batholithic rocks—the ^{18}O step of Taylor & Silver (1978)—does not correlate simply to the discontinuities in the REE variations. In most of southern California and northernmost Baja California, the ^{18}O step and the abrupt transition in REE characteristics from the western to central regions coincide, or very nearly do so. Further to the south, however, the two diverge, and the western–central REE boundary no longer separates rocks having contrasting $\delta^{18}\text{O}$. At the latitude of the southernmost samples, the step in ^{18}O is close to the boundary between the central and eastern REE regions.

A direct comparison of REE fractionations to Nd isotopic compositions reported by DePaolo (1981) is difficult because most measurements were not made on the same sample set. An evaluation of sample localities indicates that of the 14 plutonic rocks analyzed for Nd isotopic composition, 10, 1, and 3 are in the western, central and eastern REE regions, respectively. The respective ranges in $\epsilon_{\text{Nd}}(T)$ in each region are +7.9 to -0.8, +1.9, and -4.1 to -6.4. As observed with the other isotopic parameters, approximately half of the range observed for the batholith as a whole occurs within the western REE region. The Nd isotopic analysis for the single central region rock is within the range of western region values. The limited sampling for the Nd study, especially for the central and eastern portions of the batholith, precludes an evaluation of the degree to which the Nd isotopic compositions of the different REE regions do or do not overlap. Variations parallel to the batholithic axis cannot be evaluated as only two samples (from the San Telmo ring complex at the extreme western edge of the batholith) were taken outside of a fairly narrow transverse profile in southern California.

The eastward decrease in ages of the intrusives across the peninsula indicates that a general correlation between REE fractionation and age exists, but there is some local deviation from a simple correlation. The step in the age pattern (Silver *et al.*, 1979) occurs at or just to the east of the western–central REE region boundary. That is, nearly all of the central REE region rocks are part of the younger transgressive arc, but a few of the westernmost plutons of the central region were emplaced as part of the older static arc. Western and eastern region rocks occur exclusively as parts of the static and transgressive arcs, respectively.

Summary

REE patterns of plutonic rocks display large systematic but discontinuous variations from west to east across the Peninsular Ranges batholith, transverse to the long axis and structural trends of this magmatic arc. The consistent, slightly fractionated patterns of the western rocks make an abrupt transition to middle and heavy REE fractionated and depleted patterns for rocks in the central region of the batholith. Further to the east, a second well-defined transition to strongly light REE enriched rocks occurs. The slopes of the REE patterns within each of these regions are largely independent of quartz-bearing rock type; certain gabbros may show divergent trends.

These variations in REE fractionation generally correlate with other transverse asymmetries in petrologic, geochemical, isotopic, and geochronological parameters. Detailed comparisons reveal distinct and genetically significant divergences. An excellent correspondence exists among REE fractionation, Sr concentration, and petrologic characteristics in the western and central regions, suggesting a common explanation for their origin. The

eastern region can be distinguished in both REE fractionation and initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio from the central and western regions. The discontinuities in ^{18}O and age distributions in the batholith do not correlate perfectly with the REE discontinuities; they are locally divergent by the dimensions of one or two plutons ($\sim 5\text{--}15$ km).

ORIGIN OF THE REE VARIATIONS

Overview

This study presents the first detailed documentation of large, remarkably systematic regional variations in REE fractionations within a Cordilleran batholith, the emplacement of which occurred within a limited and well-defined intrusive cycle. Variations in some REE characteristics have been noted in reconnaissance and local studies of other Cordilleran batholiths (Sierra Nevada: Dodge, 1972; Frey *et al.*, 1978; Dodge *et al.*, 1982; Noyes *et al.*, 1983; Central Chile: Lopez-Escobar *et al.*, 1979), but the relationship of such variations to regional tectonic patterns and controls has not been apparent. In the Peninsular Ranges, the REE variations are clearly organized in patterns related to the prominent NNW-trending axis and structural features of the batholith. It is reasonable to infer that the REE variations bear some fundamental relationship to the origin of the batholith as a magmatic arc, and reflect the inherent geometrical and geological asymmetry of magmatism at a convergent plate boundary. Various processes and factors that may have given rise to the REE variations are evaluated below. Consideration is given to the igneous processes of crystallization differentiation, assimilation, combined crystallization-assimilation, differentiation accompanying partial melting in the source regions, and to source region heterogeneities. The approach taken in this discussion focuses on what processes can produce the marked *changes* in REE patterns across the batholith, rather than how the specific REE patterns of each region originated. The latter is addressed in subsequent discussion, where the REE data are integrated as fully as possible with observations on petrological, geochemical and isotopic characteristics to develop a viable and internally consistent model for the origins of the batholithic magmas.

As a starting point for the following discussion, sampled lithologies are assumed to represent magmas and measured REE abundances to correspond approximately to magma compositions. There are several reasons for believing this to be true. The amount of internal differentiation evident within most of the quartz-bearing plutons of the batholith appears to be very limited. Even in larger plutons where there is evidence of repeated recharge of the magma chamber, buffering and mixing has resulted in rocks that closely approximate magma compositions (Hill *et al.*, 1985). These observations and the strong family REE and other characteristics shared by most rocks from each REE region indicate that the REE features are not strongly influenced by phenomena such as local melt segregation or accumulation of crystallizing phases. Rather, the REE characteristics are primarily determined by the strong and consistent action of regional controls and must reflect to a large degree the bulk properties of the magmas that formed the plutons. Samples of many of the plutons probably approximate melt compositions. The bulk compositions of the batholithic rocks correspond closely to those of lavas found in similar tectonic settings, and lie on reasonable liquid variation curves (e.g., Larsen, 1948; Silver *et al.*, 1979; Silver & Chappell, in prep.). A detailed study of REE distribution among minerals in an eastern granodiorite, a fairly typical rock of the batholith, strongly argued that this rock corresponds closely to a melt composition and does not contain restitic (inherited) phases (Gromet and Silver, 1983, pp. 934–6). Exceptions to some of these generalizations are found in the gabbros, and may occur in certain other rocks as discussed below.

*Crystallization-differentiations**Regional REE variations*

The role of high-level crystallization-differentiation in producing the REE variations is explored below by examining REE behavior in a hypothetical differentiating system in which the fractionating mineral phases are those actually observed in the batholithic rocks. Discussion begins with major mineral assemblages and then is extended to include REE-rich accessory phases.

Textural observations and bulk chemistry indicate that the major phases appearing early in the crystallization sequences of the quartz gabbros and tonalites are plagioclase, hornblende and, to a lesser extent, clinopyroxene and Fe-Ti oxides. Clinopyroxene is a significant phase (5–15 per cent) in some quartz gabbros of the western REE region and may have participated in the crystallization differentiation of these and possibly other magmas at depth, particularly if the batholithic magmas were derived from more mafic melts. Other phases such as biotite and alkali feldspar are generally late in the crystallization sequence of many of the intermediate to felsic rocks of the batholith, precluding an important REE role for these minerals through much of any crystallization differentiation process. Moreover, the small proportions of trivalent REE that these minerals take up from melt and their weakly fractionated REE distributions (e.g., Schnetzler & Philpotts, 1970; Gromet & Silver, 1983; Noyes *et al.*, 1983) indicate that their effect on REE fractionation patterns of the batholithic magmas would be negligible. The common presence of plagioclase, hornblende, clinopyroxene, and Fe-Ti oxides as phenocrysts in volcanic rocks of intermediate composition, and the occurrence of these minerals as liquidus or near liquidus phases in experimental studies conducted in the range of crustal pressures (e.g., Eggler & Burnham, 1973; Allen & Boettcher, 1978; Nicholls & Harris, 1980) support the textural observations.

REE behavior during crystallization is principally dictated by mineral/melt partitioning. REE partitioning between melt and plagioclase, hornblende and clinopyroxene has been measured by many workers in a wide variety of volcanic rocks and in experimental studies. These studies have yielded consistent mineral/melt REE pattern shapes for the trivalent REE, which are taken as close approximations to equilibrium fractionation shapes. These shapes are controlled by crystal chemical considerations (e.g., Onuma *et al.*, 1968; Matsui *et al.*, 1977; Gromet, 1979; Nicholls & Harris, 1980), and are primarily sensitive to changes in the configuration of the sites in which the REE reside. For example, Mg-Fe substitution in high Ca clinopyroxene and calcic hornblende does not appreciably affect the configuration of the Ca-filled M2 and M4 sites, respectively, into which the REE principally substitute. Therefore, it is not surprising that mineral/melt REE distributions for these minerals show little variation in shape despite variable Mg/Fe ratios. In contrast, the magnitude of mineral/melt REE distribution coefficients for many minerals is sensitive to several other factors, the most important being melt composition (e.g., Watson, 1976; Ryerson & Hess, 1978). Consequently, the arguments developed below rest primarily on the shapes of REE fractionation patterns rather than absolute REE abundances.

Some natural examples of REE distribution coefficient patterns for plagioclase and hornblende are shown in Fig. 15. Hornblende/melt REE distributions are consistently concave-down with steep positive slopes in the lighter REE and a broad maximum at about Dy. Clinopyroxene/melt distributions are generally smaller but parallel to those for hornblende (a result of the directly analogous configurations of the Ca-filled M2 and M4 sites in both mineral structures), allowing the effect of clinopyroxene crystallization to be modeled (for REE) simply by substituting a lesser quantity of hornblende in the calculation. Plagioclase/melt REE distributions have a moderate negative slope and a strong positive Eu

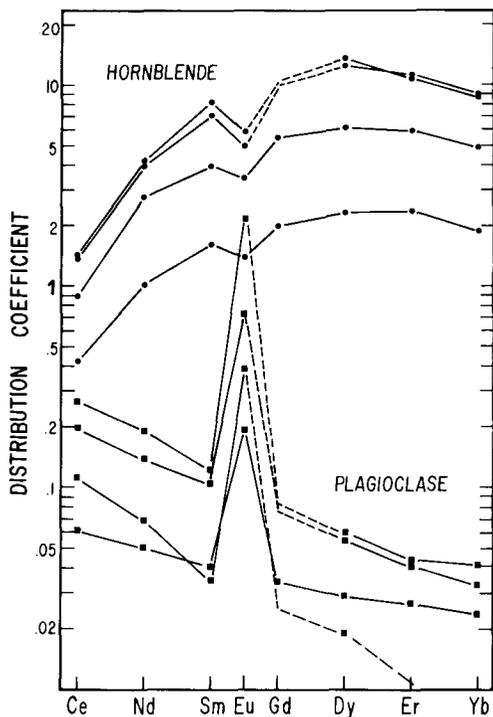


FIG. 15. Selected hornblende/groundmass and plagioclase/groundmass REE distributions for intermediate to felsic volcanic rocks (Schnetzer & Philpotts, 1970; Nagasawa & Schnetzer, 1971; Arth, 1976).

anomaly. The light REE-enriched shape of the plagioclase distribution coefficient pattern is opposite that of coprecipitating hornblende. However, plagioclase accepts such a small fraction of the trivalent REE in the system that little relative fractionation of the REE occurs in successive melts for any reasonable degree of plagioclase crystallization. The very low REE contents actually found in plagioclase from the batholithic rocks (Gromet, 1979; Gromet & Silver, 1983) confirms this expectation. Fe-Ti oxides generally contain negligible REE and act as diluents. They are not considered further here.

Whole rock normalized REE patterns of plagioclase and hornblende separated from several rocks from the Peninsular Ranges batholith are quite similar in form to the distribution coefficient patterns displayed in Fig. 15 (Gromet, 1979, work in progress; Gromet & Silver, 1983). This consistent REE behavior supports the operation of straightforward magmatic crystallization processes in the batholithic rocks and lends confidence to the application of mineral/melt REE fractionations to the interpretation of the courses of plutonic crystallization differentiation. REE distribution coefficients used in the following calculations are listed in the Appendix.

Of the quartz-bearing rocks of the batholith, quartz gabbro is the most mafic and is an appropriate starting point for discussion of REE variations associated with the generation of more felsic rock types by crystallization differentiation. Simple calculations using appropriate bulk chemistries and a range of reasonable mineral chemistries (e.g., Larsen, 1948) indicate that a quartz gabbro can yield approximately 60-65 per cent of its mass as a tonalite magma, precipitating an assemblage consisting of plagioclase and hornblende, or plagioclase, hornblende, and clinopyroxene. Further crystallization of similar assemblages

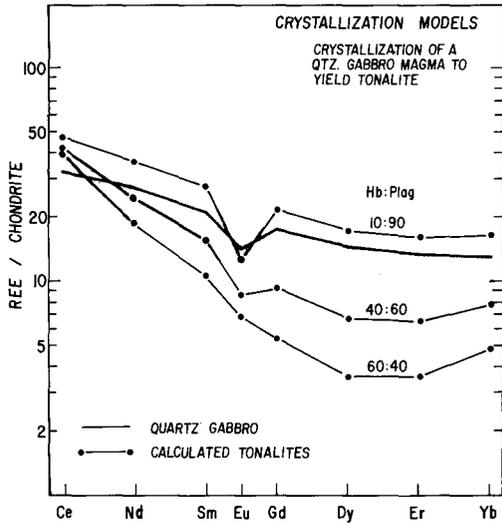


FIG. 16. Simulated effect of low-pressure fractional crystallization on the REE patterns of calculated residual tonalite melts derived from quartz gabbro magma. Sample 7, a typical quartz gabbro of the western region, is used for the starting material. All calculated tonalite melts are produced by 40 per cent crystallization, but proportions of hornblende and plagioclase, the crystallizing assemblage, are allowed to vary. REE patterns for calculated tonalites are labeled according to proportions of hornblende and plagioclase in the assemblage. Approximately subequal amounts of hornblende and plagioclase are required to generate a residual liquid with the major element chemistry of a typical tonalite. Shaded field corresponds to REE patterns of western tonalites and quartz gabbros, for comparison.

yields an approximate leucogranodiorite composition having roughly 35 per cent of the mass of the original quartz gabbro.

REE patterns of simulated derivative melts are calculated by a Rayleigh crystallization process in which 40 per cent crystallization of a solid assemblage consisting of plagioclase and hornblende in variable proportions yields residual tonalite melts. REE patterns of derivative melts are illustrated on a chondrite-normalized basis in Fig. 16 (assuming an initial melt with the REE abundances of quartz gabbro sample 7). The results indicate that the overall REE abundances in derivative liquids and the size and sign of any Eu anomaly are sensitive to the relative proportions of plagioclase and hornblende in the crystallizing assemblages. For hornblende-poor assemblages, trivalent REE abundances increase slightly and are nearly unfractionated relative to those of the initial melt. For hornblende-rich assemblages, trivalent REE abundances generally decrease for all but the lightest REE. Importantly, a relative depletion of the middle REE occurs (greatest for Dy), imparting a pronounced concave-up, spoon-shaped fractionation to the middle to heavy REE portion of the pattern. This effect and the tendency toward more positive Eu anomalies in derivative melts with increased subtraction of hornblende are caused by the strongly concave-down shape and negative Eu anomalies of hornblende REE distribution coefficient patterns. The dominance of hornblende fractionation effects, even when hornblende is not the principal crystallizing phase, occurs because its REE distribution coefficients, including Eu, are much larger than those of plagioclase and most other major phases. Clinopyroxene crystallization would produce REE pattern shapes in derivative melts similar to those arising from hornblende crystallization, but the fractionation effects are less pronounced due to smaller distribution coefficients for clinopyroxene.

An important observation already noted is that REE patterns of quartz gabbros and many

of the tonalites in the western region are indistinguishable (Fig. 4A) and do not reflect the effects predicted by the crystallization models. A second important observation from these models is that although depletion of heavier REE may be caused by crystallization of hornblende-bearing assemblages, the REE pattern shapes of derivative melts differ considerably from those observed in central and eastern region rocks. Their REE patterns are strongly sloped across the middle REE and do not display strong concavity or reversals in slope across the heavier REE. It appears that the REE pattern features of the central and eastern region rocks were acquired by a process or processes other than crystallization of hornblende- or clinopyroxene-bearing assemblages from magmas with REE patterns like those of western quartz gabbros or tonalites. The REE patterns of the calculated derivative melts do resemble those of some western tonalites and leucogranodiorites, suggesting that fractional crystallization may relate some of rocks within each REE region (see below).

REE variations somewhat similar to the regional variations observed here have been found within the zoned Tuolumne and Eagle Peak plutons in the Sierra Nevada batholith and have been attributed tentatively to hornblende crystallization (Frey *et al.*, 1978; Noyes *et al.*, 1983). In these plutons, more mafic rocks in the marginal zones have relatively flatter REE patterns, giving way inward to more felsic rocks having steeper, relatively heavy REE depleted patterns. These variations might arise from inward crystallization where the marginal rocks represent mixtures of early-formed crystals and melts (Bateman & Chappell, 1979), although this would require hornblende/melt REE distributions enriched in the heavy REE relative to the intermediate REE (contrast with Fig. 15) (Frey *et al.*, 1978; Noyes *et al.*, 1983). Heterogeneous sources (reflected in isotopic variations) may have contributed to the Tuolumne variations (Hill *et al.*, 1984; Kistler *et al.*, 1984). A similar progressive crystallization explanation for the REE variations in the Peninsular Ranges is unlikely. The variations in the Peninsular Ranges do not correlate to rock composition and are spatially separated. The tight regionality of the patterns would require the western tonalites and quartz gabbros to be mixtures of accumulated crystals and melts, but tonalites further east would not. The results of the studies on the Sierran plutons do raise the caution that some of the plutonic rocks may not represent melt compositions. Perhaps some of the local deviations from the regional patterns in the Peninsular Ranges (e.g., sample 53, Fig. 7A) could arise in such a manner.

The possible effects of REE-rich accessory mineral crystallization on bulk rock REE patterns were considered in a detailed study of a granodiorite from the eastern REE region (sample 48). It has revealed that a large fraction of the REE in this rock resides in the accessory phases sphene and allanite, and that these minerals apparently achieved saturation in the granodiorite magma relatively early in its crystallization history (Gromet & Silver, 1983). The preliminary results of a continuing study (Gromet, 1983; Gromet & Silver, in prep.) confirm that this is true of many rocks from the more easterly portions of the batholith. Therefore, sphene is a potential candidate for depleting derivative melts in the heavier REE because it is commonly the principal carrier of these elements in the eastern rocks. Interestingly, sphene is neither an early crystallizing phase nor a major REE reservoir in rocks of the western REE region and these rocks do not have heavy REE fractionated and depleted patterns.

Sphene/melt REE distributions have been reported for peralkaline phonolites (Simmons & Hedge, 1978; Wörner *et al.*, 1983) and determined experimentally (Green & Pearson, 1983). In each case the distributions show a preference for middle REE relative to lighter and heavier REE. If this fractionation behavior applies to calcic magma compositions of the batholith, sphene crystallization would result in a relative depletion of the middle REE, qualitatively like that for hornblende and clinopyroxene crystallization. As discussed above,

this fractionation pattern shape is quite unlike that required to produce the differences observed between the REE regions of the batholith.

Other REE-rich accessory minerals observed in the batholithic rocks include allanite, apatite and zircon. Allanite is an important reservoir for the lightest REE only (Gromet & Silver, 1983). It is an early crystallizing phase in some tonalites and granodiorites from the more easterly portions of the batholith, but is a late phase or is absent in all but the most felsic western rocks. Inasmuch as allanite crystallizes early in rocks with high light REE contents, its appearance seems to reflect the abundance of these elements in the magma. Because the light REE contents of the western tonalites are low and allanite reaches saturation late in these rocks, if at all, early allanite crystallization cannot be the inferred cause of the observed low values. The middle REE-enriched nature of apatite/melt REE distributions indicates that this phase, as with hornblende, cannot produce any of the observed regional REE variations. Additionally, apatite appears to be a minor reservoir of REE in these rocks (Gromet & Silver, 1983; Gromet, work in progress).

Zircon is the only phase present in the batholithic rocks that is capable of appropriately fractionating the middle and heavy REE. However, there are several factors mitigating against the possibility that zircon crystallization (or residual zircon in the source regions of the batholithic magmas) was the cause of the regional REE variations. The regularity of the regional REE variations would require precise but trace quantities of zircon to crystallize from differentiating magmas (or remain as residual grains in the source). Zircon saturation is sensitive to melt composition and temperature (Watson & Harrison, 1983), which potentially could provide strong controls on the appearance and amount of zircon. But this should lead to progressive fractionation of the middle to heavy REE with composition, yet no such changes are evident (e.g., within each REE region). It is unlikely that most of the eastern magmas left residual zircon in their source regions because rocks typical of the eastern tonalites and granodiorites contain approximately 175 p.p.m. Zr (B. W. Chappell, pers. comm.; Hill, 1984). The experimentally determined saturation surface for zircon (Watson & Harrison, 1983) indicates that metaluminous rocks such as these should have exhausted all zircon in their source regions at temperatures of only 825 °C. The temperatures of the batholithic magmas probably exceeded this value by a significant margin. For example, the pre-eruption temperatures of compositionally similar magmas at Mount St. Helens were 920–940 °C (Rutherford *et al.*, 1985). In addition, very small proportions of the REE in the bulk rocks appear to be contained in zircon (Gromet & Silver, 1983). The presence or absence of trace amounts of zircon also would offer no explanation of the other features that appear to be closely related to the depletion and fractionation of the middle to heavy REE (changes in Eu anomalies, Sr concentration, and petrologic diversity; see later discussion).

To summarize, the REE fractionation characteristics of the major and minor minerals in the batholithic rocks indicate that high-level crystallization differentiation schemes involving assemblages of these minerals do not offer satisfactory explanations for the regional REE variations. Similarly, it also may be concluded that other differentiation processes involving these minerals, such as partial melting of source materials composed of the same mineral assemblages, cannot explain the regional REE variations.

Within-region REE variations

High-level crystallization differentiation may explain to some extent the variations of REE patterns observed within each region. For example, in the western region one tonalite (sample 18) has a marked concave-up REE pattern, a small positive Eu anomaly and lower REE abundances than other tonalites (Fig. 4A)—all features that could be produced by crystallization of hornblende- or clinopyroxene-bearing assemblages (cf. Fig. 16). Several of

the leucogranodiorites have steeper slopes in the light REE and some show a reversal in slope in the heavy REE. These features are also consistent with the removal of minerals with the concave-down REE distribution patterns characteristic of hornblende and clinopyroxene. However, it is puzzling that most of the tonalites and leucogranodiorites do not show these features. If a crystallization process relates these rocks to more mafic rocks such as the quartz gabbros, the subtraction of hornblende or clinopyroxene-bearing assemblages with the proportions and quantities broadly suggested by the major element chemistry should result in considerable and progressive changes in the magma REE pattern shapes. The remarkable similarity in the REE patterns of nearly all the western quartz gabbros and tonalites is compelling in this regard. The variations observed among the leucogranodiorites would require highly variable ratios of plagioclase to hornblende or clinopyroxene in the crystallizing assemblage. Similar problems exist in the central REE region where crystallization and removal of hornblende- or clinopyroxene-bearing assemblages could account for most of the variations in REE patterns, but they do not vary systematically with rock composition. Perhaps these could be explained by variations in pressure or water activity during ascent and solidification of the magmas, by complex crystallization processes (e.g., Hill *et al.*, 1985), or by more deep-seated processes unrelated to crystallization.

The lack of systematic correlation between within-region REE variations and bulk rock composition raises the possibility that the REE variations primarily reflect the crystallization paragenesis of REE-rich accessory phases such as apatite and sphene. The REE distribution coefficient patterns of apatite and sphene are qualitatively like hornblende and could produce the type of REE variations noted above. The saturation surfaces of such accessory phases are sensitive to magma composition (e.g., Watson & Capobianco, 1981; Harrison & Watson, 1984); for the intermediate compositions of interest here, the accessory phases generally are sparingly soluble (also see Hellman & Green, 1979). Many of the batholithic magmas may have been saturated or nearly so with one or more of these phases fairly early in their crystallization history. Only small amounts of apatite or sphene crystallization would be needed to produce the within region REE variations, suggesting that the effects could be generated without producing corresponding significant shifts in melt bulk composition. Alternatively, variable apatite and/or sphene left as residual grains in the source region could give rise to the same REE variations without related bulk compositional shifts. Experimental studies suggest that apatite, sphene and other accessory phases could be left as residual phases during the production of a range of felsic magma compositions (Hellman & Green, 1979; Green, 1981; Watson & Harrison, 1984). Additional detailed studies are needed in order to more fully evaluate these possibilities.

The rocks of the eastern region allow the question of REE-rich accessory phase crystallization to be addressed more specifically. A detailed study of an eastern granodiorite (sample 48) provides some important insights into REE behavior during crystallization involving REE-rich phases. The early appearance of sphene and allanite, the large fraction of whole rock REE they contain, the strong REE concentration zoning in sphene and allanite (decreasing from core to rim), and the unusually low whole rock normalized REE contents of largely later crystallizing phases all indicate that the early precipitation of sphene and allanite in this rock caused a strong depletion of melt REE contents during crystallization (Gromet & Silver, 1983). Because these features appear to be characteristic of many but not necessarily all eastern magmas (Gromet, 1983; Hill, 1984; Gromet & Silver, in prep.), crystallization differentiation at the presently exposed level should lead to derivative magmas with lower REE contents. REE abundances of eastern tonalites and granodiorites, however, overlap almost completely, with granodiorites on average having higher REE contents than tonalites. None of the granodiorites have the greater upward concavity across the middle to

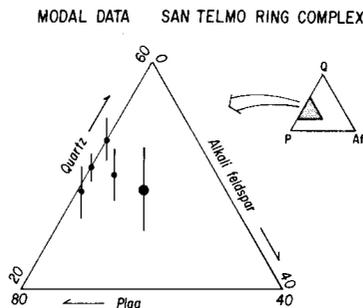


FIG. 17. Modal compositions of leucotonalites (small filled circles) and a low- K_2O granodiorite (large filled circle) from the San Telmo ring complex on a portion of the quartz-plagioclase-alkali feldspar ternary. The heights of bars on the symbols are proportional to the percentage of mafic minerals at the same scale as the other minerals. These rocks have a limited petrographic range, but there is an approximate correlation between alkali feldspar and mafic contents.

heavy REE that might be expected for a history of prior sphene, apatite, hornblende or clinopyroxene crystallization.

High-level differentiation may account for much of the REE variation among the closely related rocks of the San Telmo ring complex in extreme western Baja California. Field relationships (L. T. Silver and CIT mapping class, 1974) indicate this 13-km diameter pluton was emplaced at a very shallow level and may have fed volcanics at the surface. Present exposure is at the roof level. Small volumes of granophyre found against roof pendants of older volcanics are often hydrothermally altered and are not considered further here. Unaltered leucotonalites and low- K_2O granodiorites from San Telmo display a limited range of modal characteristics. Modal compositions of four leucotonalites and one low- K_2O granodiorite are summarized in a quartz-plagioclase-alkali feldspar ternary (Fig. 17); the heights of the bars are scaled to the percentage of mafic minerals (clinopyroxene, hornblende, biotite and oxide). The small size of the bars reflects the felsic nature of all these rocks. The low- K_2O granodiorite has the highest mafic content. Plagioclase constitutes 45–55 per cent of all rocks and is zoned from cores of sodic andesine or calcic oligoclase to rims of sodic oligoclase. Texturally, plagioclase and quartz are early crystallizing phases in these leucocratic rocks, generally preceding mafic silicates and alkali feldspars. The zoning in plagioclase implies melt composition changed significantly during crystallization, establishing the potential for differentiation effects, but the limited range of plagioclase core compositions indicates that differentiation by crystal separation could have occurred only to a limited extent.

The REE patterns of leucotonalites and low- K_2O granodiorite are parallel, confirming a close familial relationship among these rocks, but REE abundances vary by a factor of 2.5 (see Fig. 5A) and are not simply correlated with petrographic characteristics. The rock with the highest REE content and largest Eu anomaly is a leucotonalite (sample 25), and Eu anomalies do not correlate with REE concentrations in the other rocks. Because quartz and plagioclase act essentially as diluents in terms of REE, the early crystallization of these phases will result in residual melts with unfractionated but higher trivalent REE contents. A late melt fraction could contain most of the REE in such a system. The higher mafic content and high REE contents of the low- K_2O granodiorite could be explained by this rock being richer in a small but enriched late melt fraction. The two leucotonalites with the lowest REE contents (samples 26 and 27) are the most leucocratic and alkali feldspar-poor and may be correspondingly poor in an enriched late melt fraction (i.e., they are in part cumulate rocks).

These relationships suggest that the REE variations in the San Telmo rocks were somewhat controlled by the ultimate distribution of a small and variable quantity of a late melt. A setting at the roof level of a large magma chamber may have been conducive to the limited mobility of late melt fractions within the exposed upper portions of the San Telmo ring complex.

A better understanding of the factors that gave rise to the local REE variations awaits further more detailed studies. Nonetheless, the data presented here indicate that there are only limited variations in REE pattern shapes among spatially and genetically related rocks in the Peninsular Ranges batholith. Similar coherence has been observed among some closely related Aleutian plutonic rocks that probably formed in a setting analogous to the western Peninsular Ranges (Perfit *et al.*, 1980a), but not in some zoned plutons in the Sierra Nevada batholith (Frey *et al.*, 1978; Noyes *et al.*, 1983).

Assimilation and combined assimilation-crystallization

Some workers have attributed isotopic properties observed in the cratonward portions of some Cordilleran batholiths to contamination with continental crust (e.g., Armstrong *et al.*, 1977; DePaolo, 1981). Similarly, it might be suggested that the more fractionated nature of the REE patterns of the central and eastern REE regions of the Peninsular Ranges batholith have been influenced by magma contamination with upper crustal materials, which themselves are characteristically strongly enriched in light REE (e.g., Haskin *et al.*, 1968). Inasmuch as the exposed batholith was emplaced into high-level supracrustal rocks, which in the northern and eastern parts of the Peninsular Ranges include abundant clastic sedimentary rocks, the possibility of magma contamination by these and other crustal components must be addressed.

The abundant tonalites across the batholith provide a sensitive framework for considering several possible contamination processes. The strongly fractionated REE patterns and more 'continental crust-like' isotopic properties of the eastern REE region tonalites would suggest they are the most likely candidates for possible interaction with continental crust. An important constraint is provided by the very low heavy REE contents of the eastern tonalites, typically a factor of 3 to 5 lower than the western tonalites. If this major feature is to be explained by contamination of more primitive' magma such as the western tonalites or quartz gabbros, massive amounts of a diluting contaminant with very low heavy REE contents are required. Even for the end member case of a contaminant with *no* heavy REE, the resultant rock would contain of up to 80 per cent diluent. Clearly this is unreasonable. The consistent major element compositions of tonalites across the batholith alone argues strongly against such a process, whether the contaminant was added by bulk assimilation or by selective contamination (e.g., extraction of a partial melt from wall rock).

A contamination process appears even less likely when candidate upper crustal components are considered. Two prebatholithic sedimentary rocks were analyzed for REE (Appendix and Fig. 18) in order to give a more specific characterization of some of the actual wall rocks of the batholith. The samples are of a metapelite in the western REE region (from the French Valley formation; see Schwarcz, 1969) and a volcanic sandstone from Baja California in the central REE region (Silver *et al.*, 1963). Rocks similar to these make up important parts of the prebatholithic section, but it is not known if the REE patterns of the analyzed samples are representative of these rock types. The REE pattern of the metapelite is strongly fractionated and enriched in the light REE. Strong light REE enrichment is expected upon assimilation of this material, but the western region rocks that intrude it have only modest light REE contents. The volcanic sandstone has high REE contents and a relatively

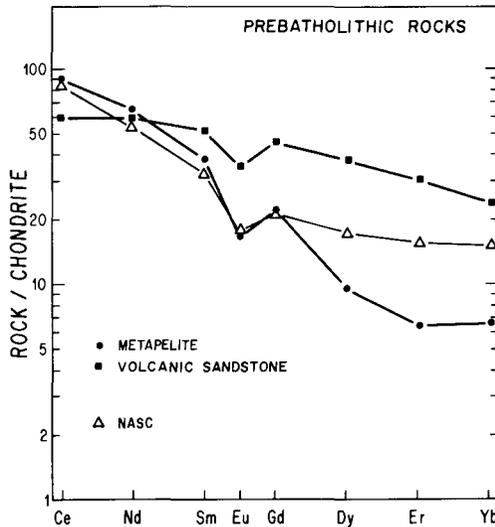


FIG. 18. REE patterns of the North American shale composite (NASC; Gromet *et al.*, 1984) and two prebatholithic rocks. The metapelite is located in the western region in southern California and the volcanic sandstone is located in the central region in Baja California.

unfractionated concave-down REE pattern. The high heavy REE contents of this rock (20–45 times chondrites) contrast to the low values of nearby plutonic rocks of the central region. The relatively unfractionated REE pattern of the sandstone would not aid in producing the fractionated REE patterns of the central and eastern regional rocks.

Shale composites from globally distributed stable platforms are often cited as representative of upper continental crust (e.g., Taylor, 1977; Taylor & McLennan, 1981). Light REE abundances and fractionations of the eastern REE region magmas are similar to those of average shales, raising the possibility that a shale component contributed to them. Average shales, however, have much higher and nearly unfractionated abundances of the heavier REE (15–20 times chondrites) and pronounced negative Eu anomalies (see Fig. 18) compared to the eastern granitoids. Assimilation of shale would tend to raise and flatten the REE pattern in the heavier REE, indicating that shales are an inappropriate component to add to western magmas to form eastern magmas. Indeed, no common crustal rock type has a REE pattern that can be mixed with the western magmas to yield the REE pattern of the eastern rocks. Note also that mixtures of western and eastern rocks do not yield rocks with the REE patterns of the central region rocks, effectively ruling out any simple mixing or assimilation process.

Some degree of assimilation cannot be ruled out if magmas parental to the eastern rocks had REE patterns already fractionated and depleted in the middle to heavy REE (i.e. this fundamental feature of the regional REE variations is an early or primary feature, the existence of which requires an explanation other than assimilation). The amounts of possible assimilation nonetheless must be small. For example, the amount of assimilated shale must be much less than 20 per cent because this amount would provide all of the Yb contents of several of the eastern tonalites and would impose a near-flat pattern across the heavy REE. Even at this level, shales are too aluminous and too potassic to have contributed significantly to the calcic plutons of the batholith.

Assimilation accompanied by fractional crystallization has additional effects that deserve consideration. The combined action of assimilation and fractional crystallization was first

considered for the batholith by E. S. Larsen, Jr. in his extensive and pioneering study (Larsen, 1948). Larsen argued that crystallization differentiation at depth modified by assimilation were the most important agents of diversification for the region he studied in detail (the northwesternmost corner of the batholith, essentially within the western REE region of the present study). Larsen emphasized the continuous range of rock compositions from quartz gabbro through leucogranite as indicative of a crystallization differentiation process, but he also recognized the problem posed by an unexpectedly large proportion of leucogranodiorite (e.g., see Fig. 11). The anomalous abundance of leucogranodiorite compelled Larsen to invoke assimilation as a means of supplying the needed additional felsic components. Of course, he could not know of the uniformity of Sr and O isotopic compositions among the rock types of a given region (Early & Silver, 1973; Taylor & Silver, 1978), which precludes assimilation as a major differentiation mechanism relating closely spaced rocks.

More recently, a possible role for assimilation-fractional crystallization in the batholith has been readdressed by Taylor (1980) and DePaolo (1981). Taylor (1980) noted that the local uniformity of isotopic compositions, linear isotopic covariation trends, and increases in Sr concentrations from west to east across the batholith were difficult to explain by an assimilation-fractional crystallization process. For example, the higher $^{87}\text{Sr}/^{86}\text{Sr}$ initial ratios and Sr concentrations of the more easterly magmas eliminates contamination by those crustal components characterized by low Sr content and high $^{87}\text{Sr}/^{86}\text{Sr}$. The supracrustal rocks intruded by the batholith fall into this category (e.g., Hill & Silver, 1983). However, DePaolo (1981) argued that Sr concentrations in derivative magmas can increase in accord with the observations if fractional crystallization occurs with little or no plagioclase fractionation, thereby allowing Sr enrichment in later differentiates (i.e. Sr behaves incompatibly). This suggestion can be evaluated further because enrichments in other incompatible elements such as K_2O and Rb in the eastern magmas should be at least as large as those for Sr. In fact, even greater enrichments should be observed for these elements because crustal contaminants generally have high alkali element contents relative to alkaline earths, and experimental evidence suggests that K_2O is preferentially extracted from contaminating crustal materials during the assimilation process (Watson, 1982). These expectations of higher alkali and alkali/alkaline earth ratios in the more easterly rocks, if assimilation-fractional crystallization operated, can be contrasted to the abundantly documented evidence for no or little regional increase in K_2O and Rb contents for similar lithologies across the batholith (Larsen, 1948; Early & Silver, 1973; Gastil *et al.*, 1975; Silver *et al.*, 1979) and the generally lower Rb/Sr ratios of central and eastern REE region tonalites (Silver & Early, 1977; Silver *et al.*, in preparation).

To explain the regional REE variations, the assimilation-fractional crystallization process would have to lead to the depletion and fractionation of the middle to heavy REE. The inability of either assimilation or fractional crystallization to accomplish this with plausible crustal contaminants and common mineral assemblages of the batholithic rocks has already been discussed. The only possible exception would be in the event that crystallization included a phase such as zircon or garnet. Objections to trace phases such as zircon controlling the regional REE variations were raised earlier, and to obtain garnet on the liquidus of mafic to intermediate metaluminous magmas appears to require pressures in excess of those attainable in the crust (see later discussion). But in the final analysis, it is the lack of progressive changes in isotopic compositions and REE patterns correlated with bulk compositions that argues so strongly against assimilation-fractional crystallization as the process that produced these features. The possibility that assimilation or combined assimilation-fractional crystallization may have played some role in the development of

batholithic magmas or their sources is not ruled out, however. If these processes did occur, their action must have preceded the processes that led to the lithologic diversity in each region of the batholith and to the depleted and fractionated heavy REE patterns of the central and eastern region rocks. The above considerations also do not rule out the possibility (considered later) that crustal materials in some form were present within the source regions of the batholithic magmas or that they contributed in a significant way to these magmas.

To conclude discussion of high-level differentiation processes, factors other than fractional crystallization, assimilation, or any combination thereof acting on a common parental magma appear to have been responsible for the major REE and Sr isotopic variations across the Peninsular Ranges batholith. The processes of crystallization differentiation and assimilation are probably of only secondary importance in producing most of the lithologic diversity of the batholith.

Source region assemblages and heterogeneities

Overview and isotopic context

The inadequacy of upper crustal crystallization–differentiation and assimilation processes in explaining the regional REE trends suggests that the first-order REE characteristics of the batholithic magmas originated at deeper levels. REE abundances of the batholithic rocks reflect both the original REE endowments of the source materials and chemical fractionations accompanying the production and evolution of the batholithic magmas. An objective of the following discussion is to distinguish among these different influences. The Sr and O isotopic properties of the batholith are potentially useful in this regard because they are independent or nearly independent of chemical fractionation effects at magmatic temperatures. Consequently the Sr and O isotopic compositions of the batholithic magmas must have been inherited from their source materials (Early & Silver, 1973; Taylor & Silver, 1978; Silver *et al.*, 1979; Taylor, 1980) and the isotopic variations observed across the batholith must reflect varying source character and prehistory. The fact that tonalites with similar bulk compositions and initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios have, in some instances, very different Sr contents (e.g., compare Figs. 12 and 13) and Rb/Sr ratios is significant. It argues that compositionally and isotopically similar source materials have given rise to magmas with diverse abundances and ratios of parent–daughter elements. An attractive way of effectively decoupling Sr concentrations and Rb/Sr ratios from initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in the magmas is by inferring different residual mineral assemblages and possibly mineral proportions in otherwise similar source regions. For example, the observed trend in Sr abundances and Rb/Sr ratio across the batholith could be explained if the residual source mineralogy of the western tonalites retained appreciable Sr whereas the residuum of the central and eastern tonalites retained much less. The possibility that the REE variations across the batholith, as exemplified by the two REE transitions, are caused by differing residual mineral assemblages in the source regions is explored below.

Western–central REE region transition

The transition from the western to the central REE-defined regions of the batholith is marked by changes in the following properties: (1) a depletion and (2) fractionation in middle to heavy REE; (3) a disappearance of negative Eu anomalies in tonalites; (4) an increase in Sr contents of tonalites; and (5) a restriction in the diversity of lithologies. Importantly, the Sr isotopic variations appear to be independent of the rather sharply defined western–central regional transitions in the above properties. This observation suggests that the

discontinuities in REE characteristics are not related to differences in source characteristics as reflected by the isotopic variations.

The observation that five significant properties of the batholithic magmas undergo coupled changes strongly suggests these changes have a common origin. A single condition which would appear to satisfy the above observations is a phase transition in the residual mineralogy of compositionally similar source materials; from a plagioclase-bearing (gabbroic) assemblage in the west to a garnet-bearing, plagioclase-poor (eclogitic or garnet-amphibolitic) assemblage towards the east. The comparatively low Sr contents and high Rb/Sr ratios of the western rocks are adequately explained if a Sr-bearing phase (plagioclase) is retained in the residual mineralogy of the source of these rocks. The feldspars are the only major rock-forming minerals capable of storing Sr. As a corollary effect, the higher Sr contents of the central rocks reflect the elimination or marked reduction in abundance of feldspar in the residuum. The negative Eu anomalies of the western tonalites suggests the involvement of feldspar in the evolution of these rocks, whereas the absence of negative Eu anomalies in the tonalites of the central region is consistent with a much less important role for feldspar in their derivation. Although the anomalous behavior of Eu compared to the rest of the REE could be eliminated under sufficiently oxidizing conditions, the strong partitioning of Eu into batholithic feldspars from each of the REE regions (Gromet, 1979; Gromet & Silver, 1983) and the lack of consistent appreciable differences in Fe redox ratios between the western and central rocks (Silver & Chappell, in prep.) suggest that differences in oxygen activity did not give rise to the changes in Eu characteristics.

Compared to the nearly unfractionated relative heavy REE abundances of the western region rocks, the fractionated and depleted heavy REE patterns of the central region rocks require the involvement of a phase or phases that would preferentially fractionate as well as retain in abundance the heavy REE. The apparent unsuitability of accessory phases such as allanite and sphene to accomplish this has been discussed. Moreover, it is difficult to envision the quite variable and relatively small amounts of these phases or zircon as being responsible for the large and consistent fractionations observed between the western and central region. Although it is not present in the principal lithologies of the batholithic rocks, garnet is a major high pressure rock-forming mineral having the requisite REE properties (e.g., Schnetzler & Philpotts, 1970; Irving & Frey, 1978). Garnet is stable and could be volumetrically important constituent across the broad range of compositional systems describing the batholithic rocks and their plausible source materials at high pressures (Green & Ringwood, 1968; Green, 1972; Wyllie *et al.*, 1976). It is emphasized that the presence of garnet and disappearance of plagioclase in the sources of central region magmas are complementary inferences: both are needed to explain the REE and Sr variations and both imply formation of central region magmas under high pressure conditions.

The last property associated with the western-central REE region boundary—the transition from a multimodal to a unimodal frequency distribution of lithologies—lends support of a different and more speculative kind to the concept of a major change in the residual phase assemblages. The lithological diversity of each of the regions is expected to bear some relationship to phase equilibria controls on magma compositions. The sharp break in lithological diversity between the western and central regions is suggestive of a major modification or readjustment in those controls. Since observed phase assemblages in the western and central region rocks do not differ, it is inferred that the controlling factors reside at depth. The loss of plagioclase and the coming in of garnet in the residual phase assemblages might provide such controls because a change in the major phases present must cause some perturbation in the phase relations (e.g., position and number of cotectic surfaces, points of reduced variance). What remains to be shown is that melting of such different

assemblages can produce tonalitic magmas of similar bulk chemistry, as is required of any model for the batholithic magmas. A thorough evaluation of this appears beyond current understanding of the relevant petrological systems, but existing constraints from experimental and theoretical studies are explored in a following section.

Central-Eastern REE transition

This transition is defined by an increase in the abundances and fractionation of the light REE. Discontinuities in other parameters have not been recognized across the central to eastern region boundary. The discontinuity in ^{18}O variations across the batholith (Taylor & Silver, 1978) does not coincide with the central-eastern REE region transition, and there is not a discontinuity in the Sr isotopic variations. It is notable, however, that initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios and $\delta^{18}\text{O}$ values of eastern region rocks are always higher, greater than about 0.7050 and +9.0 per mille, respectively. A higher proportion of granodioritic lithologies is commonly observed in at least some parts of the eastern region, but this is not a sharp transition and it does not correlate to the position of the REE transition.

The features discussed above indicate that the nature of the central-eastern transition differs considerably from the western-central transition. A major change in residual mineral assemblages is not required or indicated by the observations. The generally more radiogenic Sr and heavier O isotopic compositions of the eastern rocks suggests that their source materials differed in some important compositional characteristics and prehistory from analogous materials in the central region. Similarly, the higher light REE contents of eastern rocks (a factor of 2 or 3 higher for Ce, compared to central region rocks) suggest that the eastern source regions were comprised of materials with higher light REE contents.

Petrogenetic considerations

A central constraint on petrogenetic interpretations of the batholithic magmas is that the regional changes in REE patterns and related properties are observed in rocks of essentially the same bulk composition (i.e. the tonalites). Whatever the causes of the regional variations, the source materials in each of the regions of the batholith must be capable of producing copious volumes of magma with tonalitic bulk chemistry. This provides some broad limits on the composition of the source regions. In the unlikely event of complete melting, the source must be at least as mafic as these compositions; for smaller fractions of melting, it must be more mafic. On the other hand, tonalites (and quartz gabbros) saturated with quartz and with $\text{Mg}/(\text{Mg} + \text{Fe})$ ratios of 0.5 to 0.4 cannot be derived directly from peridotite (e.g., Green, 1973). If the tonalites represent partial melts of their sources, the composition of the source is bracketed as being approximately basaltic. The relationships discussed at length previously indicate that the suite of batholithic magmas as a whole could not have acquired their REE and other features by differentiation of a common parental magma at crustal pressures, and there are no basalts or other magmas known in oceanic island arcs that have the strongly fractionated and depleted middle to heavy REE pattern that the magmas parental to the central and eastern rocks require.

The possibility that the tonalitic magmas of the batholith represent partial melts of basaltic composition sources can be addressed with two tests: does a basalt composition under the appropriate physical and chemical conditions yield partial melts that are tonalitic? Under the appropriate conditions, are tonalitic melts saturated in the phases expected as residual phases for a basaltic protolith? Available experimental studies provide some insights into these questions.

Numerous experimental studies on natural basalt compositions indicate that melts approaching the composition of the tonalites can be produced by hydrous partial fusion at

pressures under 10 kb (Green & Ringwood, 1968; Holloway & Burnham, 1972; Helz, 1973, 1976; Spulber & Rutherford, 1983). In the Holloway and Burnham and the Helz studies, H₂O-saturated and undersaturated experimental melts whose compositions most closely approach those of the tonalites coexist with amphibole, clinopyroxene, oxides, and sometimes olivine at temperatures of about 1000 °C with approximately 30 per cent melt present. These melts differ from the tonalites in being slightly more aluminous (18.6–19.9 per cent Al₂O₃) and very poor in MgO (0.2–0.9 per cent). In the Spulber & Rutherford study, H₂O-undersaturated tonalite-like melts coexist with plagioclase, clinopyroxene, olivine and sometimes oxides and low calcium pyroxene at approximately 950 °C for systems of tholeiitic composition. These melts are rather poor in MgO (0.8–1.8 per cent) but are otherwise close to tonalitic compositions of the batholith. The differences among these results appear to reflect differing starting compositions, fluid compositions and pressures.

Partial melting of basaltic material at high pressure (> 20 kb) under anhydrous and hydrous conditions also appears to result in melts of broadly tonalitic chemistry (e.g., Green & Ringwood, 1968; Stern & Wyllie, 1978), although reported determinations of actual melt compositions are so few that they hardly constitute a test of the hypothesis. Gill (1974) presented calculations based on high pressure experiments that demonstrate the feasibility of producing melts with the bulk chemistry of Fijian andesitic rocks (whose chemistry compares closely to some Peninsular Ranges tonalites and quartz gabbros) from hydrous eclogitic sources. The results of high pressure crystallization experiments on andesitic or tonalitic melts with 2–5 per cent H₂O (Green, 1972; Stern *et al.*, 1975; Stern & Wyllie, 1978) confirm that garnet and clinopyroxene coexist as near liquidus phases for these compositions.

From these experimental studies it is clear that both low pressure gabbroic (or amphibolitic) and high pressure eclogitic assemblages are candidate sources for the abundant tonalitic magmas of the batholith. The melting of eclogite has been disfavored as the origin of orogenic magmas such as andesite because experimental melts derived from eclogite are more siliceous than andesite (e.g., Stern & Wyllie, 1978) and nearly all andesites lack the strongly depleted and fractionated heavy REE patterns expected of eclogite-derived melts (e.g., Gill, 1974). The central and eastern REE region tonalites, however, are more siliceous than andesite and have the appropriate REE patterns (also see modeling in later discussion). Moreover, these tonalites have compositions that cluster closely about the garnet-clinopyroxene-quartz cotectic in the nearly dry 1/4 SiO₂-CaO-(MgO+FeO) pseudoternary system of Stern & Wyllie (1978), indicating they are suitable direct partial melts of eclogite or quartz eclogite. Stern & Wyllie (1978) have argued that the calculated equilibrium liquid paths for basalts and andesites at 30 kb diverge from the average chemical variation trend of typical calc-alkaline magmas, especially in terms of Ca/(Mg+Fe) ratio. This problem is not particularly relevant to the batholith, where the principal problem is not the production of a basalt-andesite-dacite suite by fractional crystallization but the production of abundant tonalites in each of the REE regions. Other issues remain to be resolved. For example, all reported specific examples of experimentally produced melts deviate to some degree from common tonalite compositions, especially under low pressure hydrous conditions where not all the melts have plagioclase on the liquidus. However, the plagioclase-absent low pressure experiments were conducted at fluid pressures that probably are higher than those for the H₂O-undersaturated batholithic magmas; lower fluid pressures in the experiments would increase residual plagioclase and reduce the excessively high Al₂O₃ contents in coexisting melts (Spulber & Rutherford, 1983; Rutherford *et al.*, 1985). Within the scope of their reasonable application, the experimental observations appear compatible with the contrasts in source region mineralogies inferred from regional REE and Sr concentration variations across the batholith.

Consideration of experimental studies on more siliceous magma compositions provides evidence that directly supports the changes in source region mineral assemblages inferred from the geochemical observations. The abundant siliceous leucogranodiorites of the Woodson Mountain type in the western REE region of the batholith have a chemistry in excellent agreement with melt compositions produced by small degrees of melting of hydrous basalt at low pressure (Holloway & Burnham, 1972; Helz, 1976; Spulber & Rutherford, 1983). A possible mode of formation of the leucogranodiorites is a smaller degree of low-pressure partial melting of the same basaltic source material that gives rise to the western tonalites at larger degrees of melting. In fact, the small degree of melting necessary to produce leucogranodiorite melts may be an important factor contributing to the larger variation in their REE contents (trace element fractionations are sensitive to small variations in mineral proportions and degree of melting at low melt fractions). In contrast to the melting of basalt at low pressures, small degrees of melting of basalt at high pressure do not appear to produce highly siliceous magma. High pressure crystallization experiments (hydrous and anhydrous) reveal that quartz is the only near liquidus major phase for rhyodacitic to rhyolitic melts (Green & Ringwood, 1968; Stern *et al.*, 1975), indicating such compositions cannot be the direct partial melts of basaltic source compositions at high pressures. The significance of this is that exactly where a transition from low to high pressure source region assemblages for the batholith has been inferred from the REE and Sr concentration data, the abundance of highly siliceous magmas drops drastically (Fig. 11).

The implications of this remarkable correspondence are considerable. Not only does the relative paucity of highly siliceous magmas in the central and eastern REE regions argue that such compositions were not generated at depth, but it also reinforces the earlier conclusion that low pressure differentiation and/or contamination processes did not produce an abundance of highly evolved magmas from more primitive ones. The low abundances of highly siliceous lithologies found in the central and eastern regions are indicative of the limited operational extent of crystal fractionation on a large reservoir of tonalite and low-K₂O granodiorite. This is consistent with the observation that an intermediate magma such as a tonalite will be characterized by relatively high viscosity and significant yield strength (e.g., McBirney & Murase, 1984), resulting in inefficient crystal settling (note that yield strength may greatly inhibit crystal settling even in systems much more mafic and less viscous than the batholithic magmas; see McBirney & Noyes, 1979; Irvine, 1980).

The above lends support to the possibility that the tonalitic plutons either represent or closely approximate primary magmas, derived directly from their sources with only limited differentiation enroute to emplacement. This inference is difficult to prove or disprove with existing data, but it is noted that tonalitic melts produced by melting of basaltic rock will have a large density contrast with residual solids and even sialic crustal rocks. Tonalite magma should rise relatively rapidly to upper crustal levels. Some crystallization will occur during ascent, and in some circumstances emplacement as a crystal mush is likely (e.g., Murray, 1979), but high viscosity and yield strength probably limit the extent of crystal-melt separation. In some large plutons, the effects of differentiation were also limited by intermittent recharge of the magma chamber during solidification and local internal mixing (Hill *et al.*, 1985).

Consequently, the peaks on the histograms of Larsen indices (Fig. 11) may identify primary or near primary magma compositions, with the small tails to higher silica compositions perhaps reflecting minor modification by low pressure differentiation. The development of slight negative Eu anomalies in some of the eastern magmas (Fig. 7) and their anticorrelated Rb-Sr concentration trends (Silver & Early, 1977; Hill, 1984) suggests this process involved the limited separation of plagioclase. Perhaps an expanding stability field for plagioclase

during the rise of magma through the crust kept plagioclase on the liquidus at the expense of other phases. The general uniformity of Sr and O isotopic compositions for all granitic lithologies within any small geographic area (Early & Silver, 1973; Taylor & Silver, 1978) argues strongly that significant assimilation of upper crustal components did not accompany any such low pressure differentiation process.

The multimodal frequency distribution observed in the western REE region seems to require an explanation other than fractional crystallization. An attractive way of generating a diverse suite of magmas with high relative abundances of particular compositions from a common source region is partial melting at pseudo-invariant points or points of reduced variance. Pseudo-invariant points are difficult to determine experimentally in complex natural systems, but Egger (1974) has delimited the position of some pseudo-invariant points within the synthetic system $\text{CaAl}_2\text{Si}_2\text{O}_8\text{-NaAlSi}_3\text{O}_8\text{-SiO}_2\text{-MgO-Fe-O}_2\text{-H}_2\text{O-CO}_2$ at low pressure. Precise applicability of these results to the batholithic rocks is uncertain, but melt compositions at some of the pseudo-invariant points are analogous to leucogranodiorite and tonalite compositions.

REE modeling

A final test of the inferred change from a lower pressure gabbroic or amphibolitic residual source assemblage in the western REE region to a higher pressure eclogitic (or garnet amphibolitic) residual source assemblage in the central and eastern REE regions can be made by constructing models of REE behavior during melting of these assemblages. Such models require several assumptions to be made about variables that are poorly constrained (e.g., trace element composition of starting materials, phase proportions, and distribution coefficients), and as a result the models lead to non-unique solutions. In light of this, the intent of the models presented below is simply to demonstrate that the REE patterns of the tonalites across the batholith are plausibly derived from melting of gabbroic, amphibolitic or eclogitic source materials; no attempt is made to fine tune parameters of the models to yield precise matches to observed rocks.

To be consistent with experimental data cited previously, the models below produce tonalite melts by 30 per cent melting of a basaltic source. The residual mineral assemblages are as follows: gabbroic: 60 per cent clinopyroxene, 40 per cent plagioclase; amphibolitic: 45 per cent hornblende, 25 per cent clinopyroxene, 30 per cent plagioclase; eclogitic: 60 per cent clinopyroxene, 30 per cent garnet, 10 per cent hornblende. Mineral proportions in the residual assemblages were guided by those found experimentally. Melting under equilibrium conditions is assumed, and calculations follow the simple batch melting equation of Shaw (1970). The REE pattern of the basaltic composition source is chosen as minimally fractionated at approximately 15 to 10 times chondritic levels, as appears common for the voluminous tholeiitic to high alumina arc basalts (Kay, 1977; Lopez-Escobar *et al.*, 1977) that probably constitute important source components of the batholithic magmas (see later discussion). Distribution coefficients appropriate for tonalitic melts are used (see Appendix). Distribution coefficients are subject to considerable uncertainty in absolute value but there is much less uncertainty in pattern shape, so the discussion below emphasizes pattern shapes.

Results of the model calculations are illustrated in Fig. 19A, B for the gabbroic/amphibolitic and eclogitic assemblages, respectively. The gabbroic residue yields a tonalitic melt with a REE pattern characterized by modest light-REE enrichment and a significant negative Eu anomaly. These essential features are in excellent agreement with the REE patterns of nearly all western REE tonalites. The amphibolitic residue yields a tonalitic melt with lower REE abundances, a pronounced relative depletion in the middle REE, and a small positive Eu anomaly. These features correspond closely to the REE pattern of one analyzed western

tonalite (see sample 18, Fig. 4). Inasmuch as water pressure largely determines whether a residual assemblage will be gabbroic or amphibolitic, these results suggest the possibility that western region sources were dominantly gabbroic but locally wet enough to be amphibolitic. The eclogitic residue yields a tonalitic melt with a very strongly fractionated REE pattern. Lightest REE contents equal those of the gabbro-derived tonalite, but heavier REE contents are drastically lower and a small positive Eu anomaly is present. These features are in very good agreement with the REE patterns of central region tonalites and low- K_2O granodiorites.

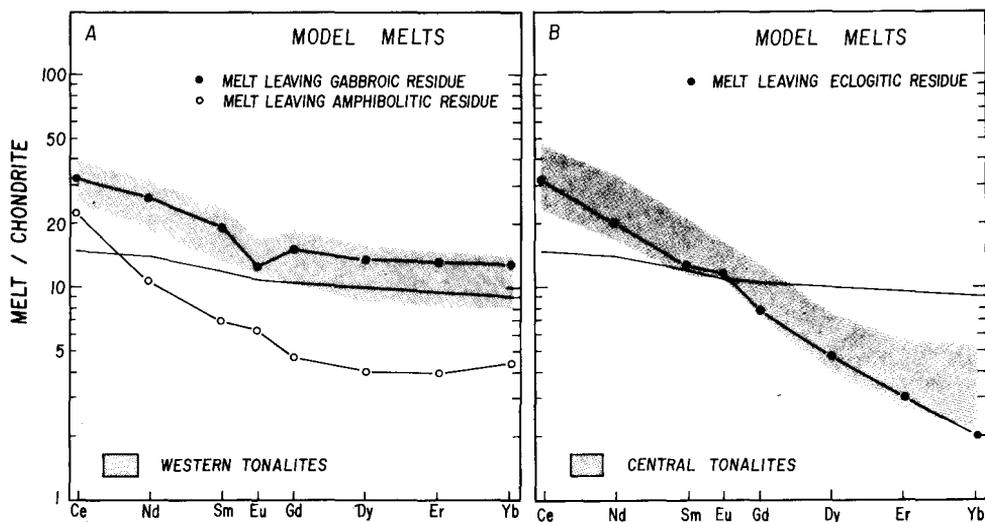


FIG. 19. (A) REE patterns of modal tonalite melts produced by 30 per cent melting of basaltic source materials at low pressure. REE pattern of basaltic source (line without symbols at 10–15 times chondritic levels) is typical of tholeiitic to high alumina arc basalts. Gabbroic residue consists of 60 per cent clinopyroxene and 40 per cent plagioclase. Amphibolitic residue consists of 45 per cent hornblende, 25 per cent clinopyroxene, and 30 per cent plagioclase. The field for western tonalites is shown for comparison. (B) REE patterns of model tonalite melts produced by 30 per cent melting of basaltic source materials at high pressures. Basaltic source material is the same as in Fig. 19A. Eclogitic residue consists of 60 per cent clinopyroxene, 30 per cent garnet, and 10 per cent hornblende. Field for central region tonalites is shown for comparison.

These results demonstrate that basaltic sources with the different residual assemblages produced in experimental studies over a range of pressures are capable of producing tonalitic melts with REE patterns closely corresponding to those of the western and central region tonalites. Even more precise fits to specific patterns could be obtained through minor manipulations of mineral proportions, melting proportions, distribution coefficients, REE patterns of starting materials and other parameters, but the lack of measured guiding constraints reduces this effort to tinkering. Variation in these parameters could account for much of the second order variations in REE patterns observed within each region. For example, f_{H_2O} will control the proportion of amphibole to anhydrous phases and therefore exert influence on the REE patterns of derived melts. This is illustrated for the case of the gabbroic and amphibolitic assemblages (Fig. 19A), but it applies as well to the eclogitic assemblage if a higher f_{H_2O} induces a higher proportion of hornblende.

None of the models shown in Fig. 19 produce melts with the strong light REE enrichment found in the eastern region tonalites. The light REE are already largely excluded from both

the gabbroic and eclogitic assemblages, so it is unlikely that melts with much higher light REE contents could be obtained from them without appealing to much smaller degrees of melting or to a light REE enriched source. The similarity in the bulk composition (including alkali elements K and Rb) of all the tonalites suggests that source bulk composition and degree of melting were broadly equivalent. Higher light REE contents in the eastern sources appear to be required, and could indicate the presence of basaltic components with more strongly light REE-enriched patterns (as are common in evolved island arcs and continental regions) or other non-basaltic components (see later discussion). Correspondingly, the flatter REE patterns of the San Telmo pluton in the extreme western region may have had sources dominated by light REE poor materials such as tholeiitic arc basalts or mid-ocean ridge basalts.

To conclude, the above simple models adequately reproduce the observed batholithic REE patterns although these solutions are far from unique. It should be recognized, however, that the simple models based on basaltic protoliths are consistent with and, in fact, have emerged from the bulk compositional constraints on the petrogenesis of the batholithic magmas.

Summary

The principal lithologies of the batholith appear to have formed by the partial melting of broadly basaltic source regions at progressively greater depths eastward. This may have been followed by limited low pressure fractional crystallization but without high-level assimilation. Different residual mineral assemblages in equilibrium with the melt and somewhat different source compositions appear to have provided the dominating influence on the distinctive western-central and central-eastern REE region transitions, respectively. Integration of observations on REE with other geochemical and petrologic characteristics and experimental studies establishes the plausibility of a gabbroic-amphibolitic source residual mineralogy for the western region magmas and an eclogitic-garnet amphibolitic source residual mineralogy for the central and eastern region magmas. The change from low to high pressure assemblages appears to explain why several different and presumably independent parameters undergo coupled transitions at the western-central region boundary. These transitions do not correlate directly to variations in isotopic properties, indicating the change in residual phase assemblages was superimposed on source regions already zoned in $^{87}\text{Sr}/^{86}\text{Sr}$, ^{18}O , and light REE abundances.

Constraints on a physical model for production of the batholithic magmas

Location and thermal requirements of the source regions

The mineral assemblages inferred for the source regions place important constraints on their depth. Plagioclase feldspar is present in significant abundance in a supersolidus assemblage of basaltic bulk composition at pressures no higher than 10–15 kb, providing a maximum depth of 30–45 km for melting in the western source regions. The eclogitic assemblage of the central and eastern sources requires depths greater than 45 km and most probably greater than 60 km. The present maximum crustal thickness as averaged seismically along the length of the peninsula is 25 ± 4 km (Thatcher, 1972; Hearn, 1984). Many geologic and petrologic features in the western Peninsular Ranges (e.g., volcanic constructs, numerous miarolitic cavities, low grade of regional metamorphism) suggest that no more than a few kilometers of crust have been eroded near the coastal part of the batholith since emplacement. In the east, a deeper exposed level of emplacement (Gastil *et al.*, 1975) and much higher grade metamorphic assemblages (Theodore, 1970; Hill, 1984) indicate

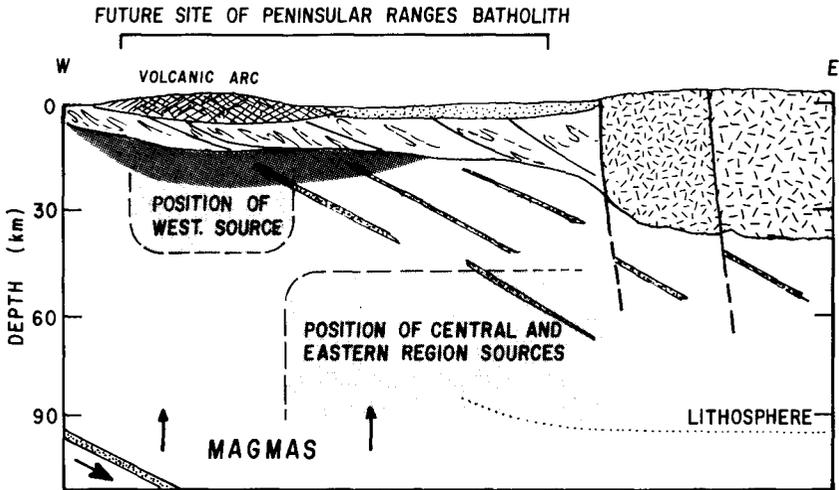


FIG. 20. Inferred lithospheric structure early in the development of the Peninsular Ranges batholith, with inferred depth limits shown for the later generation of batholithic magmas. Prebatholithic crustal rocks consist of a deformed sedimentary wedge and arc volcanics. The wedge is composed of Mesozoic and Paleozoic accretionary and perimeter apron sediments, all lying west of and in fault contact with the craton. The lithosphere beneath the wedge contains ancient slabs of oceanic crust (shown schematically) accreted in earlier cycles of subduction. An upper Jurassic-Cretaceous volcanic arc is built on the wedge, shedding debris into a back arc basin (light stipple). A basaltic underplate (dark shading) is shown in its early stage of development. The underplate thickens and expands eastward as evolution of the arc proceeds. A very thick underplate is needed to reach the inferred depths of the central and eastern REE region sources, or the underplate must convert to eclogite in the subsolidus and sink to the inferred depths.

10–15 km of crust has been removed. Restoration of eroded material suggests *post*-emplacement crustal thickness of about 15–30 km for the western region and 35–40 km for the eastern region. True pre-magmatic arc crustal thicknesses must have been much lower than these figures as the emplacement of the batholith itself and its volcanic cover constituted a major addition of material to the crust. The above estimates of source region depth and crustal thickness place the sources largely if not entirely below the base of the crust for all regions of the batholith we have studied (Fig. 20).

Based on these depths and the temperature needed to generate common batholithic magma (approximately 1000 °C or higher for H₂O-undersaturated tonalite and low-K₂O granodiorite melts), geothermal gradients of at least 30 °C km⁻¹ for the western region and about 20 °C km⁻¹ for the central and eastern regions are inferred. These are reasonable for a magmatic arc environment, but higher than gradients observed in stable environments. It would appear that substantial quantities of heat were transported into the source regions from below, the most plausible heat transport agent being mantle-derived arc basalts.

Consideration of the role of convergent plate motion

The increasing depth to the source regions from west to east is suggestive of the asymmetry associated with subduction zones. Thermal models of convergent zones show that the basaltic crust of a subducted slab will not be within its melting range at the depths indicated above (e.g., Turcotte & Schubert, 1973) and indeed may not attain melting at much greater depths (B. Hager, pers. comm.). Consequently the slab cannot be a major source region constituent. Mafic magmas derived in the vicinity of the subduction zone by fluxing the overlying mantle with slab-derived volatiles, or perhaps at higher levels by adiabatic decompression melting of rising hydrated mantle diapirs spawned from the mantle above the

slab (e.g., Nicholls & Ringwood, 1973; Marsh, 1979; Gill, 1981; Tatsumi *et al.*, 1983), could be major contributors to the source regions of the batholithic magmas. Mafic magmas derived from the mantle wedge and their differentiates appear to be the dominant eruptives in oceanic arcs and some continental margin magmatic arcs (e.g., Gill, 1981; Lopez-Escobar *et al.*, 1977), but mafic magmas intruded into a continental margin environment may tend to be arrested near the crust-mantle boundary (e.g., Gill, 1981; Hertzberg *et al.*, 1983). Mafic magma underplating the crust will deliver a great deal of heat and material into this region and may mix with pre-existing upper mantle and lower crustal materials. Perhaps this is the major process by which the fertile, basalt-rich source regions of the batholithic magmas formed.

The mantle-derived heat and material contributed by subduction-related magmatism offer a reasonable explanation of the arc-like distribution of the batholithic magmas. However, a major problem for any petrogenetic model of the batholith, whether it be based on subduction zone magmas or magmas produced at a higher level, is the abrupt nature of the western-central REE transition. This transition reflects the conversion of gabbro or amphibolite to eclogite or garnet amphibolite, which are progressive, sliding reactions occurring over considerable P - T space and passing through intermediate garnet-bearing assemblages such as garnet granulite and garnet-poor amphibolite. Derivative magmas should show a corresponding smooth progressive change in REE and related properties. The fact that they do not indicates that a mechanism is needed for producing magmas at abruptly varying depths (see Fig. 20). Moreover, the emplacement ages of western and central region rocks partially overlap, requiring simultaneous production of magmas at varying depths.

The abrupt transition to eclogitic sources suggests the possibility of a process driven by a density instability. Eclogite is a denser assemblage than any mantle peridotite and will sink through it if mantle viscosity allows. To initiate the process, basaltic material must be at pressures high enough to stabilize an eclogitic assemblage near its solidus. A possible scenario is to thicken the crust under and adjacent to the site of the static arc by addition of subduction-derived mafic magmas from depth. Mafic magmas stalled near the base of the crust solidify because ambient temperatures initially are low, but continued introduction of hot basalt warms and thickens the region. New additions of basaltic magma rise through denser previously solidified basalt, heating it and displacing it downward. Once a portion of the thickened mafic crust is at depths great enough to convert to eclogite (> 45 km), further heating and sinking can lead to the production of tonalitic magma. Some features of the batholith appear to support a density-driven process. For example, the sharp increase in observed volumes of intrusive rock in the central REE region relative to the western region and a shorter emplacement interval indicate much higher magma generation rates. This is plausibly related to the catastrophic foundering and melting of a large mass of mafic material that accumulated beneath a low density crust.

It is probably significant that the transition in space-time emplacement style of the batholith, from static emplacement arc in the west to transgressive emplacements in the east, closely follows the western-central REE transition for much of its observed length. This implies some dynamic control on REE characteristics, with the static arc tapping relatively shallow sources and the transgressive arc sampling deeper eclogitic sources as emplacements migrated. The cause of the eastward migration of the transgressive arc and why its initiation appears to have been tied in space and time to the generation of eclogite-derived magmas remain as outstanding problems. Migration across the width of the peninsula could have arisen simply from an away-from-trench migration of arc activity as has been observed in some island arcs as they mature (Gill, 1970). Alternatively, the migration may have been driven by propagation of a density instability, such as progressive delamination (Bird, 1979)

of dense eclogitic components in the lower lithosphere. These and other possibilities are being addressed in ongoing studies.

Source materials

The source regions of the batholith must contain contributions from a variety of materials in order to give rise to the range of isotopic and other properties found within the batholithic rocks. Characteristics of the source materials that must be explained include their broadly basaltic composition, the zonation (west to east) in isotopic properties and light REE contents, and the broad co-variation of Sr, Nd, and O isotopic compositions within their west to east gradients.

The major if not dominant constituents of the batholithic source regions probably were arc basalts derived from the mantle overlying the subduction zone. Such basalts may have risen and underplated the crust, where they were available as source materials as evolution of the arc proceeded. An important aspect of the mantle-derived magmas is that their geochemical and isotopic properties were likely to have been variable. They are inferred to correspond to those of the range of basalt types found in active convergent arcs, including the tholeiitic, high alumina and perhaps alkali olivine basalt types sequentially arranged across the arc. A notable feature of many of these basalts, even the tholeiitic types, is that they are variably enriched in many large ion lithophile elements compared to normal mid-ocean ridge basalts (e.g., Perfit *et al.*, 1980b). The origins of the petrological and geochemical features of these magmas and their arrangement in the arc continues to be the subject of debate (see recent discussions by Lopez-Escobar *et al.*, 1977; Kay, 1980; Gill, 1981; Morris & Hart, 1983; Tatsumi *et al.*, 1983), but the principal concern here is simply that such magmas or their immediate parents are produced within the mantle overlying an active subduction zone and rise upward to underplate the crust. The light REE contents of the tholeiitic, high alumina, and alkali olivine basalts found in oceanic island arcs vary over an order of magnitude, with REE patterns ranging from light REE depleted to strongly light REE enriched (see summary in Arth, 1981, for example). The zonal arrangement of these basalt types across an arc may have contributed to the regional variations in the light REE contents and fractionations observed across the Peninsular Ranges batholith. In contrast, the heavy REE depleted and fractionated patterns of central and eastern region magmas are unlikely to have been inherited from basaltic source rocks as such features have yet to be identified in arc basalts.

Some of the isotopic variations observed across the batholith also may have been inherited from the arc basalts. The isotopic compositions of the basalts themselves are inherited from the mantle over the subduction zone plus possible contributions from slab components. The mantle underlying and marginal to southwestern North America in the Cretaceous was structurally complex, reflecting earlier accretionary events and large-scale lateral displacements of lithospheric blocks along megashears earlier in the Mesozoic (Silver & Anderson, 1974; Anderson & Silver, 1979). The mantle beneath the peninsular region of the batholith was not subcratonic, but there is little reason to expect that it was composed only of depleted MORB-like mantle peridotite with relatively unradiogenic Sr and radiogenic Nd isotopic compositions. However, peridotitic mantle of any type appears incapable of providing the high ^{18}O values found in batholithic rocks in the eastern Peninsular ranges.

The high ^{18}O values in the eastern rocks must reflect the presence of source components exposed to weathering or alteration near the earth's surface (Taylor & Silver, 1978; Silver *et al.*, 1979). Possible high- ^{18}O sources are altered oceanic basalts (which acquire, among other features, $\delta^{18}\text{O}$ values locally as high as +12 per mille during low temperature alteration processes: Magaritz & Taylor, 1976; Gregory & Taylor, 1981; McCulloch *et al.*,

1981), and oceanic, continental margin, or accretionary prism sediments. Cratonic rocks can be ruled out because the peninsular part of the batholith formed to the west of the craton, intruding metasedimentary rocks of the perimeter apron and earlier accretionary events (Fig. 20).

A sedimentary component within the source regions of the batholith could significantly modify light REE abundances and Sr, Nd, and O isotopic properties, and could possibly explain the broad co-variation of isotopic properties across the batholith (Taylor & Silver, 1978; DePaolo, 1981). There are, however, several important constraints on the participation of sedimentary rocks that deserve emphasis here. The batholith is fundamentally an I-type granitic suite (Chappell & White, 1974; White & Chappell, 1983; White *et al.*, 1986). The sedimentary component must be of a calcic chemistry or low enough in abundance such that the overall source composition remains capable of producing the calcic magma compositions that are characteristic of the batholith. The dominance of tonalites and low-K₂O granodiorites across the batholith, even in its more easterly ranges, argues against a major change in the bulk composition of the source regions. The small to nil increase in K and Rb contents of the eastern tonalites further argues that the sedimentary component, by virtue of its composition or low abundance, provided no more than minor increases in alkali element abundances in the eastern source regions. Volcanogenic sediments and greywackes are the most plausible sediment types. The fact that even the least evolved granitic magmas of the eastern region, the tonalites, share in the same REE and isotopic properties characteristic of all eastern magmas argues that the sedimentary component must be distributed within the source regions in such a way that it contributed equally to all derived magmas.

A problem with the presence of sedimentary materials within the source regions is that the source regions were located at depths exceeding the base of the sialic crust, especially for the central and eastern part of the batholith (Fig. 20) where the largest contributions of high-¹⁸O material are needed. If the sedimentary materials were derived from the lower crust, they would have to have been displaced downward during the thickening of the crust by mafic arc magmas. Alternatively, subcrustal sedimentary material may be available in the form of subducted sediment in several different sites within an active continental margin environment. Small proportions of subducted sediment carried with the descending slab can contribute various crustal components to arc magmas, including heavy O, as has been demonstrated in intra-oceanic and continental margin settings (e.g., Armstrong, 1971; Kay *et al.*, 1978; Magaritz *et al.*, 1978; White *et al.*, 1985). Such deeply subducted sediment may have contributed crustal components to magmas in the Peninsular Ranges, although it seems highly unlikely that these components could have given rise to the large, regionally systematic variations observed in the batholith. Karig & Kay (1981) have noted, however, that most of the sedimentary cover on a subducting slab is subcreted (transferred) to the upper plate, some coming to rest at depths as great as 20–30 km. Although subcreted sediment cannot contribute to arc magmas forming concurrently (active subcretion occurs well trenchward of the active arc), a continental margin that has been the site of subduction of oceanic crust in the past will have oceanic basalts and subcreted sediments as subcrustal constituents of its lithosphere. Such is probably the case for Cretaceous western North America (Fig. 20). It appears likely that the successive accretion of oceanic slabs—including their basaltic components and remnants of their sedimentary caps—played a significant role in the development of the lithosphere in this region (Silver, in prep.). The subcreted sediments enjoy a close spatial relationship to the more abundant basaltic materials in the slab crust and therefore could be expected to contribute fairly uniformly to melts derived from the ancient slab. If altered basalts and sediments associated with previously subducted slabs have contributed to the isotopic properties across the batholith, the regularity of the

regional isotopic variations require greater proportions of such materials eastward. As discussed previously, melting of these lithospheric components must be initiated by addition of heat and material from below via rising mantle diapirs or mantle-derived basalts.

To summarize, numerous mantle and crustal reservoirs potentially have contributed to the formation of the batholithic magmas. To the extent that the mantle above the subduction zone varied from depleted on the west to less depleted and possibly enriched mantle on the east, basalts derived from this mantle have contributed to the Sr and Nd isotopic and light REE variations inferred for the source regions of the batholith. Previously existing basaltic components in the lithosphere, depending on their origin and age, also could have contributed to these variations, and to the observed O isotopic variations. An additional crustal reservoir in the form of sedimentary rocks may be needed, but they cannot constitute a large fraction of the source volume of any batholithic magma unless the sediment is largely of igneous parentage.

IMPLICATIONS FOR GROWTH AND EVOLUTION OF THE CONTINENTAL CRUST

Modern plate tectonic theory suggests that magmatism at convergent plate boundaries has played an important if not dominant role in the growth and evolution of the continents. It is generally believed that differentiation of the mantle ultimately leads to production of the continental crust, although there is hardly a consensus on the range of processes that may be involved, much less their details. In considering how differentiation of the mantle ultimately results in the growth of continental crust at convergent boundaries, much emphasis has been given to intraoceanic island arcs where continentally derived material cannot be directly involved, save for small amounts of subducted sediments. Early petrologic models of arc magmatism (e.g., Green & Ringwood, 1968) called for a two-stage evolution from the mantle, with formation of basaltic oceanic crust at mid-ocean ridges and remelting of oceanic basalt in subduction zones to yield andesite. Although attractive in many regards, this type of model became increasingly difficult to accept as it was realized that the predominant eruptives in many oceanic arcs are not andesites but basalts and basaltic andesites (e.g., Jakes & Gill, 1970; Ewart *et al.*, 1973), and that island arc magmas probably do not originate by melting of oceanic crust in subduction zones (see extensive summary of the problem by Gill, 1981). Consequently, more recent models to consider the role of arc magmatism in continental growth view arc magmas as being mantle derived and basaltic, with some recycling of pre-existing crustal components occurring through the subduction zone (e.g., Armstrong, 1981; Kay, 1980). In the case of continental margin batholiths, extensive contamination of arc basalts within the crust has been proposed (DePaolo, 1981).

If intraoceanic arc magmas are viewed as being representative of the mantle-derived component in all convergent arcs, the net new addition of material to the crust by the process is basaltic in composition. As recognized by Kay (1980) and Anderson (1982), unless some process exists for extracting a silicic component and returning the residue to the mantle, arc magmatism is causing the continental crust to become more mafic with time, and formation of sialic continental crust must have been achieved by processes other than arc magmatism or any process producing mantle-derived basalts. Arculus (1981) has noted some additional difficulties with crustal models based on immature oceanic arcs.

The results and interpretations of the present study provide an important new perspective on this problem. It is argued that the magmatic products of evolved magmatic arcs, to the extent that they are represented by the Peninsular Ranges batholith, differ from less mature oceanic arc magmas not because of contamination, but because arc basalts intrude to different levels in each environment. In oceanic arcs, basalt is able to rise through a thin

mafic crust and is largely extruded. Small high-level magma chambers produce minor quantities of more differentiated lavas from the abundant basalts. In contrast, observations in a batholithic arc such as the Peninsular Ranges batholith point to an origin by melting of predominantly basaltic source regions that accumulated beneath a low density crust.

Most magmas in modern continental margin magmatic arcs (e.g., the Aleutians and the Andes) are high alumina basalts and basaltic andesites that are mantle-derived melts or their differentiates. There appears to be little evidence for magmas representing melts of basaltic materials. Many of the subordinate andesites and other more siliceous magmas in these regions are probably low pressure differentiates of the more mafic magmas (e.g., Lopez-Escobar *et al.*, 1977; Kay *et al.*, 1978; Thorpe *et al.*, 1982; Kay & Kay, 1985). However, andesites with REE patterns distinctively fractionated and depleted in the heavier REE occur in the Cascades (Halliday *et al.*, 1983) and in the central Andes (Thorpe *et al.*, 1976; Lopez-Escobar *et al.*, 1977; Whitford, 1977) where a thick crustal (basaltic?) root exists. These magmas could be high pressure melting products of predominantly basaltic materials formed in a manner analogous to that suggested for the Peninsular Ranges. Perhaps more importantly, Lopez-Escobar *et al.* (1979) have recognized a suite of plutons in the batholith of central Chile that also share these characteristics. This observation is quite significant because a very high proportion of the Mesozoic to Recent magmatic activity in the Andes appears to be plutonic, not volcanic (Thorpe *et al.*, 1981). If this can be extended as a general observation for intermediate to silicic magmas (Shaw, 1985), the batholithic components of exposed continental margin magmatic arcs deserve predominant consideration in models of continental growth (also see Weaver & Tarney, 1982).

Therefore, the formation of the Peninsular Ranges batholith may be representative of a major differentiation process in which mantle-derived basalt is remelted and contributes its silicic fraction to the continental crust and so augments the crust. The basaltic source materials are in large part new additions from the mantle, but potentially include older additions such as ancient oceanic crust previously subcreted to the continent. If an origin by melting of basalt is shared by significant portions of other Cordilleran batholiths—as seems likely given the overall similarities among many circum-Pacific batholith belts, the dominance of intermediate lithologies such as tonalite and granodiorite, and the more felsic compositions of all these rocks as compared to less mature oceanic arcs (e.g., Reed & Lanphere, 1973; Pitcher, 1978; Aguirre, 1983; Roddick, 1983)—then it appears that evolved continental margin magmatic arcs differ fundamentally from immature oceanic arcs in that a configurational environment conducive to the subcrustal accumulation and remelting of basalt is provided in the mature arcs.

A feature critical to the role of this process in continental growth is the fate of the residues. Because the basaltic reservoirs are principally subcrustal, partial melting leaves most of the mafic to ultramafic residues in the lithospheric upper mantle. Furthermore, if sinking of eclogitic residues or delamination of the lithosphere occurs, the residues are actually returned to the deeper mantle. In this manner, the more felsic components of the basaltic contributions from the mantle are extracted and added to the crust, preserving its more felsic character, while the residues of the basaltic additions founder and are denied incorporation into the crust. In this sense, much of the basaltic additions from the mantle to the base of the crust are metastable.

To conclude, remelting basalt in evolved magmatic arcs is probably a basic process in the growth and evolution of the continental crust. Whether a model of real continental growth from the mantle (e.g., Moor bath, 1978) or a model of steady-state, no-net continental growth (e.g., Armstrong, 1981) is advocated, new silicic additions to the crust are required. This need is fulfilled by the petrogenetic scheme identified in the Peninsular Ranges batholith, but not

by that identified in immature oceanic island arcs. The general observation that most ancient orogenic belts contain higher proportions of intermediate composition granitic plutons than basalts and gabbros suggests that the processes that give rise to continental margin magmatism have been much more effective at adding to the continents than those that give rise to oceanic island arc magmatism. It is relevant to note that even in the Archean, extensive tracts of intermediate composition granitic magmas similar in many regards to those in the Peninsular Ranges appear to have formed by melting of basaltic protoliths in both granulitic and eclogitic facies (e.g., Arth & Hanson, 1975; Hanson, 1981). While the tectonic environment in which these magmas formed probably differed somewhat from modern convergent boundaries, the observations indicate that remelting of mantle-derived basalt produced rather similar rocks regardless of age. Consequently, remelting of basalt in various tectonic environments may be a necessary and fundamental process for the generation of sialic continental crust throughout much of earth history.

ACKNOWLEDGEMENTS

This work was drawn from a portion of the senior author's doctoral dissertation done at the California Institute of Technology under NSF grants EAR74-00155 and EAR76-23153 and DOE grant EY-76-G-03-1305 to L. T. Silver. The senior author acknowledges the National Science Foundation for support under a Graduate Traineeship and an Energy Related Graduate Fellowship. Preparation of this manuscript was partially supported by NSF grant EAR82-06659 and by Brown University.

We thank B. W. Chappell, H. P. Taylor, Jr., the late A. K. Baird, T. O. Early, J. D. Murray and R. I. Hill for many discussions during the course of this study. We are indebted to Chappell for kindly providing some major element analyses and to Baird for providing early access to his extensive set of chemical analyses. The manuscript has benefited from early reviews by Hill, Paul Hess, Mac Rutherford, and Bruno Giletti. Journal reviews by F. A. Frey and M. A. Lanphere are sincerely appreciated. Lisa Sheehan's skill on the word processor was invaluable. Contribution 4349, Division of Geological and Planetary Sciences, California Institute of Technology.

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APPENDIX

Major element compositions of representative tonalites

Sample	Western Region		Central Region		Eastern Region	
	1	2*	40*	32*	51*	42*
SiO ₂	63.11	61.16	62.99	62.23	61.07	63.27
TiO ₂	0.73	0.69	0.72	0.89	0.99	0.95
Al ₂ O ₃	16.50	17.19	17.53	17.89	17.51	16.76
Fe ₂ O ₃	1.09	1.16	1.25	0.70	1.45	0.90
FeO	4.28	4.56	2.87	3.86	3.44	3.59
MnO	0.08	0.10	0.07	0.07	0.05	0.06
MgO	2.48	2.52	2.14	1.95	2.16	1.74
CaO	5.72	6.14	5.40	6.04	5.66	5.27
Na ₂ O	3.42	3.12	4.44	3.95	3.89	3.83
K ₂ O	1.69	1.87	1.48	1.36	1.75	1.86
P ₂ O ₅	0.15	0.11	0.16	0.20	0.26	0.22
H ₂ O ⁺	0.81	0.89	0.63	0.75	1.02	0.90
Total	100.06	99.50	99.68	99.87	99.25	99.35

* Analyses provided by B. W. Chappell.

Rare earth element concentrations in p.p.m.

Sample No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Ce	28.5	25.3	53.6	10.3	46.9	8.91	26.4	23.3	29.16	34.2	33.6	28.0	28.0	31.4	28.1	4.78
Nd	16.8	16.5	21.5	6.92	22.8	5.95	16.2	15.0	15.85	21.5	21.4	14.4	19.4	9.68	16.14	6.27
Sm	4.13	4.20	3.71	1.87	4.84	1.59	4.14	4.04	3.80	5.25	5.14	3.44	4.70	2.04	3.98	2.02
Eu	1.12	1.05	0.675	0.731	0.749	0.918	1.07	1.06	0.973	1.15	0.995	0.730	1.24	0.590	1.012	0.863
Gd	4.32	4.49	3.28	2.26	4.35	1.87	4.60	4.63	4.04	5.30	5.50	3.99	4.72	1.99	4.45	0.225
Dy	4.27	4.52	3.08	2.37	3.91	1.95	4.79	5.05	4.12	5.08	5.64	4.41	4.22	2.13	4.57	1.80
Er	2.56	2.69	1.82	1.44	2.02	1.17	2.90	3.13	2.49	2.83	3.24	2.96	2.27	1.26	2.79	0.854
Yb	2.37	2.52	1.70	1.32	1.92	1.10	2.74	3.05	2.33	2.53	2.95	3.13	1.96	1.36	2.70	0.639
Sample No.	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
Ce	43.0	22.4	48.8	32.0	64.1	20.0	13.9	17.9	29.7	11.9	10.2	17.0	8.60	22.2	18.27	32.0
Nd	22.3	11.2	21.7	18.4	40.1	12.4	12.0	14.3	28.5	9.12	7.83	12.85	7.47	19.1	9.91	18.3
Sm	4.81	2.53	4.69	4.41	9.83	3.29	5.81	4.34	7.23	2.71	2.34	3.72	2.57	5.25	2.11	3.97
Eu	0.974	0.923	1.02	1.07	1.63	0.82	0.737	1.18	1.12	0.955	0.841	1.53	7.20	1.65	0.947	1.19
Gd	4.99	2.69	4.99	4.77	10.6	3.79	5.09	5.55	8.24	3.45	2.88	4.61	3.44	6.22	1.92	3.42
Dy	5.10	2.73	5.35	4.53	12.8	4.20	6.56	6.55	8.79	4.07	3.26	5.02	4.31	6.56	1.44	2.44
Er	2.93	1.67	3.41	2.67	8.35	2.66	4.57	4.30	5.60	2.78	2.10	3.15	2.89	4.24	0.689	1.11
Yb	2.47	1.68	3.43	2.49	8.61	2.69	4.50	4.25	5.34	2.70	2.05	3.01	2.89	4.17	0.594	0.899
Sample No.	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48
Ce	32.3	38.0	37.3	36.8	5.15	16.0	19.5	37.6	32.3	55.5	88.3	2.30	62.8	61.8	103	64.5
Nd	15.8	18.3	16.0	15.8	5.62	10.1	11.3	19.8	14.6	24.7	37.1	1.48	24.5	33.6	41.8	25.0
Sm	3.30	3.66	2.81	2.71	2.02	2.31	2.32	3.86	2.59	4.05	6.53	0.408	4.02	7.04	7.42	4.32
Eu	1.06	1.06	0.910	0.873	0.897	0.954	0.792	1.12	0.874	0.995	1.53	0.295	1.07	1.51	1.55	1.07
Gd	2.97	3.00	2.25	2.15	2.64	2.24	1.92	3.17	1.97	2.92	4.90	0.480	3.03	5.99	6.13	3.46
Dy	2.38	2.14	1.54	1.50	2.60	1.87	1.43	2.29	1.27	1.96	3.18	0.482	1.99	4.85	4.68	2.63
Er	1.20	0.956	0.718	0.709	1.33	1.00	0.737	1.11	0.586	0.928	1.45	0.264	0.843	2.35	2.37	1.32
Yb	1.11	0.835	0.629	0.630	1.02	0.911	0.666	0.959	0.470	0.686	1.16	0.222	0.633	1.93	2.04	1.12
Sample No.	49	50	51	52	53	54	55	56	A*	B†	C1‡	C2‡	C3‡	D§		
Ce	105.2	51.0	102.6	67.7	67.8	75.2	57.3	40.9	71.8	48.0	54.0	53.4	53.8	0.813		
Nd	42.2	25.2	45.4	27.2	38.7	26.9	24.3	15.3	38.3	35.1	29.3	29.1	29.4	0.597		
Sm	7.05	4.69	6.16	5.15	7.67	4.25	3.95	2.57	7.24	9.93	6.61	6.53	6.69	0.192		
Eu	1.64	1.205	1.65	1.25	1.75	1.10	1.09	0.789	1.20	2.51	1.97	1.94	2.01	0.072		
Gd	5.42	3.55	4.08	4.37	6.40	2.83	2.80	2.07	5.72	11.8	6.87	6.63	6.93	0.259		
Dy	3.77	2.21	2.50	3.35	5.07	1.57	1.66	1.48	3.14	12.1	6.37	6.35	6.41	0.325		
Er	1.75	0.917	1.01	1.59	2.51	0.529	0.674	0.714	1.38	6.44	3.75	3.68	3.75	0.213		
Yb	1.44	0.730	0.761	1.34	2.14	0.368	0.532	0.602	1.38	4.93	3.36	3.29	3.41	0.208		

REE PATTERNS OF PLUTONIC ROCKS

* A: Metasediment, French Valley formation, Riverside County, California. † B: Volcanic sandstone, San Jose area, Baja California. ‡ C1-C3: Replicate analyses of USGS standard BCR-1. § D: Normalizing values.

Rock type and location of analyzed samples

<i>Sample</i>	<i>LTS no.</i>	<i>Rock type</i>	<i>Lat.</i>	<i>Long.</i>
1	5	hb-bio tonalite	33°49.5'	117°16.9'
2	17	hb-bio tonalite	33°46.9'	117°08.6'
3	20	bio leucogranodiorite	33°27.7'	117°08.2'
4	116	hb gabbro	33°27.4'	117°02.0'
5	31	bio leucogranodiorite	33°26.0'	116°55.9'
6	21	pyrox gabbro	33°22.3'	117°02.6'
7	18	qtz gabbro	33°13.9'	117°11.2'
8	32	bio-hb tonalite	33°13.7'	116°58.0'
9	34	qtz gabbro	33°16.4'	116°50.8'
10	33	bio-hb low-K ₂ O granodiorite	33°15.7'	116°46.2'
11	130	hb-bio low-K ₂ O granodiorite	33°06.0'	117°13.6'
12	1	hb-bio leucogranodiorite	32°59.9'	116°58.4'
13	71	hb tonalite	33°03.8'	116°49.0'
14	108	bio leucogranodiorite	32°52.5'	116°37.2'
15	2	qtz gabbro	32°50.4'	116°47.0'
16	59	hb gabbro	32°43.8'	116°34.5'
17	9	bio leucogranodiorite	32°33.1'	116°37.3'
18	118	bio-hb tonalite	32°32.5'	116°27.8'
19	47	hb-bio low-K ₂ O granodiorite	32°21.9'	116°33.5'
20	15	bio-hb tonalite	31°53.9'	116°27.8'
21	126	hb-bio leucogranodiorite	31°27.5'	116°06.2'
22	55	hb-bio tonalite	31°19.9'	116°15.0'
23	39	hb leucogranodiorite	31°01.7'	116°07.2'
24	119	hb leucogranodiorite	30°58.9'	116°05.8'
25	102	bio-hb leucotonalite	30°59.7'	116°03.1'
26	104	hb leucotonalite	31°01.7'	116°05.7'
27	105	hb leucotonalite	31°02.9'	116°00.8'
28	106	hb leucotonalite	31°03.3'	116°00.1'
29	173	qtz gabbro	31°01.9'	116°00.7'
30	117	hb-bio low-K ₂ O granodiorite	31°01.4'	115°59.2'
31	111	hb-bio tonalite	33°34.4'	117°00.5'
32	30	hb-bio tonalite	33°31.6'	116°53.1'
33	73	hb-bio tonalite	33°22.0'	116°41.4'
34	112	hb-bio tonalite	33°17.1'	116°37.2'
35	61	hb-bio low-K ₂ O granodiorite	32°43.3'	116°25.1'
36	96	hb-bio low-K ₂ O granodiorite	32°30.3'	116°13.8'
37	14	hb gabbro	32°29.5'	116°12.7'
38	38	pyrox gabbro	31°11.3'	115°42.2'
39	22	bio-hb tonalite	30°58.9'	115°45.9'
40	25	hb-bio tonalite	31°00.9'	115°29.3'
41	24	hb-bio tonalite	30°59.3'	115°34.1'
42	147	hb-bio tonalite	33°42.7'	116°43.0'
43	152	bio tonalite	33°51.0'	116°43.4'
44	27	olv-pyrox gabbro	33°35.2'	116°38.0'
45	7	bio-hb tonalite	33°30.0'	116°42.0'
46	29	hb-bio low-K ₂ O granodiorite	33°34.0'	116°30.1'
47	8	bio granodiorite	33°36.6'	116°28.0'
48	6	hb-bio granodiorite	33°43.1'	116°17.8'
49	28	hb-bio low-K ₂ O granodiorite	33°34.0'	116°13.5'
50	3	hb-bio tonalite	33°06.7'	116°18.4'
51	113	hb-bio tonalite	32°43.0'	116°02.9'
52	101	hb-bio granodiorite	32°09.5'	115°47.2'
53	11	hb-bio tonalite gneiss	32°17.8'	115°19.6'
54	10	musc-bio monzogranite	32°00.6'	115°14.1'
55	26	hb-bio tonalite	31°03.4'	115°19.5'
56	16	hb-bio granodiorite	31°02.5'	114°52.4'

hb—hornblende, bio—biotite, qtz—quartz, pyrox—pyroxene, olv—olivine, musc—muscovite.

REE distribution coefficients used in model calculations

	<i>Plagioclase</i>	<i>Clinopyroxene</i>	<i>Hornblende</i>	<i>Garnet</i>
Ce	0.24	0.208	0.889	0.039
Nd	0.17	0.427	2.80	0.094
Sm	0.13	0.681	3.99	0.395
Eu	1.1	0.635	3.44	0.610
Gd	0.090	0.875	5.48	1.39
Dy	0.086	0.980	6.20	4.57
Er	0.084	0.932	5.94	9.40
Yb	0.077	0.896	4.89	16.6

Sources of data: Plagioclase: Arth (1976) except for Eu, where an arbitrarily lower value was used. Clinopyroxene: Schnetzler & Philpotts (1970). Hornblende: Arth (1976). Garnet: Values obtained by multiplying average garnet/clinopyroxene distribution of Philpotts *et al.* (1972) by clinopyroxene/liquid distribution given in this table.