Neodymium isotopic constraints on the origin of the Pikes Peak Batholith

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Introduction

Neodymium and strontium isotopic ratios of igneous rocks provide useful information concerning the origin and evolution of the magmas from which they solidified. The radioactive isotopes ^{143}Sm and ^{87}Rb decay to the stable daughter isotopes, ^{144}Nd and ^{87}Sr, respectively. The decay involves very long half lives (1.06 x 10^{11} years and 4.88 x 10^{10} years, for ^{143}Sm and ^{87}Rb, respectively; *Faure*, 1987) and insures the presence of the parent isotope even after much time has passed. In addition, Nd and Sr have large atomic masses, and thus no fractionation of the isotopes of Nd or Sr occurs during melting and crystallization processes. Sm and Nd are rare earth elements and as such are considered immobile during regional metamorphism, hydrothermal alteration and chemical weathering (*Faure*, 1986). In contrast, Rb and Sr are susceptible to alteration processes, so caution is warranted when using Sr isotopic ratios as geochemical tools (*Faure*, 1986). Because the mantle and crust have different Sm/Nd and Rb/Sr ratios, they have evolved along different isotopic paths. Thus, the study of Nd and Sr isotopes in igneous rocks allow evaluation of the source rock compositions and possible interactions between mantle-derived magmas and crust. Also, Nd isotopic analyses of Precambrian granitic rocks have the potential to define the "crust-formation"age, i.e. , the time of differentiation of the crust from the mantle (e.g., *Nelson and DePaolo*, 1985).

Barker et al. (1976) provided a preliminary investigation of Sr isotopes in 14 rocks of the Proterozoic Pikes Peak batholith (PPB), and DePaolo (1981) analyzed one sample from the batholith for Nd isotopes. Due to the relative paucity of information regarding the isotopic character of the PPB, this project focussed on the acquisition of Sr and Nd isotopic data for selected samples of the PPB. The data are used to (1) evaluate mantle source characteristics, (2) evaluate possible interactions between mantle-derived magmas and crust, and (3) determine crustal formations ages (cf. DePaolo, 1981).

Samples

Sixteen rock samples were taken from the Spring Creek, West Creek, Sugarloaf, Mt. Rosa, and Lake George plutons, the five sodic plutons in the Pikes Peak batholith (cf. Figure 1, Noblett et al., this volume). The samples include a variety of rock types ranging from lamprophyres and gabbros, to syenites and granodiorites, to fayalite and riebeckite granites and fine-grained potassic granite (Table 1). Petrographic descriptions and major and trace element data for the samples are given in this volume in abstracts by Goldman (lamprophyres), Davis (gabbros), Beane (syenites), Stewart (granodiorites), Kay (riebeckite granites), Saltoun (fayalite granites, fayalite bearing quartz syenites), and Gustavson (fine-grained potassic granite).

TABLE 1.

SAMPLE	Sm	Nd	^{143}Nd/^{144}Nd initial	Initial ε_{Nd}
	(ppm)	(ppm)	(t = 1.03-1.10 Ga)	(t = 1.03-1.10 Ga)
MBC-8-SG	9.6	42.6	0.51141 - 0.51147	+3.7 - +3.1
CCN-19B-CD	11.7	52.6	0.51125 - 0.51131	+0.5 - 0.0
CCN-19-CD	7.8	40.2	0.51107 - 0.51113	-2.8 - -3.5
WC-38-CD	11.7	60.8	0.51132 - 0.51138	+2.1 - +1.4
LG-12-JD	16.4	81.5	0.51129 - 0.51135	+1.4 - +0.7
LG-10-JD	25.5	160.6	0.51126 - 0.51131	+0.8 - -0.1
GM-12-RB	14.1	81.1	0.51134 - 0.51139	+2.4 - +1.6
GM-35-RB	29.6	199.1	0.51132 - 0.51136	+1.9 - +1.0
GM-6-JS	17.4	88.5	0.51112 - 0.51118	-1.9 - -2.6
P-26-JS	19.1	99.3	0.51120 - 0.51125	-0.4 - -1.1
MBC-6-BS	22.0	117.0	0.51122 - 0.51128	+0.1 - -0.6
MBC-9-GK	21.6	106.8	0.51124 - 0.51130	+0.5 - -0.2
MBC-12-GK	13.9	64.12	0.51124 - 0.51130	+0.5 - -0.1
MBC-7-BS	26.8	137.4	0.51127 - 0.51132	+0.9 - +0.2
MBC-20-BS	21.8	97.2	0.51119 - 0.51125	-0.5 - -1.1
PP-31-BG	13.6	77.9	0.51116 - 0.51121	-1.2 - -2.0

Analytical Procedures

Rock powders were prepared from ≥ 0.5 kg samples for fine grained rocks and ~2 kg samples for coarse grained rocks, and were ground in tungsten carbide to avoid strontium contamination which can result from grinding in alumina ceramic. Rb and Sr concentrations in all samples were measured via XRF at XRAL (a commercial laboratory). Nd and Sm concentrations, $^{143}Nd/^{144}Nd$ ratios, and $^{87}Sr/^{86}Sr$ ratios were determined via mass spectrometry at Rice University. The measured $^{143}Nd/^{144}Nd$ ratios were normalized to $^{146}Nd/^{144}Nd = 0.72190$. Nd and Sm concentrations have errors < 3% (relative to the amount present), and Sr and Rb have errors of 3 and 8% (relative), respectively. $^{143}Nd/^{144}Nd$ ratios are precise to ± 0.00001, and $^{87}Sr/^{86}Sr$ ratios are precise to ± 0.00009.

Results

Sm-Nd data are presented in Table 1. Using the measured $^{143}Nd/^{144}Nd$ and $^{147}Sm/^{144}Nd$ ratios , the initial $^{143}Nd/^{144}Nd$ ratios of the rocks were calculated using

$$(^{143}Nd / ^{144}Nd)_{initial} = (^{143}Nd / ^{144}Nd)_{meas.} - [(^{147}Sm / ^{144}Nd)_{meas.} (e^{\lambda t} - 1)]$$

where λ is the decay constant of Sm ($6.54 \times 10^{-12} yr^{-1}$) and t is the age of the rock (in years) (*Faure*, 1987). Barker et al. (1976) cite a relatively young age of 1.03 Ga for the batholith, whereas more recent determinations indicate a 1.07 Ga age for the batholith (Unruh, pers. comm.); absolute ages for individual plutons within the batholith are unknown. Thus both a maximum age of 1.10 Ga and a minimum age of 1.03 Ga were used in the initial $^{143}Nd/^{144}Nd$ calculations. Also initial ε_{Nd} values for each sample were calculated using

$$\varepsilon_{Nd}^{initial} = \left[\frac{^{143}Nd / ^{144}Nd \; initial_{SAMPLE}}{^{143}Nd / ^{144}Nd \; initial_{CHUR}} - 1 \right] \times 10000$$

where $^{143}Nd/^{144}Nd$ initial ratio of CHUR (chrondritic uniform reservoir) is calculated using first equation and the present day ratio of CHUR (*Faure*, 1986) The intial ε_{Nd} values indicate how the initial $^{143}Nd/^{144}Nd$ ratio of a rock compares to the $^{143}Nd/^{144}Nd$ ratio in CHUR at the time that the rock formed (DePaolo, 1988),in this case, ~1.05 Ga. A positive ε_{Nd} value indicates that the sample has a higher Nd isotopic ratio than CHUR, indicating that the source material for the magma was enriched in Sm (vs. Nd) relative to CHUR. Such enrichment occurs when the source undergoes a melting event with preferential removal of Nd (versus Sm), i.e., a depleted mantle source. Conversely, a negative ε_{Nd} value means that the rock has a lower Nd isotopic ratio than CHUR, indicating that the source material for the rock was enriched in Nd (vs. Sm) relative to CHUR. Such sources include crustal rocks, themselves having been derived by melting of mantle (e.g., during orogeny and crust formation) or by mantle which is relatively enirched in Nd (vs. Sm) via metasomatism (*Turner et al.*, 1992) or mantle differentiation (*Anderson*, 1982).

The Sr isotopic data indicate that most, if not all, PPB samples of this study have either lost or gained Rb and/or Sr since their formation. Initial $^{87}Sr/^{86}Sr$ ratios were calculated (*Faure*, 1987) and yielded values as high as 4.2, whereas reasonable initial ratios for Proterozoic granites are usually < 0.72. Some of the PPB samples have initial ratios less than 0.72; however, the fact that the others were so anomalously high, coupled with the inability to find geochemical trends associated with the isotopic ratios, indicate that the Sr data are suspect. Thus, the emphasis of this abstract is on Sm-Nd systematics of the PPB.

Discussion

Initial $^{143}Nd/^{144}Nd$ ratios range from 0.51107 to 0.51147, resulting in a range in ε_{Nd} values from -3.5 to +3.7 (Figure 1). There is no obvious correlation with silica content, as data for the gabbros alone span nearly the entire range for all rock types. Clearly, a single source and/or parental magma type cannot be invoked for the origin of magmas emplaced in the batholith.

Gabbros

Wide variations in ε_{Nd} values for the gabbros (-3.5 to +2.9) could be due to either variation in source composition or small degrees of contamination of mantle-derived magma by crustal material. Sample CCN-19-CD has geochemical characteristics (e.g., high Mg#, high compatible element contents) suggesting that it has undergone little FC or crustal contamination., whereas the other gabbros appear somewhat evolved (cf. *Davis*, this volume). The CCN-19-CD was used as a parental magma in AFC models in attempts to generate the other gabbros. Assimilants included estimates for upper and lower crust given by Taylor and McClennen (1985). The AFC models did not successfully produce the observed Sm/Nd and $^{143}Nd/^{144}Nd$ initial ratios of the evolved gabbros. Thus the observed range in ε_{Nd} is believed to be a mantle source characteristic rather than the result of crustal contamination.

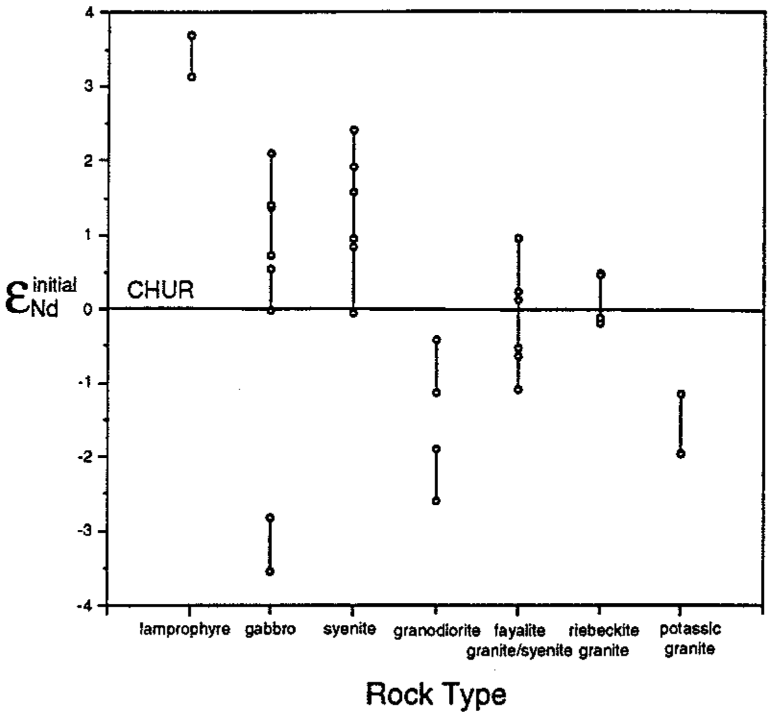

Figure 1. Initial $^{143}Nd/^{144}Nd$ ratios for PPB samples. Data for individual samples are plotted as bars rather than single points, reflecting uncertainty in absolute age of the rocks.

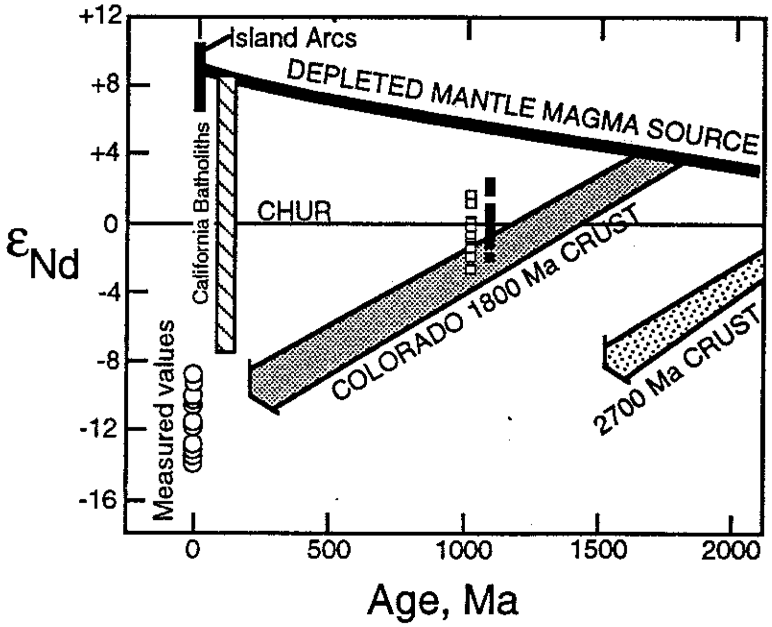

Figure 2. Measured ε_{Nd} values for PPB samples are shown at zero age (filled circles) and time corrected ε_{Nd} values are shown at 1100 (open squares) and 1030 Ma (filled squares). Large arrows show ε_{Nd} evolution for typical 1800 Ma Colorado crust and typical 2700 Ma crust; the depleted mantle evolution curve is also shown (from DePaolo, 1981). Mesozoic batholiths of California are included to illustrate mixtures of mantle-derived components and older crust (DePaolo, 1981).

When considering mantle source characteristics, it is important to remember that the mantle is heterogeneous due to crustal formation processes and mantle differentiation (*Anderson*, 1982). As a result of prior extraction of melts and crust formation, a depleted mantle source is often used in modeling crustal formation processes. A reasonable source would be a LREE depleted mantle that formed 1.8 Ga (from CHUR) resulting in a present day $^{147}Sm/^{144}Nd = 0.23$ and $\varepsilon_{Nd} = +8$, but a ε_{Nd} of ~+6 at the time of formation of the PPB (*McCulloch and Chappell*, 1982; cf. Figure 2).

Depleted mantle could not have been the source for the PPB gabbros, as evidenced by their ε_{Nd} values of $\leq +2.2$ (cf. Figure 1). An enriched source, however, would have the major element characteristics of the mantle (resulting in mafic melts) and ε_{Nd} values overlapping with crust. Thus, partial melting models involving an enriched mantle source were tested. According to Anderson (1982), enriched mantle would exhibit Sm/Nd ratios 18% lower than primitive mantle. Sm/Nd in primitive mantle is estimated to be ~3.1 (*Taylor et al.*, 1985), therefore a Sm/Nd ratio of 2.54 was used in the models. The Sm/Nd ratios of the gabbros range from 0.192 to 0.222 and can be reproduced by partial melting of enriched mantle. The best results are from models involving 7 - 12% partial melting of garnet lherzolite. Primitive and depleted mantle sources produce the Sm/Nd ratios of some of the gabbros, but only at very low degrees of melting (1 - 5%) of a garnet-rich source.

Intermediate and Felsic compositions

Crustal formation ages have been determined to be ~1800 Ma for central Colorado (DePaolo, (1981; Nelson and DePaolo, 1985). Crustal formation ages determined with Nd isotopic data for PPB granitoids are somewhat younger, ranging from ~1300 to 1600 Ma. These lower estimates are interpreted *not* as reflecting true ages of crustal separation from the mantle, but rather as the result of the involvement of mantle material in the origin of PPB intermediate to felsic magmas. Samples with the lowest ε_{Nd} values, the granodiorites and fine grained potassic granites, may be direct melts of crust which evolved along the Colorado crustal evolution line, but samples which plot above that line towards depleted mantle seemingly require a mantle component. If these granites were generated by crustal anatexis, data indicate a distinct source for the potassic vs. the fayalite/riebeckite granitic rocks.

Barker et al. (1975) suggested that the origin of the PPB syenites involved contamination (accompanied by fractional crystallization) of mantle-derived magma by K_2O-poor, lower crust, and the sodic-trend granites were the result of differentiation of the syenitic magma. AFC models indicate that a parental magma similar to gabbro sample LG-12-JD crystallized and assimilated upper crust, resulting in liquids with $^{143}Nd/^{144}$ Nd and Sm/Nd ratios observed for the granodiorites. The syenites may also be generated via AFC of parental mafic magma, but the crustal assimilant may be isotopically similar to the gabbros (interpreted to be derived from enriched mantle, and hence would have similar Nd isotopic signature as crust), or the parental magmas are not represented by the gabbros studied here.

Conclusions

New Nd isotopic data for sixteen samples of rocks spanning the compositional spectrum of the PPB document the involvement of mantle material in their genesis. The variation of initial ε_{Nd} values for the gabbros indicate heterogeneity within an enriched mantle source, not variable degrees of interaction with crust. Initial ε_{Nd} variations in the intermediate and felsic rocks may be due to a mixture of crust and mantle-derived materials, but some of the granitoids may be crustal anatectic melts.

References

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