

Crustal signatures in the Serra Geral flood-basalt province, southern Brazil: O- and Sr-isotope evidence

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ABSTRACT

Strontium and oxygen isotopes in igneous rocks from a 35 000-km² region of the Serra Geral (Paraná) continental flood-basalt province, southern Brazil, indicate that certain mantle-derived magmas that formed during the rifting and breakup of Gondwana incorporated continental crust. Sr-O and trace-element assimilation-fractional crystallization models point to variable amounts and types of "warm" Archean granulitic crust, $\delta^{18}\text{O} > 15$ and $^{87}\text{Sr}/^{86}\text{Sr}_{(t)} \sim 0.735$, having contaminated ascending mafic magmas. Resulting products include evolved rocks, basaltic andesite to rhyolite, that have $\delta^{18}\text{O}$ 11 to 15 and $^{87}\text{Sr}/^{86}\text{Sr}_{(t)}$ 0.714 to 0.729, and basaltic rocks that have $\delta^{18}\text{O}$ 8 to 10 and $^{87}\text{Sr}/^{86}\text{Sr}_{(t)} \sim 0.710$.

INTRODUCTION

Deciphering geochemical and isotopic characteristics of source materials for continental flood-basalt (CFB) provinces requires information on the influence that continental crust had on the magmas rising through the crust. In most CFB provinces, that information must come from the magmas (rocks) themselves. Studies thus far, however, indicate that no categorical evaluation can be made for flood-basalt provinces. There are arguments for little or no magma/crust interaction (Brooks and Hart, 1978; DePaolo and Wasserburg, 1979; DePaolo, 1983; McDougall, 1976;

Compston et al., 1968) as well as for substantial interaction (Carter et al., 1978; Carlson et al., 1981; Mahoney et al., 1982; Furnes et al., 1982; Carlson, 1984). In the Serra Geral (Paraná) CFB province in southern Brazil, sorting out continental-crust components from upper-mantle source characteristics is especially relevant. The Serra Geral province is among the world's largest CFB provinces ($\sim 10^6$ km²) and represents one end member of the Cretaceous magmatism that bridged continental and oceanic regimes during the breakup of Gondwana and the opening of the South Atlantic Ocean (continental lithosphere gave way to oceanic

lithosphere). Also, earlier isotopic evaluations of the Gondwana mantle beneath Brazil were based on no interaction between basalt and Brazil crust (Compston et al., 1968; Brooks and Hart, 1978; DePaolo and Wasserburg, 1979), and this should be reinvestigated in light of more recent findings for CFB elsewhere.

Our approach to evaluating crustal contamination in the Serra Geral igneous province was to select ten samples representative of the extreme southern part of this varied-rock province (largely basalt and basaltic andesite, but also andesite, rhyodacite, and rhyolite) for combined geochemical and oxygen- and strontium-isotope analyses. In this paper we emphasize the isotopic aspect as the discriminator of crustal interaction, but we apply the geochemical data and descriptions presented elsewhere (Fodor et al., 1985) for these samples. Among the conclusions reached are that the Serra Geral province has a history of magmas assimilating crustal material during fractional crystallization processes of basaltic magmas.

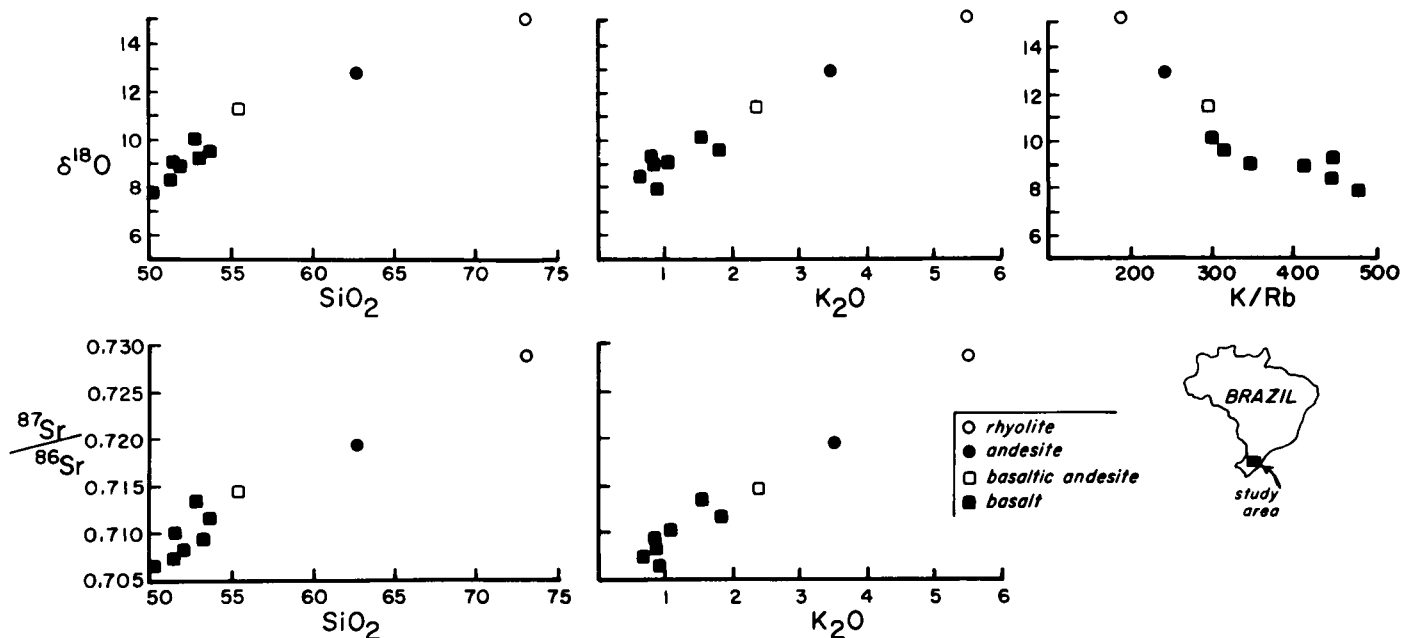


Figure 1. Variations in $\delta^{18}\text{O}$ and $^{87}\text{Sr}/^{86}\text{Sr}_{(t)}$ with SiO_2 and K_2O contents and K/Rb ratios for basalt, basaltic andesite, andesite, and rhyolite from Serra Geral continental flood-basalt province, southern Brazil. Index map shows general geographic location for samples, Rio Grande do Sul state, Brazil. Specific locations in Fodor et al. (1985).

RESULTS AND DISCUSSION

One pertinent point of the independent geochemical study of the Serra Geral province (Fodor et al., 1985) is that crystal fractionation of mafic magmas produced basaltic andesites and is a viable process to account also for andesites, rhyolites, and rhyolites. This feature is illustrated here by the ranges in SiO_2 , K_2O , and K/Rb in the basalt, basaltic andesite, andesite, and rhyolite compositions depicted in Figure 1 and by the geochemical profiles of Table 1. The samples come from an area of about 35 000 km^2 in the state of Rio Grande do Sul (specific locations are illustrated in Fodor et al., 1985). They are not all related to one source, but the ten samples can be considered representative of this extreme southern part of the huge Serra Geral province.

The $\delta^{18}\text{O}$ value of about 8‰ in the most mafic samples is much higher than those values

of about 5 to 6 typically observed in basalt (Kyser et al., 1982), indicating continental-crust components. And the $\delta^{18}\text{O}$ values of >12 for andesite and rhyolite are particularly indicative of sedimentary or metasedimentary components in these evolved rocks (Taylor, 1980). Petrography shows little in the way of secondary minerals to account for these high $\delta^{18}\text{O}$ values, and the correlation coefficient between $\delta^{18}\text{O}$ and LOI (loss on ignition, largely H_2O^+) is -0.35 , eliminating weathering as an important reason for the $\delta^{18}\text{O}$ values. We therefore turn to models involving assimilation-fractional crystallization (AFC) processes in the Brazilian Archean crust during the rifting of South America-Africa landmass.

Constraints assigned to the AFC models are similar to those considered by Taylor (1980): (1) The starting basaltic magma has $\delta^{18}\text{O} +5.7$, $^{87}\text{Sr}/^{86}\text{Sr}$ 0.703, and 500 ppm Sr, and is

modeled as a 1000-g batch that continually assimilates crust in 1-g increments. (2) The crust has $\delta^{18}\text{O} >15$, $^{87}\text{Sr}/^{86}\text{Sr}$ 0.735, and Sr between 100 and 330 ppm, accounting for M/C_{Sr} (magma/crust Sr concentration) ratios of 5 to 1.5. All of these crustal conditions are reasonable, as based on studies of Brazilian crust (Almeida et al., 1973; Sighinolfi et al., 1981; Oliveira et al., 1982; Wernick and Oliveira, 1982) which show largely granulites and gneisses that are granitic to intermediate in compositions (provided that they had sediment protoliths to account for $\delta^{18}\text{O} >15$).

Figure 2a presents a model for a "warm" crust (perhaps preheated by earlier magmas) where $C/A = 2$ and $\delta^{18}\text{O} = +17$ for the crustal contaminant ($C/A = 2$; i.e., 2 g of magma crystallized for every 1 g of crust assimilated). Data points are bracketed by curves that represent a relatively high bulk distribution coefficient (D), 1.5, for the crystallizing magma and some that represent high Sr contents in the contaminant (>300 ppm, low M/C). High D requires substantial plagioclase crystallization, but this can be tempered by increasing the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the contaminant. On the other hand, because of the progressive decrease in Sr for the basalt-rhyolite trend (Table 1), bulk D was probably not <1 . The 60%–80% crystallization to account for the evolved rocks plotted in Figure 2 is reasonable. In contrast, "cold" crust models, $C/A \approx 7$, require abnormally high $\delta^{18}\text{O}$ in the contaminant to achieve reasonable crystallization percentages of a magma fractionating to evolved liquids.

An additional feature in Figure 2 is the dashed curve for $\delta^{18}\text{O} = 15$ for the contaminant. It demonstrates the flexibility in the curves with respect to geologic characteristics that likely vary with crustal location and type.

Overall, the curves indicate that plausible starting-magma and assimilant compositions yield viable AFC models for the Rio Grande

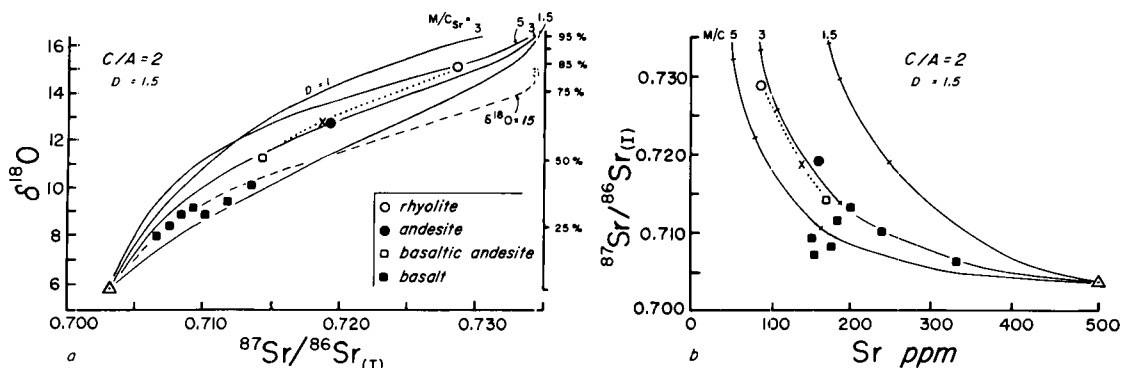
TABLE 1. GEOCHEMICAL AND ISOTOPIC PROFILE OF BASALT, BASALTIC ANDESITE, ANDESITE, AND RHYOLITE FROM SERRA GERAL CONTINENTAL FLOOD-BASALT PROVINCE, SOUTHERN BRAZIL

	SiO_2	K_2O	Rb	Sr	Mg#	$^{87}\text{Sr}/^{86}\text{Sr}_{(m)}$	$^{87}/^{86}\text{Sr}_{(I)}$	$\delta^{18}\text{O}$	LOI*
EV01	51.64	1.09	26	238	59.8	0.71060 ± 0.00013	0.71006	8.98	0.90
MO2	52.85	1.55	43	200	57.9	0.71427 ± 0.00025	0.71321	10.09	1.59
RS20	51.50	0.63	12	152	51.7	0.70759 ± 0.00011	0.70721	8.36	0.81
RS73	50.13	0.90	16	327	49.2	0.70663 ± 0.00007	0.70639	7.91	1.17
IO2	53.74	1.83	48	185	45.9	0.71285 ± 0.00010	0.71156	9.53	1.28
RS60	51.96	0.84	17	177	45.4	0.70875 ± 0.00020	0.70826	8.86	1.02
RS80	53.11	0.81	15	151	35.1	0.70877 ± 0.00038	0.70928	9.19	1.00
MRO3	55.54	2.38	68	170	29.7	0.71624 ± 0.00043	0.71428	11.34	0.95
RS65	62.69	3.48	120	162	34.1	0.72292 ± 0.00034	0.71927	12.82	0.87
RS50	73.01	5.51	244	89	17.5	0.74206 ± 0.00018	0.72855	15.11	0.76

Note: Geochemical data from Fodor et al. (1985), arranged here in basalt to rhyolite order. For Sr isotopic ratios, m = measured, and I = initial (based on ages of 120 Ma). Mg# = 100 X molecular Mg/(Mg+Fe).

*LOI = loss on ignition (largely H_2O), in wt%.

Figure 2. a: Assimilation-fractional crystallization curves for starting basalt magma (triangle) of $\delta^{18}\text{O} = 5.7$, $^{87}\text{Sr}/^{86}\text{Sr}_{(I)} = 0.703$, and Sr = 500 ppm. In fashion of Taylor (1980), 1000 g of magma consumes 1 g of continental crust. Contaminant is $\delta^{18}\text{O} = 17$ and $^{87}\text{Sr}/^{86}\text{Sr} = 0.735$. Conditions are $C/A = 2$, or 2 g of magma crystallized in response to assimilating 1 g of crust (i.e., relatively warm crust). Bulk distribution coefficient of Sr in magma is 1.5, except one curve labeled as $D = 1$. Sr in contaminant varies from 100 to 333 ppm, accounting for magma/crust $_{\text{Sr}}$ (M/C_{Sr}) of 1.5 to 5; top of each curve is labeled with M/C_{Sr} . Dashed curve is for crust $\delta^{18}\text{O} = 15$; dotted curve is for magma mixing between basaltic andesite (MR03) and rhyolite (RS50); X marks 60:40 mix proportions. Percentages are for crystallization of starting magma. Serra Geral sample data points identified in Table 1. b: Same conditions as in a, except curve $D = 1$, $M/C = 3$ not shown; it falls directly on curve $D = 1.5$, $M/C = 1.5$. Tick marks represent 50%, 75%, and 90% crystallization. Dotted curve is for magma mixing, as in a, where X = 60:40 mix.



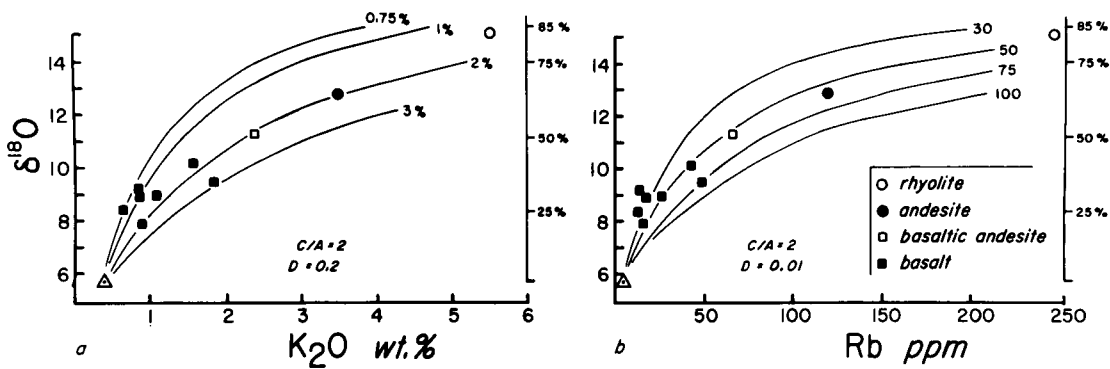


Figure 3. Assimilation-fractional crystallization curves for same conditions as in Figure 2; starting magma (triangle) has 0.4 wt% K_2O and 5 ppm Rb. K_2O and Rb contents of contaminants labeled at ends of curves; bulk distribution coefficients for K and Rb are 0.2 and 0.01, respectively. Percentages refer to magma crystallization.

do Sul part of the Serra Geral basalt-rhyolite sequence. Figures 2b and 3 show supporting plots for trace-element concentrations. For example, parameters that apply to Sr-O isotope variations also apply to Sr plotted against $^{87}Sr/^{86}Sr$. Where curves are too Sr-rich to accommodate data points, Sr content proposed for the starting magma can be decreased (which does not appreciably affect Sr-O curves in Fig. 2a). Incompatible-element figures indicate that K_2O in the contaminant varied between 1 and 3 wt% at a reasonable bulk D of 0.2, and Rb was between about 30 and 100 ppm.

The geologic situations we present do not, of course, precisely constrain geochemical and isotopic parameters or indicate that all of these rocks had similar petrogenetic histories. Rather, the $C/A = 2$ curves in Figures 2 and 3 indicate that the quantity and quality of crustal contamination of basaltic magmas varied. Contamination of the southern Serra Geral magmas probably ranges from negligible (for samples such as RS20, RS60, and RS80; Table 1) to notable, involving continental crust having high and inhomogeneous values for $\delta^{18}O$, Sr, $^{87}Sr/^{86}Sr$, and incompatible-element concentrations (for samples EV01, M02). The combinations of variable geologic conditions, such as the characteristics of Brazilian crustal-rock types and the parental Serra Geral magmas, the efficiency of magma ascension through fracture channelways in rifted Gondwana crust, and magma residence time in chambers, all account for rocks of the Serra Geral flood-basalt province displaying large ranges of geochemical and isotopic crustal signatures (Bellieni et al., 1984; Fodor et al., 1985). It is indisputable that at least part of the large geochemical range (basalt to rhyolite) is due to extensive fractional crystallization attended by assimilation.

Finally, once rhyolitic magmas formed, other igneous processes were likely active. Geochemically, andesite RS65 meets the requirements of a 60:40 mix of magma represented by basaltic andesite MR03 and rhyolite RS50 (Table 1; Fodor et al., 1985). Isotope mixing curves in Figure 2 support this magma-mixing origin for the andesite.

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