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LUNAR PETROGENESIS IN A WELL-STIRRED MAGMA OCEAN

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The "Highland Basalt" glass compositions of Reid et al. (1972) are probably a good approximation to the average composition of the lunar crust. The crustal composition does not correspond to that of a reasonable primordial planetary material, or that of a magma type derived by partial melting from some reasonable parent rock. Instead it appears that the lunar crust is a plagioclase cumulate layer, formed by crystal fractionation from a massive early surface magma system, of global extent and at least 100 km depth.

Fractionation on such a large scale would have established certain moon-wide chemical and mineralogical trends in the rocks that now comprise the lunar crust. A primary goal of petrologic investigations must be to detect and understand these first-order trends in the lunar highland samples. It is important to recognize, however, that effects of the primary differentiation will have been blurred by secondary processes that have affected the rocks; in particular the remelting and refractionation of limited crustal volumes by later major impacts, and the comminution and mixing of early fractionate lithologies, by continued bombardment of the lunar surface, to form polymict breccias.

A straightforward assessment of large-scale chemical trends in the highlands samples has been made difficult by

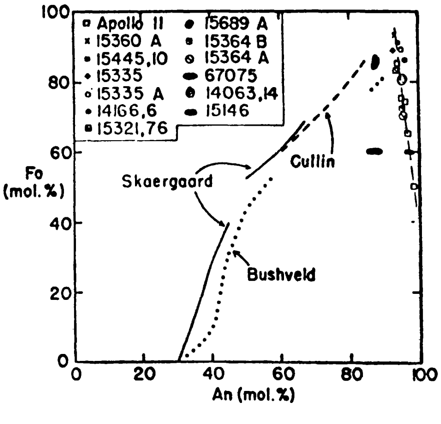
(1) the very large number of analyses, analysts, techniques, and sampling sites involved;

(2) the varied petrographic character of the rocks, clasts, and soil fragments analyzed, and uncertainty as to the relations between them;

(3) the likelihood that many of the above are polymict breccias; and

(4) the question of how or whether to discriminate between KREEP-rich and KREEP-poor samples, since the former do have the composition of a magma type obtainable by partial melting (Walker et al., 1972), and were probably formed by processes other than the primary crystal fractionation we seek to understand.

Steele and Smith (1973) approached the question by plotting the compositions of coexisting olivine and plagioclase in igneous samples (Fig. 1). They discovered a trend opposite to that predicted by the Bowen reaction principle, i.e., as plagioclase becomes more sodic, olivine becomes more magnesian. Since samples from three highland sites are involved, the effect cannot be attributed to an insignificant local anomaly. (The very steep slope of the lunar curve in Fig. 1 follows from the low lunar abundance of Na, in common with all other volatile elements.)



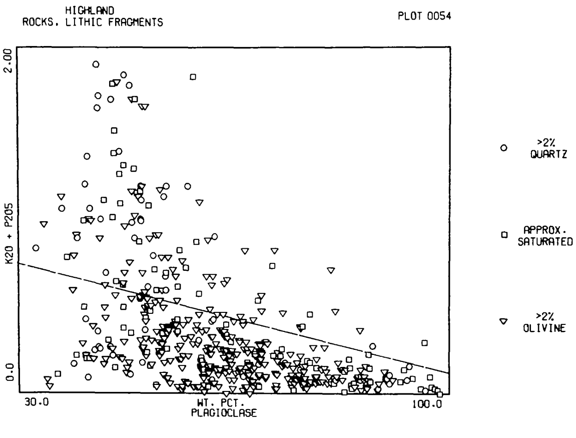


Fig. 1 (left): Compositions of coexisting plagioclase and olivine in terrestrial mafic stratiform bodies, and in low-KREEP lunar highland materials (Steele and Smith, 1973). Fig. 2 (right): Criterion by which analyses of low-KREEP highlands materials were separated from high-KREEP samples; former analyses appear in Fig. 3.

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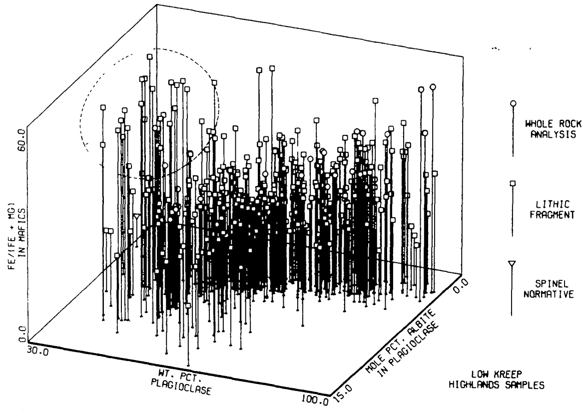

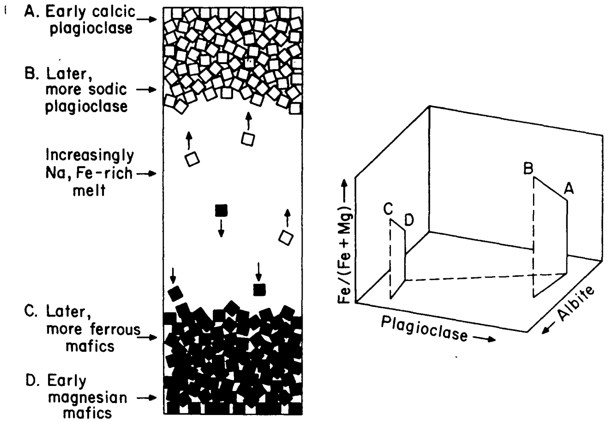

Fig. 3 (left): 408 analyses of low-KREEP highlands samples, in a plot of three differentiation parameters. References are to normative mineralogy. Entries within dashed line are high-Al mare basalts that mare/highlands chemical criterion failed to exclude. Fig. 4 (right): Crystal fractionation under quiescent conditions.

I have collected 892 analyses of lunar rocks, clasts, and lithic fragments from the literature and from the data files of my own group; these are recorded on magnetic tape, and can be used to generate variation diagrams that might reveal large-scale petrologic trends. Chemical criteria can be used to separate highland from mare samples, and KREEP-rich from KREEP-poor highland samples (Fig. 2). Difficulties (2) and (3), noted earlier, have been largely ignored in generating plots, in the expectation that use of very large numbers of data points will reveal overall trends in spite of the blurring effect of secondary processes, inadequate sample sizes, etc.; and that such plots will reveal end-member compositions, even if uncertainty remains as to intermediate trends, which may be mixing lines (polymict breccias).

A plot of differentiation parameters in KREEP-poor highland rocks, made from this data file, confirms and extends the trend of Steele and Smith (Fig. 3). This plot encompasses pyroxene as well as olivine compositions, breccias as well as igneous rocks, and data from all missions and many analysts. It also shows a clear relationship between the abundance of plagioclase, and mineral compositions.

A naive analogy drawn between crystallization in the early lunar surface magma system and quiescent crystallization in a terrestrial mafic intrusive would picture mafic minerals sinking to the floor and plagioclase rising to the surface of the lunar system (Fig. 4). One could postulate that early calcic plagioclase at A and magnesian mafics at D were accompanied by intercumulus liquid of moderate Na and Fe content, accounting for positions of end members of the sequence in Fig. 3; intermediate positions in the sequence might be filled by breccia mixtures of these end-members. However, continued crystallization in the magma system could not help driving cumulate compositions toward B and C. Rock types containing substantially more of both Na and Fe than A and D would inevitably be produced, and Fig. 3 contains no evidence of a sodic ferrogabbro end member. Lithologies of this type are conspicuously lacking from the literature of lunar petrography.

For comparison, a similar plot of 499 analyses of rocks from terrestrial layered mafic intrusives is shown in Fig. 5. The plot is dominated by high-Na, high-Fe granites, ferrogabbros, and norites. (Granites were, in fact, excluded from Fig. 3 by the KREEP criterion of Fig. 2; however, it is known from petrographic surveys of lunar soils and breccias that granite is not an abundant highland rock type.) The dissimilarity of Figs. 3 and 5 suggests that processes producing the two rock collections were substantially different.

The fundamental problem is to avoid creation of a body of late residual liquid, enriched in Na and Fe. A solution is proposed in Fig. 6. If conditions were turbulent rather than quiescent during crystallization, the evolving residual liquid might be kept well-mixed with early crystals until crystallization had consumed most (>~ 65%) of the liquid, at which point the effective viscosity of a liquid-solid suspension increases abruptly (Roscoe, 1952). The system would then stabilize, and should show little tendency to segregate a layer of pure liquid

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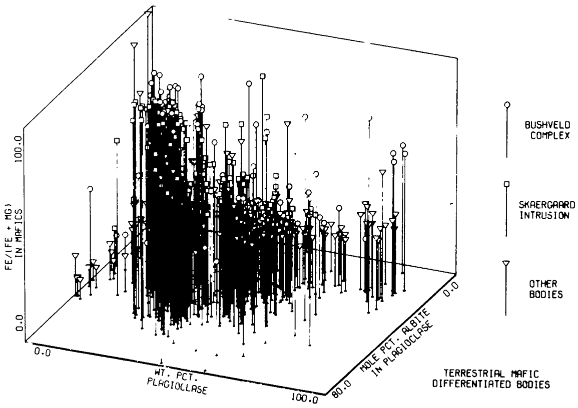

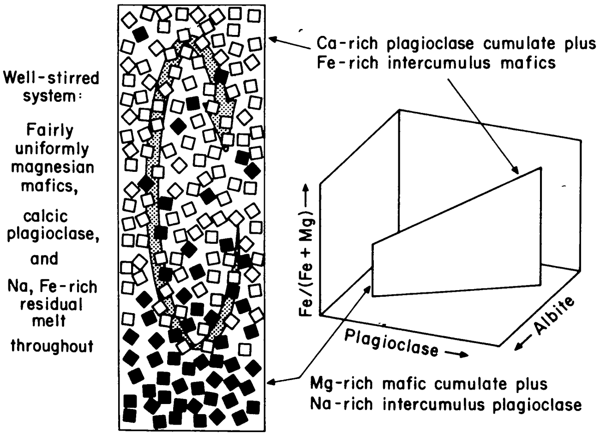

Fig. 5 (left): 500 analyses of rocks from terrestrial mafic stratiform intrusives, plotted as in Fig. 3 (except for expanded scales). "Other bodies" are Stillwater, Rhum, Guadalupe, Duluth, Bay of Islands, Usushwana, and Fethiye. Fig. 6 (right): Crystallization under turbulent conditions.

ferrogabbro at intermediate depth. When stabilization occurred, early-formed mafic crystals would be distributed throughout the column, but would be concentrated toward the bottom (as suggested by Fig. 6) because of their high density. Plagioclase, with density similar to that of the residual liquid, would not tend to separate from the latter, and would be concentrated at the top of the system simply by virtue of the absence of mafics. At the top of the column, the final plagioclase composition would be dominated by the early-formed relatively calcic crystals, but the mafic minerals would be those that crystallized from the intercumulus liquid, and therefore would be relatively rich in Fe. Conversely, at the base of the system, the mafic mineral composition would be dominated by early-formed magnesian crystals, while the plagioclase present would have been derived from the intercumulus liquid and would be sodic. All gradations would occur at intermediate depths; the run of compositions would result from varying proportions of early plagioclase, early mafics, and late liquid.

It is difficult to model such a column accurately or uniquely, but it appears that the trend in Fig. 3 would be reproduced if, at the time of column stabilization, mean Fe/(Fe+Mg) was ~0.13 in the early-formed mafic minerals and ~0.40 in the residual liquid; early-formed plagioclase was ~An_{98} on average, while normative plagioclase in the residual liquid was ~An_{78}; and the ratio plagioclase/mafics/liquid was 90/0/10 at the top of the system and 37.5/37.5/25 at depths corresponding to the left end of the trend in Fig. 3. At the ultramafic base of the system, compositions would be An_{78} and Fs_{14} or Fa_{14}. Ultramafic rocks are rare among lunar materials; apparently impact gardening has not sampled beneath the gabbroic level in the postulated column. Compositions of minerals and liquids assumed to coexist (above) are close to coexisting solid/liquid compositions in the binary systems forsterite-fayalite (Bowen and Schairer, 1935) and albite-anorthite (Tuttle and Bowen, 1950).

The lunar surface magma system would have been more turbulent and stayed better mixed than terrestrial mafic intrusives because it was exposed to space: heat would have been lost rapidly, promoting thermal convection in the magma. The system would have been prevented from crusting over prematurely by the early intense meteoroid bombardment. The bombardment would have also mechanically stirred the magma system, and might even have been the principal agent of turbulence.

References

Bowen, N.L. and J.F. Schairer (1935). Am. J. Sci., 5th Ser., 29, 163.
Reid, A.M., J. Warner, W.I. Ridley, D.A. Johnston, and R.S. Harmon (1972). Proc. Third Lunar Sci. Conf., 363.
Roscoe, R. (1952). British J. Appl. Phys., 3, 267.
Steele, I.M. and J.V. Smith (1973). Lunar Science IV, 689.
Tuttle, O.F. and N.L. Bowen (1950). J. Geol., 58, 582.
Walker, D., J. Longhi, and J.F. Hayes (1972). Proc. Third Lunar Sci. Conf., 797.