

Modeling of Lunar Basalt Petrogenesis: Sr Isotope Evidence from Apollo 14 High-Alumina Basalts

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Trace-element modeling indicates that assimilation of KREEP by a fractionating parental magma [i.e., AFC (assimilation and fractional crystallization)] can account for the range in high-alumina basalt compositions at the Apollo 14 site. However, variability of magnesium number (MG#) with trace-element contents has been used to argue against such a hypothesis (Shih and Nyquist, 1989a,b), but these as well as Sr isotope data can be interpreted in terms of an AFC process at the Apollo 14 site. Positive linear correlations of $^{87}\text{Sr}/^{86}\text{Sr}$ with $^{87}\text{Rb}/^{86}\text{Sr}$ and Sr abundance (both leading to KREEP) are used as evidence of such an AFC process in the petrogenesis of Apollo 14 high-alumina basalts. Calculation of AFC paths on Sr isotope and MG# vs. La (ppm) diagrams has been undertaken. In the case of MG# vs. La (ppm), the effect of the KREEP assimilate upon the major element contents of the residual melt, the errors associated with the MG#, and the cyclicity of the AFC process were considered. Comparison of the amounts of AFC required to generate high-alumina basalts from both trace element and Sr isotope plots are similar. However, trace-element modeling suggests higher amounts of AFC are required to generate the "Group 1" basalt reported by Dasch et al. (1987) than in the Sr isotope modeling. This is probably due to the fact that the sample analyzed for Sr isotopes was a mixture of five small "Group 1" basalt clasts. The most trace-element enriched basalt should contain the most radiogenic initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio, if AFC was a single-stage process or the basalts were derived from a single source. This is not the case, as the "Group 3" or "intermediate" basalt contains the highest initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio. We conclude that the AFC process occurred more than once. This requires that each AFC cycle evolved essentially the same path, but as the Apollo 14 site has a "KREEP-rich" signature (e.g., Wood and Head, 1975; Etchegaray-Ramirez et al., 1983), this is a feasible supposition. Although subject to large errors, age determinations demonstrate that magmatism could have occurred on at least three occasions at the Apollo 14 site (4.3, 4.1, and 3.95 Ga). It is apparent that further precise Sr isotope analyses of Apollo 14 high-alumina basalts are required.

INTRODUCTION

Petrogenesis of Apollo 14 high-alumina basalts has been the subject of considerable study (e.g., Hubbard et al., 1972; Dickinson et al., 1985; Shervais et al., 1985), particularly as the more evolved types appear to contain a KREEP signature. Breccia "pull-apart" efforts have dramatically increased the number of "new" Apollo 14 high-alumina basalt samples. Correspondingly, there has been an evolution in the models proposed for their petrogenesis as more data became available. Dickinson et al. (1985) and Shervais et al. (1985) concluded that there were five groups of Apollo 14 high-alumina basalts, some related by KREEP assimilation, but with at least three distinct source regions. Dickinson et al. (1985) suggested that these high-alumina basalts were formed by different degrees of partial melting of a common source or similar sources at different times. However, with the acquisition of more data, Neal et al. (1987, 1988, 1989) noted that rather than distinct groups, a continuum of high-alumina basalt trace-element compositions existed. This continuum was modeled by progressive assimilation of KREEP by a fractionating, Mg-rich parental magma [i.e., an "AFC" (assimilation and fractional crystallization) process] depleted in incompatible elements (Neal et al., 1987, 1988, 1989).

In this paper we reexamine the limited Sr isotope data available for the Apollo 14 high-alumina basalts in light of the proposed AFC model. We demonstrate that these isotope data are entirely consistent with a petrogenesis for the Apollo 14

high-alumina basalts by AFC with KREEP. However, the small sample size of these clasts has precluded a comprehensive isotopic study of Apollo 14 high-alumina basalts. Papanastassiou and Wasserburg (1971) reported Sr isotopic data from basalt 14053 and a basalt clast from breccia 14321. Unfortunately, this latter sample was given no subnumber, so the whole-rock chemistry cannot be traced. Taylor et al. (1983) reported Sr isotope data from another Apollo 14 basalt clast (14305,122), noting that it yielded a pre-4.2 Ga crystallization age (4.23 ± 0.05 Ga), which made it the oldest dated basalt at the time. However, we will not include this sample in our study, because it is not a high-alumina basalt, containing only 4 wt.% Al_2O_3 (see Table 2 of Taylor et al., 1983). Dasch et al. (1986, 1987) analyzed some of the largest basalt clasts from breccia 14321 for Sr isotopes and three of these for Nd isotopes. One of these ("14321") was a combination of five clasts defined by Dickinson et al. (1985) as being from "Group 1" of their classification. Also included in the study of Dasch et al. (1987) was the tridymite ferrobasalt described by Shervais et al. (1985). As demonstrated by Neal et al. (1988), this basalt is unrelated to the Apollo 14 high-alumina suite and, as such, also will not be discussed here.

GENERATION OF APOLLO 14 HIGH-ALUMINA BASALTS BY AFC

Inasmuch as the AFC model of Neal et al. (1987, 1988, 1989) will be extended to include Sr isotope data, it is deemed

TABLE 1. Selected trace-element abundances and Sr isotopic ratios from Apollo 14 high-alumina basalts.

Sample	"Group"	La	Hf	Sc/Sm	Sr	$^{87}\text{Sr}/^{86}\text{Sr}(\text{P})$	$^{87}\text{Sr}/^{86}\text{Sr}(\text{I})$	Age	Rb	$^{87}\text{Rb}/^{86}\text{Sr}$
"14321"	1	25.5	8.7	4.8	103.6	0.70398±5	0.69939±8	4.12±0.08	2.83	0.0791
9056	2	20.7	7.7	5.4	105.6	0.70414±4	0.69940±3	4.07±0.03	2.95	0.0809
1318/1394	2	20.8	8.2	5.7	102.3	0.70349±3	0.69934±14	4.12±0.15	2.54	0.0719
14053	3	13.0	4.7	8.5	97.3	0.70276±7	0.69948±6	3.96±0.04	2.39	0.0572
9059	5	3.9	2.3	25.4	77.7	0.70073±3	0.69913±5	4.33±0.13	0.685	0.0255
1161/1384	5	2.9	1.8	28.9	61.7	0.70117±5	0.69908±6	4.24±0.14	0.736	0.0345

Data from *Sbervais et al. (1985)*, *Dickinson et al. (1985)*, *Neal et al. (1988)*, *Papanastassiou and Wasserburg (1971)*, and *Dasch et al. (1987)*. Trace-element abundances are in ppm and 2 σ errors are given on isotope and age determinations.

necessary to give a brief description of parameters used in this petrogenetic model.

The AFC model was developed in order to generate the continuum of high-alumina basalt compositions and the similarity of REE patterns of the more evolved (i.e., incompatible trace-element rich) basalts to those of KREEP. The more evolved basalts, corresponding to "Groups 1 and 2" of *Dickinson et al. (1985)*, require a maximum of 70% fractional crystallization and 15.4% KREEP assimilation, where $r = 0.22$ ($r = \text{mass assimilated}/\text{mass crystallized}$). The "IKFM" KREEP composition 15386 of *Vaniman and Papike (1980)* was taken as the assimilant. The most primitive high-alumina basalts (i.e., incompatible trace-element poor) correspond to "Group 5" of *Dickinson et al. (1985)* and were taken as parental. The basalts forming their "Groups 3 and 4" were described as "intermediate" by *Neal et al. (1987, 1988, 1989)*. It should be emphasized that the categorizing of Apollo 14 high-alumina basalts into "groups" is not justified, as subsequent data have proven a continuum of basalt compositions at this site. However, the isotopic study of *Dasch et al. (1986, 1987)* adhered to this earlier classification.

Major-element modeling was undertaken on an Ol-Q-An pseudoternary, and this was used, as well as petrographic observations, to estimate the compositions and proportions of crystallizing phases. During the first 14% crystallization (i.e., $F = 0.86$), olivine (90%) and chromite (10%) were liquidus phases. Between 15% and 21% crystallization (i.e., $F = 0.85-0.79$), plagioclase (50%), olivine (40%), and chromite (10%) crystallized, followed by pyroxene (60%), plagioclase (30%), and ilmenite (10%) after 21% (i.e., $F = 0.79$) of the parental magma had crystallized. A parental magma composition was calculated on the basis of low incompatible trace-element abundances and position on the Ol-Q-An pseudoternary.

Sr ISOTOPES

Those Apollo 14 high-alumina basalts that have been analyzed for Sr isotopes range in crystallization ages from 3.96 to 4.33 Ga, and in initial $^{87}\text{Sr}/^{86}\text{Sr}$ from 0.69908 to 0.69948 (Table 1). Present-day $^{87}\text{Sr}/^{86}\text{Sr}$ ratios range from 0.70073 to 0.70414, and Sr and Rb abundances from 61.7 to 105.6 ppm and 0.685 to 2.95 ppm, respectively. As crystallization age becomes younger, initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios and abundances of Sr increase. Those basalts containing the most radiogenic present-day Sr isotope ratios also contain the highest abundances of incompatible trace elements (Fig. 1).

DISCUSSION

In their Sr isotope study, *Dasch et al. (1987)* analyzed Apollo 14 high-alumina basalts belonging to "Groups 1-5" of *Dickinson et al. (1985)*. Whole-rock chemical data for the samples reported by *Dasch et al. (1987)* can be found in *Hubbard et al. (1972)* for 14053; *Sbervais et al. (1985)* for 14321, 1161/1384; and *Dickinson et al. (1985)* for "14321", 14321, 9056, and 14321, 9059. However, the "Group 4" basalt (14321, 1394) reported by *Dasch et al. (1987)* is more evolved than this classification suggests, as stated by these authors. The Sm-Nd data required this subsample to be from a basalt more enriched in the REE (*Dasch et al., 1987*). Curatorial records describing the dissection of breccia 14321 revealed that the subsample from which the whole-rock composition of 1394 was determined was not 14321, 1149 as reported by *Dasch et al. (1987)*. Rather, the whole-rock

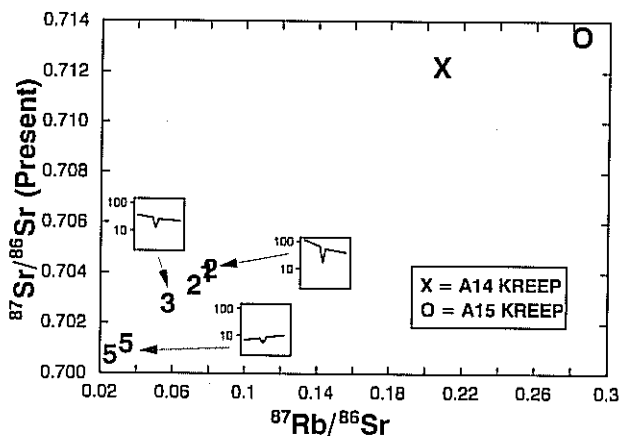


Fig. 1. Strontium isotope isochron plot for Apollo 14 high-alumina basalts and Apollo 14 and Apollo 15 KREEP. There is no age significance in this correlation due to different crystallization ages of the basalts plotted. Also plotted on this diagram are the relative REE profiles and abundances of the samples analyzed—those with a more radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ signature possess KREEP-like REE profiles. This diagram illustrates the possibility of a mixing relationship between a primitive, parental "Group 5" Apollo 14 high-alumina basalt and KREEP. Large, bold numbers refer to the basalt group. Data from *Papanastassiou and Wasserburg (1971)*, *Dasch et al. (1987)*, *McKay et al. (1978, 1979)*, and *Nyquist et al. (1973, 1975)*.

composition was reported as 14321,1318 by Neal *et al.* (1988) (JSC Curatorial Staff, personal communication, 1988). This is supported by the similarity of Sm and Nd abundances between ,1394 and ,1318 reported by Dasch *et al.* (1987) and Neal *et al.* (1988) (Sm = 11.2 and 10.4 ppm; Nd = 38.9 and 30 ± 4 ppm respectively). Therefore, this composition is more akin to a "Group 2" basalt (20.8 ppm La; 8.15 ppm Hf).

Dasch *et al.* (1987) suggested that the range in crystallization ages and initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the Apollo 14 high-alumina basalts negates a petrogenesis involving KREEP but could be resolved by assimilating urKREEP residuals (after Binder, 1982, 1985). These authors also supported the contention of Dickinson *et al.* (1985), that the high-alumina basalts evolved by different degrees of partial melting of a common source, or similar sources at different times early in the history of mare volcanism. Furthermore, the Sr isotope data indicated that most "groups" of Apollo 14 high-alumina basalts could have been erupted at different times from either a single source or from different sources containing the same Rb/Sr ratio, but with different absolute amounts of Rb and Sr (Sibb and Nyquist, 1989a). Although on their own these Sr isotope data do not negate a partial melting model, such as that proposed by Dickinson *et al.* (1985), they cannot be used as absolute proof of such a petrogenesis for Apollo 14 high-alumina basalts.

Isotopic Evidence for AFC

Isotopic evidence for KREEP assimilation can be found in the positive correlation of the $^{87}\text{Sr}/^{86}\text{Sr}$ (present-day) ratios with $^{87}\text{Rb}/^{86}\text{Sr}$, and $^{87}\text{Sr}/^{86}\text{Sr}$ (initial) with Sr ppm (Figs. 1 and 2, Table 1). In Fig. 1, an isochronous relationship is displayed between the Apollo 14 high-alumina basalts. Note that Apollo 14 and 15 KREEPy basalts plot at the upper end of this correlation and that the REE profiles of the high-alumina basalts become more KREEP-like from "Group 5" to "Group 1."

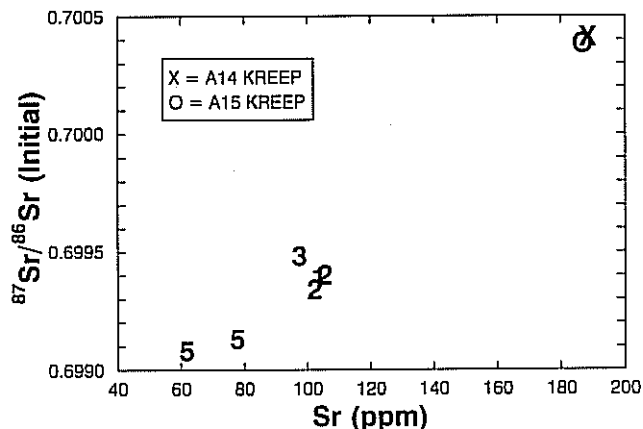


Fig. 2. Initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios plotted against Sr (ppm). Large, bold numbers refer to the basalt group. Data from Papanastassiou and Wasserburg (1971), Dasch *et al.* (1987), McKay *et al.* (1978, 1979), and Nyquist *et al.* (1973, 1975).

However, this type of plot can have no age significance because the Apollo 14 high-alumina basalts yield different crystallization ages (Dasch *et al.*, 1987). We conclude that this correlation represents a mixing line or AFC trend between "Group 5" basalts and KREEP.

This contention is borne out in Fig. 2 where a general positive correlation exists between initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios and Sr (ppm) for the Apollo 14 high-alumina basalts. The intermediate and evolved Apollo 14 high-alumina basalts contain progressively more radiogenic initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios and a greater abundance of Sr (Fig. 2). An exception to this is the intermediate "Group 3" basalt 14053, which contains the highest initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio (Fig. 2), inconsistent with the trace-element AFC modeling (Neal *et al.*, 1987, 1988, 1989). The significance of this observation will be discussed below. Hawkesworth and Vollmer (1979) demonstrated that positive correlations between $^{87}\text{Sr}/^{86}\text{Sr}$ and Sr abundance could be the result of two-component mixing. This can be extended to an AFC process, which in its simplest form is essentially the mixing of two components. Note that the initial Sr isotope ratio and Sr ppm increase from the most primitive "Group 5" basalts (i.e., LREE-depleted, low incompatible-/high compatible-element abundances, low SiO_2) to the more evolved basalts (Fig. 2), which exhibit KREEP-like REE profiles.

If the process was simply mixing (i.e., bulk assimilation with no fractional crystallization), a plot of initial $^{87}\text{Sr}/^{86}\text{Sr}$ vs. Sr (ppm) would yield a curved trend (Langmuir *et al.*, 1978; Fig. 5 of Sibb and Nyquist, 1989b). However, a somewhat linear trend is portrayed (Fig. 2). This suggests something other than simple mixing or bulk assimilation is affecting the evolution of these basalts (i.e., fractional crystallization).

In order to interpret the Sr isotopic evolution of these samples, we have plotted crystallization age against initial $^{87}\text{Sr}/^{86}\text{Sr}$ for all Apollo 14 high-alumina basalt samples for which data are available (Fig. 3; Table 1). A negative correlation is apparent, which indicates a progressive increase in initial Sr isotopic ratio with younger basalts. Dasch *et al.* (1987) suggested that these data can be interpreted in terms of a single-stage evolution of several source regions from a whole Moon (estimated using the Sr isotope value of BABI), with a $^{87}\text{Rb}/^{86}\text{Sr}$ ratio of 0.06 (similar to the bulk Moon value of 0.05 proposed by Nyquist, 1977). Such an evolution line passes through the errors on age and initial $^{87}\text{Sr}/^{86}\text{Sr}$ determinations, except for one "Group 5" basalt (1384). However, in light of trace-element modeling, the abundances of which can be adequately modeled by AFC (Neal *et al.*, 1987, 1988, 1989), we have placed a different interpretation upon these data.

Sr Isotope Modeling

The Sr isotope compositions of these basalts have been modeled by AFC (with KREEP) using equations (6a) and (15a) of DePaolo (1981). Unlike the trace elements (Neal *et al.*, 1987, 1988, 1989), modeling of the Sr isotopes requires that age relationships be taken into account. The Apollo 14 high-alumina basalts range in crystallization age from 3.96 to 4.33 Ga (Papanastassiou and Wasserburg, 1971; Dasch *et al.*, 1987; see Fig. 3, Table 1). Although errors on these ages are

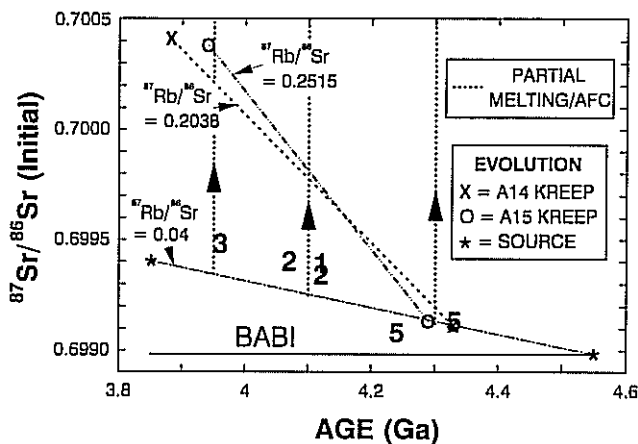


Fig. 3. Evolution diagram of the Apollo 14 high-alumina basalt source and resulting melts. The high-alumina basalt source is considered to have evolved along a single-stage evolution path similar to that of the bulk Moon. The evolution paths of the Apollo 14 and 15 KREEP components have been constructed by assuming crystallization of urKREEP at 4.29–4.33 Ga (i.e., the Sr model ages of Apollo 14 and 15 KREEP basalts) and subsequent evolution at a higher Rb/Sr ratio. The data points at the other end of the KREEP evolution paths correspond to crystallization ages and calculated initial ratios at the time of KREEP basalt extrusion. The different periods of magmatism and AFC are shown as vertical dotted lines. Large, bold numbers refer to the basalt group. Data from Papanastassiou and Wasserburg (1971) and Dasch et al. (1987), McKay et al. (1978, 1979), and Nyquist et al. (1973, 1975).

large (Table 1), it is evident that a single-stage AFC process cannot account for the distribution of the basalts in Fig. 3—such a process between two isotopically distinct end members would form a vertical trend on this plot. However, because the trace-element data define a single AFC trend (Neal et al., 1988, 1989), each AFC cycle must have followed essentially the same path. This cyclical AFC process is not unreasonable, considering the Apollo 14 site has a “KREEP-rich” signature (e.g., Wood and Head, 1975; Eitcheberry-Ramirez et al., 1983).

As illustrated in Fig. 3, we consider that the source region for the high-alumina basalts evolved along an evolution line of $^{87}\text{Rb}/^{86}\text{Sr}$ 0.04 (\cong whole Moon value proposed by Nyquist, 1977), similar to Dasch et al. (1987). However, at various points along the source evolution path, melting occurred, producing the primitive “Group 5” parental magma. From the clustering of the isotope data and taking into account the trace-element contents of these basalts, the first event occurred at \cong 4.3 Ga, the second at 4.1 Ga, and the third at 3.95 Ga. It is the position of 14053, the “Group 3” basalt (classified as “intermediate” by Neal et al., 1988), in Fig. 3 that indicates that single-stage evolution of a single source coupled with one AFC cycle are inadequate to generate all the observed Sr isotopes. If single source evolution or one AFC cycle was responsible for the range of high-alumina basalt compositions at the Apollo 14 site, this basalt should contain an intermediate initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio basalts of “Groups 1 and 2” and “Group 5.”

14053 can be adequately generated by a later (i.e., \cong 3.95 Ga) AFC cycle. However, more Sr isotope data from Apollo 14 high-alumina basalts are required to constrain more definitively the number and nature of the proposed AFC cycles.

The present-day isotopic signatures of the two “Group 5” basalts may be the result of a heterogeneous source with respect to absolute abundances of Rb and Sr (Sibb and Nyquist, 1989a,b). The initial ratios of these basalts are similar (Fig. 3, Table 1), but as shown by Dasch et al. (1987), the error parallelograms for these two basalts are not overlapping. This heterogeneity, which may also have been induced by variable degrees of partial melting, is witnessed in a higher present-day $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 1384, which has lower Sr abundances (Table 1).

In our previous trace-element studies (Neal et al., 1987, 1988, 1989), 15386 “IKFM” KREEP basalt was taken as the assimilant. This representative KREEPy sample was also used by Neal and Taylor (1989) in a preliminary report on the Sr isotopic evidence for AFC in the petrogenesis of Apollo 14 high-alumina basalts. However, in the present study we have undertaken a more detailed approach to the determination of the Sr isotopic compositions of the assimilant. The initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 15386 (0.70038) and the average Sr abundance of all Apollo 15 KREEP basalts (186.7 ppm; Nyquist et al., 1973, 1975) were utilized in this modeling. Furthermore, we have also used an average Apollo 14 KREEPy basalt composition (Table 2: data from Papanastassiou and Wasserburg, 1971; McKay et al., 1978, 1979). The average Apollo 14 KREEP possesses an initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.70041 and 188.3 ppm Sr. Both Apollo 14 and Apollo 15 KREEPy compositions plot at the end of the positive correlation delineated by the high-alumina basalts in $^{87}\text{Sr}/^{86}\text{Sr}$ (present) vs. $^{87}\text{Rb}/^{86}\text{Sr}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ (initial) vs. Sr (ppm) (Figs. 1 and 2).

The crystallization ages of KREEPy basalts are younger (Apollo 14 = 3.88 Ga; Apollo 15 = 3.94 Ga) than the Apollo 14 high-alumina basalts. However, model ages for Apollo 14 (McKay et al., 1978, 1979; Papanastassiou and Wasserburg, 1971) and Apollo 15 KREEPy basalts (Nyquist et al., 1973, 1975) range from 4.29–4.33 Ga. Dowty et al. (1976) suggested that the model ages represent the creation or crystallization of the “urKREEP” (pristine, unadulterated KREEP) reservoir from the “lunar magma ocean” (Warren and Wasson, 1979; Warren, 1985). This reservoir was subsequently remelted at \cong 3.9 Ga and erupted as KREEPy basalts. These basalts are the best representatives of the proposed KREEP assimilant. In Fig. 3 we have plotted average Apollo 14 and Apollo 15 KREEPy basalts and drawn a tie line between their respective initial ratios at time of crystallization and the bulk Moon evolution path at 4.29 Ga (Apollo 15) and 4.33 Ga (Apollo 14). These tie lines trace the evolution of the urKREEP reservoir prior to KREEPy basalt magmatism. As such, the Sr isotopic composition of KREEP can be estimated at the inferred times of magmatism. We assume that Sr abundances do not change. Modeling parameters can be found in Table 2, and F values shown are those calculated from the major-element modeling (Neal et al., 1988; see previous section).

The effect of KREEP assimilation by a parental “Group 5”

TABLE 2. Modeling parameters.

F Value	4.1 Ga $^{87}\text{Sr}/^{86}\text{Sr}$	Sr (ppm)	F	3.95 Ga $^{87}\text{Sr}/^{86}\text{Sr}$	Sr(ppm)																		
<i>Apollo 14 KREEP</i>																							
0.95	0.699260	75.4	0.95	0.699360	75.4																		
0.90	0.699278	82.6	0.90	0.699390	82.6																		
0.86	0.699292	88.9	0.86	0.699412	88.9																		
0.79	0.699312	89.9	0.79	0.699445	89.9																		
0.70	0.699336	95.7	0.70	0.699484	95.7																		
0.60	0.699363	103.0	0.60	0.699527	103.0																		
0.50	0.699389	111.4	0.50	0.699570	111.4																		
0.40	0.699415	121.1	0.40	0.699612	121.1																		
Parent	0.699240	69.0	Parent	0.699328	69.0																		
Apollo 14 KREEP	0.699780	188.3	Apollo 14 KREEP	0.700200	188.3																		
<i>Apollo 15 KREEP</i>																							
0.95	0.699260	75.4	0.95	0.699365	75.4																		
0.90	0.699279	82.5	0.90	0.699399	82.5																		
0.86	0.699294	88.8	0.86	0.699425	88.8																		
0.79	0.699315	89.8	0.79	0.699462	89.8																		
0.70	0.699340	95.6	0.70	0.699507	95.6																		
0.60	0.699367	102.8	0.60	0.699557	102.8																		
0.50	0.699395	111.1	0.50	0.699606	111.1																		
0.40	0.699422	120.8	0.40	0.699654	120.8																		
Parent	0.699240	69.0	Parent	0.699328	69.0																		
Apollo 15 KREEP	0.699800	186.7	Apollo 15 KREEP	0.700335	186.7																		
<table border="1"> <thead> <tr> <th>Mineral</th> <th>Sr Kd</th> <th>Reference</th> </tr> </thead> <tbody> <tr> <td>Olivine</td> <td>0.02</td> <td>(1)</td> </tr> <tr> <td>Plagioclase</td> <td>2.25</td> <td>(2,3)</td> </tr> <tr> <td>Pyroxene</td> <td>0.02</td> <td>(4)</td> </tr> <tr> <td>Ilmenite</td> <td>0.005</td> <td>(5)</td> </tr> <tr> <td>Chromite</td> <td>0.005</td> <td>Estimated</td> </tr> </tbody> </table>						Mineral	Sr Kd	Reference	Olivine	0.02	(1)	Plagioclase	2.25	(2,3)	Pyroxene	0.02	(4)	Ilmenite	0.005	(5)	Chromite	0.005	Estimated
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Ilmenite	0.005	(5)																					
Chromite	0.005	Estimated																					

References: (1) *Hart and Brooks* (1974); (2) *Drake and Weill* (1975); (3) *Philpotts and Schnetzler* (1970); (4) *McKay and Weill* (1976); (5) *Binder* (1982).

magma has been evaluated at 4.3, 4.1, and 3.95 Ga. At 4.3 Ga the parental magma and KREEP assimilant will contain virtually identical $^{87}\text{Sr}/^{86}\text{Sr}$ ratios (Fig. 3). We would predict that all Apollo 14 high-alumina basalts erupted at 4.3 will contain initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of between 0.6991 and 0.6992. Until more data is collected, it is uncertain whether basalts spanning the complete range of observed trace-element compositions were erupted at this time.

The one "Group 1" and two "Group 2" high-alumina basalts were erupted at ≈ 4.1 Ga. These basalts contain the most evolved trace-element compositions. According to the model of *Neal et al.* (1987, 1988, 1989), between 45–54% fractional crystallization of a parental "Group 5" magma (9.9–11.9% KREEP assimilation) is required to generate these compositions. We have calculated an AFC path between a parental "Group 5" basalt and Apollo 14 and 15 KREEP (Fig. 4). The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for both Apollo 14 and 15 KREEP and the

parental magma were estimated from the evolution paths in Fig. 3. In our previous trace-element AFC modeling of Apollo 14 high-alumina basalts, a primitive "Group 5" basalt was taken as the parental magma (*Neal et al.*, 1988, 1989). Although Sr abundance and initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the "Group 5" basalt source region was heterogeneous (see previous section), we have for simplicity taken as our parental magma an average of the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio and Sr (ppm) of the two "Group 5" basalts (Table 2). Modeling parameters are presented in Table 2. The initial Sr isotopic ratio of the "Group 3" basalt 14053 can only be generated by a separate AFC cycle (at 3.95 Ga), different from that which produced the "Group 1 and 2" basalts (Fig. 3). Therefore, an AFC path between a parental "Group 5" basalt and Apollo 14 and 15 KREEP at 3.95 Ga has also been calculated (the upper two paths in Fig. 4), in order to generate the "Group 3" basalt 14053.

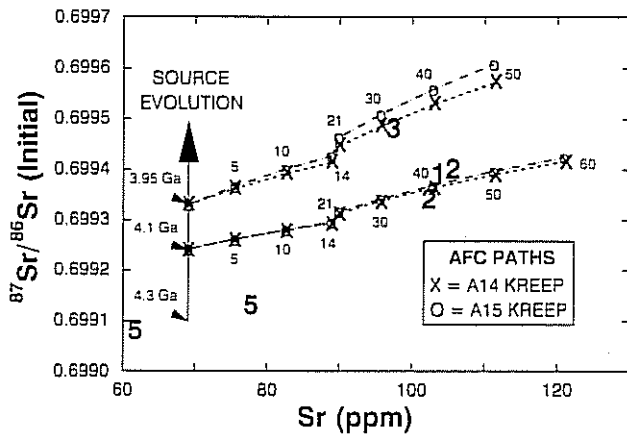


Fig. 4. AFC modeling of initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios and Sr (ppm) using equations (6a) and (15a) of DePaolo (1981) for Apollo 14 high-alumina basalts and Apollo 14 and 15 KREEP as assimilants. Large, bold numbers refer to the basalt group and small numbers refer to the percent crystallized. Data from Papanastassiou and Wasserburg (1971), Dasch et al. (1987), McKay et al. (1978, 1979), and Nyquist et al. (1973, 1975). The average parental basalt and KREEP assimilant compositions are estimated from Fig. 3 ($^{87}\text{Sr}/^{86}\text{Sr}$ ratio) and averaging the two analyzed "Group 5" basalts (Sr abundance).

The calculated AFC paths between a parental high-alumina basalt and KREEP indicate the applicability of this process in generating the Sr isotopic compositions of Apollo 14 high-alumina basalts (Fig. 4, Table 2). Note that the increase in Sr is slowed when plagioclase becomes a liquidus phase after 14% fractional crystallization ($F = 0.86$). Such results can be related to trace-element modeling by examining selected trace-element contents (Table 1). These elements have been plotted on definitive graphs (La vs. Hf and Sc/Sm vs. La) used by Neal et al. (1988, 1989) to illustrate the applicability of an AFC process to Apollo 14 high-alumina basalt petrogenesis (Figs. 5a,b). Also plotted are the calculated AFC paths (Neal et al., 1988, 1989), from which can be estimated the amount of fractional crystallization and KREEP assimilation required to generate each sample that has been analyzed for Sr isotopes. The parental basalt used in these trace-element AFC calculations was the one defined by Neal et al. (1988) in order to be consistent with previously published models (Neal et al., 1988, 1989). We consider the average Sr isotope value of the "Group 5" basalts reported by Dasch et al. (1987) to be representative of the parental magma.

The AFC calculations involving trace-elements are presented in Figs. 5a,b. For each basalt, the amount of required AFC is approximately the same, both for the trace elements and the Sr isotopes (Figs. 4 and 5, Table 3). However, the amount of AFC required for the "Group 1" ("14321") basalt is somewhat higher for trace-element modeling than that in the modeling of the Sr isotope data (Table 3). This may be due to the fact that this sample is a mixture of five different "Group 1" basalt clasts.

Shib and Nyquist (1989a,b) used a plot of MG# vs. La (ppm) (Fig. 6) to demonstrate the groupings of the Apollo 14 high-alumina basalts. These authors demonstrated that the AFC path of Neal et al. (1988) does not pass through the central portion of the data on such a plot. However, in the construction of this AFC path, the major elements were modeled by fractional crystallization alone (after the method of DePaolo, 1981), not allowing for the influence of the assimilant.

In Fig. 6, we have reevaluated the AFC process inasmuch as it affects the major elements. We have plotted the original AFC curve (dotted line) from Neal et al. (1988) along with two AFC curves that include the effect of the KREEP assimilant (IKFM 15386 KREEP from Vaniman and Papike, 1980) on the major element contents of the residual melt (solid lines). These curves are drawn from the parental "Group 5" basalt defined by Neal et al. (1988) and the "Group 5" basalt

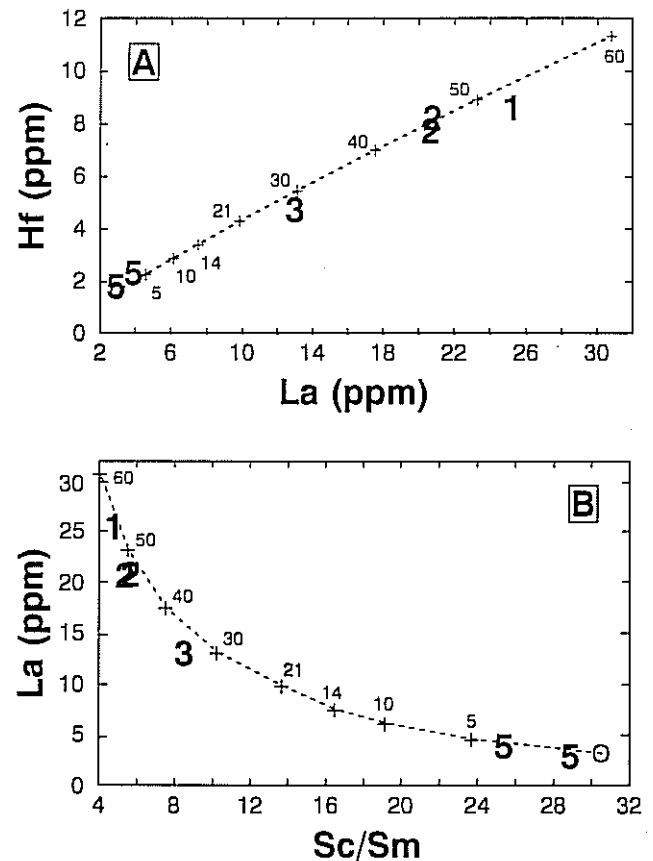


Fig. 5. Trace-element modeling for all Apollo 14 high-alumina basalts that have been analyzed for Sr isotopes. Large, bold numbers refer to the basalt group and small numbers refer to the percent crystallized. (a) La (ppm) vs. Hf (ppm); (b) Sc/Sm vs. La (ppm). Parental basalt composition from Neal et al. (1988). Apollo 14 high-alumina basalt trace-element data from Shervais et al. (1985), Dickinson et al. (1985), and Neal et al. (1988). AFC paths were calculated by Neal et al. (1988, 1989).

TABLE 3. Comparison of amounts of AFC required to generate the trace-element contents and isotopic signatures of Apollo 14 high-alumina basalts.

Sample	"Group"	La vs. Hf		La vs. Sc/Sm		Sr Isotopes	
		A	FC	A	FC	A	FC
"14321"	1	11.2-11.7	51-53	11.4-11.9	52-54	9.1-9.2	41-42
9056	2	9.9-10.3	45-47	10.3-10.8	47-49	9.7-9.9	44-45
1318/1394	2	10.1-10.6	46-48	10.3-10.8	47-49	8.5-8.6	38-39
14053	3	6.2-6.6	28-30	6.8-7.3	31-33	6.6-6.9	30-32

A = assimilation; FC = fractional crystallization.

containing the highest MG#. Drawing more than one AFC curve is feasible due to the cyclical nature of the AFC process at Apollo 14 (see above). Also shown on Fig. 6 are bulk mixing lines between the two parental "Group 5" basalts and our KREEP assimilant (dashed lines).

Like the original AFC curve (Neal *et al.*, 1988), the two mixing paths miss the bulk of the data, but these mixing lines do not rule out the possibility of post-KREEP-assimilation olivine fractionation as proposed by Shib and Nyquist (1989a,b). However, much of the horizontal scatter may be a function of the large errors associated with the MG# calculation. When the affect of the assimilant on the major elements, the magnitude of the errors associated with the MG# calculation and the cyclical nature of AFC at the Apollo 14 site are taken into consideration, this plot does not negate a petrogenesis for these high-alumina basalts by AFC with KREEP.

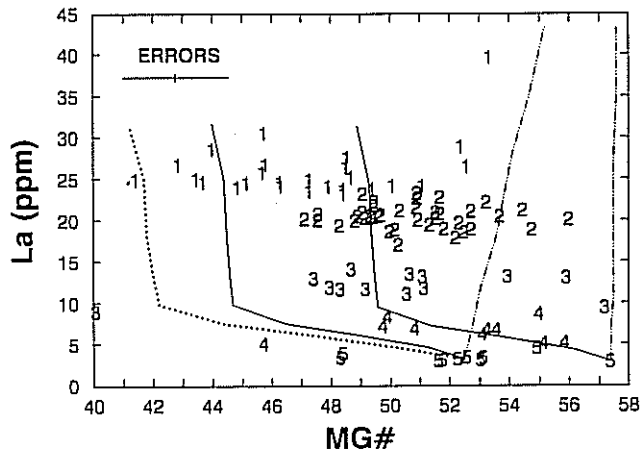


Fig. 6. A plot of MG# vs. La (ppm) for all Apollo 14 high-alumina basalts (data from Hubbard *et al.*, 1972; Dickinson *et al.*, 1985; Sbervais *et al.*, 1985; Neal *et al.*, 1988, 1989). Numbers correspond to the different basalt "groups" defined by Dickinson *et al.* (1985). The dotted line represents the original AFC path reported by Neal *et al.* (1988). Solid lines represent AFC paths where the effect of the assimilant on the major elements has been taken into consideration. These curves have been derived from the parent defined by Neal *et al.* (1988) and the "Group 5" basalt with the highest MG#. Dashed lines represent bulk mixing lines between these parents and the KREEP assimilant (15386 "IKFM" of Vaniman and Papike, 1980). Maximum errors were calculated from INAA data.

GEOLOGICAL SETTING AND THE AFC PROCESS

When interpreted in terms of an AFC process, the existing Sr isotope data for Apollo 14 high-alumina basalts suggest that there were three AFC cycles. The primitive ("Group 5"-type) parental magma was generated from a source region that essentially underwent Sr isotope evolution along a bulk Moon trend. This source region was isotopically heterogeneous (Dasch *et al.*, 1987), and absolute abundances of Rb and Sr were variable (Shib and Nyquist, 1989a,b). The nature of the present-day Sr isotope ratios indicates this variability in Rb/Sr ratios (Figs. 1 and 2) either within the source or induced by slight variations in the degree of partial melting.

The holding chamber for the parental "Group 5" magma was situated in a KREEP-rich area, allowing the progressive incorporation of a KREEPy signature into the evolving melt. The initial AFC cycle at 4.3 Ga between the "Group 5" parent and KREEP would have produced basalts of limited range in initial $^{87}\text{Sr}/^{86}\text{Sr}$. This is because both KREEP and the "Group 5" parent source region contained similar Sr isotope ratios at this time (Fig. 3). It is unclear whether high-alumina basalts spanning the whole compositional range defined by Neal *et al.* (1988, 1989) were erupted at this time. Subsequent AFC cycles will produce a range in initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios because the evolution paths of the source and assimilant have diverged sufficiently (Fig. 3).

Although the range in ages and initial Sr isotopic composition of the five analyzed basalts requires three AFC cycles (at 4.3, 4.1, and 3.95 Ga), the trace-element AFC trends (Figs. 5a,b) are not sensitive to age relationships. These trends suggest that one AFC cycle generated all observed Apollo 14 basalt compositions. Only when the Sr isotopes are considered can the cyclicity of this process be demonstrated. Each cycle must follow essentially the same evolutionary path in order for the trace-element and isotopic data to form coherent trends. This study highlights the need for an increased number of more accurate Sr isotope data for Apollo 14 high-alumina basalts in order to thoroughly evaluate their petrogenesis.

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