LIMITS ON THE BULK COMPOSITION OF THE MOON.

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Model lunar bulk compositions containing 8.1, 11.6, 17.4, and 27.2% Al₂O₃ have been proposed by several authors (1, 2, 3, 4 respectively). To be viable, any model lunar bulk composition must be capable of explaining the formation of mare basalt magmas. Three hypotheses of mare basalt formation should be considered, (a) direct partial melting of the bulk composition (b) partial melting of cumulates formed in an earlier differentiation event (c) hybridization between magmas from the primordial interior and early-formed cumulates. Experimental investigations (5) demonstrate that direct partial melting (≤40%) of all of the above compositions produces basaltic magmas containing >17% Al₂O₃. This is much higher than that observed in primitive mare basalts (~8.5% Al₂O₃) and the discrepancy shows that, according to the direct-melting hypothesis, the source regions should contain much less than 8% Al₂O₃.

A detailed high P,T experimental investigation has also been made of the least-aluminous of the above compositions (Taylor-Jakes, 8.1% Al₂O₃) in terms of the cumulate-remelting hypothesis. The following possible cases were studied (a) melting and differentiation of the entire moon (b) melting and differentiation of an outer shell several hundred km thick. In each case two important boundary conditions apply. Firstly, because the melting point gradient exceeds the adiabatic gradient below 200 km, crystallization necessarily commences at the base of the molten zone and progresses upwards. Thus, formation of a crust cannot occur until crystallization has extended upwards to about 200 km. Above 200 km, the adiabatic and melting point gradients are similar; moreover the residual liquid has a basaltic composition (~17% Al₂O₃) and plagioclase is able to crystallize, thereby making it possible to form a crust. Secondly, the presence of trapped intercumulus liquid in thick layers of cumulates causes extreme convective instability (thickness of liquid ~). This necessarily leads to convective motions within the cumulates accompanied by segregation of intercumulus liquid into overlying regions. Thus, intercumulus liquids cannot play an important role in subsequent petrogenetic events (5).

The internal structures of differentiated lunar models of TJ composition based upon the experimental results are shown in Fig.1. Several features of these models demonstrate that cumulates formed during the early melting of any bulk composition with 8% or more Al₂O₃ provide unsatisfactory source regions for the subsequent formation of mare basalts: (a) The clinopyroxenes in the potential source region between 200 and 400 km are too high in Al₂O₃, after acceptable amounts of partial melting, to have been in equilibrium with primary mare basalt magmas (~8.5% Al₂O₃). (b) The REE distributions of low-Ti basalts cannot be quantitatively explained by the partial melting of clinopyroxene cumulates between 200-400 km. (c) Plagioclase crystallization occurs only above 200 km. Cumulates at deeper levels have never "seen" plagioclase and hence do not possess a complementary Eu anomaly. Moreover calculations based on measured Eu partition coefficients show that after the elutriation of sufficient plagioclase into the crust to account for its composition (1) the mean negative Eu anomaly remaining in the region between 60 and 200 km is only 1/10 as large as that observed in Apollo 12 and 17 mare basalts. Cumulate
remelting is thus unable to account satisfactorily for the magnitudes of Eu anomalies in mare basalts. (d) Above 180-200 km large amounts of plagioclase are present at the solidus. Any magma produced by acceptable degrees of partial melting would necessarily be plagioclase-saturated. Primitive mare basalts, however, are markedly undersaturated in plagioclase. This region, therefore, is unsatisfactory as a source of mare basalts. (e) Ilmenite-bearing cumulates precipitate only when differentiation is 90-95% complete, so the potential source regions for the high-Ti suite would lie at depths of 100 km or less, immediately beneath the crust. However, experimental studies (6,7) are instead consistent with high-Ti magma genesis at much deeper levels, 170-240 km.

Formation of the crust would not have occurred until crystallization reached depths of ~200 km, and the residual magma had a basaltic composition with a sufficiently high Al\textsubscript{2}O\textsubscript{3} content (~17%) to precipitate plagioclase. Our experimental studies also show that the pyroxene precipitating in this "crustal" system is subcalcic with >10% CaO, whereas the average pyroxene component of the crust has a much lower CaO content (<5%) (1).

The above inconsistencies show that the model lunar bulk compositions suggested by authors (1-4) are all too rich in involatile elements Al, Ca, U etc. relative to elements of intermediate volatility Si, Mg, Fe etc. to provide satisfactory source regions for mare basalts, either by direct melting, or by remelting of early-formed cumulates. Taylor and Bence (8) have proposed a model bulk composition with only 6% Al\textsubscript{2}O\textsubscript{3}, but our recent experimental investigations show that this is similarly unsatisfactory in terms of mare basalt petrogenesis, and therefore the bulk moon probably contains less than 6% Al\textsubscript{2}O\textsubscript{3}.

Some major difficulties with the cumulate-remelting hypothesis for mare basalt origins have been pointed out elsewhere(5,9). An alternative hypothesis attributes a hybrid origin to mare basalts, involving complex assimilative interactions between sinking Ti-rich 4.6-4.4 b.y. residual cumulate pods on the one hand, and the primordial lunar interior on the other (9). Primitive (= least fractionated) mare basalts with the best "memory" of their primordial source, are those which have experienced the least contamination by the sinking cumulates, e.g. some Apollo 15 basalts and Green Glass. Their low Al\textsubscript{2}O\textsubscript{3} contents of about 8% imply derivation from a primordial source region containing no more than 4 to 5% Al\textsubscript{2}O\textsubscript{3}, i.e. about twice chondritic levels. Likewise the low abundances of involatile incompatible elements, e.g. REE, U in these samples (X4-12 chondritic) in relation to the degree of partial melting and permissible contamination required to explain their composition, imply a source region containing only about twice the ordinary chondritic abundances of REE, U, Al, Ca etc.

In conclusion, geochemical and experimentally-based constraints on mare basalt petrogenesis indicate that the bulk moon contains no more than 4 or 5% Al\textsubscript{2}O\textsubscript{3} and that its bulk composition is similar in many respects to that of the earth's mantle with the principal difference that in the moon, the more volatile elements are depleted relative to involatile elements.

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Fig. 1: Diagrams based on high P,T experimental results showing the mineralogical zoning which would occur if a moon of Taylor-Jakes (1) bulk composition were (a) completely melted throughout followed by fractional crystallization, or (b) melted only to a depth of 400-500 km followed by fractional crystallization of this outer layer. (Note that an anorthositic gabbro mean crustal composition is specified by the TJ model, and does not represent our own preferred crustal bulk composition; see also (10)).