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Isotopic data bearing on the origin of Mesozoic and Tertiary granitic rocks in the western United States

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A regional survey of initial Nd and Sr isotopic compositions has been done on Mesozoic and Tertiary granitic rocks from a 500 000 km² area in California, Nevada, Utah, Arizona, and Colorado. The plutons, which range in composition from quartz diorite to monzogranite, are intruded into accreted oceanic geosynclinal terrains in the west and north and into Precambrian basement in the east. Broad geographic coverage allows the data to be interpreted in the context of the regional pre-Mesozoic crustal structure. Initial Nd isotopic compositions exhibit a huge range, encompassing values typical of oceanic magmatic arcs and Archean basement. The sources of the magmas can be inferred from the systematic geographic variability of Nd isotopic compositions. The plutons in the accreted terrains represent mantle-derived magma that assimilated crust while differentiating at deep levels. Those emplaced into Precambrian basement are mainly derived from the crust. The regional patterns can be understood in terms of: (1) the flux of mantle magma entering the crust; (2) crustal thickness; and (3) crustal age. The mantle magma flux apparently decreased inland; in the main batholith belts purely crustal granitic rocks are not observed because the flux was too large. Inland, crustal granite is common because mantle magma was scarce and the crust was thick, and hot enough to melt. The ϵ_{Nd} values of peraluminous granite formed by melting of the Precambrian basement depend on the age of the local basement source.

Introduction

A substantial amount of field, geochemical, and experimental evidence supports the hypothesis that magma of broadly granitic composition (quartz diorite to monzogranite) must form by melting of the crust in large part (see, for example, Tuttle & Bowen 1958; Winkler 1967; Chappell & White 1974; Wyllie 1977; Armstrong *et al.* 1977; Lee *et al.* 1981; Clemens & Wall 1981). However, isotopic evidence from some batholiths, such as mantle-like initial ratios of $^{87}Sr/^{86}Sr$, $^{143}Nd/^{144}Nd$, $^{176}Hf/^{177}Hf$, and $^{18}O/^{16}O$ (see, for example, Kistler & Peterman 1973, 1978; Taylor & Silver 1978; Moorbath 1977; DePaolo 1987*a*, *b*; Patchett *et al.* 1981) suggests that not all 'granitic' magma is derived from the crust. The major question with regard to the source of these magmas has, therefore, now come to a stage where the focus is on how much of a particular batch of magma is derived from the crust against the mantle, and in a broader sense, are the relative contributions of the two sources systematically related to the tectonic setting in which the magmatism occurs?

To investigate these questions we chose to study the Mesozoic and Tertiary silicic magmatism of the western United States. This area is particularly well suited for providing answers because contemporaneous plutons are distributed over a large area that includes at least three different Precambrian basement age provinces plus accretionary terrains composed of eugeosynclinal-type materials. The pre-Mesozoic geology and geochronology in this area is sufficiently well understood, that it is possible to compare regional patterns in the isotopic compositions of granitoids with the regional crustal-age structure to determine the nature of the magma sources. This reconnaissance approach, involving sampling of a large area (*ca.* 10^6 km^2) allows us to see beyond the isotopic variability encountered in individual plutons and in smaller sampling areas (10^4 km^2), and to focus on larger scale patterns (see also Zartman 1974).

Geologic setting and samples

The sample localities and some relevant aspects of the pre-Mesozoic structure are summarized in figures 1 and 2. The western margin of North America formed in late Precambrian time as a result of a mid-continent rifting process (Dickinson 1981). The location of the basement edge that was formed at that time has been inferred from the sedimentary facies patterns observed in northern Nevada, which indicate a late Precambrian and early Paleozoic Atlantic-type margin (Stewart 1972, 1980), and from Sr isotope patterns in Tertiary volcanic rocks (Kistler & Peterman 1973; Armstrong *et al.* 1977).

The Precambrian basement rocks are believed to have attained their present configuration by about 1.4–1.7 Ga ago (Muehlberger 1980). Extensive geochronological investigations have been carried out in the southeastern province, which contains 1.7–1.8 Ga old rocks, and in the northern Archaean province (see Condie 1982 for summary, and Peterman 1979). The central province, which occupies the physiographically defined eastern Great Basin, has not been studied in as much detail, and the chronology of events there is relatively poorly defined (see, for example, Lanphere *et al.* 1963).

The region to the west of the Precambrian basement edge has had a complicated Phanerozoic history. The details of this history are still in a state of flux (see, for example, Roberts *et al.* 1958; Dickinson 1981; Stewart 1980; Speed 1979; Coney *et al.* 1980; Burchfiel & Davis 1981*a*, *b*), but clear evidence exists for accretion of oceanic-type materials during events in Devonian time (Antler Orogeny) and in Permo-Triassic time. The accreted materials include terrigenous clastic rocks with intermixed ocean-floor type greenstones and arc-type volcanic rocks (Dickinson 1981; Stewart 1980). The clastic sedimentary rocks contain detritus that probably was derived from the continent to the east.

Mid- to late-Mesozoic and Tertiary magmatism was superimposed on this pre-Mesozoic crustal structure. Plutonism can be subdivided into three main epochs: Jurassic, Cretaceous to earliest Tertiary, and mid-Tertiary (Armstrong & Suppe 1973; Farmer 1983). A Jurassic magmatic arc extended from the Klamath Mountains south through southeastern California, southern Arizona, and into Sonora (Bateman *et al.* 1963; Burchfiel & Davis 1981*a*, *b*; Shaffiqullah *et al.* 1980; Damon *et al.* 1981). Scattered plutons of this age also occur in eastern Nevada (Stewart 1980). The main Cretaceous magmatic arc includes the Sierra Nevada, Idaho, and Peninsular Ranges batholiths (see, for example, Armstrong *et al.* 1977; Evernden & Kistler 1970; Silver *et al.* 1975). The locus of intrusion migrated inland during the Cretaceous, and at about 80 Ma ago the zone of magmatism became greatly enlarged and extended far inland, particularly in Sonora (Silver *et al.* 1975; Damon *et al.* 1981) and the southwestern United States (Coney & Reynolds 1977). The inland migration of magmatism ended 60–70 Ma ago in Colorado and west Texas (Lipman 1981; Simmons & Hedge 1978). Magmatism in mid-Tertiary time occurred over almost the entire study area in a rather complex pattern involving coeval intrusive activity over broad areas with irregular time–space relations (Cross & Pilger

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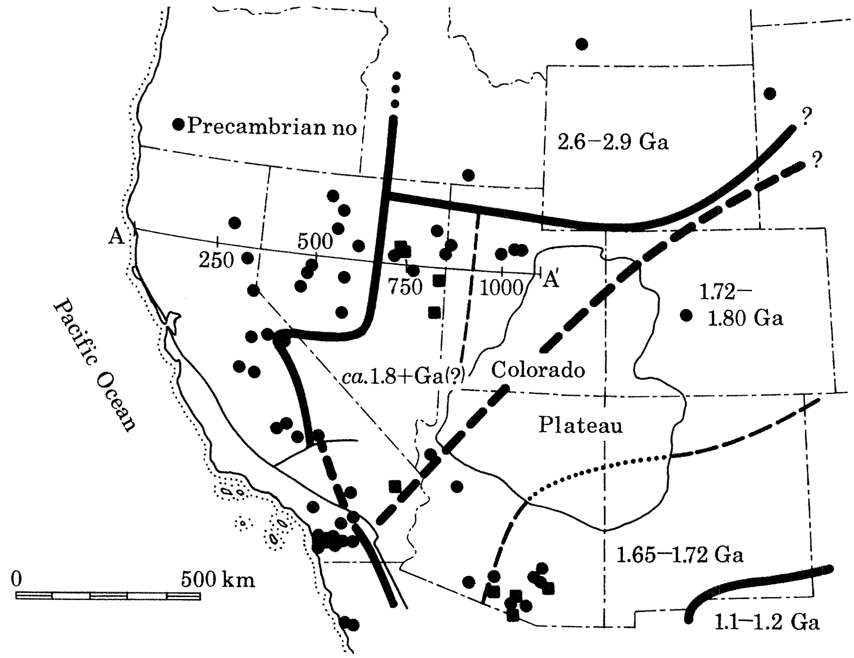

FIGURE 1. Sample localities and age provinces in the Precambrian basement of the western U.S. ●, Mesozoic or Tertiary biotite, or biotite and hornblende-bearing granitic rocks; ■, Mesozoic or Tertiary muscovite-bearing granitic rocks.

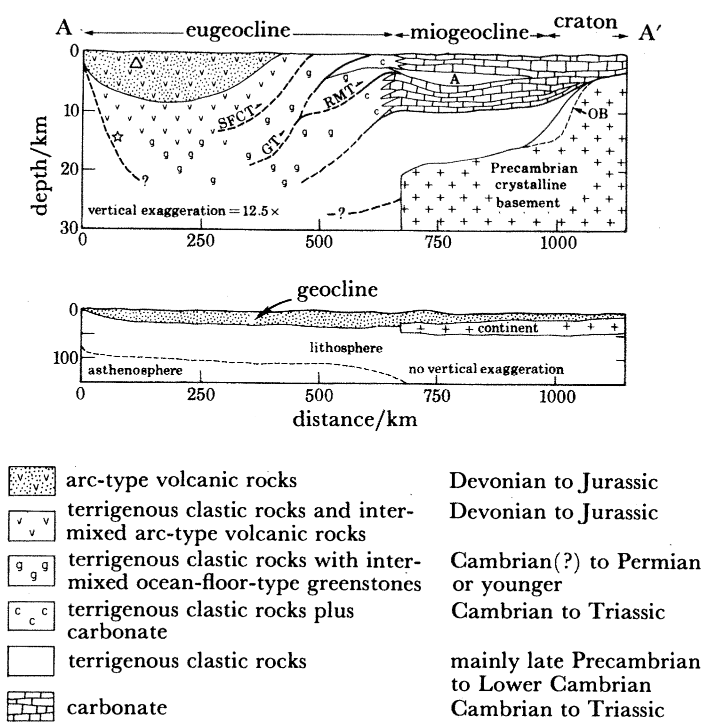

FIGURE 2. Generalized pre-Mesozoic cross section along the line AA′ (figure 1), uncorrected for Cenozoic extension. SFCT, Shoo Fly–Calaveras thrust; GT, Golconda thrust; RMT, Roberts Mountains thrust; A, Antler flysch; OB, Oquirrh Basin. ☆, location of sedimentary composite samples (see figure 5); △, location of volcanic composite sample (see figure 5). The lithologies and structures are inferred from compilations by Speed & Moores (1980), Schweikert & Snyder (1981) and Stewart (1980).

1978; Damon *et al.* 1981; Marvin *et al.* 1980; Snyder *et al.* 1976; Lipman 1980; Coney & Reynolds 1977).

The samples measured are from each of the magmatic episodes, and from localities that span much of the spatial extent of each episode. A total of 68 samples have been measured, from an area of about 5×10^5 km^2. Sample descriptions are given by DePaolo (1981*a*), Farmer (1983) and Farmer & DePaolo (1983*a*, *b*).

Data representation

All $^{143}Nd/^{144}Nd$ ratios are represented by the parameter ϵ_{Nd}, which indicates the fractional difference between the ratio in the sample and the ratio in a reference chondritic reservoir (CHUR). The $^{143}Nd/^{144}Nd$ ratio in the reference reservoir changes with time according to the following equation:

$$^{143}\mathrm{Nd}/^{144}\mathrm{Nd}_{\mathrm{CHUR}}(\mathrm{T}) = {}^{143}\mathrm{Nd}/^{144}\mathrm{Nd}_{\mathrm{CHUR}}(0) - {}^{147}\mathrm{Sm}/^{144}\mathrm{Nd}_{\mathrm{CHUR}}(0)\,[e^{\lambda_{\mathrm{Sm}}\mathrm{T}} - 1],$$

where

$$^{143}\mathrm{Nd}/^{144}\mathrm{Nd}_{\mathrm{CHUR}}(0) = 0.511836, \quad ^{147}\mathrm{Sm}/^{144}\mathrm{Nd}_{\mathrm{CHUR}}(0) = 0.1967, \quad \lambda^{\mathrm{Sm}} = 0.00654\ \mathrm{Ga}^{-1},$$

and T is time measured backward from the present (age). The ϵ_{Nd} value is given by

$$\epsilon_{\mathrm{Nd}}(\mathrm{T}) = 10^4\left[\frac{^{143}\mathrm{Nd}/^{144}\mathrm{Nd}_{\mathrm{sample}}(\mathrm{T})}{^{143}\mathrm{Nd}/^{144}\mathrm{Nd}_{\mathrm{CHUR}}(\mathrm{T})} - 1\right].$$

The $^{87}Sr/^{86}Sr$ ratios are represented by an analogous parameter, ϵ_{Sr}, that is referenced to a model reservoir that has the present-day ratios: $^{87}Sr/^{86}Sr = 0.7045$ and $^{87}Rb/^{86}Sr = 0.0827$. A complete development of this data representation scheme can be found in DePaolo (1981*a*).

Regional isotopic patterns

The regional variations of Nd and Sr isotopic compositions of the Mesozoic and Tertiary granitoids can be conveniently discussed in two parts; the Precambrian basement terrains and the geosynclinal terrains. The data from the areas underlain by Precambrian basement are shown in figure 3. In each of the geochronological provinces (figure 1) the ϵ_{Nd} values show a consistent pattern. The highly peraluminous granites have a limited range of ϵ_{Nd} values, and have the lowest values. The metaluminous granitoids have a larger range of ϵ_{Nd} values, that extends from values similar to those of the peraluminous granites to higher values. For comparison, ϵ_{Nd} values have also been measured in typical intermediate-to-silicic rocks of the Precambrian basement in the southeastern province (Colorado and southern Arizona), and the northern (Archaean) province (Wooden *et al.* 1983; DePaolo & Wasserburg 1979). In each case the initial ϵ_{Nd} values of the highly peraluminous granites are identical to the average ϵ_{Nd} value that the Precambrian rocks would have had at the time of the formation of the granites. The highly peraluminous granites of the Great Basin have ϵ_{Nd} values that cluster at values intermediate between those of the granites from the other two provinces.

The granitoids of the geosynclinal regions display an overall range of ϵ_{Nd} values from $+8$ to about -8. The $^{87}Sr/^{86}Sr$ ratios of those rocks are correlated with the ϵ_{Nd} values (figure 4). The ϵ_{Nd} values decrease from west to east in a fairly regular fashion, although there are some complications in the southern Sierra Nevada batholith.The total range of ϵ_{Nd} values is similar for each latitude, but the distance over which this range is distributed is variable. In the southern

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Sierra Nevada and the Peninsular Ranges, the range of values is distributed over a distance of about 100 km perpendicular to the trend of the magmatic arc. In the northern Sierra Nevada-Northern Great Basin region, the range of ϵ_{Nd} values is distributed over a distance of about 400–600 km (which would correspond to about 250–400 km after correction for Cenozoic extension, Stewart (1980)). The rate of change of ϵ_{Nd} with distance inland appears to be related to the distance between the main magmatic front and the Precambrian basement edge (figure 1).

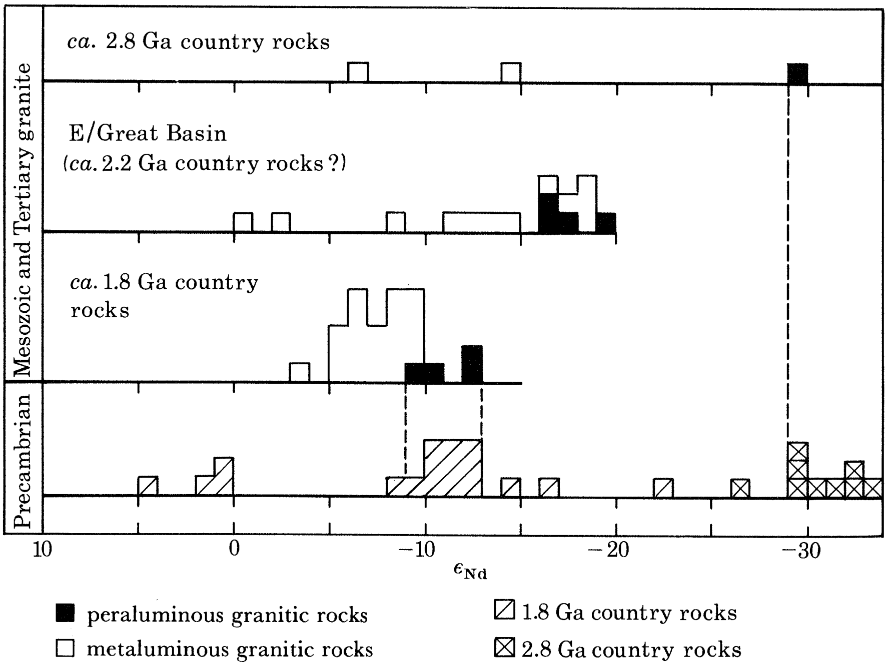

FIGURE 3. Initial ϵ_{Nd} values of Mesozoic and Tertiary granitic rocks grouped according to the age of the Precambrian country rocks (see figure 1) and measured ϵ_{Nd} values in the Precambrian rocks (corrected to 100 million years before present).

GENETIC MODELS AND CRUSTAL STRUCTURE

The striking correspondence of ϵ_{Nd} values between the highly peraluminous granites and the local Precambrian rocks clearly indicates that these granites are derived from the crystalline basement. In northeastern Nevada, the peraluminous granites are intruded into amphibolite facies metasedimentary rocks, but apparently the granites were primarily derived by melting of the basement rocks rather than from anatexis of the sedimentary rocks. This inference is based on the initial $^{87}Sr/^{86}Sr$ ratios, which are far lower than the ratios in the metasedimentary rocks, and the observation that granite in the Old Woman Mountains of eastern California has a nearly identical chemical and isotopic composition and is intruded into basement rocks only (Miller & Stoddard 1981). The melting within the crust that produced these granites apparently served to average over sufficient volumes of the crust so as to yield only a limited range of ϵ_{Nd} values that is close to the expected crustal average.

Some of the metaluminous and weakly peraluminous granitoids in the regions underlain by Precambrian basement also appear to be derived entirely from the crust. In general, however, these have somewhat higher ϵ_{Nd} values, which could be explained in either of two ways. The

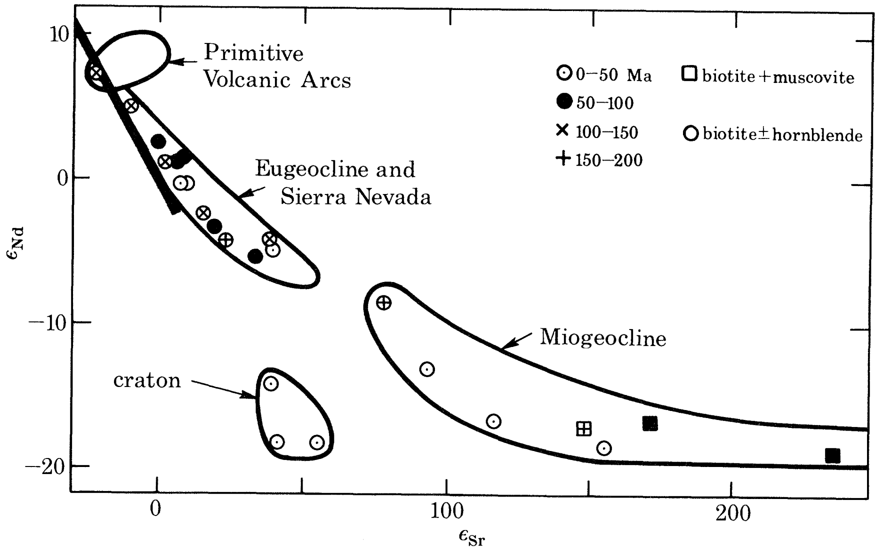

FIGURE 4. Initial ϵ_{Nd} and ϵ_{Sr} values of granitic rocks in the northern Great Basin. The groupings eugeocline, miogeocline and craton correspond to the cross section shown in figure 2. The granitic rocks in the 'craton' region appear to be derived from melting of low-Rb/Sr lower crustal rocks, while the granitic rocks in the miogeocline are derived from relatively high-Rb/Sr lower crustal rocks. The boundary between these two lower crustal subprovinces (which are apparently of the same age) is shown as the light dashed line on figure 1. Field of values for the Sierra Nevada batholith are also shown.

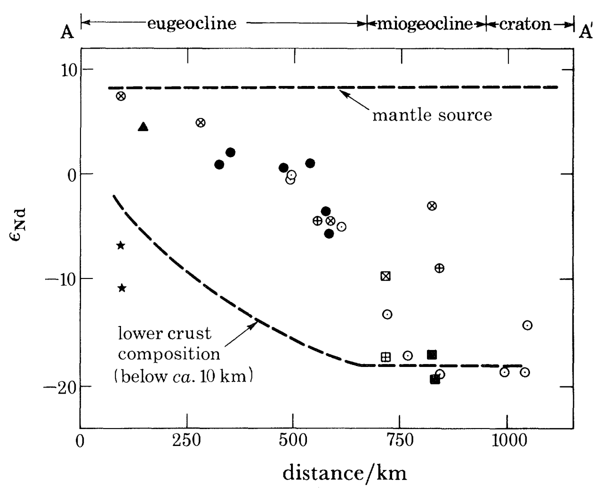

FIGURE 5. Initial ϵ_{Nd} values of granitic rocks in the northern Great Basin, projected onto the line AA′ (figures 1 and 2). Dashed lines represent the estimated ϵ_{Nd} values of the lower crust and mantle at the time the granites formed.

magmas could have been the end products of a process that involved originally mantle-derived magma that became differentiated and heavily contaminated with crust. Alternatively, the magmas could have been derived entirely from the crust, with the magma source including some more mafic rocks with less fractionated Sm/Nd ratios and correspondingly higher ϵ_{Nd} values. We favour the model that involves mantle-derived magma by analogy with the granitoids from the accreted geosynclinal terrains.

In the northern Great Basin the geology of the pre-Mesozoic crust (figure 2) is sufficiently well known to allow the isotopic characteristics of the crust to be estimated (Schweikert &

Snyder 1981; Speed & Moores 1980). These can then be compared with the isotopic characteristics of the granitoids (figure 5). Throughout the geosynclinal region of northern California and northwestern Nevada, the granitoids have ϵ_{Nd} values that are intermediate between the values estimated for the crust and mantle. From this we conclude that the magmas were mixtures of materials derived from the crust and mantle. Furthermore, because there is no

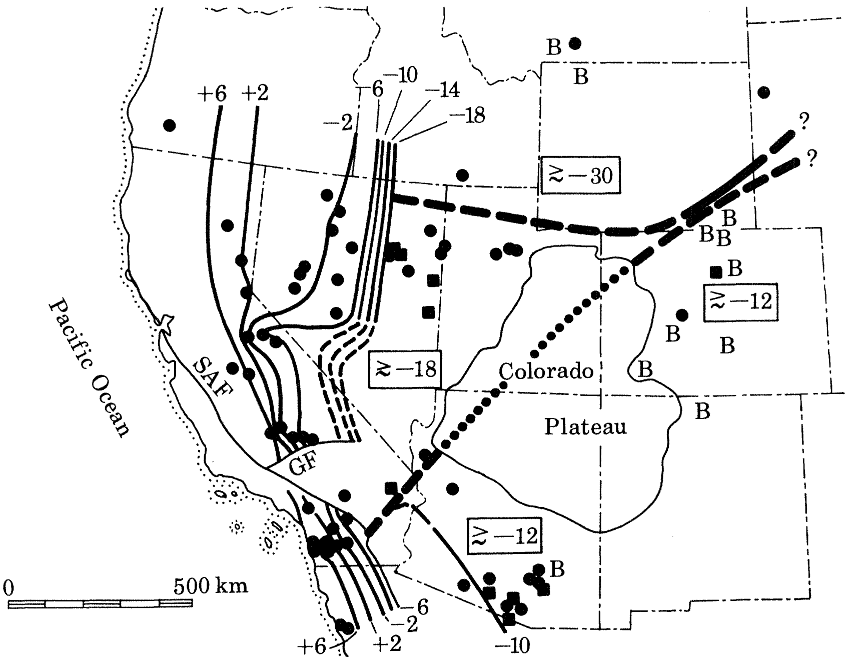

FIGURE 6. Summary of regional variations in initial ϵ_{Nd} values of Mesozoic and Tertiary granitic rocks. The dashed contour lines are inferential. SAF, San Andreas Fault; GF, Garlock Fault. The contour line labelled 6 indicates that ϵ_{Nd} values lower than -6 occur only to the east of the line. The other contours should be interpreted analogously. B is location of analysed basement sample.

evidence for the presence of Precambrian crystalline basement in this region, the 'continental crust' component must be composed of sedimentary rocks that were originally deposited on oceanic crust. The proportion of the continental crust component in the granitoids increases inland. This is interpreted as being inversely related to the amount of magma from the mantle that was entering the crust. In the main magmatic arc the flux of mantle magma was probably very large. In this situation the magmas tend to become less contaminated before the final emplacement in the upper crust, and also the magmas generally become less differentiated. Hence, the typical rock type is tonalite and the isotopic compositions are only slightly displaced from the values in primitive oceanic arcs ($\epsilon_{Nd} \approx +8$, see, for example, DePaolo & Johnson 1979). Further inland the magma flux was progressively smaller, and in addition the crustal thickness was probably greater. These two effects result in greater amounts of crustal assimilation.

It is noteworthy that the effects of the inland-decreasing mantle magma flux are superimposed on different crustal structures in the northern Great Basin and the southern Sierra Nevada and the Peninsular Ranges. In the Great Basin, the Precambrian basement edge was located so far from the main magmatic front that, east of the basement edge, crustal magmas (undiluted by mantle contributions) are the rule (figure 5). In contrast, in the southern batholiths

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

the basement edge was so close to the main magmatic arc that purely crustal magmas are entirely absent, even in the regions underlain by Precambrian basement.

The overall pattern of ϵ_{Nd} variations in the granitoids of the southwestern U.S.A. is represented qualitatively by contours on figure 6. The peraluminous granites of the eastern Great Basin have initial ϵ_{Nd} values that cluster near a distinctive value of about -18. This value is much different from that observed in Arizona and Colorado, and from it we infer the existence of a separate basement province that has an apparent age greater than 1.8 Ga, but less than

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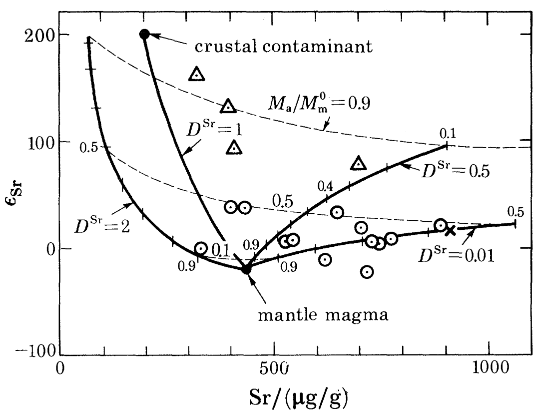

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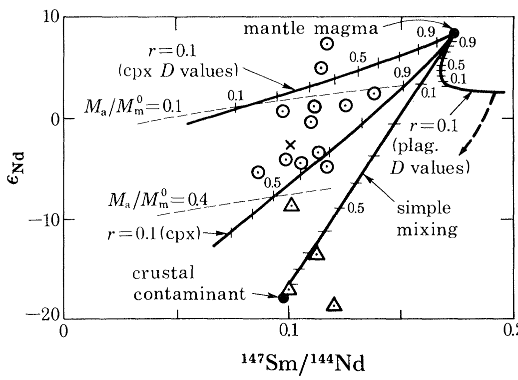

FIGURE 7. Strontium concentrations and initial ϵ_{Sr} values of granitic rocks from the Northern Great Basin. Solid lines are 'mixing lines' between mantle magma and crustal contaminant for a model involving concurrent assimilation and fractional crystallization. The relatively high strontium concentrations of some of these granites could be explained if the crystallizing mineral assemblage was poor in plagioclase ($D^{Sr} \approx 2$). The calculated mixing lines represent a specific ratio of assimilation rate to crystallization rate ($r = 0.5$). The dashed lines show the ratio of assimilated mass to the original mass of mantle magma. The tick marks give the mass of the remaining contaminated, fractionated magma as a fraction of the mass of original mantle magma. ⊙, granitic rocks from the eugeoclinal region (see figure 2); △, granitic rocks from the miogeoclinal region (see figure 2).

FIGURE 8. Measured $^{147}Sm/^{144}Nd$ ratios and initial ϵ_{Nd} values in granitic rocks from the northern Great Basin, and calculated mixing trajectories for the assimilation-fractional crystallization model. The mixing lines were calculated using Sm and Nd distribution coefficients appropriate to clinopyroxene–liquid or plagioclase–liquid equilibria, and for $r = 0.1$ and 0.5. Other symbols correspond to those in figure 7. The dashed line at right shows the effect of increasing the value of r for the plagioclase fractionation model.

2.8 Ga (figure 6). The tectonic significance of this province is poorly constrained with the existing data, but we note that some of the isotopic characteristics correspond closely to those of the so-called Penokean terrain of central Wisconsin (Van Schmus & Bickford 1981; Nelson & DePaolo 1983).

Isotopes against chemistry

The inferences made from the isotopic data can be tested for consistency with the chemical compositions of the rocks. A particular problem is the nature of the interaction between the mantle-derived magma and the crust, which we infer has taken place in the accreted geosynclinal terrains and elsewhere. Previous workers (see, for example, Kistler & Peterman 1973) have noted that the high Sr concentrations of many of the granites in the Sierra Nevada batholith appear to be particularly inconsistent with crustal assimilation models. However, it has been pointed out by DePaolo (1981*b*) that assimilation may be accompanied by crystallization of Sr-poor phases so that the Sr concentration in the magma can increase rather than decrease with progressive crustal contamination when the assimilation takes place at relatively high pressures corresponding to the lower crust. Figure 7 shows calculated ϵ_{Sr}–Sr concentration trajectories for the assimilation-fractional crystallization (a.f.c.) model. The parameter r is the ratio of the assimilation rate to the fractional crystallization rate (DePaolo 1981*b*). Considering that the ϵ_{Sr} value of the crust may be lower than that used for the calculations (especially in the westernmost localities) it is possible to model the Sr concentrations of the granitoids with

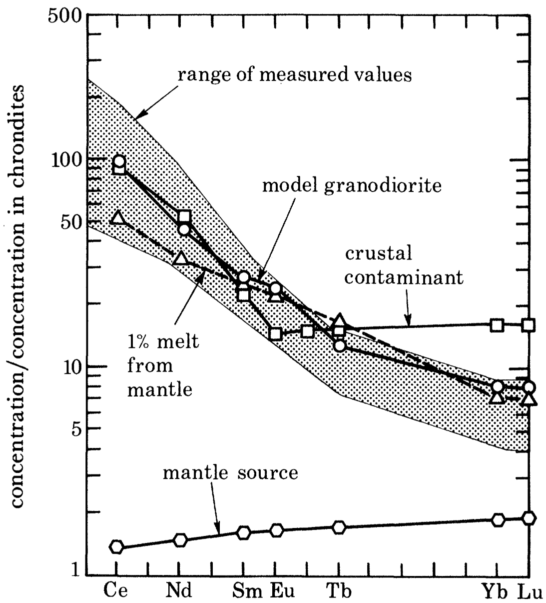

FIGURE 9. Rare-earth patterns of granitic rocks from the eugeosynclinal region of the Noıthern Great Basin (figures 2, 4 and 5) and a calculated model pattern that assumes a 1% melt of light rare earth element-depleted mantle, and assimilation of average continental crustal rock accompanied by crystallization.

the a.f.c. process provided that plagioclase ($D^{Sr} \approx 2$) is not the dominant fractionating mineral phase (Farmer & DePaolo 1983*a*). The same conclusions arise from the ϵ_{Nd}–Nd concentration data (figure 8). The rare-earth patterns of the granitoids can also be reproduced rather well by the a.f.c. model (figure 9). None of these calculations proves that assimilation-fractional crystallization was the process that actually occurred, but they serve to demonstrate that this model encounters no serious problems with the available trace element data.

For the granitoids that are wholly derived by crustal melting, the age of the basement source can be used to deduce the Sm/Nd fractionation that occurred during magma genesis. For this purpose, we define the parameter $\alpha_{Sm/Nd}$:

$$\alpha_{Sm/Nd} = \frac{Sm/Nd_{sample}}{Sm/Nd_{source}},$$

where the Sm/Nd ratio of the source is calculated from the age of the (crustal) source and the initial ϵ_{Nd} value of the sample (cf. Farmer & DePaolo 1983*a*). Applying this to the granitoids of the eastern Great Basin and central Utah shows that there is a consistent difference between the peraluminous granites and the granodiorites. Both have initial ϵ_{Nd} values of about -18, indicating a crustal origin, but the peraluminous granites have $\alpha_{Sm/Nd}$ values of 1.01 ± 0.08

while the granodiorites have $\alpha_{Sm/Nd}$ values of 0.78 ± 0.05 (the age assumed for the source was 2.2 Ga (Farmer & DePaolo 1983*a*)). The peraluminous granites probably represent relatively large melt fractions or melt plus restite, from source materials that did not contain minerals that greatly fractionate rare-earths. The granodiorites, on the other hand, were apparently derived from a pyroxene- and garnet-bearing source (granulite facies), and represent a sufficiently small melt fraction that there was substantial rare-earth fractionation. These conclusions are consistent with the inferences made from the isotopic data (Nd and Sr) about the nature of the source materials.

The relation between isotopic composition and major element chemical composition is complicated at best. On the one hand, fairly similar types of granodiorite can have drastically different ϵ_{Nd} values (0 in western Nevada, -18 in central Utah) which indicate much different modes of magma genesis. On the other hand, metaluminous and strongly peraluminous granite and monzogranite in eastern Nevada can have nearly identical ϵ_{Nd} and ϵ_{Sr} values. In the latter case, both types appear to be wholly derived from the crust. The similarity of major element compositions in differentiated magma types formed by various petrogenetic processes is a logical consequence of control by the governing phase equilibria (Bowen 1956). In other instances, the diversity of magma types derived from a similar source is testimony to the effects of variations in pressure, degree of melting, volatile content, and the extent of late stage magmatic differentiation.

Conclusions

The regional patterns in the initial Nd isotopic ratios of Mesozoic and Tertiary granitoids in the western United States correspond closely to known Precambrian-age province boundaries and suggest the presence of an additional, previously unrecognized province in the eastern Great Basin. Highly peraluminous granites are formed by anatexis of crustal rocks in all cases. Most metaluminous granitoids appear to be differentiates of mantle-derived mafic magma that assimilated copious amounts of lower crustal rocks, although some appear to be products of crustal anatexis with no involvement of mantle magma. A model involving an inland-decreasing flux of magma from the mantle, associated with subduction along the western margin of North America, can account for most of the observations.

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