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There is a group of rocks from the lunar highlands with marked enrichments in "incompatible" elements (e.g., K, REE, P), relative to other highlands samples. These KREEP-rich rocks are also characterized by major element compositions which, when plotted in the OL-SI-AN pseudoternary liquidus diagram (Fig. 1), tend to lie near the OL-PL and PX-PL cotectic curves, and near the OL-PX-PX peritectic point. Most of these samples are breccias, although a few have igneous textures (e.g., 15386). The crystallization ages of the igneous KREEP samples cluster near 3.9AE, but their Rb-Sr model ages cluster between 4.3 and 4.4AE, suggesting that a major fractionation of Rb/Sr from primitive lunar values occurred somewhat prior to 4.3AE. The ancient model ages and extreme enrichment in incompatible elements of the KREEP-rich samples place important constraints on models for early evolution of the lunar crust.

Last year, we proposed a model in which samples along the OL-PL cotectic were parental to more evolved KREEP-rich material. The average composition of these cotectic samples (C in Fig. 1) is very similar to the Low-K Fra Mauro composition. According to our model, liquids with compositions similar to C were produced by fractionation of large amounts of olivine and lesser amounts of plagioclase (and possibly other phases) from undifferentiated lunar material at ~4.4AE. During the same igneous episode some of these liquids differentiated to form a series of more evolved members of the KREEP suite, including material of peritectic bulk composition (P in Fig. 1). In a later igneous event at ~3.9AE, some of this more evolved material further differentiated, producing highly evolved KREEP samples, including 15386. This model is consistent with observed major and trace element abundances, experimental phase equilibria and distribution coefficient data, and Rb-Sr isotopic data. This year we will further test and elaborate upon the model. Preliminary results are reported below.

Experimentally determined crystal/liquid distribution coefficients for several trace elements are given in Table 1. D's were measured using the electron microprobe on doped charges. Liquid compositions corresponded closely to C (Fig. 1 and [3]). Charges were run at 1240°C and oxygen fugacity of 10^-12.5(H2CO2).

<table>
<thead>
<tr>
<th>Element</th>
<th>PL/L</th>
<th>OL/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ce</td>
<td>0.048</td>
<td>0.011</td>
</tr>
<tr>
<td>Sm</td>
<td>0.035</td>
<td>0.007</td>
</tr>
<tr>
<td>Eu</td>
<td>1.25</td>
<td>0.13</td>
</tr>
<tr>
<td>Yb</td>
<td>0.030</td>
<td>0.013</td>
</tr>
<tr>
<td>K</td>
<td>0.22</td>
<td>0.036</td>
</tr>
<tr>
<td>Ba</td>
<td>0.15</td>
<td>0.005</td>
</tr>
<tr>
<td>Rb</td>
<td>0.026</td>
<td>0.26</td>
</tr>
<tr>
<td>Sc</td>
<td>0.003</td>
<td>1.08</td>
</tr>
<tr>
<td>Cr</td>
<td>0.002</td>
<td>0.05</td>
</tr>
</tbody>
</table>

The distribution coefficients in Table 1 are consistent with values we have reported previously. Our values for DOL/L are significantly higher than those recently reported by Akella et al. and by Huebner et al. for systems of different bulk composition. This disagreement is probably due to the strong compositional dependence of this coefficient.
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Last year we focused on 15386 as an example of highly evolved igneous KREEP. Several other A-14 and 15 KREEP-rich samples with igneous textures have crystallization ages of \(^{3.9}\text{AE}[9,10,11,12]\). We now consider whether the sort of origin we proposed for 15386 is consistent with the observed chemical and isotopic compositions of these other igneous-textured KREEP samples.

It is possible to use Fig. 1 and values for D\(^{\text{Fe}}\) and D\(^{\text{Mg}}\) for olivine and pyroxene[3] to calculate the weight fractions of coexisting plagioclase, olivine, pyroxene, and liquid at any stage during the crystallization of C. These weight fractions and the distribution coefficients from Table 1 and [3] may then be used to calculate the evolution of trace element abundances during the crystallization of C. The curve in Fig. 2 shows the variation in Rb/Sr with Sm. P is the hypothetical peritectic composition which was derived from C (4.4AE) and is parental to 15386 (3.9AE). The x's represent A-14,15 igneous-textured KREEP. Their proximity to the calculated curve is consistent with their proposed origin as differentiates of material similar to P.

We now consider whether the Rb-Sr isotopic compositions of the igneous-textured KREEP samples are consistent with our model. Fig. 3 is a Rb-Sr evolution diagram as it would have appeared at T, the time of crystallization of these samples (3.87-3.94AE). Material formed in the proposed 4.4AE differentiation event will lie along an isochron defined by the isotopic ratios for the bulk moon (M)[3], C, and P, and the slope of this isochron will change with time. In Fig. 3 the isochron is shown at 3.87 and 3.94AE. The isotopic ratios for the igneous-textured KREEP samples at the times of their crystallization are shown as dots. According to our model, these samples were derived from material lying along the M-C-P isochron. A horizontal line connects each dot with its parent material on the isochron, with the left end of the line indicating \(^{87}\text{Rb}/^{86}\text{Sr}\) of the parent material at the time of crystallization of that sample. Six of the 7 samples were derived from parent materials with a very narrow range of \(^{87}\text{Rb}/^{86}\text{Sr}\), which is indicated by a bar at the bottom of the figure. The corresponding range of Rb/Sr is shown as a bar along the left edge of Fig. 2.

Figures 2 and 3 indicate that the Rb, Sr, and Sm contents and the Rb/Sr isotopic ratios of the A-14,15 igneous-textured KREEP samples are consistent with their having been derived at \(^{3.9}\text{AE}\) from material similar in composition to P, which was derived from C during the proposed 4.4AE event. Our model is summarized in Figure 4. An important implication of the model is that the bulk composition of C, the parent to more evolved KREEP, is not controlled by low-pressure equilibration with an orthopyroxene-bearing refractory assemblage.

References:
Formation of C (=LKFM?) from primitive material through fractionation of large amounts of olivine + lesser amounts of plagioclase +?. C may represent residual liquid from crystallization of magma ocean, possibly modified by reaction with minerals in lunar crust. Alternatively, it may represent partial melts of pods of late-falling primitive material[2]. T=4.4 is time of isolation of C from its refractory residual assemblage. Large amount of C reaches upper levels of crust, where it is (later?) excavated to form noritic breccias.

At the same time, some C differentiates to form series of more evolved liquids whose compositions are controlled by low-pressure equilibria. These are intruded as sills or lenses in crust. Some have peritectic composition. Some are (later?) excavated to form KREEP breccias.

Large fraction partial melting of some peritectic KREEP. This time is close to the beginning of large-scale mare-filling volcanism, and heat sources may be related. Some of these partial melts are extruded and crystallize on surface.

Note: F=wt. fraction of liquid for any differentiation step relative to immediate parent for that step.