

Trace element and Sr-Nd isotopic constraints on the compositions of lithospheric primary sources of Serra Geral continental flood basalts, southern Brazil

S. S. HUGHES¹, R. A. SCHMITT¹ and Y. L. WANG^{1*} and G. J. WASSERBURG²

Departments of Chemistry and Geology and the Radiation Center, Oregon State University, Corvallis, Oregon 97331¹, and The Lunatic Asylum, Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, California 91125² U.S.A.

(Received December 12, 1985; Accepted April 23, 1986)

Multi-element abundances in twenty-four samples from the Serra Geral continental flood basalt system (Parana Basin) were determined by INAA to assess the trace element signature of primary magmatic sources. Isotopic Sr and Nd data were obtained on a 24-sample composite and three individual samples of the suite to constrain the influences of older enriched material. Twenty basaltic samples have enriched LILE commensurate with most continental tholeiites and display fractionated REE patterns similar to those in the Columbia River Group and other flood basalt provinces. The mafic units exhibit low-moderate Ti, variable V, Cr and Ni and relatively uniform Co and Sc abundances. Four intermediate to silicic units exhibit higher overall incompatible element abundances, strongly fractionated patterns and depletions of compatible elements consistent with derivation by fractionation of basaltic parents. Isotopic data for two basalts and the composite analysis indicate $^{87}\text{Sr}/^{86}\text{Sr} = 0.7090$ to 0.7105 and $\epsilon\text{Nd} = -6.6$ to -6.9 requiring magma genesis in an evolved LILE-enriched upper mantle or lower crust. A silicic sample has $^{87}\text{Sr}/^{86}\text{Sr} = 0.7219$ and $\epsilon\text{Nd} = -9.2$ reflecting a stronger crustal influence.

Chemical comparisons within the basaltic members allow the delineation of ten least-evolved compositions having a regionally characteristic trace element pattern and two additional samples (of one flow) representing a second, less fractionated pattern. Trace element models for both types predict magma segregation from lower lithospheric sources having relatively uniform enrichments of incompatible elements *via* regional metasomatism. The most viable scenarios for basalt magma production require either enriched mantle partial-melt liquids, some of which comingle with crustal components, or partial melting of ultramafic, LILE-enriched lower crust. Either process requires a zone of primary magma extraction in a region where initially uniform source enrichments act independently of subsequent contamination, probably in the crust/mantle transition zone.

INTRODUCTION

Source regions of continental flood basalts (CFBs) and the nature of subcontinental lithosphere are enigmatic in light of equivocal trace element and isotopic constraints. Trace element studies of late Precambrian (Keweenaw and Coppermine River) and Mesozoic-Tertiary (Karoo, Parana, Siberian Platform, Deccan and Columbia River) CFB provinces (e.g., BVSP, 1981; Balashov and Nesterenko, 1966; Dupuy and Dostal, 1984; Mahoney *et al.*, 1982; Nelson,

1980; Ruegg, 1976; Smith and Schmitt, 1981; Hughes *et al.*, 1983; Mantovani *et al.*, 1985) have shown that (1) Cr and Ni contents are often too low for the equilibration of large volumes of CFB magma with unaltered mantle and (2) abundances of incompatible elements, e.g. K, Rb, Ba, REE (rare earth elements) and Th, are variable and high compared to oceanic tholeiite chemistries. As an example, La in basaltic members of CFB systems ranges from less than 5 to over 50ppm whereas normal mid-

* Permanent address: Chengdu Geological College, Chengdu, Sichuan, P.R.C.

ocean ridge basalts (Sun *et al.*, 1979) contain typically 1 to 7ppm La. The higher incompatible element signatures in CFB magmas cannot be attributed entirely to fractional crystallization of picritic parents (e.g., Cox, 1980), but reflect LILE (large ion lithophile element) enrichments owing to source metasomatism, subsequent crustal contamination or a combination of these processes.

Generally, CFB lavas display wide ranges in $^{144}\text{Nd}/^{143}\text{Nd}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (e.g., DePaolo and Wasserburg, 1979; BVSP, 1981; Carlson *et al.*, 1981b; Mahoney *et al.*, 1981; Mantovani *et al.*, 1985) which suggest crustal interaction (Carlson *et al.*, 1981a). Combined Nd, Sr and O isotopic data for Columbia River Basalts (Nelson, 1983; Carlson *et al.*, 1981b) and Nd-Sr isotopic evidence from Deccan flows (Mahoney *et al.*, 1982) argue for significant crustal interaction in most CFB provinces. But the cluster of data around $\epsilon\text{Nd} = 0$ and $(^{87}\text{Sr}/^{86}\text{Sr})_1 = 0.705$ for the volume-weighted major proportion of CFB lavas (DePaolo, 1983) supports a primordial mantle source (DePaolo and Wasserburg, 1976, 1979). While CFB lavas portray gross similarities in trace element and isotopic characteristics, the influences of mantle *versus* crustal processes are probably unique for an individual province or subsystem. The tectonic association of Serra Geral (SG) lavas of southern Brazil (Parana Basin) with the Jurassic-Cretaceous breakup of Gondwanaland (Fodor *et al.*, 1985) affords an opportunity to evaluate possible source compositions and crust development during the transition from continental to oceanic magmatism.

Trace element data by Ruegg (1976), although not including REE analyses, indicate somewhat higher incompatible element abundances in Parana rocks relative to most CFB lavas. Cl chondrite normalized (N) trace element patterns of SG-CFB compositions including REE were first reported by Hughes *et al.* (1983). The patterns indicated wide ranges in LILE, but relatively uniform basaltic compositions correlated well with better-known CFB systems. On the basis of Ba, Sr, REE and Sc

signatures, Hughes *et al.* (1983) proposed that the Parana mafic magmas represent a series of partial melts from an enriched plagioclase peridotite source. Silicic compositions, and their fractionated patterns were further attributed to an extensive crustal history involving fractional crystallization rather than contamination although the possibility of crustal influence was not totally dismissed.

Recently reported trace element abundances in the LPT (low P and Ti) Parana CFB samples by Mantovani *et al.* (1985) are consistent with worldwide CFB systems and agree with the patterns reported earlier by Hughes *et al.* (1983). Mantovani *et al.*, (1985) also report wide ranges in $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (0.7074 - 0.7163) for the LPT samples which are commensurate with ranges in other CFB provinces. Models calculated by Mantovani *et al.* (1985) show that the magmas parental to the LPT series originated in a variably LILE enriched and heterogeneous garnet-free mantle source. They attributed the LPT series to plagioclase dominated fractionation and progressive contamination, thereby confirming the suggestion by Hughes *et al.* (1983) that plagioclase was an important residual phase.

Additional isotopic data available for SG-CFBs include the average initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.7057 for six samples by Compston *et al.* (1968), and Sr-Nd data on two samples (DePaolo and Wasserburg, 1979) that yield similar $^{87}\text{Sr}/^{86}\text{Sr}$ ratios and ϵNd values of -1.5 and -4.2. These few data are consistent with SG-CFB sources in a LILE-enriched upper mantle and preclude derivation from a depleted mantle unless enrichment occurred subsequent to magma genesis.

The 24 Serra Geral CFB samples documented by Fodor *et al.* (1985) were provided for trace element and isotopic assessment of the SG-CFB source region. These samples, whose trace element patterns were originally shown in the preliminary report by Hughes *et al.* (1983), represent four arbitrary geographic sectors (our designations) in a 300km \times 300km region near Port Alegre (see Fig. 1 in Fodor *et al.*

al., 1985) in the southern portion of this CFB province. Multi-element data obtained by instrumental neutron activation analysis (INAA) are reported in detail along with Nd-Sr isotopic analyses on selected samples in order to demonstrate the trace element characteristics of the lower lithospheric source at the time of magma segregation and to evaluate further the possibility of crustal involvement in primary magma genesis. We address these problems in light of (1) the comparison of (low Ti) SG-CFB chemistries with better-known CFB systems and the likely prevalence of regional uniformities which can be related to primary sources of most CFB magmas, (2) initial Nd/Sm ratio in the source as determined by trace element modeling and Nd isotopic systematics, and (3) the feasibility of mathematical models which satisfy trace elements and Nd-Sr isotopic constraints. While previous arguments for crustal contamination are accepted for silicic CFB compositions, we question the need for contamination and source heterogeneity in the generation of mafic magmas having uniform trace element signatures.

ANALYTICAL PROCEDURES

Approximately 10 grams of each sample was processed through a 99.9% pure alumina-plate jaw crusher and rotary mill to insure homogeneous samples and similar counting geometries. Multi-element abundances were determined using a sequential INAA procedure similar to that described by Laul and Schmitt (1973). Aliquants (~0.5g) of samples and rock standards BCR-1, BHVO-1, GSP-1 and PCC-1, plus primary standards, were weighed and irradiated for short-lived radionuclide analyses for 3 minutes at 25kW in the Oregon State University TRIGA reactor *via* a pneumatic transfer system for a total neutron fluence of 4×10^{13} . Each sample and standard was counted for 400 seconds with a horizontal Ge(Li) gamma-ray detector coupled to a multichannel spectral analyzer to obtain Ti, Al, Mg, Ca and V abundances. After 4-8 hours decay, subsequent countings of 1-2k seconds on similar equipment

yielded analyses for Na, Mn and Dy. Data for long-lived radionuclides were obtained by activation of ~200mg samples (accurately weighed) and rock standards (plus a primary REE standard) for 5 hours at 1MW for a neutron fluence of 5×10^{16} . After 3-6 days decay time, samples were initially counted 1-2k seconds for K and U, then 8-10k seconds to determine abundances of Na, La, Sm, Yb and Lu. Continued sequential countings using longer decay and count times (several weeks and 20-40k seconds, respectively) enabled data acquisition for Fe, Sc, V, Cr, Co, Ni, Se, Rb, Sr, Cs, Ba, Ce, Nd, Eu, Tb, Zr, Hf, Ta and Th abundances. Isotopic data for Nd and Sr were determined at the California Institute of Technology following the procedures outlined by DePaolo and Wasserburg (1976) and Papanastassiou *et al.* (1977).

RESULTS

Chemical compositions determined by sequential INAA are listed in Table 1 according to the four geographic sectors. Isotopic and elemental Nd and Sr data are presented in Table 2. Group 1 has been further subdivided on the basis of relative trace element abundances (primarily for clarity in presentation of data); although G-648 does not fit readily into any subgroup, it is assigned to group 1c. The low-moderate TiO₂ abundances, together with the LILE abundances, suggest that all of these samples belong to the LPT series of Mantovani *et al.* (1985). The twenty basaltic samples show moderate ranges in LILE abundances exemplified by K₂O = 0.6-1.7wt.%, Rb = 14-69ppm, La = 9-27ppm, Th = 2-6ppm and U = 0.3-2.0ppm while much greater ranges and higher LILE concentrations are evident in the four intermediate to rhyolitic samples with K₂O = 2.2-5.4wt.%, Rb = 73-210ppm, La = 25-46ppm, Th = 8-19ppm and U = 0.4-4.7ppm. The elements V, Cr and Ni are widely variable in basaltic units with V = 250-540ppm, Cr = 6-250ppm and Ni = 10-160ppm compatible with wide ranges in other Parana rocks (Ruegg, 1976); whereas less variation is shown by Sc =

Table 2. Isotopic data for Serra Geral samples

Sample	Sr (ppm)	$^{87}\text{Sr}/^{86}\text{Sr}$	Nd (ppm)	ϵNd	Sm (ppm)	$^{147}\text{Sm}/^{144}\text{Nd}$
RS-65	161	0.72187 \pm 3	35.31	-9.22 \pm 0.37	7.40	0.127
RS-71	214	0.70899 \pm 6	22.97	-6.63 \pm 0.33	5.32	0.140
EV-01	242	0.71010 \pm 3	17.76	-6.61 \pm 0.47	3.66	0.125
Composite-24	207	0.71052 \pm 5	24.10	-6.9	5.8	

32-44 ppm and Co = 39-49 ppm. The uniformity of Sc and Co abundances in basaltic units contrasts with strong depletions of these elements in more silicious rocks as shown for Co vs. La in Fig. 1.

Relative abundances of REE plotted in Fig. 2 as La/Sm vs. La/Yb, vary systematically and show enrichment of light REE (LREE) over CI chondritic (minus volatiles) abundances (Anders and Ebihara, 1982). Also plotted in Fig. 2 are typical LREE-depleted mid-ocean ridge basalts (MORB, Sun *et al.*, 1979) which complement the higher LREE in the continental units yielding a curve which passes through the CI value and may possibly pass through the origin. The curve reflects the tendency for La/Yb ratios to increase faster relative to La/Sm ratios indicating less fractionation of LREE with overall increases in incompatible elements. Figure 2 also portrays minor REE differences between some geographic locales, especially

group 1b, although the less-evolved units of most sectors overlap in the ranges La/Sm = 3.3-4.5 and La/Yb = 4.7-8.0.

Rare earth element abundances in SG samples and other basaltic types, plotted as La vs. Yb and Sm vs. Yb in Fig. 3 show the demarcation which is evident between CFB and MORB (Sun *et al.*, 1979); however, alkalic basaltic compositions from Hawaii (Chen and Frey, 1983; Frey and Clague, 1983), the Rio Grande Rise (Thompson *et al.*, 1983) suggest chemical overlaps of tholeiitic CFB with alkalic oceanic basalts of aseismic ridges, especially at higher total REE contents. At lower REE abundances SG and other CFB lavas maintain a more definitive segregation from the basalts of aseismic

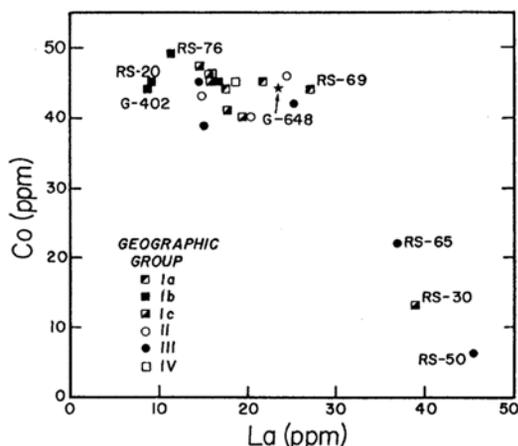


Fig. 1. Co vs. La in all Serra Geral CFB units. RS-30, RS-50 and RS-65, silicic members of the suite, have strongly depleted Sc as well as Co abundances.

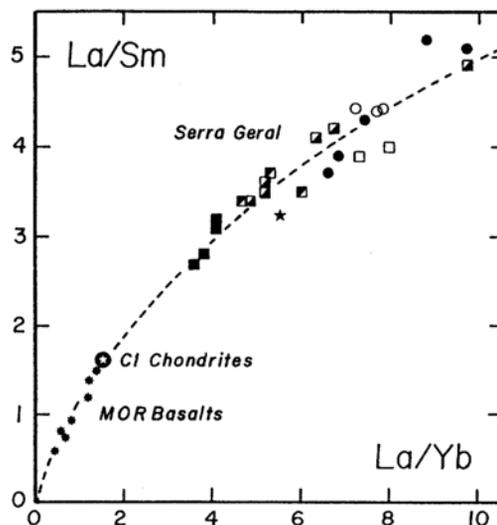


Fig. 2. Ratios of La/Sm vs. La/Yb in Serra Geral compositions relative to CI chondrites (Anders and Ebihara, 1982). The curve reflects a complementary relation between LREE-depleted MORB compositions (Sun *et al.*, 1979) and LREE-enriched Serra Geral primary magmas. Symbols are the same as in Fig. 1.

ridges in the southern Atlantic.

CI chondrite-normalized Sr, Ba, REE, Sc, Hf, Ta and Th patterns of all SG-CFB samples are shown in Fig. 4 with the REE segments spaced according to ionic radii. Depletions in Sr, Eu and Sc, produce negative anomalies in evolved members of groups 1c and 3 which are coupled to higher total REE, Hf, Ta and Th.

All units display low Sr and many samples, except in group 4, have REE patterns with small negative Eu anomalies. Although minor aberrations are evident in some SG samples, the basaltic trace element patterns within each group (except 1b) are essentially parallel and overall pattern variations between groups are minimal.

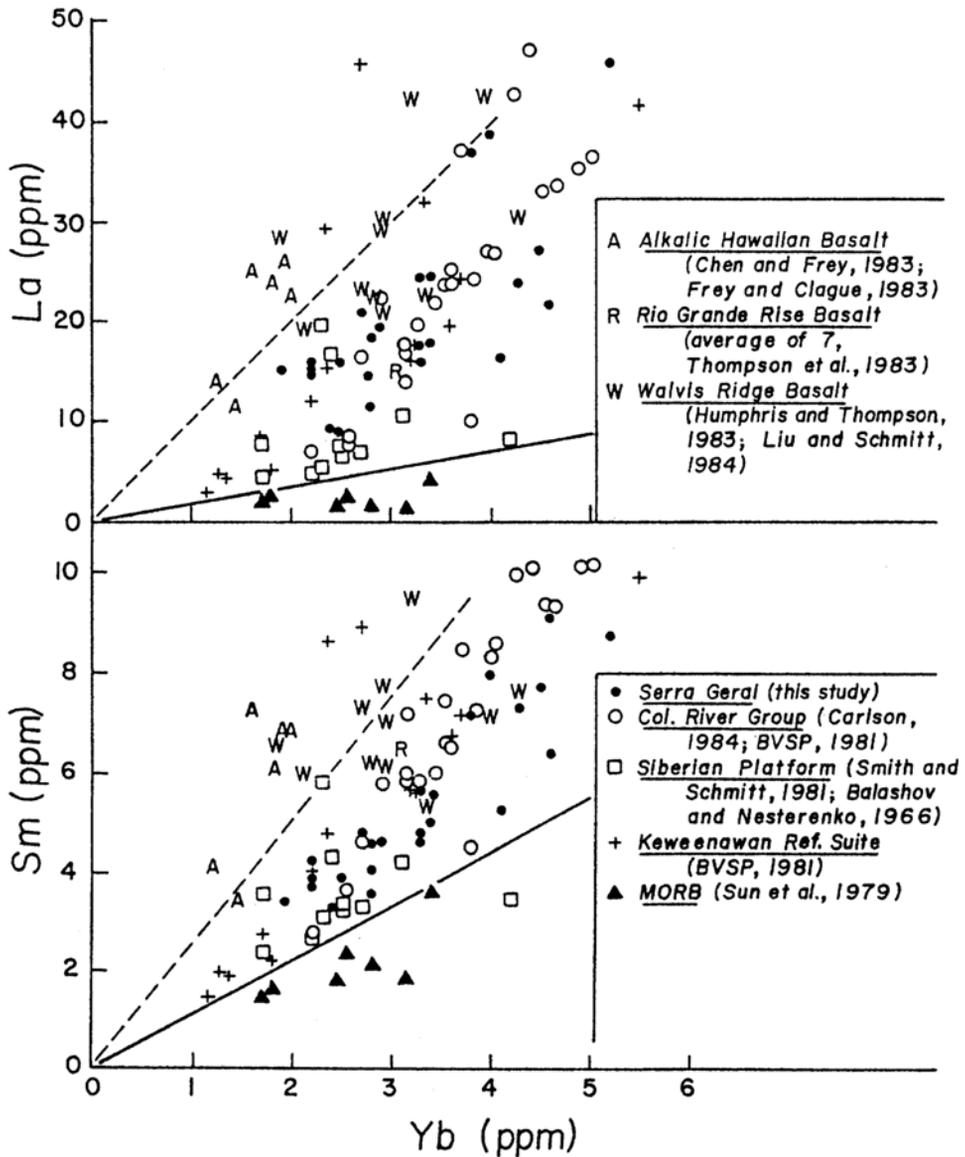


Fig. 3. La vs. Yb and Sm vs. Yb for a variety of continental and oceanic basalts. The lower solid lines represent the well-defined boundary between MORB and continental tholeiites, whereas the upper dashed lines represent a less tenable boundary of alkalic compositions.

Figure 5 illustrates the maximum and minimum trace element patterns representing group: (1) Saddle Mountains formation and SG basalts and the same for reference samples (2) CR members stratigraphically below the

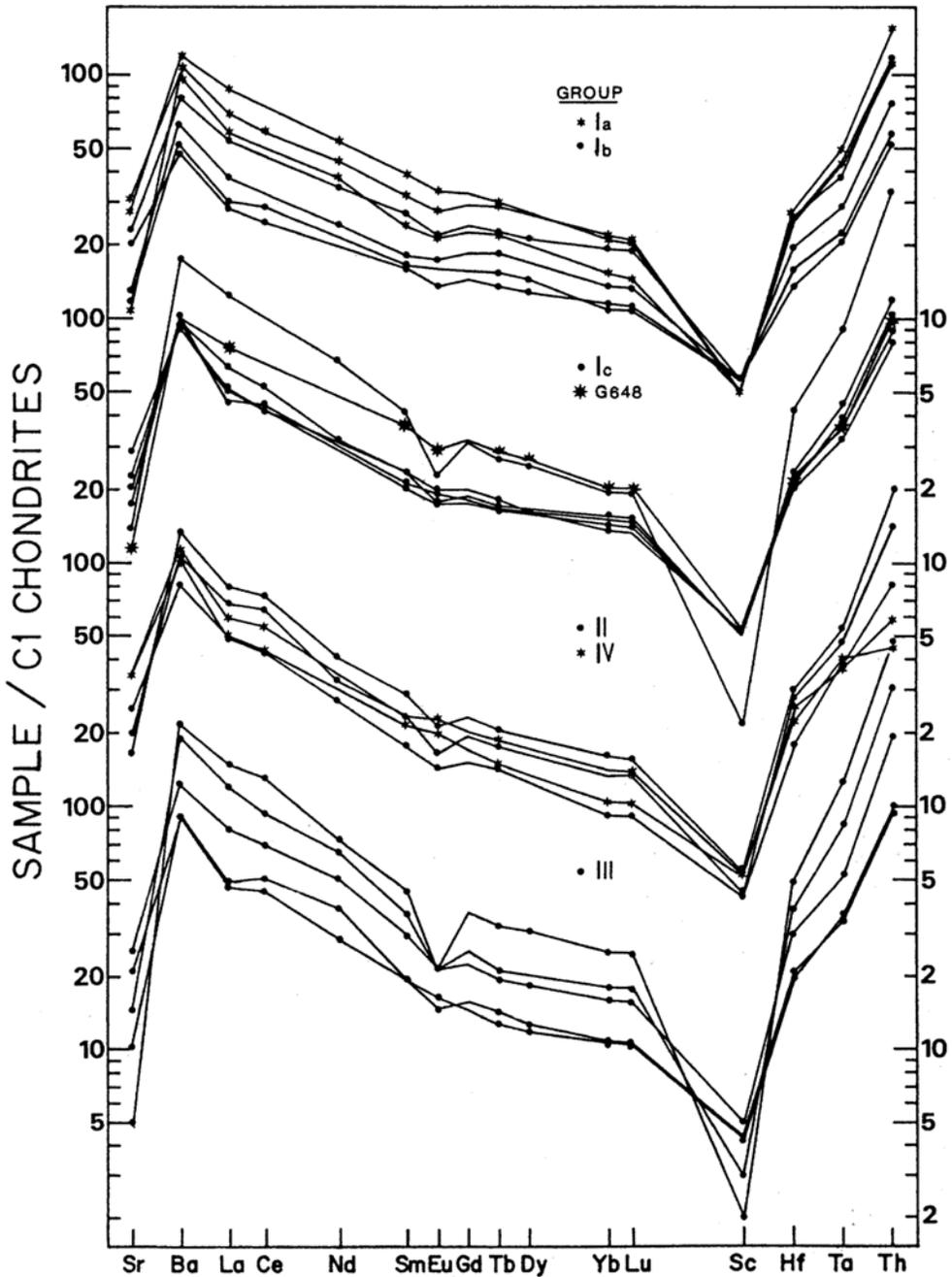


Fig. 4. Sr, Ba, REE, Sc, Hf and Th plotted (REE ionic radii) relative to volatile-free (minus C and H₂O) C1 chondritic abundances (Anders and Ebihara, 1982). Major group divisions are geographic sectors reported by Fodor et al. (1985). Scale on right is for Sc only.

Saddle Mountains section (BVSP, 1981). The REE segments in the CR patterns are nearly identical with the CR data in Carlson (1984) which exhibit increases in total REE and in the ratio of light to heavy REE roughly with stratigraphic position. Isotopic data for the CR system (McDougall, 1976; Nelson, 1980; Carlson, 1981a) indicate an increasing radiogenic component with higher stratigraphic position and argue in favor of crustal contributions to the Saddle Mountain lavas. However, the low sequences in the CR group have less radiogenic compositions and are more likely derived with minimal amounts of crustal interaction. The patterns in Fig. 5 portray strong geochemical similarities of SG basalts in this study (although not stratigraphically controlled) to the basalts in the lower CR sequence, an argument in favor of similar petrogenesis.

Isotopic data (Table 2) for two basaltic samples (EV-01 and RS-71), a rhyodacite (RS-65) and a composite analysis of all 24 units indicate high $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (0.709 to 0.722) relative to mantle xenolith minerals (e.g., Menzies and Murthy, 1980a,b; Jagoutz *et al.*, 1979; Stosch *et al.*, 1980). Negative ϵNd values (-6.6 to -9.2) are within the mantle mineral realm and argue for a LREE enriched ($\text{Nd}_N > \text{Sm}_N$) source. The fact that Nd-Sr data for the two basaltic samples are similar to the composite analysis suggests that RS-65 and other silicic derivatives are petrologically distinct from the main sequence of SG-CFB liquids. The displacement of silicic units is also evident in Figs. 1 and 4.

DISCUSSION

Trace Element Constraints

The bulk and trace element geochemistries of mafic SG units, as well as REE (Figs. 3 and 5), are virtually indistinguishable from those of most CFB systems despite minor variations within individual groups. This likeness argues in favor of a unifying geochemical process which can be generalized to sources of CFB systems on a worldwide basis although the continental

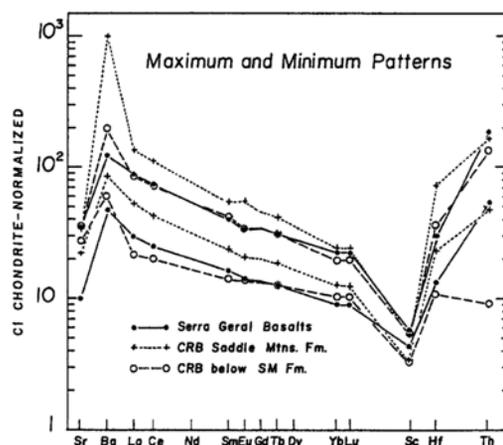


Fig. 5. Upper and lower boundaries of trace element patterns (from Fig. 4) in Serra Geral basalts, Columbia River basalts stratigraphically below the Saddle Mountains Fm., and CRB Saddle Mountains Fm. Columbia River data from BVSP, 1981.

tectonic settings are not always uniform. The timely breakup of Gondwanaland certainly allowed for changes in depth of mantle sources beneath eruptive zones, but the rifting itself probably had little impact on the regional geochemistry of pre-established magma sources in the subcontinental lithosphere.

Descriptions of CFB primary sources is complicated by the requirement of either picritic parents (Krishnamurthy and Cox, 1977; Cox, 1980) which fractionate to magmas having lower Mg/Fe ratios or melting of an evolved (Fe-enriched) source. Also, any viable scenario for a CFB origin requires large volumes of chemically uniform magma, high rates of extrusion and, therefore, a regional "magmafer". If the least-evolved units of a CFB system display a characteristic trace-element pattern over a wide area, that pattern should reflect a relatively homogeneous stage of primary magma evolution prior to divergences produced by assimilative mixing or fractional crystallization. Assuming that fractionation of a picritic parent will not appreciably alter incompatible element ratios, the average least-evolved trace-element pattern is primary and was determined before or during initial magma extraction.

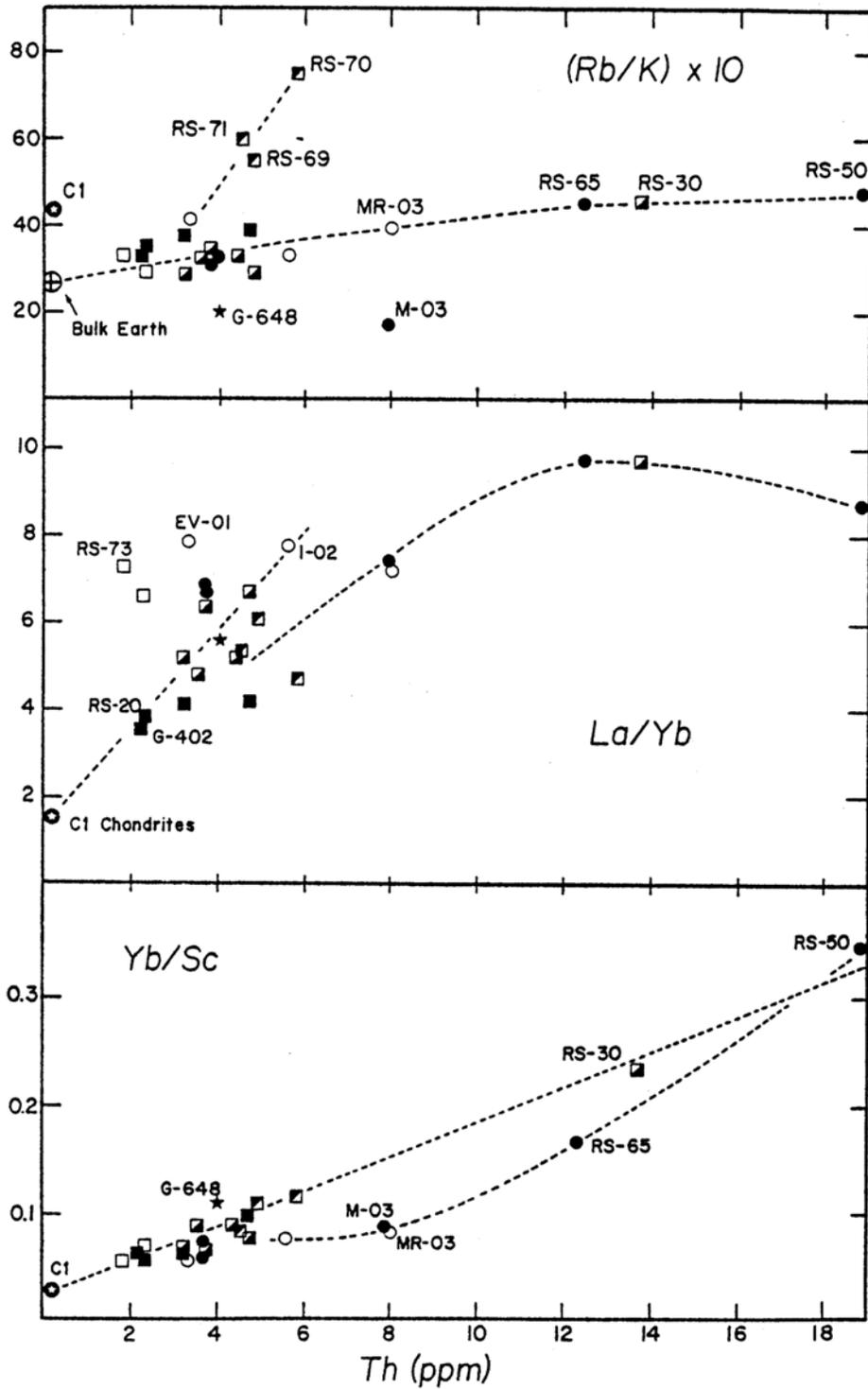


Fig. 6. Rb/K , La/Yb and Yb/Sc vs. Th in Serra Geral lavas. Bulk earth composition from DePaolo, 1983; C1 chondritic values from Anders and Ebihara (1982). Symbols as in Fig. 1.

The nearly parallel configurations in Fig. 4 suggest a regional trace element uniformity of basaltic units, although G-648 has higher REE abundances and subgroup 1b exhibits lower overall abundances (except Sc) and lower La/Yb ratios. The members of group 1b, especially RS-20 and G-402, exhibit the lowest LILE abundances; however, siderophile and major elements fall within the ranges shown for all basaltic units and do not support a lesser degree of magma evolution. The observation that REE patterns of 1b members, which have lower total REE abundances, are not parallel to other groups argues for a separate line of descent for subgroup 1b and a source region with lower La/Yb ratios and total LILE abundances.

Figure 6 illustrates the behaviors of Rb/K, La/Yb and Yb/Sc ratios relative to the highly incompatible element Th. The slight increase of Rb/K in evolved members portrays a systematic trend from the assumed bulk earth composition (DePaolo, 1983), but it is offset by G-648, M-03 and members of subgroup 1a which follow an alternate line of evolution (discussed in greater depth by Fodor *et al.*, 1985). Variations in La/Yb ratios with Th (Fig. 6) are less systematic, although mafic members cluster around La/Yb = 4-6. A positive trend from the C1 chondritic value passes through basaltic compositions and subtle differences in REE chemistry between groups are evident. The Yb/Sc vs. Th data for most basaltic units plot along a line extending from the C1 chondritic value through the most silicic members of the suite. Offsets of Yb/Sc ratios in M-03, MR-03 and RS-65 suggest that diverging evolutionary patterns are initiated below Th = 5 ppm, the cut-off used herein for least-evolved magmas.

The clustering in Fig. 6 of most basaltic compositions compared to the scattered points for silicic and divergent units allows the delineation of samples which best represent the least-evolved trace element signature. A regionally characteristic trace-element pattern is established by averaging these basaltic compositions, but excluding certain samples for the following reasons: (1) G-648 (Fig. 4) has absolute REE

abundances roughly 50 percent higher than REE in other SG basaltic rocks; (2) subgroup 1a (RS-69 and RS-71) has excessive Rb (Fig. 6) and high FeO, V and Th, suggesting a divergence in petrogenesis; and (3) subgroup 1b has lower total LILE abundances and lower La/Yb ratios (Fig. 6), although bulk chemistry and siderophile trace elements do not substantiate a more primitive stage.

The average of 10 SG basaltic compositions considered to be least-evolved and regionally represented is depicted in Fig. 7 as SGAV10. A second compositional average of G-402 and RS-20 (SUB1b, Fig. 7) indicates either LILE depletion from previous melt extraction or less LILE enrichment in an alternate source. Our petrogenetic models of the SG basaltic magmafer assume that (1) the SGAV10 pattern is inherent in magmas at the zone of basaltic magma extraction, regardless of the magmafer location (crust or mantle), and (2) the processes that determined the geochemical character of the least-evolved magmas are uniformly operative on a regional scale. Differentiation to more silicic compositions, accompanied by an increase in total incompatible elements and more fractionated patterns (Figs. 2-4), is dominated by fractional crystallization of mafic parents (Hughes *et al.*, 1983; Fodor *et al.*, 1985;

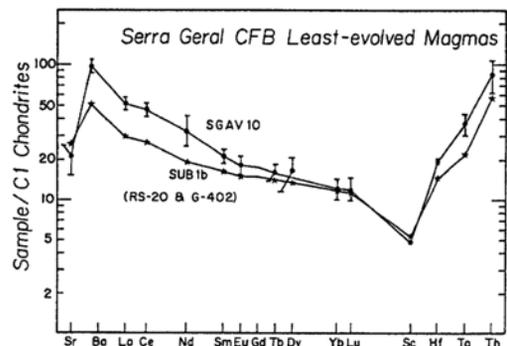


Fig. 7. SGAV10: trace element pattern with standard deviations, representing least-evolved Serra Geral magmas is average of RS-16, RS-26, RS-37, RS-60, RS-68, RS-73, M-01, M-02, I-02 and G-215. SUB1b: identical patterns of two samples from one flow which, although less representative, reflects a second source for SG primary magmas.

Mantovani *et al.*, 1985) with an allowance for subordinate effects of crustal assimilation. Similarities between evolved SG compositions and post-Archean continental crust (McLennan *et al.*, 1980) would probably cause the effects of crustal contamination to be cryptic in trace elements. However, the uniformity of fractionated compositions in basalts precludes the random effects of secondary assimilation and supports an enriched lower lithospheric source.

Isotopic Constraints

The isotopic data in Table 2 suggest crustal influence on the SG-CFB system in addition to magma equilibration in LILE-enriched regions of the lithosphere. Figure 8 illustrates ϵNd vs. $^{87}Sr/^{86}Sr$ data of this study plus those for two other SG basalt samples of DePaolo and Wasserburg (1979) obtained from a drill core near Santa Catarina (PAR, see Fig. 1, Fodor *et al.*, 1985). The higher $^{87}Sr/^{86}Sr$ ratio and lower ϵNd of RS-65 places it near the "upper crust" realm (DePaolo, 1981a), indicating that RS-65, and

probably other evolved samples contain upper-crust material. The less-evolved units, RS-71 and EV-01, and the composite SG analysis are consistent with a basaltic magmafer in either the lower crust or an enriched upper mantle although equilibration with mantle material is not supported by major elements ($MgO \leq 10\%$) or transition metal abundances. By contrast, PAR 1 and 2 plot closer to the present day bulk-earth composition supporting a less-evolved basaltic magma source. The isotopic differences between these sources are consistent with either variable amounts of older LILE-enriched material assimilated into the liquid or variations in the age of source-enrichment prior to magma extraction.

Assuming little or no difference in source ages, the SG-CFB source is petrologically positioned between primary mantle and upper crust as shown by combined fractional crystallization and mixing curves in Fig. 7. The curves follow equations given by DePaolo (1981b) using a primary magma composition of $^{87}Sr/^{86}Sr =$

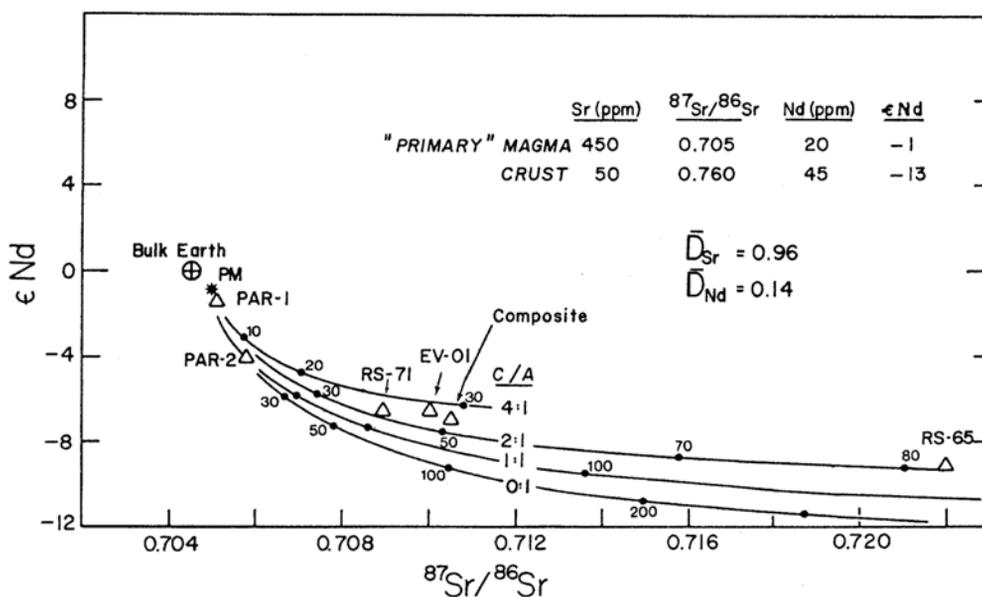


Fig. 8. ϵNd vs. $^{87}Sr/^{86}Sr$ for PAR-1 and PAR-2 (DePaolo and Wasserburg, 1979) and RS-71, EV-01, RS-65 and a 24-sample composite (this study). Curves represent combined effects of crustal assimilation and fractional crystallization using an assumed primary magma and the "E" crustal component of Carlson *et al.* (1981b). C:A Values indicate cumulate to assimilate ratios and labelled points show the percentage of original mass added by assimilation.

0.705 and $\epsilon\text{Nd} = -1$. The assimilated composition is assumed to be similar to the "E" component used by Carlson *et al.*, (1981a) with $^{87}\text{Sr}/^{86}\text{Sr} = 0.760$ and $\epsilon\text{Nd} = -13$, but with an absolute Nd abundance (45 ppm) more compatible with silicic SG rocks. The evolutionary lines represent specific ratios of cumulate lost to assimilate added (C:A) and the numbered points mark the percentage of original mass added by assimilation. The position of RS-65 on the C:A = 2:1 curve implies an evolutionary trend marked by more than 80 percent crustal assimilation with twice that amount (of original mass) being removed as cumulate. Basaltic SG-CFB units lie above the 2:1 line and simulate a system controlled by 30-50% assimilation of the the crustal component along with larger amounts of crystallization. However, 30-50% upper-crust addition to regionally uniform basaltic magmas seems fortuitous unless a shallow homogenization process can be demonstrated.

Alternatively, the positions of basaltic SG units in Fig. 8 represent magma generation in an older enriched lithospheric source, possibly in the mantle/crust transition zone. The differences between regional Parana magmaferers become those of location and age of LILE enrichment, assuming similar petrogenetic behavior and somewhat variable isotopic signatures. This discretion is supported by similar or lower Sm/Nd ratios in the two PAR samples (Sm/Nd = 0.17 and 0.22, DePaolo and Wasserburg, 1979) compared to that of the SGAV10 composition (Sm/Nd = 0.21). It is likely that source enrichments for PAR 1 (Fig. 8) occurred within a relatively short time before magma genesis.

TRACE ELEMENT MODELING

Models of SG-CFB source regions follow three inherent premises. First, absolute trace element abundances can only be approximated due to ranges in partition coefficients for most minerals (e.g., Fujimaki *et al.*, 1984; Irving, 1978), whereas relative behaviors are more

accurately predicted. Second, uncertainties in the relative amounts of partial melting and fractional crystallization for large magmatic volumes force a combination of mineral/melt calculations into a single, presumably equilibrium, process. Residual minerals in source models may be either unmelted solids at the original point of extraction or subsequent precipitates. Third, the most viable model should predict a flat chondrite-relative pattern for the most compatible elements, HREE, Sc and Hf which will remain relatively unfractured during source enrichments or depletions. Assuming that the SG lavas are not derived from an initially depleted reservoir, enrichments determined by modeling represent sources prior to magma segregation.

Predicted sources for SGAV10 and SUB1b, shown in Fig. 9 were calculated using the equilibrium non-modal melting equation of Shaw (1970) to simulate the combined effects of anatexis and crystallization. Partition coefficients (D-values, Appendix) are those applicable to tholeiitic basalt systems and D-values for Th are assumed zero. The strong depletions in Sr compared with minor negative Eu anomalies support higher and lower relative D-values for Sr and Eu, respectively, of plagioclase equilibrated at elevated f_{O_2} and lower temperatures (Drake and Weill, 1975). Melting proportions correspond approximately with observed mass modal proportions of minerals (excluding late-stage Fe-Ti oxides) in tholeiitic basalts although the modeled sources depend more on residual proportions.

The preferred model for SGAV10 (Fig. 9) assumes 10 percent melting of an initial plagioclase peridotite source and a residual mineralogy of ol 60 opx 10 cpx 1 pl 29. The greater relative amounts of residual olivine and plagioclase may be related to subsequent crystallization of these phases and do not necessarily indicate the initially solid proportions at greater depths. Enrichments in Sr, Ba, LREE and Th are consistent with melting of metasomatized ultramafic lithosphere having an initial $(\text{Sm}/\text{Nd})_{\text{N}}$ ratio of 0.65. Lower degrees of melting, even for a less

reasonable source mineralogy required to minimize inflections in the REE-Sc-Hf pattern, require similar or lower $(\text{Sm}/\text{Nd})_N$ ratios as shown for $F = 5$ percent melting.

The SUB1b composition yields a viable source at 15 percent melting (Fig. 9) which is similar to the SGAV10 source in HREE, Sc and Hf. Lower incompatible element abundances

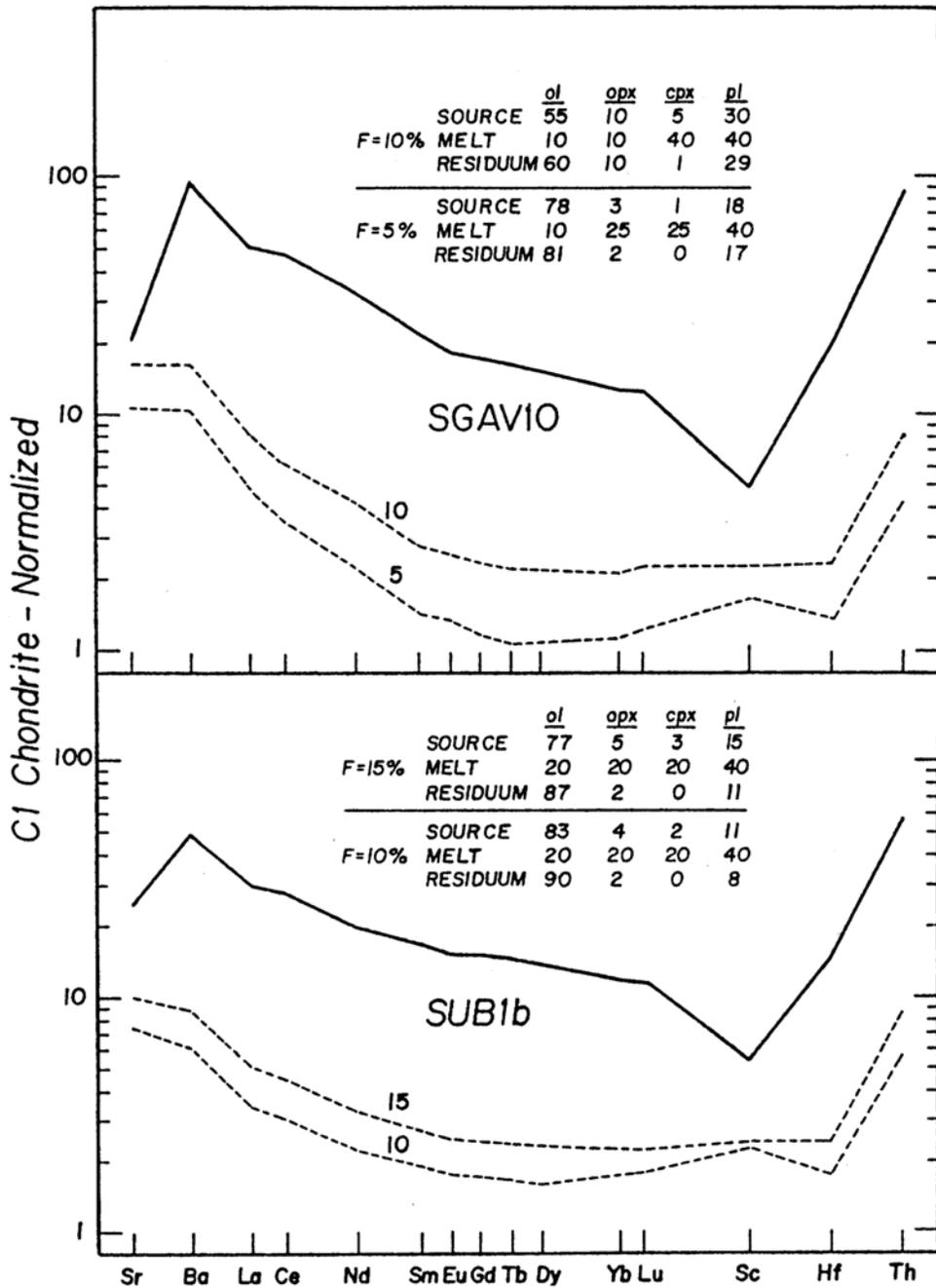


Fig. 9. Trace element models using non-modal batch melting equations (Shaw, 1970) for primary sources of SGAV10 and SUB1b Serra Geral magmas. D -values given in Appendix.

indicate a less enriched or evolved source having a $(\text{Sm}/\text{Nd})_N$ ratio of 0.85. Similar relative enrichments are portrayed by the modeled source at 10 percent melting. Models for both magma compositions from Fig. 7 indicate LREE-fractionated sources with $(\text{Sm}/\text{Nd})_N$ ratios similar to the observed ratios. Essentially no fractionations of Ba and LREE are obtained due to their low bulk D-values in the residual mineralogy. It is likely that PAR-1 and PAR-2 (DePaolo and Wasserburg, 1979; Liu and Schmitt, 1984) compositions also yield source $(\text{Sm}/\text{Nd})_N$ ratios that are similar to their observed ratios. Model-dependent sources for PAR-1 and PAR-2 (not shown) should have minimum $(\text{Sm}/\text{Nd})_N$ ratios of 0.52 and 0.67, respectively, which suggest slightly greater source enrichments despite the more primitive isotopic signatures.

PRIMARY MAGMA SOURCES

The apparent disparity between source composition and the observed ϵNd values argues in favor of source enrichments to produce the observed trace element patterns as well as source variability between subprovinces in the SG-CFB system. Added crustal components are operative in altering some isotopic signatures, but do not significantly alter the overall trace element pattern. Slightly different trace element patterns in sources required by SGAV10 and SUB1b derive from regional differences in the subcontinental mantle not unlike those which have been proposed for the Columbia River Basalt group (Carlson, 1984). Isotopic differences, apart from the pronounced effects in silicic compositions, may be imparted with variable ages of enriched lithospheric sources or variable proportions of crustal components added to isotopically uniform primary magma. In light of similar Sm/Nd source ratios required for most SG-CFB magmas, variations in source age appear to be the more viable hypothesis. Assimilation of a crustal component to alter isotopic ratios requires that the contaminant have a trace element signature close to that in

the primary melt.

At least two geologically reasonable scenarios are possible: (1) primary melts from enriched lithospheric mantle comingle and homogenized with underplated crustal components of variable ages, probably in stratigraphic succession; and (2) primary magmas were derived by partial melting of enriched lithosphere at variable time-stratigraphic horizons. Both hypotheses allow the existence of regional homogeneous primary magma subsystems and require the placement of CFB magmaferers within the crust/mantle transition at levels permissible for regionally uniform partial melting. In either scenario trace element enrichments are obtained in the zone of primary magma production.

CONCLUSIONS

Basaltic low-moderate Ti members of the Serra Geral CFB system display characteristic trace element signatures that reflect a regional constancy of magmatic processes. Trace element models require at least two separate sources enriched in incompatible elements *via* metasomatic processes. Isotopic data indicate variable contributions of crust or evolved upper mantle in some basaltic magmas, a more substantial crustal component in silicic units, and support models of magma genesis in LILE-enriched sources. The basaltic magmaferer for a given subprovince in the SG-CFB system may be obtained by either of two mechanisms: (1) primary melts from enriched mantle comingle with assimilated lower crustal components of a particular age or (2) partial melting of ultramafic LILE-enriched lower lithosphere occurs within a specific time-stratigraphic horizon. Similarity of these two scenarios requires the placement of SG-CFB magmaferers in the mantle/crust transition zone allowing proportioned contributions from variable-evolved LILE-enriched material.

The similarity of modeled SG-CFB source chemistries, especially incompatible trace element ratios, with better known CFB systems

reflects the processes of primary source enrichment on a regional scale and not the random effects of subsequent contamination by crustal components. Evolution of the SG-CFB source region, despite the breakup of Gondwanaland, represents a possibly uniform and continuous global process of LILE enrichment in the continental lower lithosphere.

Acknowledgements—We thank A. Roisenberg for providing the suite of Serra Geral samples and T. V. Anderson, W. T. Carpenter and D. Pratt for assistance with neutron activations in the Oregon State University TRIGA reactor. Helpful comments and criticisms by R. V. Fodor greatly improved the manuscript. Financial support was provided by NASA grant NAG9-63 to R. A. Schmitt and grant NAG9-49 to G. J. Wasserburg.

REFERENCES

- Anders, E. and Ebihara, M. (1982) Solar system abundances of the elements. *Geochim. Cosmochim. Acta* **46**, 2363–2380.
- Arth, J. G. (1976) Behavior of trace elements during magmatic processes - a summary of theoretical models and their applications. *J. Res. U. S. Geol. Surv.* **4**, 41–47.
- Balashov, Y. A. and Nesterenko, G. V. (1966) Distributions of the rare earths in the traps of the Siberian Platform. *Geochem. Int.* **3**, 672–679.
- BVSP (Basaltic Volcanism Study Project, 1981) *Basaltic Volcanism on the Terrestrial Planets*. Pergamon Press: New York. 1286p.
- Carlson, R. W. (1984) Isotopic constraints on Columbia River flood basalt genesis and the nature of the subcontinental mantle. *Geochim. Cosmochim. Acta* **48**, 2357–2372.
- Carlson, R. W., Lugmair, G. W. and McDougall, J. D. (1981a) Crustal influence in the generation of continental flood basalts. *Nature* **289**, 160–162.
- Carlson, R. W., Lugmair, G. W. and McDougall, J. D. (1981b) Columbia River volcanism: the question of mantle heterogeneity or crustal contamination. *Geochim. Cosmochim. Acta* **45**, 2483–2499.
- Chen, C.-Y. and Frey, F. A. (1983) Origin of Hawaiian tholeiite and alkalic basalt. *Nature* **302**, 785–789.
- Compston, W., McDougall, I. and Heier, K. S. (1968) Geochemical comparison of the Mesozoic basaltic rocks of Antarctica, South Africa, South America and Tasmania. *Geochim. Cosmochim. Acta* **32**, 129–149.
- Cox, K. G. (1980) A model for flood basalt volcanism. *J. Petrol.* **21**, 629–650.
- DePaolo, D. J. (1981a) A neodymium and strontium isotopic study of the Mesozoic calc-alkaline granitic batholiths of the Sierra Nevada and Peninsular ranges, California. *J. Geophys. Res.* **86**, 10470–10488.
- DePaolo, D. J. (1981b) Trace element and isotopic effects of combined wallrock assimilation and fractional crystallization. *Earth Planet. Sci. Lett.* **53**, 189–202.
- DePaolo, D. J. (1983) Comment on “Columbia River volcanism: the question of mantle heterogeneity or crustal contamination” by R. W. Carlson, G. W. Lugmair and J. D. McDougall. *Geochim. Cosmochim. Acta* **47**, 841–844.
- DePaolo, D. J. and Wasserburg, G. J. (1976) Inferences about magma sources and mantle structure from variations of $^{143}\text{Nd}/^{144}\text{Nd}$. *Geophys. Res. Lett.* **3**, 743–746.
- DePaolo, D. J. and Wasserburg, G. J. (1979) Neodymium isotopes in flood basalts from the Siberian Platform and inferences about their mantle sources. *Proc. Natl. Acad. Sci. U.S.A.* **76**, 3056–3060.
- Drake, M. J. and Weill, D. F. (1975) The partition of Sr, Ba, Ca, Y, Eu^{2+} , Eu^{3+} and other REE between plagioclase feldspar and magmatic silicate liquid: an experimental study. *Geochim. Cosmochim. Acta* **39**, 689–712.
- Dupuy, C. and Dostal, J. (1984) Trace element geochemistry of some continental tholeiites. *Earth Planet. Sci. Lett.* **67**, 61–69.
- Fodor, R. V., Corwin, C. and Roisenberg, A. (1985) Petrology of Serra Geral (Paraná) continental flood basalts, southern Brazil: crustal contamination, source material, and South Atlantic magmatism. *Contrib. Mineral., Petrol.* **91**, 54–65.
- Frey, F. A. and Clague, D. A. (1983) Geochemistry of diverse basalt types from Loihi Seamount, Hawaii: petrogenetic implications. *Earth Planet. Sci. Lett.* **66**, 337–355.
- Fujimaki, H., Tatsumoto, M. and Aoki, K. (1984) Partition coefficients of Hf, Zr, and REE between phenocrysts and groundmasses. *Proc. Lunar Planet. Sci. Conf. 14th, J. Geophys. Res.* **89**, B662–B672.
- Hughes, S. S., Wang, Y. L., Schmitt, R. A., Fodor, R. V., Corwin, C. and Roisenberg, A. (1983) Parana Basin lavas: chemical and petrographic characteristics. *Lunar Planet. Sci.* **14**, 337–338.
- Irving, A. J. (1978) A review of experimental studies of crystal/liquid trace element partitioning. *Geochim. Cosmochim. Acta* **42**, 743–770.
- Jagoutz, E., Palme, H., Baddenhausen, H., Blum, K., Cendales, M., Dreibus, G., Spettel, B., Lorenz, V. and Wanke, H. (1979) The abundances of major, minor and trace elements in the earth's mantle as derived from primitive ultramafic nodules. *Proc.*

- Lunar Planet. Sci. Conf. 10th* 2031–2050.
- Krishnamurthy, P. and Cox, K. G. (1977) Picrite basalts and related lavas from the Deccan Traps of western India. *Contrib. Mineral. Petrol.* **62**, 53–75.
- Laul, J. C. and Schmitt, R. A. (1973) Chemical composition of Luna 20 rocks and soil and Apollo 16 soils. *Geochim. Cosmochim. Acta* **37**, 927–942.
- Lindstrom, D. J. (1976) Experimental study of the partitioning of the transition metals between clinopyroxene and coexisting silicate liquids. Ph. D. Thesis, Univ. Oregon, 188p.
- Liu, Y.-G. and Schmitt, R. A. (1984) Chemical profiles in sediment and basaltic samples from Deep Sea Drilling Project Leg 74, Hole 525A, Walvis Ridge. *Initial Rep. Deep Sea Drill. Proj.* **74**, 713–730.
- Mahoney, J., MacDougall, J. D., Lugmair, G. W., Murali, A. V., Sankar, Das. M. and Copalón, K. (1982) Origin of the Deccan Trap flows at Mahabaleshwar inferred from Nd and Sr isotopic and chemical evidence. *Earth Planet. Sci. Lett.* **60**, 47–60.
- Montovani, M. S. M., Marques, L. S., DeSousa, M. A., Civetta, L., Atalla, L. and Innocenti, F. (1985) Trace element and strontium isotope constraints on the origin and evolution of Parana continental flood basalts of Santa Catarina State (Southern Brazil) *J. Petrol.* **26**, 187–209.
- McDougall, I. (1976) Geochemistry and origin of basalt of the Columbia River Group, Oregon and Washington. *Geol. Soc. Am. Bull.* **87**, 777–792.
- McKay, G. A. and Weill, D. F. (1977) KREEP petrogenesis revisited. *Proc. Lunar Sci. Conf. 8th* 2339–2355.
- McLennan, S. M., Nance, W. B. and Taylor, S. R. (1980) Rare earth element-thorium correlations in sedimentary rocks, and the composition of the continental crust. *Geochim. Cosmochim. Acta* **44**, 1833–1839.
- Menzies, M. and Murthy, V. R. (1980a) Nd and Sr isotope geochemistry of hydrous mantle nodules and their host alkali basalts: Implications for local heterogeneities in metasomatically veined mantle. *Earth Planet. Sci. Lett.* **46**, 323–334.
- Menzies, M. and Murthy, V. R. (1980b) Mantle metasomatism as a precursor to the genesis of alkaline magmas - isotopic evidence. *Am. J. Sci. Jackson Vol.* **280A**, 622–638.
- Nelson, D. O. (1980) Strontium isotopic and trace element geochemistry of the Saddle Mountains and Grande Ronde Basalts of the Columbia River Group. Ph. D. Thesis, Oregon State Univ., 224p.
- Nelson, D. O. (1983) Implications of oxygen-isotope data and trace-element modeling for a large-scale mixing model for the Columbia River Basalt. *Geology* **11**, 248–251.
- Papanastassiou, D. A., DePaolo, D. J. and Wasserburg, G. J. (1977) Rb-Sr and Sm-Nd chronology and genealogy of mare basalts from the Sea of Tranquility. *Proc. Lunar Sci. Conf. 8th* 1639–1672.
- Philpotts, J. A. and Schnetzler, C. C. (1970) Phenocryst-matrix partition coefficients for K, Rb, Sr and Ba, with applications to anorthosite and basalt genesis. *Geochim. Cosmochim. Acta* **34**, 307–322.
- Ruegg, N. R. (1976) Características de distribuição e teor de elementos traços dosados em rochas basálticas de bacia do Parana. *Naturalia* **2**, 23–45.
- Shaw, D. M. (1970) Trace element fractionation during anatexis. *Geochim. Cosmochim. Acta* **34**, 237–243.
- Smith, M. R. and Schmitt, R. A. (1981) Petrogenesis of continental flood basalts from the Siberian Platform and a model of mantle evolution. *Lunar Planet. Sci.* **12**, 1011–1013.
- Stosch, H. G., Carlson, R. W. and Lugmair, G. W. (1980) Episodic mantle differentiation: Nd and Sr isotopic evidence. *Earth Planet. Sci. Lett.* **47**, 263–271.
- Sun, S.-S., Nesbitt, R. W. and Sharaskin, A. Y. (1979) Geochemical characteristics of mid-ocean ridge basalts. *Earth Planet. Sci. Lett.* **44**, 119–138.
- Thompson, G., Humphris, S. and Schilling, J. G. (1983) Petrology and geochemistry of basaltic rocks from Rio Grande Rise, South Atlantic: Deep Sea Drilling Project Leg 72, Hole 516F. *Initial Rep. Deep Sea Dri. Proj.* **72**, 457–466.

APPENDIX

Distribution coefficients used in trace element models

	<u>Olivine</u>	<u>Orthopyroxene</u>	<u>Clinopyroxene</u>	<u>Plagioclase</u>
Sr	0.009	0.017	0.12	2.7**
Ba	0.009	0.013	0.026	0.23
La	0.0056	0.022	0.105	0.21
Ce	0.0056	0.024	0.125	0.12
Nd	0.0058	0.033	0.287	0.081
Sm	0.0078	0.054	0.477	0.067
Eu	0.0086	0.054	0.562	0.10**
Gd	0.010*	0.091	0.595	0.063
Tb	0.011	0.11*	0.61*	0.059*
Dy	0.012	0.15	0.622	0.055
Yb	0.042	0.34	0.601	0.059*
Lu	0.053	0.42	0.560	0.060
Sc	0.37	1.4	3.8	0.044*
Hf	0.022	0.051	0.121	0.01
Th	0.0	0.0	0.0	0.0

* Values which are interpolated or estimated from several sources.

** Estimated values for D_{Sr} and D_{Eu} in plagioclase at higher fO_2 values (see text).

Sources of data:

Sr, Ba: Philpotts and Schnetzler (1970), Arth (1976).

REE, Hf: Fujimaki *et al.* (1984), Arth (1976).

Sc: Lindstrom (1976), McKay and Weill (1977).