Geochemical and Isotopic Evidence for the Origin of Continental Flood Basalts with Particular Reference to the Snake River Plain Idaho, U.S.A. [and Discussion]

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Geochemical and isotopic evidence for the origin of continental flood basalts with particular reference to the Snake River Plain Idaho, U.S.A.

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Voluminous outpourings of olivine and quartz tholeiite cover vast tracts of the western U.S.A. around the Columbia and Snake Rivers. Voluminous eruptive units within each province are petrographically and chemically homogeneous and generally lack significant lateral or temporal variation. These features suggest relatively homogeneous source regions. A possible scenario for the Snake River Plain involves extraction of tholeiitic melts from enriched spinel lherzolite mantle ($^{87}Sr/^{86}Sr > 0.7058$, $^{143}Nd/^{144}Nd < 0.51252$) which contains at least a component of 2.5 Ga material. Subsequent fractionation of olivine, plagioclase, apatite and magnetite in crustal magma chambers and simultaneous assimilation of crust (*ca.* 20 %) accounts for the isotopic variability in the more evolved ferrolatites and ferrobasalts. Unlike the olivine tholeiites these evolved volcanic rocks exhibit all the classic elemental and isotopic correlations consistent with an origin involving combined assimilation and fractional crystallization.

1. Introduction

Characterization of the mantle source regions of continental flood basalts (c.f.b.) is hampered by uncertainties regarding the extent of modification of the magmas by interaction with the continental crust, and is also plagued by ignorance of the chemical and isotopic heterogeneity of the sub-continental mantle. Evidence from mantle xenoliths (Menzies & Murthy 1980; Erlank *et al.* 1982) demonstrates that some portions of the sub-continental mantle are both old and relatively enriched in incompatible elements, consistent with suggestions that much of the continental lithosphere may stabilize soon after the last major thermal event registered in the overlying crust (Oxburgh & Parmentier 1978). This may produce mantle of sufficient age that any enrichment in incompatible elements (namely, increase in Rb/Sr and Nd/Sm) will be reflected in the isotope ratios. Isotopically heterogeneous mantle represents a time-integrated response to various enrichment processes that vary both in style and timing (Hawkesworth *et al.* 1983*b*). The debate concerning the origin of continental flood basalts surrounds the question of whether such portions of the sub-continental mantle are genetically important as source regions or voluminous outpourings of tholeiitic magma. Also considerable controversy centres around whether the isotopic and trace element characteristics of the mantle source are ever observed in basalts erupted at the surface, or whether variable degrees of crustal contamination, with or without fractional crystallization, have effectively obliterated the chemical and isotopic fingerprint of the mantle source. Several recent contributions (DePaolo & Wasserburg 1979*a*; Carlson *et al.* 1981) on the origin of c.f.b. have tended to assume that all members of a flood basalt sequence originated in mantle of a single uniform isotopic composition, and that variable interaction with the crust has produced the observed isotopic heterogeneity. However, unequivocal evidence of crustal contamination in a single eruptive unit does not necessarily imply that all magmas in that province have evolved similarly.

Clearly the most satisfactory approach to the problem of c.f.b. volcanism is to consider each province separately, and within that province to evaluate each eruptive unit in the context of crust-mantle processes. In the case of the Karoo, an integrated geochemical investigation has demonstrated the complexities of continental volcanism (Hawkesworth *et al.* 1983*a*). In this review we shall concentrate on flood volcanism in the Snake River Plain Idaho, U.S.A. (figure 1). If it can be unequivocally established that certain volcanic rocks are uncontaminated an attempt will be made to identify the mantle source region. In the case of contaminated magmas we will evaluate their polybaric evolutionary history and outline possible crustal contaminants in either the upper or the lower crust or both.

2. Snake River Plain, Idaho

2.1. *Tectonic setting*

The volcanic and tectonic setting of western North America was dominated by subduction related processes in the mid-Tertiary (figure 1) (Lipman *et al.* 1972; Christiansen & McKee 1978). Consumption of the Farallon plate along the western edge of the American plate caused a widespread thermal disturbance east of the subducting plate (Armstrong 1978; Barrash & Venkatakrishnan 1982). Tholeiitic flood basalts issued from several dike swarms in the Columbia River plateau (C.R.), Washington and Oregon (17–13.5 Ma), and British Columbia (figure 1*a*) in response to extensional tectonism in a back arc setting. Concomitant eruption of a bimodal suite of basalt and rhyolite in the Snake River Plain (S.R.P.), began around 16–15 Ma, and continued unabated to the present; the latter volcanism is believed to be related to migration of the American plate over a stationary hot spot (Leeman 1983*a*). An apparent increase in the rate of volcanicity was observed at about 10 Ma and again at 5 Ma (figure 1*c*) when the tectonic régime was influenced by the opening of the Gulf of California. Clearly, the flood volcanism of the western U.S.A. is related to thermal disturbances in the crust and mantle above a subduction zone. The complexities of tectonic evolution of the northwestern U.S.A. may in part be recorded in the chemical heterogeneities of the volcanic products. Magma genesis may have involved a subduction component from the Farallon plate; contributions from the overlying mantle wedge and the sub-continental mantle and variable amounts of crustal material from within the upper (and lower) crust. Systematic consideration of the trace element and isotopic characteristics of the Snake River Plain basalts will help to ascertain the relative contributions of these components.

2.2. *Basalt chemical variation*

Recent updates on the major element geochemistry of c.f.b. (Cox 1980; Leeman 1983*a*; Thompson *et al.* 1983) conclude that virtually all flood basaltic magmas have experienced either fractionation or contamination or both during their magmatic history. Consequently very few c.f.b. can be considered as primary mantle derived melts with respect to their major and trace element geochemistry. However, fractionation will not in itself modify the isotopic characteristics of c.f.b. unless accompanied by assimilation of crustal roof rock or wall rock. The degree of wall rock contamination within the crust may vary from province to province. Furthermore, the residence time required for magmas to fractionate in the crust makes them susceptible to the combined affects of assimilation and fractional crystallization (a.f.c.) (DePaolo 1981). The extent of such processes can only be properly evaluated after careful consideration of the incompatible element abundances and isotopic variations of individual eruptive suites. For ease of discussion we shall adopt a previous sub-division of the S.R.P. magmas into three groups (Leeman 1983*a*, *b*). These groups are (1) olivine tholeiites, (2) evolved magmas, and (3) hybrid and xenolith bearing magmas.

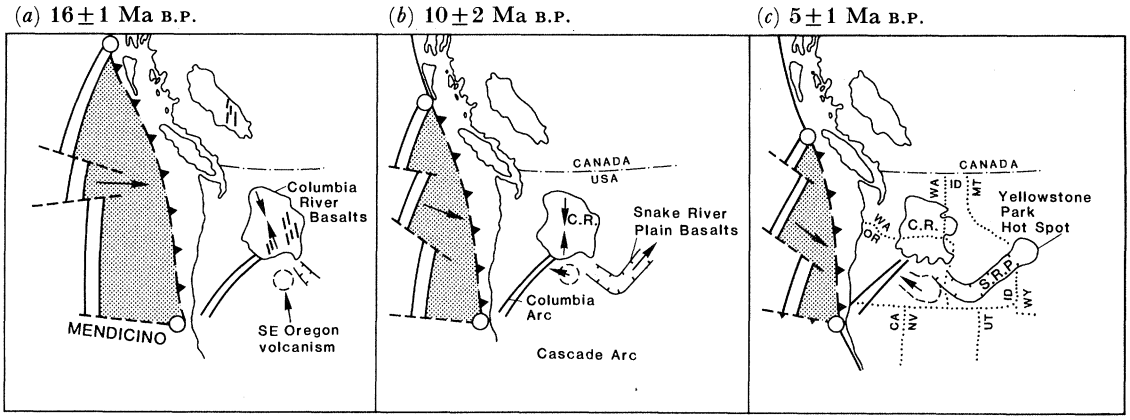
(*a*) 16 ± 1 Ma B.P. (*b*) 10 ± 2 Ma B.P. (*c*) 5 ± 1 Ma B.P.

FIGURE 1. Tectonic evolution of the northwestern U.S.A. (after Barrash & Venkatakrishnan 1982) depicting the eruption of c.f.b. in the Columbia River (C.R.); Snake River Plain (S.R.P.) SE Oregon, and British Columbia. Widespread volcanism was a response to thermal disturbances in the crust and mantle above the subducting Farallon Plate. Note that the bulk of the c.f.b. was erupted at the beginning of volcanic activity and that the volcanism in the S.R.P. and Yellowstone National Park trace the locus of a 'hot spot'.

(*a*) *Olivine tholeiites*

Mantle normalized trace element patterns of c.f.b. from the northwestern U.S.A. are shown in figure 2*a*. All the analysed olivine tholeiites are enriched in incompatible elements relative to N-type m.o.r.b.: hence the relatively smooth convex upward curves. The extent of incompatible and compatible element variation in c.f.b. from the Snake River Plain and the Columbia River approximates that of E-type m.o.r.b. Comparative oceanic examples are shown from the Atlantic Ocean. Any compositional variation observed in the S.R.P. olivine tholeiites can be attributed to fractionation of olivine and plagioclase (Leeman 1983*a*), and the overall normalized pattern can be interpreted in terms of incompatible element enriched source regions. For future reference it is perhaps worth noting that those elements affected by crustal contamination (K, Rb, Ba, Th etc.) are not preferentially enriched in the S.R.P. and C.R. magmas relative to E-type m.o.r.b. This is perhaps best illustrated in trace element plots involving elements that tend to be preferentially enriched in the crust. In figure 3*a* the S.R.P. olivine tholeiites are seen to have relative abundances of Th–Hf–Ta identical to E-type m.o.r.b. Involvement of crustal melts in the genesis of the S.R.P. tholeiites would tend to displace the data towards the fields occupied by crustal xenoliths and basement rocks. However the lack of any significant crustal component in the S.R.P. olivine tholeiites is apparent in figure 3*a*, and is further illustrated in figure 3*b*. Present evidence suggests that this figure often discriminates between (*a*) basaltic magmas that have experienced crustal contamination or whose source region has been modified by addition of a slab component, and (*b*) basaltic magmas erupted at a mid-ocean or within-plate setting that have experienced no crustal contamination (Pearce 1983). All available analyses of S.R.P. olivine tholeiites lie within the latter field, yet again demonstrating that the trace element geochemistry of these continental tholeiites has not been greatly affected by contributions from the continental crust. We can therefore deduce from the relatively uncontaminated nature of the S.R.P. olivine tholeiites, that the initial melts formed in a mantle source enriched in Th and Ta relative to both the bulk earth (figure 3*b*) and m.o.r.b. (figure 2*a*), a conclusion consistent with all aspects of their major and trace element geochemistry. Subsequent low pressure fractionation of olivine and plagioclase before eruption (Leeman 1983*a*) modified their chemistry. However no elemental abundance data unequivocally demonstrate involvement of significant amounts of crust during upwelling of these tholeiitic magmas through the continental crust.

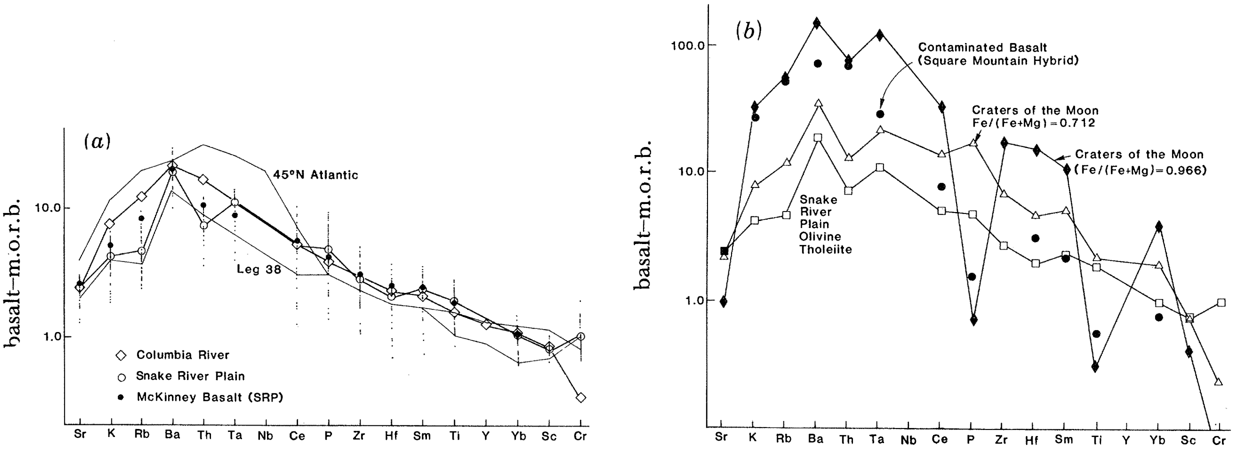

FIGURE 2. (*a*) Incompatible – compatible elemental variations in c.f.b. from the northwestern U.S.A. and oceanic analogues (Wood *et al.* 1979). The range of Snake River Plain data is shown by the vertical trails of small black dots and the average of 200 analyses shown by the large circles (Leeman 1983*a*). An average of Columbia River basalts (Basaltic Volcanism Study Project 1981) is shown for comparison (◊). Note that the incompatible element contents of the continental basalts are within the range of oceanic alkaline magmas. Data normalized to m.o.r.b. (Pearce *et al.* 1981).

(*b*) Incompatible – compatible element variations in evolved and hybrid xenolith bearing magmas from Craters of the Moon and King Hill respectively. Note that the least fractionated C.o.M. lava (Fe/(Fe+Mg) = 0.712) has a normalized element profile similar to, but more fractionated than, the average S.R.P. tholeiite. Furthermore the most fractionated C.o.M. magma (Fe/(Fe+Mg) = 0.966) has 'troughs' at Sr, P, Ti due to fractionation of plagioclase, apatite and magnetite respectively. The hybrid xenolith-bearing volcanic rock from Square Mountain has a more irregular normalized profile.

(*b*) *Evolved magmas*

Small volumes of ferrobasalts and ferrolatites found around the margins of the Snake River Plain, in particular at Craters of the Moon (C.o.M.) are highly evolved rocks with tholeiitic affinities (Leeman *et al.* 1976; Leeman 1983*b*). Trace element variations, in a ferrobasalt ($Fe/(Fe+Mg) = 0.712$) and a ferrolatite ($Fe/(Fe+Mg) = 0.966$) (Leeman *et al.* 1976) are compared with an average S.R.P. olivine tholeiite in figure 2*b*. The most striking aspect of their chemistry is that they are highly fractionated ($Fe/(Fe+Mg) \geqslant 0.71$) and enriched in trace elements relative to the most fractionated S.R.P. tholeiite. For example mafic C.o.M.

volcanic rocks have phosphorus contents that are five times that of normal olivine tholeiite, and are enriched in alkalies, Fe, Zr, Ba etc. Attempts to model the evolution of the C.o.M. magmas by fractionation of a 'basaltic' parent by removal of olivine ± plagioclase ± magnetite ± apatite have been successful (Leeman *et al.* 1976). Variations in all elements with decreasing MgO or any other index of fractionation are identical to those determined theoretically. The entire range of C.o.M. lavas require in excess of 70% solidification of an initial tholeiitic liquid

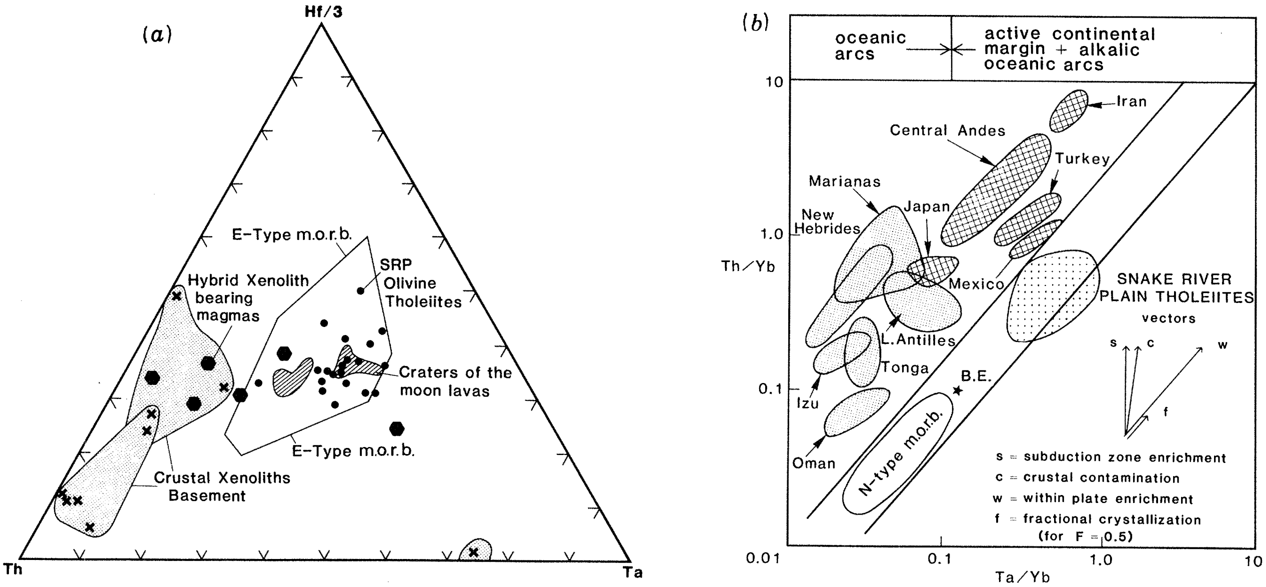

FIGURE 3. (*a*) Th–Hf/3–Ta variation in S.R.P. olivine tholeiites (●), Craters of the Moon (cross-hatched) evolved magmas and hybrid xenolith-bearing magmas from Square Mountain, Craters of the Moon and elsewhere (●). Fields occupied by E-type m.o.r.b. and continental crustal xenoliths and basement are shown for comparison. Note that the chemically evolved C.o.M. lavas are similar, within the constraints of this figure, to S.R.P. tholeiites and E-type m.o.r.b. However, the hybrid xenolith-bearing magmas have anomalous Th–Hf–Ta signatures more akin to crustal rock types.

(*b*) Th/Yb against Ta/Yb variation in volcanic rocks from oceanic arcs, active continental margins and non-subduction settings. Note that the S.R.P. magmas plot within the 'array' defined by m.o.r.b. and other 'within plate basalts' (after Pearce 1983). This indicates no detectable 'slab derived component' or crustal component in the S.R.P. tholeiites, but implies that the source region was enriched in Th and Ta relative to bulk Earth (B.E.).

similar to the least fractionated C.o.M. lava (Fe/(Fe + Mg) = 0.712). Incompatible element variation provides unequivocal evidence that all the C.o.M. lavas can be genetically related through fractional crystallization of a common parent. Stagnation and crystallization in crustal magma chambers makes the addition of crustal material a definite possibility, but it cannot be invoked to explain the bulk of the trace element variations since many of the elements highly enriched in C.o.M. magmas are depleted in the crust (e.g. Zr, Hf, Sm). As a consequence of this most of the C.o.M. evolved lavas have retained a trace element signature that one would normally associate with uncontaminated continental basaltic rocks. The relative proportions of Ta, Hf and Th for the C.o.M. evolved magmas are compared with E-type m.o.r.b. and crustal rocks in figure 3*a*. The C.o.M. magmas plot within the field occupied by E-type m.o.r.b. and the S.R.P. olivine tholeiites consistent with their derivation from a mantle enriched in Th and Ta relative to primordial mantle. As previously mentioned, crustal rocks normally have fairly high concentrations of Th, and to a lesser extent Ta, relative to Hf. As a consequence of this, crustal contributions to basaltic magmas tend to result in relatively elevated Th (and possibly Ta) contents. In the cases of the S.R.P. olivine tholeiites and the evolved magmas from C.o.M. the similarities with E-type m.o.r.b. are unmistakable (figure 3*a*). However, certain isotopes are more sensitive to crustal contamination than inter-element variations, as the latter can be effectively masked by fractional crystallization. It will be demonstrated later that the C.o.M. evolved magmas have isotopic characteristics indicative of combined crustal assimilation and fractional cyrstallization in their pre-eruptive history.

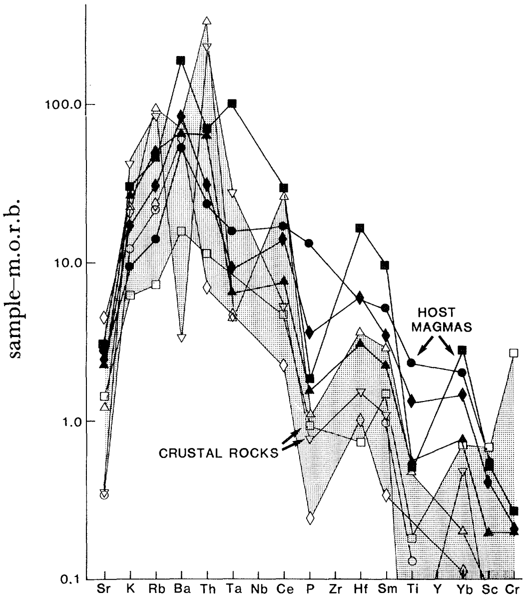

FIGURE 4. Incompatible–compatible element variations in either hybrid or xenolith bearing magmas and crustal rocks occurring as xenoliths and basement rocks in the northwestern U.S.A. Note the Ta depletion and elevated Hf contents of several of the host magmas. The troughs at Sr, Ti, and P may well result from precipitation of plagioclase ± magnetite ± apatite. Evolution via either fractional crystallization or assimilation of both seems appropriate for most of these evolved magmas. Key to the hybrid and xenolith bearing magmas: Square Mountain (◆); Crystal Butte (●); and Craters of the Moon (■). Crustal rocks (shaded) are from the Columbia River (○) (Carlson *et al.* 1981); Albion Range (△); Kilgore – High Point (□); Idaho Batholith (▽) and Square Mountain (◇).

(*c*) *Hybrid and xenolith bearing magmas*

The third group of rocks is found at Square Mountain, Craters of the Moon, Crystal Butte and King Hill (Leeman 1983*b*). Many of the magmas at these localities contain partly fused and disrupted crustal xenoliths of variable composition. Consequently, to help assess any contamination, the trace element variation of these magmas is compared with basement and xenolith lithologies (figure 4). Relative to S.R.P. olivine tholeiite or E-type m.o.r.b. the majority of the hybrid and xenolith-bearing magmas are enriched in alkaline earths, light r.e.e., Th and Hf. Depletions are evident at Ta, P and Ti and by inference Nb (Thompson *et al.* 1983). Several of the crustal rocks, and hybrid-xenolith bearing host magmas have similar trace element characteristics. During disaggregation and fusion of crustal xenoliths the concentrations of incompatible elements would be enhanced preferentially if the host magma were to be contaminated by partial melts of the entrained fragments of wall rock. Furthermore, the hybrid and xenolithic magmas have anomalous Th–Hf–Ta contents relative to uncontaminated S.R.P. olivine tholeiite or E-type m.o.r.b. (figure 3*a*). Several of the magmas overlap the fields occupied by crustal xenoliths and basement rocks, which, as potential contaminants, are adequate sources of Th, alkaline earths and light r.e.e. Clearly the majority of the magmas containing entrained fragments of crust are contaminated relative to an assumed uncontaminated precursor similar to the S.R.P. olivine tholeiites. However, not all host magmas to the xenolithic material have the trace element characteristics just described. The Crystal Butte host magma (figure 4) has a trace element profile not unlike the least fractionated C.o.M. lava. Similarly the C.o.M. host magma has rather marked depletions in P and Ti, features that have already been attributed to a dominant fractionation process. Although the Crystal Butte and C.o.M. magmas may have inherited the bulk of their trace element characteristics from igneous processes like shallow fractionation, closer scrutiny of the trace element data indicates possible involvement of crustal material. One could argue that the extremely high contents of Ba, Th, Ta and light r.e.e. in the C.o.M. magmas result from incorporation of a low melting fraction from the crustal wall rocks. Incorporation of such an incompatible element enriched melt into an essentially 'tholeiitic' parent would tend to produce highly evolved magmas by fractional crystallization processes. Evidence for such combined assimilation and fractional crystallization will be pursued later. It should be noted, however, that the presence of partially fused xenoliths in a particular lava (*a*) does not imply that crustal contamination was the dominant process controlling the elemental and isotopic geochemistry of the host magma (e.g. C.o.M.) and (*b*) does not preclude the involvement of other crustal lithologies in the evolution of the magma.

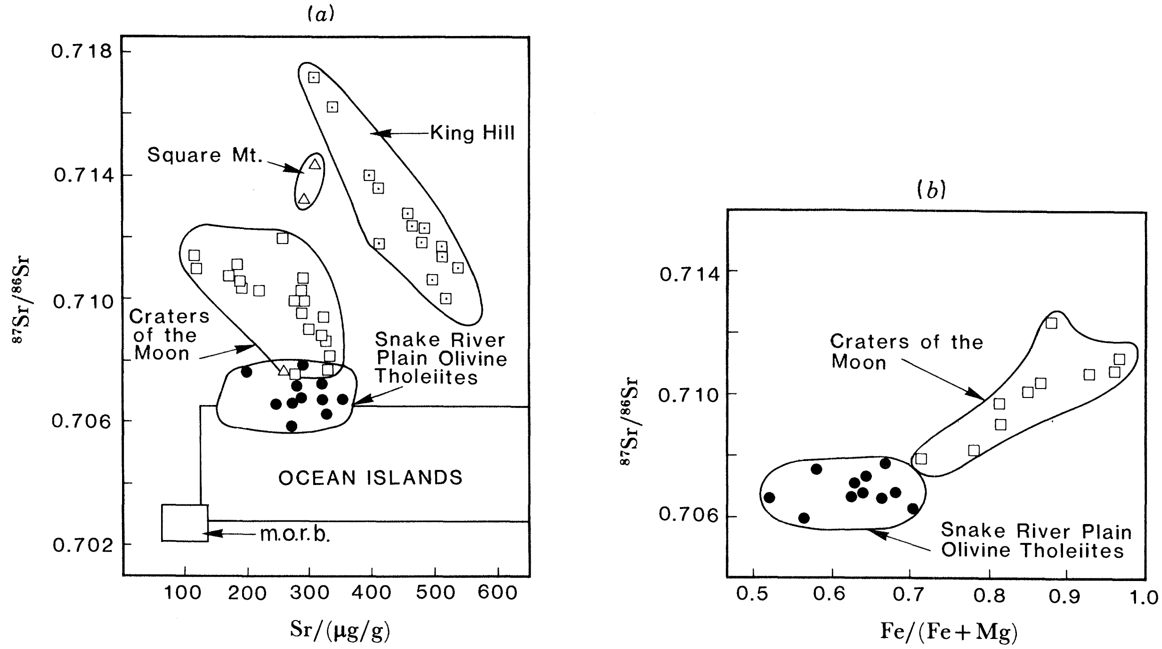

FIGURE 5 (*a*) $^{87}Sr/^{86}Sr$ against Sr content. Note the scatter of the S.R.P. tholeiite data and the linear anti-correlation evident in the volcanic suites from Craters of the Moon, King Hill and Square Mountain, all believed to be contaminated by crustal rocks. (*b*) $^{87}Sr/^{86}Sr$ against fractionation index (Fe/Fe+Mg) for the uncontaminated S.R.P. olivine tholeiites and the evolved C.o.M. magmas, the latter believed to be produced by combined assimilation and fractional crystallization.

In this section we have attempted to illustrate that within a single flood basalt province there are genetically distinct suites of volcanic rock. Clearly some are fractionated mantle derived melts chemically similar to oceanic equivalents, others have experienced extreme fractionation in shallow crustal magma chambers, while a further group has disrupted and consumed crustal material to various degrees.

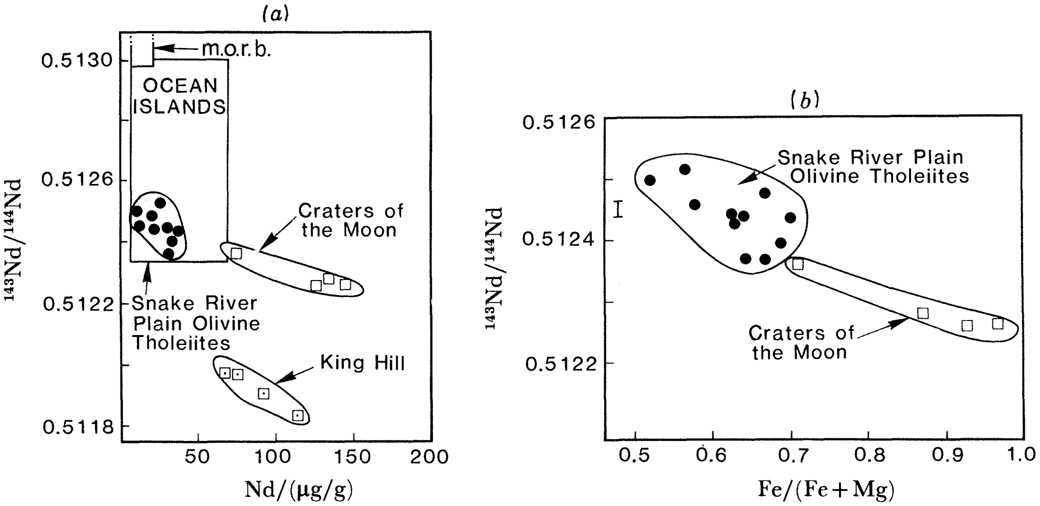

FIGURE 6. (*a*) $^{143}Nd/^{144}Nd$ against Nd content for the S.R.P. olivine tholeiites and evolved hybrid rocks relative to the range observed in m.o.r.b. and oceanic islands. Note that the parental magma for the C.o.M. evolved suite may have an isotopic signature like the S.R.P. tholeiites. However, it would also need to be considerably more fractionated as the Nd content of the least evolved C.o.M. magma is twice that of the S.R.P. olivine tholeiites.

(*b*) $^{143}Nd/^{144}Nd$ against fractionation index Fe/(Fe+Mg). Note that the change in $^{143}Nd/^{144}Nd$ from the least to the most fractionated C.o.M. magma is negligible compared with the change in $^{87}Sr/^{86}Sr$. The majority of the S.R.P. olivine tholeiites show little or no change in Nd isotopic composition with fractionation except for three samples (Nd > 30 μg/g). This may indicate that some of the olivine tholeiites have minimal amounts of a crustal component. (Note: Error on Nd analyses is shown on the vertical axis.)

2.3. *A mantle source for the tholeiitic basalts?*

Olivine tholeiites erupted in the Snake River Plain have all the major and trace element characteristics of mantle-derived melts whose chemistry has been modified by igneous fractionation. Crustal contamination is not indicated by consideration of elemental variations, but this may be simply because it was effectively masked by fractionation processes. We shall now evaluate the isotope geochemistry of these tholeiites in the context of crust-mantle processes. The S.R.P. olivine tholeiites have a range in $^{87}Sr/^{86}Sr = 0.7058–0.7079$ (Leeman & Manton 1971; Menzies *et al.* 1983) higher than that observed in the majority of ocean island or m.o.r. basalts. There is no correlation between $^{87}Sr/^{86}Sr$ ratio and Sr content (figure 5*a*) or SiO_2 content, the latter taken as a crude measure of contamination. Furthermore a more sensitive index of fractionation (Fe/(Fe+Mg)) (figure 5*b*) does not display the systematic change with Sr isotopic composition observed to be the case in lavas believed to have experienced assimilation and fractional crystallization. Addition of crustal melts tends eventually to produce an anti-correlation between Sr content and isotopic composition, and a positive correlation with fractionation. One can infer from the lack of such correlations that crustal contamination was either minimal or non-systematic during the uprise of the tholeiites. From similar scrutiny of the Nd isotopic geochemistry we come to the same conclusion. However, a possible correlation between $^{143}Nd/^{144}Nd$ ratio and differentiation index requires some explanation (figure 6*b*).

The bulk of the olivine tholeiites show no anti-correlation with Fe/(Fe+Mg) (figure 6*b*) yet the lowest ^{143}Nd/^{144}Nd ratios are observed in the most fractionated olivine tholeiites. This is curious because contrary to the flat-laying trend in figure 7, the trend in figure 6 implies that Nd is more sensitive than Sr. Furthermore, attempts to contour the Nd isotope–Sr isotope diagram (figure 7) for differentiation index are non-systematic. One could speculate that some of the S.R.P. olivine tholeiites have experienced a minimal amount of contamination but we note that the contamination trends inferred from figures 5 and 6 could not be responsible for the flat-lying ϵ_{Nd}–ϵ_{Sr} trend which plots slightly to the right of the 'mantle array' (figure 7).

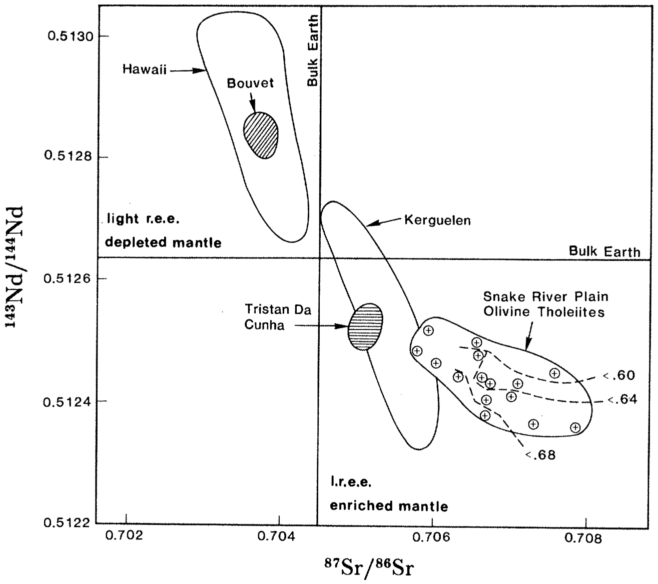

FIGURE 7. ^{143}Nd/^{144}Nd and ^{87}Sr/^{86}Sr isotopic variation in the S.R.P. olivine tholeiites relative to oceanic islands (Allegre *et al.* 1979; O'Nions *et al.* 1979 and references therein; Dosso & Murthy 1980). The contours, which represent changes in fractionation index Fe/(Fe+Mg), do not appear to be very systematic. Note that the *least* fractionated S.R.P. olivine tholeiites require an *enriched* mantle source region with ^{143}Nd/^{144}Nd = 0.51245–0.51252 and ^{87}Sr/^{86}Sr = 0.706–0.7075.

Owing to the possibility of minor contamination of some of the S.R.P. olivine tholeiites we shall consider only the least fractionated members in the remaining discussion. The least fractionated tholeiitic rocks exhibit a narrow range in Nd isotopic composition (0.51252–0.51245) and a larger range in Sr isotopic composition (0.706–0.7075) (figure 7).

Combination of these data on a ^{143}Nd/^{144}Nd against ^{87}Sr/^{86}Sr diagram reveals that while the majority of oceanic basalts conform to the 'mantle array' the S.R.P. basalts plot to the right of the array (figure 7). The narrow range in Nd isotopic ratio is within that observed in oceanic islands, but the Sr isotopic composition is more radiogenic. These data imply that the source area of these continental tholeiites represents a time-integrated response to high Rb/Sr and Nd/Sm ratios, characteristic of trace element enriched mantle source regions. This is consistent with the relative enrichments of Th, Ta and other incompatible elements in the source region of the olivine tholeiites. Although one could argue for involvement of crustal material the previously discussed elemental abundance data and the O and Pb isotope data are consistent with a mantle-derived origin with minimal crustal interference. The S.R.P. olivine tholeiites have a range in δ^{18}O = 5.0 to 6.5‰ (Leeman & Whelan 1983) similar to that of mantle-derived magmas. Furthermore the $^{206}Pb/^{204}Pb$ ratios of S.R.P. olivine tholeiites (Doe *et al.* 1982) fall within the range reported for alkaline and tholeiitic magmas from the Hawaiian Islands (Tatsumoto 1978). The S.R.P. olivine tholeiites are also characterized by a lack of correlation between (i) $^{87}Sr/^{86}Sr$ and Rb/Sr and contents of SiO_2, K_2O, and incompatible elements; (ii) $\delta^{18}O$ and $^{87}Sr/^{86}Sr$ or $^{143}Nd/^{144}Nd$; (iii) $^{206}Pb/^{204}Pb$ and $^{143}Nd/^{144}$ Nd or $^{87}Sr/^{86}Sr$; and

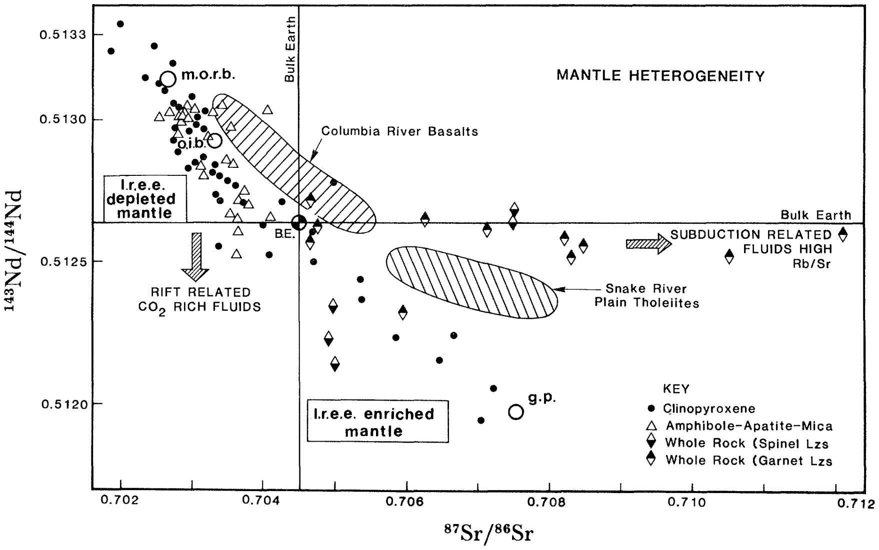

FIGURE 8. $^{143}Nd/^{144}Nd$ against $^{87}Sr/^{86}Sr$ in spinel and garnet lherzolites (Lzs) (see Menzies 1983 for references). Note that the vector defined by the S.R.P. olivine tholeiites to the right of the 'mantle array' is similar to that observed in spinel and richterite bearing lherzolites. The range in isotopic chemistry in the S.R.P. olivine tholeiites represents a time-integrated response to a high Rb/Sr and a low Sm/Nd ratio in the mantle source region. The enriched nature of the source is compatible with K, Rb, Ba, Ta, and Th data. Average mid-oceanic ridge basalt m.o.r.b., ocean island basalt o.i.b., bulk Earth B.E., and garnet peridotite g.p., are shown for comparison (Allègre *et al.* 1979 and references therein; Menzies & Murthy 1980; Erlank *et al.* 1982).

(iv) $^{208}Pb/^{204}Pb$ and $^{87}Sr/^{86}Sr$. However, the C.o.M. magmas provide an interesting comparison in that they display all the isotopic and elemental correlations compatible with crustal assimilation and fractional crystallization.

Because the majority of trace element and isotopic parameters in S.R.P. olivine tholeiitic basalts are so similar to those of oceanic basalts we conclude that these magmas were erupted at the surface without significant modification by crustal material (Leeman 1977; Menzies *et al.* 1983). It is therefore useful to evaluate the isotopic and chemical variations of these tholeiites and their possible source regions in the light of what is known about mantle geochemistry.

The sub-continental lithosphere, as sampled by ultramafic xenoliths entrained in alkaline and kimberlitic magmas, is chemically and isotopically heterogeneous. Ultramafic xenoliths record distinct styles of trace element enrichment that occur at different times in the sub-continental mantle. From the available Sr and Nd isotopic and trace element data for spinel and garnet peridotites and their constituent minerals (figure 8), it appears that mantle enrichment events are either relatively recent (not older than 0.2 Ga) or ancient (not less than 1.0 Ga).

(*a*) *Recent enrichment events*

The bulk of spinel lherzolite xenoliths entrained in basanites and erupted in extensional environments have isotopic characteristics identical to m.o.r.b. and ocean island basalts. The radiogenic Nd and non-radiogenic Sr isotopic compositions of many of these peridotites imply that the mantle sampled by spinel lherzolites has Sm/Nd $>$ chondrite and Rb/Sr $<$ chondrite. However, this is not the case as the majority of the spinel lherzolite xenoliths are light r.e.e. enriched (Sm/Nd $<$ chondrite). This decoupling of the trace elements and the isotopes can be explained by an enrichment process that modified the chemistry of the source, but that insufficient time has elapsed for the isotopes to fully respond to the new trace element régime. However, it should be remembered that source areas with extremely high Rb/Sr ratios, produced as a result of trace element enrichment, may generate a significant range in ^{87}Sr/^{86}Sr in a comparatively short time period. In the case of amphibole lherzolites from South Africa (Erlank *et al.* 1982) high Rb/Sr ratios are prevalent and ^{87}Sr/^{86}Sr $= 0.705$–0.710 evolved in less than 200 Ma. The resultant heterogeneity in Sr isotopes is evident as a vector that deviates to the right of the mantle array (figure 8). Furthermore, these peridotites verify the existence of portions of the mantle with highly radiogenic Sr isotopic compositions. Since the inferred mantle source for the S.R.P. olivine tholeiites has an Sr and Nd isotopic composition lying to the right of the mantle array, the processes that brought about such trace element (and isotopic) changes are of particular relevance.

(*b*) *Ancient enrichment events*

Older enrichment events are best reported in the trace element and isotopic variations of clinopyroxenes, a ubiquitous phase in aluminous mantle peridotites. Spinel (10–20 kbar)† and garnet (18–27 kbar) lherzolites contain pyroxene with a considerable range in present day ^{87}Sr/^{86}Sr (0.702–0.708) and ^{143}Nd/^{144}Nd (0.5133–0.5119) (figure 8). This range is greater than, but overlaps with, that observed in uncontaminated oceanic and continental volcanic rocks. These data also confirm the presence of enriched mantle regions with ^{87}Sr/^{86}Sr < 0.708 and ^{143}Nd/^{144}Nd > 0.5120. Model age calculations reveal that although some of the mantle below South Africa is Archaean in age most of it stabilized in the Proterozoic (Hawkesworth *et al.* 1983*b*). This is compatible with the age provinces in the overlying crust and it may be relevant to the S.R.P. olivine tholeiites since they were generated in a stable cratonic area more than 2.5 Ga old.

It is important to stress that with the available data there is no doubt that below continental regions there exists mantle of sufficient age that trace element inhomogeneities are reflected in isotopic heterogeneity. Furthermore the Sr and Nd isotopic variability shown by the S.R.P. olivine tholeiites and their displacement to the right of the array, has been observed in spinel (Menzies & Halliday 1983, unpublished data) and garnet lherzolites (Erlank *et al.* 1982) which have experienced recent (less than 0.2 Ga) enrichment. Whether the S.R.P. olivine tholeiites originated within spinel or garnet lherzolite is best constrained by consideration of their rare earth element geochemistry. The r.e.e. geochemistry of the S.R.P. olivine tholeiites is characterized by a consistently small fractionation of the heavy r.e.e. (Leeman 1983*a*) which suggests that the magmas originated in the spinel lherzolite stability field. Furthermore, partial melting calculations show that the source region must be garnet free (Leeman 1983*a*) or that garnet

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† 1 bar $= 10^5$ Pa.

was not involved. Leeman (1983*a*) proposed that the S.R.P. olivine tholeiites were extracted from spinel lherzolite mantle source region isolated for 2.5×10^9 years. He interpreted the lead isotopic compositions of the S.R.P. olivine tholeiites as corresponding to an age of 2.5 Ga rather than a mixing line of mantle and crustal components. It is implicit in this model that the Rb–Sr, and, presumably the Sm–Nd, characteristics of the source area are of equivalent age. Stabilization of continental lithosphere shortly after the last major thermal event registered in the crust is likely to produce regions of the sub-continental mantle that are ancient and have radiogenic Sr and non-radiogenic Nd isotopic compositions. It could be argued that the sub-continental mantle beneath the northwestern states is isotopically identical to m.o.r.b. type mantle (cf. Carlson *et al.* 1981), and that it was re-activated by a recent influx of high Rb/Sr, Nd/Sm fluids from the subducted slab. The observed isotopic heterogeneity in the S.R.P. olivine tholeiites would then result from subduction zone related processes. However, addition of any slab component should preferentially enrich the source region in Th relative to Ta (Pearce 1983), and this is inconsistent with the observed variation in Th and Ta in the S.R.P. olivine tholeiites (figure 3*b*). Thus it would appear that neither crustal contamination *sensu stricto*, nor the introduction of subducted material, satisfactorily explain the trace element and isotope characteristics of the S.R.P. olivine tholeiites. Rather they reflect old, trace element enriched sub-continental mantle reactivated, perhaps in part, by the thermal effects of subduction or, more likely, impingement of a hot spot.

2.4. *Origin of evolved and hybrid magmas*

The C.o.M. evolved magmas have all the major and trace element characteristics of a fractionated rock suite with a tholeiitic parent like the S.R.P. olivine tholeiites. However, the C.o.M. magmas also display remarkable correlations between Sr isotopic composition and the relative abundance of Sr (figures 5*a* and 5*b*). It seems highly plausible that the parental magma of the C.o.M. rocks was similar to that of the S.R.P. olivine tholeiites, yet in detail there is no simple relation between the two suites. Fe/(Fe+Mg) in the olivine tholeiites ranges from 0.5–0.7, Nd = 8–35 μg/g, and Ce/Yb is highly variable. In contrast the C.o.M. magmas have Fe/(Fe+Mg) = 0.71 to 0.98, Nd = 70–150 μg/g, and Ce/Yb remains remarkably constant (figures 5, 6 and 9). Thus many chemical trends exhibit a sharp change, or kink, between the two data sets which presumably reflects an important change in the conditions under which the two suites evolved. In summary:

Snake River Plain olivine tholeiites have evolved in a closed system in the mantle involving variable degrees of partial melting. Little or no crustal interaction occurred, but fractionation of olivine ± plagioclase was significant.

Craters of the Moon magmas have evolved from a fractionated S.R.P. olivine tholeiite and differentiation involved a different mineral assemblage (olivine ± plagioclase ± clinopyroxene ± apatite ± magnetite) to the S.R.P. tholeiites. This event presumably took place within the crust and could therefore have been accompanied by crustal assimilation.

Within the C.o.M. lavas $^{87}Sr/^{86}Sr$ increases and $^{143}Nd/^{144}Nd$ decreases as Fe/(Fe+Mg) increases from 0.70 to 0.96. Thus, despite the fact that most of the major and trace element variations are compatible with closed system fractionation (Leeman *et al.* 1976), differentiation was apparently accompanied by progressive contamination with crustal material as predicted, for example, by the assimilation-fractional crystallization model (a.f.c.) of DePaolo (1981). A plot of SiO_2 against Fe/(Fe+Mg) contoured for $^{87}Sr/^{86}Sr$ (figure 10*a*) illustrates these

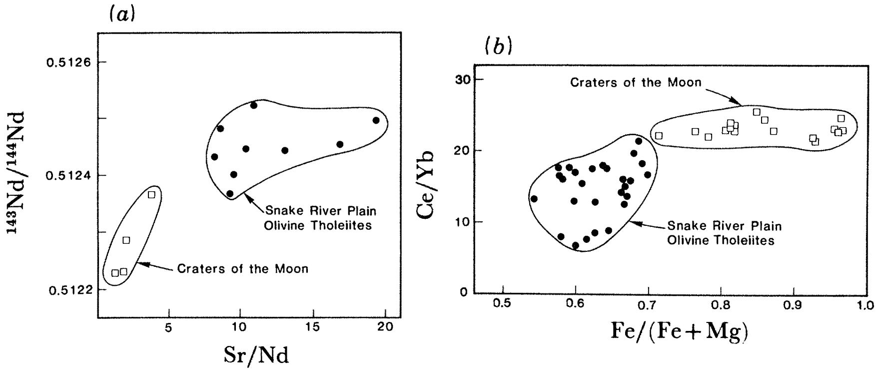

FIGURE 9. (*a*) $^{143}Nd/^{144}Nd$ against Sr/Nd ratio in the S.R.P. tholeiites and the evolved C.o.M. magmas. Note that the parental magma to the C.o.M. magmas is isotopically similar to the S.R.P. tholeiites, but the discrepancy in Sr/Nd ratio implies that the parental magma to the C.o.M. magma is highly fractionated relative to the average S.R.P. tholeiite.

(*b*) Ce/Yb against Fe/Fe+Mg as an index of fractionation believed to be insensitive to contamination. The C.o.M. magmas have a narrow range in Ce/Yb ratio that remains constant throughout the complete magma series. This is compatible with fractional crystallization as a dominant genetic process. However the range in Ce/Yb ratio of the S.R.P. tholeiites is highly variable and therefore more consistent with variable degrees of partial melting of a mantle source region (Leeman 1983*a*).

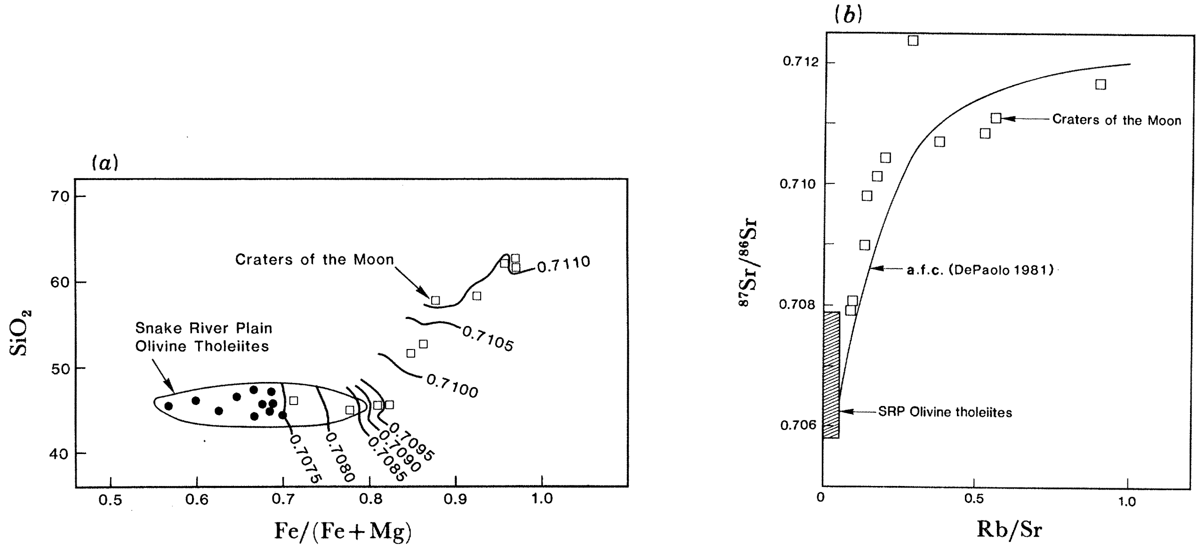

FIGURE 10. (*a*) SiO_2 against Fe/Fe+Mg (fractionation index) for the S.R.P. tholeiites and the C.o.M. evolved magmas with contours for Sr isotopic composition. In the C.o.M. magma series fractional crystallization processes have controlled much of the elemental variations including Fe/(Fe+Mg) variation and perhaps SiO_2 variation. Contamination is most detectable as changes in $^{87}Sr/^{86}Sr$ of the C.o.M. magmas even at relatively constant SiO_2 content.

(*b*) $^{87}Sr/^{86}Sr$ against Rb/Sr variation in the Craters of the Moon magmas that are believed to have formed by combined assimilation and fractional crystallization (a.f.c.). The curve represents the evolutionary path of a magma rising through the crust and experiencing a.f.c. Note the similarity between the C.o.M. data and the hypothetical curve. The range in $^{87}Sr/^{86}Sr$ and Rb/Sr for the S.R.P. tholeiites is shown as that of possible parental magmas.

systematic changes. It is interesting to note that this style of crustal contamination is very different from that described by Cox & Hawkesworth (this symposium) in the lower lavas in the Deccan Traps where contamination results in a small increase in SiO_2 with little change in Fe/Mg ratio, and the most contaminated rocks are among the most primitive of these basalts.

The possible effects of a.f.c. were illustrated by DePaolo (1981) using variations in $^{87}Sr/^{86}Sr$, Rb/Sr and Sr contents, and the changes he described are very similar to those observed in the C.o.M. lavas (figures 5*a*, 10*b*). In figure 10*b* we have assumed that the parental magma to the C.o.M. magmas is a S.R.P. olivine tholeiite ($^{87}Sr/^{86}Sr > 0.7058$ and $Rb/Sr = 0.05$); the estimated path of magma evolution is close to that of the C.o.M. rocks. In this model the least fractionated magmas record the least contamination, and the most evolved magma ($Fe/Fe + Mg > 0.95$, $Rb/Sr = 1.0$) is the most contaminated. Interestingly, on a diagram of $^{87}Sr/^{86}Sr$ against Sr content a hypothetical evolution path for a magma can define a sharply curved trend, principally because D^{Sr} increases significantly with fractionation. Close examination of figure 5*a* suggests a similar curved path between a parental magma with $^{87}Sr/^{86}Sr$ and Sr equivalent to an evolved S.R.P. olivine tholeiite ($^{87}Sr/^{86}Sr = 0.7075$, Sr = 300 μg/g) and a highly contaminated, low Sr ferrolatite with $^{87}Sr/^{86}Sr = 0.711$. We conclude that a.f.c. processes have greatly affected the evolution and chemistry of the C.o.M. magmas. During the early stages of a.f.c. the magmas are not markedly different from the parental magma except for slightly elevated Sr isotopic compositions. However, the advanced stages of a.f.c. processes produced ferrolatites with high $^{87}Sr/^{86}Sr$ ratios and highly evolved major and trace element chemistry. It is interesting to note that during this process the C.o.M. magmas retain a Th–Hf–Ta signature similar to the parental S.R.P. olivine tholeiite or E-type m.o.r.b. (figure 3*a*). Leeman (1983*b*) noted that the spatial distribution of evolved and hybrid magmas reflects proximity of parental S.R.P. magmas to crustal wall rocks along the boundaries of the volcanic field, and the vicinity of suspected caldera structures. Although a few occurrences are noted within the axis of the S.R.P. volcanic province it may prove to be important that no hybrid suites have been recorded during the early facies of volcanism. Perhaps the processes of a.f.c. are most active during the waning stages of volcanism when magma batches stagnate for sufficient periods of time in crustal magma chambers. These chambers must have existed at some depth in the crust since some of the less evolved magmas are cotetic at 8 kbar (Thompson 1975).

In attempting to define the chemistry of the crustal contaminant involved in a.f.c. we must evaluate the nature of the underlying crust. Primitive lead isotope ratios (Leeman 1979) in crustal xenoliths from the S.R.P. established the presence of early Archaean crust beneath the Snake River Plain. Low grade Archaean metasediments are known to outcrop in the Albion Range in the southern S.R.P. (Armstrong & Hills 1967). These Archaean rocks exhibit extreme heterogeneity for both Sr and Nd isotopes (figure 11); in the majority of the crustal samples, $\epsilon_{Nd} = -20$ to -45 and $\epsilon_{Sr} = -50$ to $+1800$ (Leeman & Menzies, unpublished data.) This emphasizes the extreme fractionation of Rb/Sr relative to Sm/Nd in the crust.

Before considering any of the crustal rocks as potential contaminants it is necessary to constrain the isotopic composition of the mantle-derived end member. Logical choices are average E-type m.o.r.b. or o.i.b. and S.R.P. olivine tholeiite. The latter has all the chemical attributes of E-type m.o.r.b., and for the reasons already outlined and summarized elsewhere (Leeman 1983*a*; Menzies *et al.* 1983), it is believed that the isotopic signature of the S.R.P. olivine tholeiites reflects that of their mantle source region. Consequently, S.R.P. olivine tholeiite was assumed to be the uncontaminated mantle-derived magma. For any of the crustal rocks to have adversely affected the isotope geochemistry of the Craters of the Moon magmas they should define a mixing hyperbola with this mantle-derived liquid, along which the C.o.M. magmas must lie. However, if a.f.c. processes are involved in the production of the Craters of the Moon magmas, the mixing curves need not necessarily intersect the crustal end-member (DePaolo

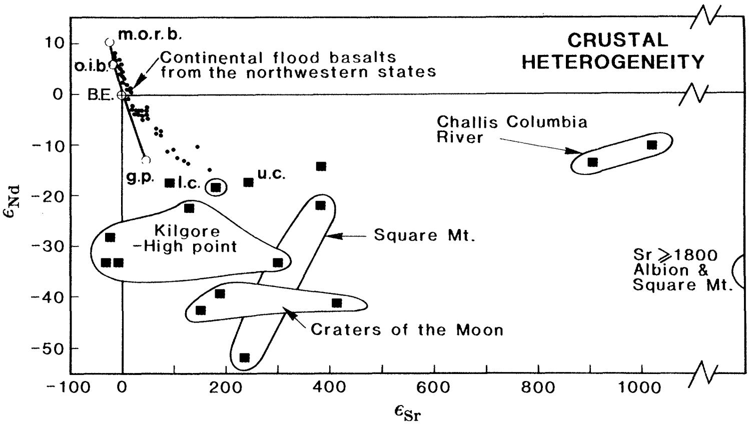

FIGURE 11. Isotopic heterogeneity in the exposed crustal basement and crustal xenoliths of the Snake River Plain plotted as ϵ_{Nd} against ϵ_{Sr} (DePaolo & Wasserburg 1976). The Hf–Th–Ta variation in these samples is shown in figure 3*a*. The m.o.r.b.–g.p. line helps to relate this figure to figure 8. Averages of lower crust (l.c.) and upper crust (u.c.) are shown for comparison (DePaolo & Wasserburg 1979*b* and references therein). Some of the crustal xenoliths (*ca.* 3000 Ma) disrupted and entrained by S.R.P. magmas have too low a Nd and Sr isotopic composition to act as suitable contaminants for the evolved or hybrid magmas of the S.R.P.

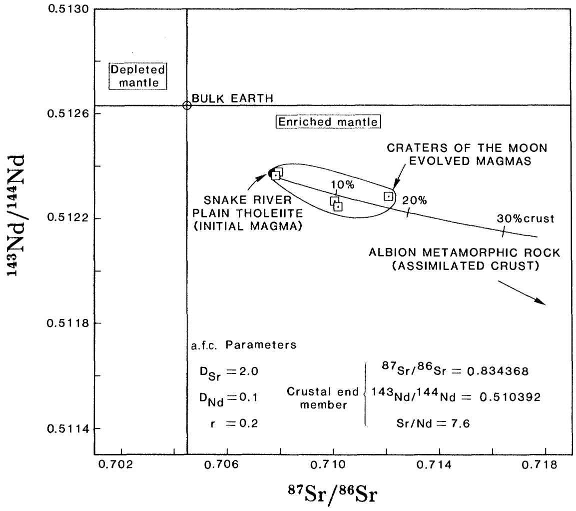

FIGURE 12. Co-variation of $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ for a magma undergoing a.f.c. Fractionation of a S.R.P. tholeiite and simultaneous assimilation of less than 20 % Albion basement reproduces the gradual change in Nd isotopes and the rapid change in Sr isotopes observed in the C.o.M. magmas. It is not known to what extent this degree of contamination reproduces the major and trace element variations.

1981). This is an important observation since conventional mixing calculations exclude several of the crustal rocks (figure 11) as potential contaminants (e.g. Idaho batholith) whereas a.f.c. processes do not. The co-variation in Nd and Sr isotopes (figure 12) was calculated for an S.R.P. olivine tholeiite undergoing fractional crystallization and simultaneous assimilation of an Albion metamorphic rock. Geologically plausible bulk distribution coefficients, were chosen, and the Sr/Nd ratio of the crustal end-member varied according to that observed in S.R.P. crustal rocks. The vector shown in figure 12 mimics the isotopic variation of the C.o.M. magmas and indicates that less than 20 % contamination is required in the evolution of highly fractionated rocks like those found at Craters of the Moon. Furthermore the low level of contamination in the most highly evolved C.o.M. magma ($Fe/(Fe+Mg) > 0.95$) is compatible with the similarity in Th–Hf–Ta between the initial S.R.P. magma and the C.o.M. magmas (see figure 3*a*). Relative abundances of Th–Hf–Ta are believed to be an extremely sensitive indicator of crustal contamination (Wood 1980). Clearly in the case of the C.o.M. magmas, Sr isotopic composition is a more sensitive indicator of contamination, since fractionation has totally obscured the elemental consequences of less than 20% contamination.

The evolved magmas of C.o.M. are considered to be derivatives of a tholeiitic parent, and the more mafic variants (ferrobasalts) are believed to evolve into the ferrolatites at lower pressures (Leeman 1983*b*). The systematic variations in Sr, Pb and O isotopes towards crustal values concurrently with progressive differentiation supports an origin involving combined assimilation and fractional crystallization.

3. CONCLUSIONS

Continental flood basalt provinces are highly complex regions of terrestrial basaltic volcanism. The chemical and isotopic heterogeneities known to exist in the sub-continental mantle, and the grossly inhomogeneous nature of the overlying crust must complicate the evolutionary processes. Magmas erupted during the early stages of extensional volcanism in a continental setting are susceptible to crustal contamination. Furthermore, subsequent magmas that stagnate and fractionate within the crust also risk isotopic re-equilibration with the roof and wall rocks. This is evident in the Snake River Plain where the highly evolved magmas erupted at the Craters of the Moon National Park have all the elemental and isotopic characteristics of magmas that have experienced fractional crystallization and simultaneous assimilation of less than 20% crust. However, once crustal conduits are established massive volumes of mantle-derived tholeiitic magma can reach the surface, having experienced fractionation en route, but little or no crustal contamination. In this context the bulk of the Snake River Plain olivine tholeiites are believed to be fractionated mantle derived liquids that experienced minimal crustal interaction. Our preferred interpretation of the tholeiite trace element and isotopic data is one involving partial melting of enriched spinel lherzolite mantle that contains at least a component of 2.5 Ga material. Reactivation of this ancient mantle by a recent influx of fluids enriched in alkalies, and light r.e.e. from the subducted slab is believed to be rather unlikely. Rather the S.R.P. olivine tholeiites are believed to provide evidence for the existence below continental regions of ancient (2.5 Ga) mantle enriched in Rb/Sr and l.r.e.e. and characterized by $^{87}Sr/^{86}Sr > 0.7058$ and $^{143}Nd/^{144}Nd < 0.51252$.

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Discussion

R. J. PANKHURST (*British Antarctic Survey, c/o Institute of Geological Sciences*, 64–78 *Grays Inn Road, London WC*1*X* 8*NG, U.K.*). Support for the idea of an enriched sub-continental magma source such as that proposed by Dr Menzies, Dr Leeman and Dr Hawkesworth for the Snake River Plain basalts comes from the Ferrar magmatic province of Antarctica and Tasmania. In early Jurassic times, a wide range of products of continental tholeiite parent magmas were emplaced as lava flows, dykes, sills and at least one massive layered intrusion. All are characterized by high K, Rb, U and Th contents and low Sr. The most unusual feature is variably high initial ^{87}Sr/^{86}Sr ratios (up to 0.716). Over the past decade workers at the Ohio State University (see, for example, Faure *et al.* 1974) have developed a crustal contamination hypothesis whereby the range of observed chemical and isotopic variations is modelled by up to 40 % bulk assimilation of an old, high-Sr, acid phase or melt into a mantle-derived basaltic magma with a primary $^{87}Sr/^{86}Sr$ ratio of 0.704.

Detailed analysis of new samples from southern Victoria Land (Kyle *et al.* 1984) has been directed towards disentangling the effects of crustal contamination, fractional crystallization and source characteristics. Various lines of evidence (element plots against initial $^{87}Sr/^{86}Sr$, Sr–O correlation, leaching experiments and observation of relatively unevolved high-MgO rocks) all lead to the conclusion that the true initial $^{87}Sr/^{86}Sr$ ratio of the parental magmas was in the region of 0.709 before interaction with the upper crust. The apparent validity of this conclusion over the entire 3000 km length of the trans-Antarctic Mountains points to an enormous sub-crustal source region enriched in ^{87}Sr and lithophile elements. It may be possible to relate this to the prolonged contamination of mantle above the active Pacific margin of Gondwana, which was over-riding oceanic lithosphere from late Precambrian until Mesozoic times.

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