"Very High Alumina Basalt": A Mixture and Not a Magma Type

The proposal by Hubbard *et al.* (*1*) that "Very High Alumina basalt" ("VHA basalt") may represent an important primary lunar magma type neglects consideration of certain well-characterized high-magnesium highland rocks, among them spinel troctolite from Luna 20 (*2*) and Apollo 16 samples (*3*) and dunite from Apollo 17 samples (*4*), and the possibility that "VHA basalt" may in fact have originated by impact mixing and remelting of these and anorthositic rocks with KREEP (alkalic high-alumina) basalt. We suggest that the latter hypothesis accounts in a more satisfactory manner for many of the properties of "VHA basalt" discussed by Hubbard *et al.* (*1*) than their hypothesis that "VHA basalt" is a widespread volcanic rock.

Hubbard *et al.* (*1*) point out correctly that the compositions of "VHA basalts" cannot be derived by a two-component mixing model with KREEP basalt and either anorthosite or "highland basalt" (anorthositic norite or gabbro) as end-members. However, if it is considered that KREEP basalt is mixed with a suite of cumulate rocks consisting of various proportions of plagioclase, low-calcium pyroxene, olivine, and spinel, the major element compositions of "VHA basalts" and some other brecciated highland rocks can be accounted for. This is illustrated in Fig. 1, which, in terms of the MgO content versus the FeO content, shows the fields for lunar rock types defined by Hubbard *et al.* (*1*) together with the fields for the high-magnesium rocks mentioned above. The "VHA basalts" fall in the interior of a triangle roughly defined by KREEP basalt, anorthositic rocks, and any one of several high-magnesium rocks and thus may be accounted for as a mixture of these three components. Schonfeld (*5*) has used anorthosite, KREEP basalt, and dunite as end-members; however, we emphasize that in actuality "anorthositic rocks," anorthositic norite, and high-magnesium rocks are presumed to be parts of a continuum, and the mixing model is not a simple three-component one. Similar relations are evident on plots of any of the other major elements.

Although complete trace element data are not yet available for the high-magnesium rocks, it is known that the contents of alkalies and phosphorus are low, suggesting that the contents of all KREEP or large-ion lithophile trace elements (LIL) are low. In order to account for the trace element properties of "VHA basalt" by mixing as suggested above, the KREEP element content in the high-magnesium rocks is required to be low, like that of anorthosite 15415; this is to be expected if the high-magnesium rocks are cumulates, as anorthosite 15415 is commonly presumed to be. Spinel troctolites 67435 (*3*) and 65785 (an Apollo 16 rake sample) have textures that are clearly igneous and apparently cumulate; in fact, these are probably the best examples of "cumulate" textures found to date in highland rocks. The Luna 20 (spinel) troctolites (*2*) are small recrystallized fragments which may themselves be mixtures, but their composition demonstrates the existence of high-magnesium rocks at the Luna 20 site.

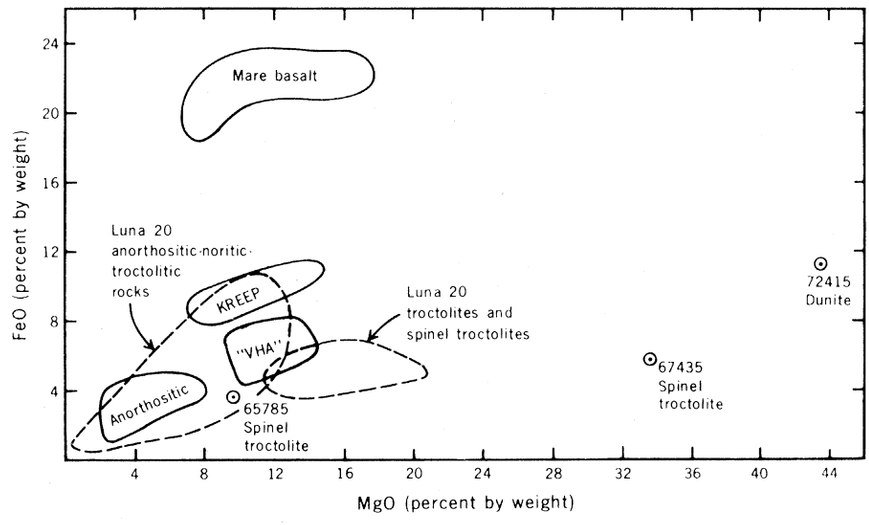

Fig. 1. Plot of the MgO content versus the FeO content for major lunar rock types. Fields for anorthositic rocks, KREEP basalt, "VHA basalt," and mare basalt are from Hubbard *et al.* (*1*). Fields of Luna 20 anorthositic-noritic-troctolitic rocks and troctolite and spinel troctolite rocks are from Prinz *et al.* (*2*). The analysis for spinel troctolite 67435 is from Prinz *et al.* (*3*); that for dunite 72415 is from Rhodes (*4*); and that for spinel troctolite 65785 is from our laboratory (unpublished results).

Schonfeld has pointed out (*5*) that most highland rocks with appreciable contents of rare-earth elements (REE) have a remarkable similarity in the slope of the trivalent REE patterns, which is identical to that of KREEP basalt. This applies to "VHA basalts" as well, as pointed out by Hubbard *et al.* and shown in their figure 2 in (*1*). This identical slope would not be expected if KREEP basalt and the other highland rocks, including "VHA basalt," are partial melts from the same source. For this reason Hubbard *et al.* (*1*) postulate that KREEP basalt and "VHA basalt" have different source regions. If this were correct, the identical REE slopes of the two "basalt" types would be fortuitous. However, an essentially identical trend is to be expected for all the rocks if practically all the trivalent REE in these rocks come from admixture of KREEP basalt, with the cumulate rocks contributing very little trivalent REE. If we consider that highland rocks present a spectrum of trace element patterns like that shown in figure 2 of Hubbard *et al.* (*1*), owing to the admixture of KREEP basalt with cumulate rocks that are trace element–poor and that "VHA basalts" are a group somehow selected from this spectrum in such a way that they have similar abundances of the trivalent REE (see below), all of the apparently unique properties of "VHA basalts" follow from this selection process. For example, Hubbard *et al.* (*1, 6*) point out that the europium-strontium-aluminum relations among "VHA basalts" are such as to suggest control by feldspar-liquid partitioning of the amounts of strontium and europium. However, a careful analysis of the problem shows that, if the amounts of europium, strontium, and aluminum in the cumulate rocks

are controlled by the amounts of plagioclase, as would be the case if the rocks contain little or no intercumulus liquid, linear relations among these elements are to be expected when only those rocks are selected which have a certain amount of trivalent REE, or KREEP component (*7*).

The "VHA basalts" have a wide range of Fe/(Fe + Mg) ratios, which is not consistent with their crystallization from a single liquid. Rock 62295 in particular is much more magnesian than the others. We could consider "VHA basalt" to be a magma type which may have fractionated to produce varying Fe/(Fe + Mg) ratios, but the very similar REE abundances of "VHA basalts" are not suggestive of significant fractionation. Such variation in the Fe/(Fe + Mg) ratios is to be expected in cumulate rocks.

Petrographic descriptions of "VHA basalts" lend no support to the contention that they are primary volcanic rocks. Rock 61156 is evidently a recrystallized or partially remelted breccia of the poikilitic type (*8*), containing clasts of olivine and plagioclase. The relict clasts are of such size as to suggest plutonic rather than volcanic origin for this part of the rock. Rock 61016 is a breccia, the light part of which consists of clasts of nearly pure anorthosite (*9*); the dark part [sampled by Hubbard *et al.* (*1*)] is evidently the matrix, which has a very different composition from the anorthositic part. Rocks 22006 and 22007 have been described as "highly recrystallized polymict breccias" (*10*). Rock 62295 has largely "igneous" texture but contains apparent relics of spinel and highly magnesian olivine (*11*), which suggest impact remelting of a preexisting rock or rocks.

The alternate hypothesis outlined here is only one of several which may be advanced to account for the properties of lunar feldspathic rocks, including "VHA basalts," and several objections may be raised against it. It must be admitted that the widespread occurrence of the presumed cumulate rocks with very low trace element contents is somewhat conjectural, and that most highland rocks seem to have moderately large amounts of trivalent REE and a negative europium anomaly. Rocks that have cumulate-type trace element patterns and intermediate major element composition, for example, anorthositic norite, which we would presume to be the most common type of cumulate rock prior to intermixing of KREEP basalt, seem to be very rare, and the best examples of cumulate-type trace element patterns are found in the extreme rock types, such as anorthosite. Moreover, it is not completely clear how "VHA basalt" has been "selected" from a wider spectrum of impact-mixed highland rocks, as suggested above. A certain amount of this selection was done by Hubbard *et al.* (*1*) when they omitted rocks which did not quite fit the pattern of "VHA basalt," but there seems to be some evidence for a concentration of trace element patterns at "VHA basalt" composition. One may envisage ways in which such a concentration might be created in natural processes, but these are also conjectural. Clearly, these questions must be taken up again when a wider sampling and more complete data are available for the highland rocks.

Despite such objections to the cumulate hypothesis, we feel that it has a sufficient number of advantages, some of which have been outlined above, that it must be considered in any attempt to account for the compositional properties of lunar highland rocks. Perhaps the principal advantage of this hypothesis is that it allows all the major lunar rock types to be related to each other by a simple petrogenetic scheme [for example (*2*, *11*)] involving early fractionation of a moonwide melt layer, producing the cumulate rocks, and later remelting of various differentiated layers to produce mare basalts (from the latest iron-rich liquid plus mafic cumulate crystals) and KREEP basalts (from the feldspathic cumulates). On the other hand, the hypothesis that "VHA basalt" is an important highland volcanic rock type leaves us with a number of apparently unrelated magma types, the origin of which is uncertain.

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References and Notes

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7. This may be demonstrated by reference to figure 5 of Hubbard *et al.* (*6*), a plot of the europium content versus the Al_2O_3 content. Consider that all cumulate rocks have low and relatively uniform contents of the trivalent REE, but that europium resides primarily in feldspar. The cumulate rocks will then lie along a line with positive slope at the base of the plot, with the position on the line determined by the amount of plagioclase present. The two ends of this line and the composition of KREEP form a triangle. If variable amounts of KREEP basalt are added to the cumulate rocks, a scatter of points in the middle of the triangle will be obtained. If we select from these mixtures only those that have a given concentration of trivalent REE, these mixtures will have identical amounts of the KREEP basalt component, since essentially all trivalent REE are derived from KREEP basalt. Such selected compositions will fall on a line parallel to the base of the triangle. Obviously, the "plagioclase–liquid distribution coefficients" imputed from such relationships have little meaning.
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