CAN A GEOPHYSICALLY REASONABLE MOON MAKE MARE BASALTS? Guy J. Consolmagno, Judith M. Harrigan*, and W. Roger Buck, Department of Earth and Planetary Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139. *also, Department of Geology, Wellesley College, Wellesley, MA 02181.

Buck and Toksöz (1980) have modelled the mineralogy of the lunar interior by determining what combinations of minerals and mineral compositions are consistent with the seismic velocity, crustal thickness, center-of-mass offset, mean density, and moment of inertia data. Assuming that the crust was derived from the outer 400 km of an initially homogeneous moon, they conclude that the moon today has a 60 km crust of anorthositic gabbro, a 400-450 km mantle rich in orthopyroxene (55%), olivine (37%), clinopyroxene (5%) and minor ilmenite, chromite, and Al-bearing phases. Below a transition zone is a lower mantle of "bulk moon" composition (44% opx, 25% olivine, 12.5% cpx, and the rest various high pressure Al-rich phases, mostly garnet). Their most recent work (this volume) shows the sensitivity of their results to the uncertainty of the geophysical data, but they still prefer this opx-rich model. Their model differs from most others (c.f. Morgan et al., 1978) in having opx dominate over olivine.

On the basis of experimental petrology, it has been postulated that high titanium mare basalts were derived from the upper mantle, at a depth of 70-200 km, while low titanium basalts are thought to come from a deeper source, possibly from the upper mantle-lower mantle transition zone.

The question addressed here is whether the mantle compositions given above are consistent with the observed chemistry of the mare basalts. The principle major element test is the Mg number (Mg/Mg+Fe) for the source, which must be consistent with the observed FeO abundances of the basalts. Many workers (c.f. Morgan et al., 1978) estimate a range of 0.75-0.8 is needed; the Buck and Toksöz number is 0.80. Trace elements are much more critical; they are also much more difficult to model since a large number of assumptions must be made concerning initial abundances and partition coefficients.

THE MODEL. We have attempted to model the evolution of REE abundances in melts with the composition of hi-Ti and lo-Ti mare basalts from source regions of the above composition, using the computer program of Drake and Consolmagno (1976). Initial REE abundances were found by assuming that the crust and upper mantle are both homogeneous, with complementary REE patterns, while the lower mantle is undifferentiated.

Total moon REE abundances are found by noting that the REE and Al are all refractory condensates and should be enriched in the moon to similar degrees. The Buck and Toksöz preferred composition has an Al abundance of 3 x chondrites; the REE should start out likewise enriched.

We assume that the crust of the moon is, in bulk, similar to "pristine" highland gabbros, and have taken the REE abundance of 60626 to represent the average REE for the crust. For the five REE we modelled, La=6.5, Sm=6, Eu=11, Gd=6, Lu=5 x chondrites (Laul and Schmitt, 1972). This assumption is quite arbitrary, given our lack of knowledge about the early crust. Howevers, samples with considerably higher REE abundances are probably contaminated by KREEP; and any abundance higher than 20 times chondrites is impossible as a crustal average, given our assumptions for the size of the crust and upper mantle, and our initial REE abundances. The complementary abundances for the upper mantle are La=2.4, Sm=2.5, Eu=1.7, Gd=2.5, Lu=2.7 x chondrites. The lower mantle is 3 x chondrites for all REE, representing undifferentiated material.

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MARE BASALT REE MODEL

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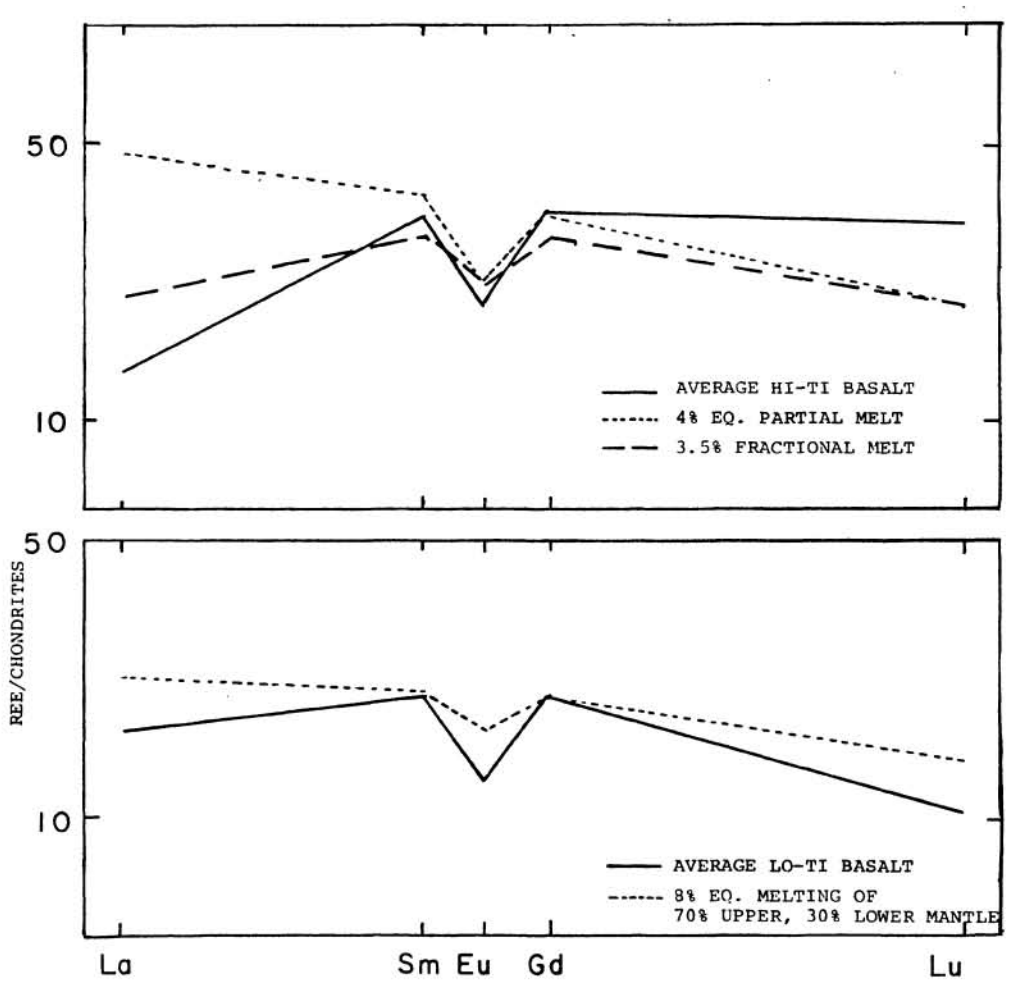
This model assumes that vigorous convection led to an averaging of REE abundances throughout the upper mantle. Clearly, it is also possible that different areas of the upper mantle may have been depleted to different degrees as suggested by Drake (1976). Hi-Ti basalts are assumed to come entirely from upper mantle material; the lo-Ti basalt source region is made from some mixture of upper and lower mantle material.

The results of this very simple model are shown in the figure. Given the nature of our assumptions, it is not surprising that the fit is not perfect. It is encouraging that the total REE abundances can be reached in this very simplistic way; however, the failure to match the patterns is significant.



HI-TI BASALTS. In all cases, the model light REE are too enriched and the heavy REE too depleted, relative to observed patterns. This comes as a direct consequence of the large amounts of pyroxene in the source region, since both opx and cpx tend to reject the lighter REE into the melt.

This is a significant problem, since a basic difference between the Buck and Toksöz composition and the other compositions proposed for the moon is their lower Mg/Si ratio, resulting in more pyroxene and less olivine.

There are several ways, however, that our initial assumptions might be adjusted to resolve this difficulty. Our initial assumption for the REE in

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the crust could be adjusted, increasing the light REE abundances in the crust and thus dropping them in the mantle. This solution is not satisfactory, however, since to produce the observed light REE depletion in the equilibrium melting model, the La abundance in the crust would have to be increased nearly to the level of the Eu anomaly. While crustal rocks do show a light REE enrichment, none of them are enriched to this extreme.

Second, our assumption of a uniform upper mantle may be too naive. For example, our models need an uncomfortably small degree of melting, both in order to match the absolute REE abundances and also because ilmenite, which makes up 25% of these basalts, is exhausted from our source region at 4% melting. However, a heterogeneous mantle could have regions enriched in both late crystallizing (and early melting) phases such as ilmenite which would also be enriched in incompatible elements like the REE. Drake and Consolmagno (1976) showed an ilmenite-rich source region could match light REE patterns and also be consistent with Sm-Nd isotopic systematics; the discrepency they found in heavy REE could be due to their initial heavy REE abundances.

Finally, it is possible that REE partition coefficients for pyroxenes at high pressure may be substantially different from those measured at room pressure. Mysen (1978) has reported low-Ca pyroxene partition coefficients measured at 20 kbars which are essentially flat. Unfortunately, his system used temperatures and compositions more appropriate for the Earth upper mantle than for the moon. Partition coefficients for a high pressure system at high tempreature, with low silica and no water, can only be guessed at.

LO-TI BASALTS. The match, while not perfect, is close enough to be encouraging. The light REE are still too high, and the heavy REE are also too high, but the differences are not as extreme as in the hi-Ti case.

Many of the arguments used above can also be applied to the lo-Ti basalt model. Changing the average crust abundances is more reasonable; for example, using 76536 REE patterns as a crustal average yields a much better fit to the Eu and Lu abundances (though such a crust would only exacerbate the hi-Ti problem). Likewise, coming from a deeper source region, the effects of high pressures on the partition coefficients may be even more extreme.

SUMMARY. We have shown that the Buck and Toksöz bulk moon composition is consistent with FeO abundances, and not totally inconsistent with REE patterns observed in mare basalts. The problems remaining do not seem to be so insurmountable as to rule out the Buck and Toksöz model. It is worth remembering that no other model of the moon has completely succeeded in matching the mare basalt REE patterns, either.

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