

Lunar Igneous Rocks and the Nature of the Lunar Interior

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Lunar igneous rocks, properly interpreted, can give useful information about mineral assemblages and mineral chemistry as a function of depth in the lunar interior. Though intensely brecciated, terra rocks reveal, in their chemistry, evidence for a magmatic history. Partial melting of feldspathic lunar crustal material occurred in the interval 4.6 to 3.9 Gy. Melting of ilmenite-bearing cumulates at depths near 100 km produced parent magmas for Apollo 11 and 17 titaniferous mare basalts in the interval 3.8 to 3.6 Gy. Melting of ilmenite-free olivine pyroxenites (also cumulates?) at depths greater than 200 km produced low-titanium mare basalts in the interval 3.4 to 3.1 Gy. No younger igneous rocks have yet been recognized among the lunar samples, and present-day melting seems to be limited to depths greater than 1000 km.

Returned lunar samples from six Apollo and two Luna landing sites, remote chemical analyses from Lunokhod and Surveyor space vehicles, and orbital spectrographic observations have given us a reasonably comprehensive view of the chemistry and mineralogy of the lunar surface (refs. 1–8). Unfortunately, very few of the returned lunar samples seem to be of deep-seated origin. Gooley et al. (ref. 9) have described a coarse-grained plagioclase-bearing rock (76535) which they interpret as a product of slow cooling at a depth of at least 10 km. Several ultramafic clasts in breccias have been interpreted as deep-seated cumulates although the evidence is not unambiguous (refs. 10, 11, and 12). The great majority of returned lunar samples, however, appear to have been formed at the lunar surface or within a few kilometers of it. Thus our knowledge of the mineralogy and chemistry of the lunar interior remains indirect and unsatisfactory.

Nevertheless, isotopic studies, geophysical evidence, and geochemical arguments all lead to a growing consensus that at least the outer several hundred kilometers of the Moon were subjected to partial or complete melting at a

very early stage in lunar history (refs. 13–17). If this view is correct, then the outer portion of the Moon and perhaps the entire Moon should consist of layers of cumulus crystals combined with the crystallization products of trapped residual liquids. The chemical and petrological character of these layers, the initial composition of the magmatic system, the proportion of the lunar mass involved, and the nature of the differentiation process are among the major unsolved problems of lunar science, and, by implication, of the early history of other planetary bodies as well.

In the absence of more than fragmentary direct evidence from geophysics, the petrographic, geochemical, and experimental study of lunar igneous rocks is the best available approach to the solution of these problems.

Method of Approach

Let us suppose that a certain primary magma originates by partial melting within the lunar interior and is then transported

directly to the lunar surface without modification of its chemistry (major element, minor element, or isotopic). If a lunar rock sample can be shown to be the crystalline or glassy equivalent of such a primary liquid, then careful geochemical and experimental study of this sample will reveal the depth of origin of the primary liquid and the mineralogy and mineral chemistry of the residuum left after partial melting. Lunar igneous rocks, therefore, are potentially a most powerful probe to explore the nature of the lunar interior. This tool was first exploited with respect to the moon by Ringwood and Essene (ref. 18). Unfortunately, most lunar igneous rocks show clear-cut evidence either of contamination by lunar soil, including meteoritic debris, or of near-surface crystal-liquid fractionation processes that cause the chemistry of the final rock product to differ significantly from that of the parental liquid.

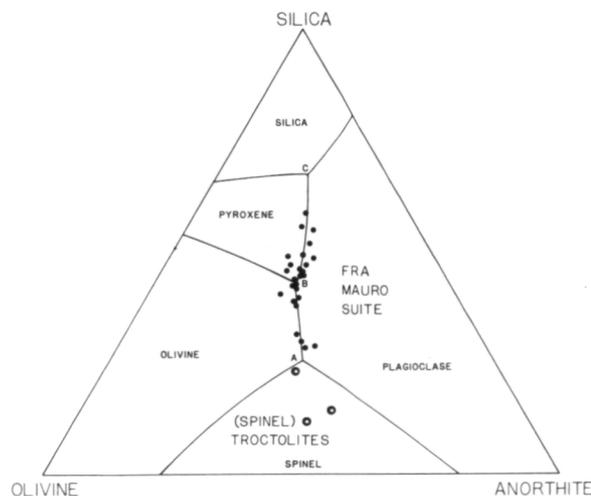


Figure 1.—Pseudoternary liquidus projection for feldspathic lunar rocks. The liquidus field of plagioclase occupies the right portion of the composition plane adjacent to anorthite. The liquidus fields of olivine and silica are in the lower left and top, respectively. The liquidus field of low-calcium pyroxene occurs in the left center between those of olivine, silica, and plagioclase. The spinel liquidus field occupies the bottom central region of the plane. Details of the projection may be found in reference 32. Solid circles represent compositions of the Fra Mauro suite interpreted to be partial melts of the feldspathic lunar crust. Open circles represent various spinel-bearing microtroctolites.

In applying this approach, therefore, it is important to detect and allow for the effects of possible near-surface contamination or fractionation processes.

We have used the quenching technique to study low-pressure equilibrium crystallization behavior of various lunar compositions at the very low oxygen fugacities appropriate for lunar surface conditions. By means of electron microprobe analyses of coexisting crystals and liquid at various stages of the crystallization process, we have mapped out the low-pressure "liquid lines of descent" for lunar magmas and the loci of multiple saturated liquids within the complex chemical system to which the lunar rocks belong. Results of these studies and details of the methods used are given in references 19–23. These results are combined with petrographic observations in the interpretation of the origins and crystallization histories of the specific samples studied and in the evaluation of their potential as probes of the lunar interior (refs. 23–27). High-pressure phase equilibrium studies of promising compositions are carried out in the manner pioneered by Ringwood and Essene (ref. 18), and O'Hara et al. (ref. 28).

Terra Samples and the Lunar Crust

Lunar samples from terra (highland) sites have been intensely brecciated and texturally modified by surface impact processes. Multiple generations of brecciation, thermal metamorphism, and partial melting are common (refs. 6 and 7). The few rocks showing unquestioned igneous textures may well have crystallized from pools of impact melt. Nevertheless, chemical variations from site to site and within the sample suites from individual sites are present, indicating that chemical evidence for early magmatic activity may have survived the impact mixing process. This is especially clear in statistical studies of glass and lithic fragment compositions in the coarse soil samples (e.g., refs. 29, 30, and 31).

Figure 1 (ref. 27) is a plot of "preferred compositions" recognized by various groups

from glass or lithic fragment studies. Each point represents the average of a large number of individual analyses that cluster about that point. Clusters that obviously represent compositions of mare basalts or anorthositic rocks are excluded, but otherwise all "preferred compositions" reported in the literature are shown. These compositions are projected onto the pseudoternary liquidus for the system olivine (Fo^{70})-anorthite-silica (refs. 19 and 20). The tendency of these preferred compositions to lie along the curves of twofold saturation and to cluster about the two peritectic points, A and B, is apparent. We interpret this to mean that these recurrent chemical types among the terra rocks are related by the crystal-liquid equilibria indicated. We have argued at length (ref. 27) that KREEP and KREEP-related compositions near point B are produced by partial melting of rocks consisting of plagioclase, olivine, and low-calcium pyroxene, and that some of the "very-high alumina basalts" of Apollo 16 and Luna 20, with compositions near point A, and some so-called "spinel troctolites," may be produced by partial melting of rocks consisting of anorthite, olivine (Fo_{93}), and spinel ($\text{Mg, Fe}(\text{Al, Cr})_2\text{O}_4$) (ref. 32).

Since the crystal-liquid equilibria shown in figure 1 were determined at low pressures, and the equilibrium curves shift position with increasing pressure, the inferred partial melting events must have occurred at relatively shallow depths (≤ 60 km), i.e., within the lunar crust. Thus, the crust contains rocks having the mineral assemblages of anorthositic gabbro or norite (ANT) and of pink-spinel troctolite (PST). Presumably both these materials are among the crystal cumulate products of the early crust-forming event. Phase relationships do not allow us to say if these contrasting crustal materials represent widespread layers at different depths, but if they do, the abundance of ANT rocks at the surface, and the paucity of PST rocks, suggest that the latter would represent a deeper level within the crust. Isotopic studies indicate that the crustal melting processes, whether the energy sources

were external (impact) or internal, took place prior to 3.8 Gy, and possibly much earlier (ref. 33).

Mare Basalts and the Deep Lunar Interior

The dark, iron-rich, alumina-poor basaltic rocks from the mare basins present a different problem. Their textures and isotopic ages leave little doubt that they crystallized from internally generated lavas that reached the lunar surface after the intense bombardment recorded by the highland rocks had largely subsided (refs. 4, 5, 8, and 34). There has been much debate, however, about the degree to which their compositions have been affected by near-surface fractionation processes (refs. 28, 35, and 37). It is not yet clear which, if any, mare basalt compositions represent primary unmodified melts from the lunar interior, and may therefore be used to infer the nature of the interior.

In order to discuss these questions, we divide the mare basalts into two groups: the old (3.6 to 3.8 Gy), titaniferous ($\text{TiO}_2 > 8$ percent) basalts from Mare Tranquilitatis (Apollo 11) and Mare Serenitatis (Apollo 17); and the younger (3.1 to 3.4 Gy), low-titanium ($\text{TiO}_2 < 5$ percent) basalts from Oceanus Procellarum (Apollo 12), Mare Imbrium (Apollo 15), and Mare Fecunditatis (Luna 16). It is not yet certain whether this distinction based on TiO_2 content is a real one or whether it is an artifact of the small number of sampling localities. Among the titaniferous group the rapidly cooled members tend to have high TiO_2 values, while rocks with TiO_2 near the lower limit of 8 percent appear on textural grounds to have cooled more slowly with consequent opportunity for loss of FeTi oxides by crystal settling. The compositional gap may, therefore, be even larger than it appears. We tentatively conclude that it is real, and attribute the marked difference in TiO_2 content between the groups to the presence or absence of a titanium-rich phase (ilmenite?) in their respective source materials.

The low-titanium basalts are, for the most part, porphyritic, and show systematic chemical variations that can be accounted for by simple low-pressure fractionation of observed phenocryst and matrix compositions (refs. 5, 34, 37, 38, and 39). These rocks are, therefore, widely acknowledged to have been subjected to near-surface fractional crystallization. Nevertheless, certain compositions (e.g., 12009) appear to have existed at the surface as liquids, have compositions not obviously related to low-pressure cotectics, and are capable of serving as parent to related rock compositions by means of low-pressure fractional crystallization. These arguments have been presented by Green et al. (refs. 40 and 41), Kushiro et al. (ref. 38), and Grove et al. (ref. 26). (For a contrary view, however, see Biggar et al. (ref. 42) and O'Hara and Biggar (ref. 43).)

If these authors are correct in their interpretation that the basalts they studied accurately represent the compositions of primary liquids generated by partial melting in the lunar interior, then high-pressure phase-equilibrium studies on the compositions will reveal the nature and depth of the source region. The argument follows: (1) a liquid produced by equilibrium partial melting must be saturated with all crystalline phases remaining in the residue; (2) these crystalline phases will, therefore, appear simultaneously on the liquidus of the basalt composition at the pressure corresponding to magma generation (or to last equilibrium of liquid with residual crystals); (3) if a pressure range exists where several crystalline phases appear simultaneously on the liquidus, this pressure range yields the inferred depth of origin, and the nature and chemical compositions of the observed liquidus crystals yield the nature and chemistry of the residual crystals in the source region. If the degree of partial melting is small, the residual crystals will not differ greatly from those present prior to the partial melting event, although their proportions will ordinarily be changed.

By following this line of reasoning, Green et al. (refs. 40 and 41), Kushiro et al. (ref.

38), Green and Ringwood (ref. 44), Longhi et al. (ref. 25), and Chappell and Green (ref. 45), have all concluded that low-titanium mare basalts are ultimately derived by partial melting of olivine pyroxenite (typically spinel-bearing) at various depths ranging from 150 to 400 km. Reported variations in source depth and mineral chemistry may reflect real heterogeneities in the lunar interior and differences in the depths of melting or simply varying degrees of deviation from the initial assumption that the basalt compositions studied represent unmodified primary liquids.

Unfortunately, this method yields only the nature and mineral chemistry of the phases present in the source region. The proportions of the various crystalline phases present (and hence the bulk chemistry of the source region) do not greatly affect the major element chemistry of the liquid produced as long as no crystalline phase is completely consumed (ref. 46). Minor element chemistry of the liquid, however, is sensitive to the proportions of phases initially present as shown by Gast (ref. 47) and Shaw (ref. 48). Full, quantitative exploitation of this powerful tool remains to be done.

Isotopic age determinations on the low-titanium mare basalts indicate crystallization ages of 3.1 to 3.4 Gy. Presumably this is the time of partial melting at depths of 200 to 400 km. It should be noted that these basalts have Rb-Sr model ages near 4.6 Gy (ref. 15), requiring that the inferred partial melting event quantitatively extracted Rb and Sr from the source region (or at least extracted these elements without significant fractionation). This observation apparently precludes the presence of plagioclase or any other Sr-bearing phase from the residual assemblage unless elaborate processes are invoked to prevent Sr homogenization (e.g., ref. 49).

High-Titanium Mare Basalts

The titaniferous mare basalts returned by Apollo 11 and Apollo 17 are nearly free of

phenocrysts and form tight compositional groupings, within which compositional trends are not conspicuous. It has been argued by Ringwood and his colleagues that these rocks represent insignificantly modified primary melts from the lunar interior (refs. 18, 35, 50, and 51). O'Hara has argued, to the contrary, that these compositions represent low-pressure cotectic compositions, and that the rocks are therefore products of extensive, near-surface, fractional crystallization possibly accompanied by large-scale loss of volatiles (refs. 28, 42, and 52).

In order to resolve this apparent conflict, we have traced the course of residual liquids produced during the equilibrium crystallization of two Apollo 17 titaniferous mare basalts. Because the $\text{CaO}/\text{Al}_2\text{O}_3$ molar ratio

of mare basalts differs from unity, and because the TiO_2 content cannot be neglected, the simplified system used to discuss melting and crystallization behavior in terra compositions is not adequate for the study of mare basalt compositions. Excess CaO is expressed by the presence of high-calcium pyroxenes, and high TiO_2 content results in early saturation with an FeTi-oxide phase—armalcolite or ilmenite. Figure 2 attempts to represent compositions within this complex system in two-dimensional projections; several different projections are required to display all of the significant variables. Details of the projection scheme will be published elsewhere (ref. 23). The lower right-hand portion of figure 2 shows a portion of the FeTi-oxide saturated liquidus surface for the complex natural system; curves shown were

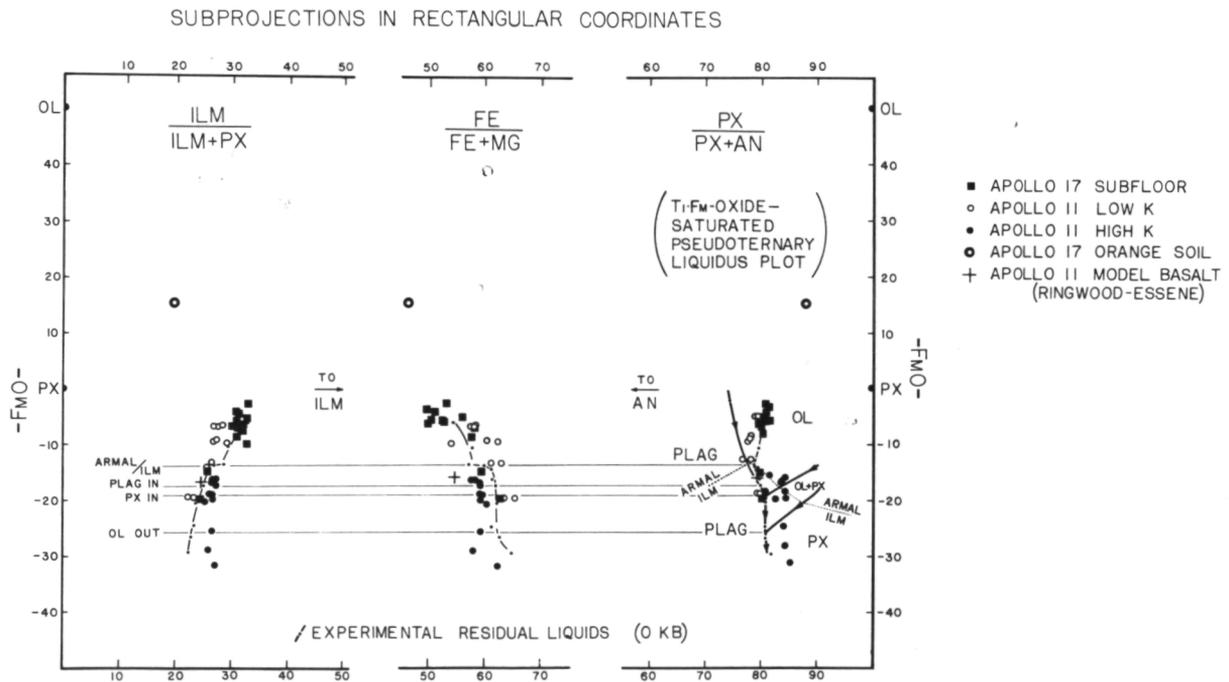


Figure 2.—Subprojections in $\text{FmO}-\text{CaAl}_2\text{Si}_2\text{O}_8-\text{FmTiO}_3-(\text{FmSiO}_3 + \text{CaFmSi}_2\text{O}_6)$ composition space. Molar units are used throughout. $\text{FmO} = \text{FeO} + \text{MgO}$. All subprojections have FmO as the ordinate. Decreasing FmO correlates with increasing silica saturation and with decreasing temperature of the experiments (range $1200-1125^\circ\text{C}$). The first subprojection is from $\text{CaAl}_2\text{Si}_2\text{O}_8$ and can be used to visualize the locus of titaniferous oxide saturation. Armalcolite and ilmenite saturation volumes are to the right. The second subprojection shows variation with respect to $\text{Fe}/\text{Fe} + \text{Mg}$. The third subprojection is from FmTiO_3 and behaves as if it were a pseudoternary liquidus diagram. Silicate saturation volumes coexisting with armalcolite or ilmenite are located on this composition plane. Details of the experiments and the projection method are discussed in reference 23.

located by microprobe analyses of glasses quenched from liquids saturated with an FeTi-oxide (armalcolite or ilmenite, as indicated) and one or more additional crystalline phases.

On each portion of figure 2 is plotted the locus of residual liquids produced during the equilibrium crystallization of two Apollo 17 high-titanium basalts (70215 and 70017). Also plotted are the compositions of analyzed Apollo 11 and Apollo 17 basaltic rocks. Apollo 11 ophitic rock compositions fall along the trend of Apollo 17 residual liquids in confirmation of their inferred crystallization sequence: FeTi-oxide—olivine—plagioclase—pyroxene (ref. 53). Apollo 11 intersertal rocks show a parallel trend, but lie off the curves of plagioclase saturation, confirming the petrographically inferred and experimentally demonstrated late appearance of plagioclase in these rocks.

It seems clear that the contention that these rock compositions bear no relation to low-pressure fractionation trends is false; it is also clear, however, that these compositions cannot all have been produced by simple near-surface fractional crystallization. It seems to us that the proximity of titaniferous mare basalt compositions to the path of residual liquids and the parallelism of the compositional trends is strong circumstantial evidence that these rocks, like most of the low-titanium mare basalts, have been affected to some extent by near-surface crystal liquid fractionation processes. Obviously, if a primary magma is to be sought among this group, care must be taken in its identification. Absence of liquidus plagioclase is not a sufficient criterion.

Among the titaniferous suite, one of the compositions most remote from low-pressure multiple saturation (and hence most likely to be a primitive partial melt) is the vitrophyre 70215. A liquid of this composition is in near-liquidus equilibrium with olivine, pigeonite, ilmenite, and spinel at 5 kb (ref. 23) and could, therefore, be produced by partial melting of an olivine-pigeonite-ilmenite-spinel assemblage at a depth of 100 km. The inferred time of melting at this depth would

The shallow source depth inferred for Apollo 17 basaltic magma, the Eu anomaly (ref. 55), and the high TiO₂ content of the magmas, all point to a source within the zone of mafic cumulates believed to lie beneath the feldspathic lunar crust. Partial remelting of cumulates consisting of olivine, pigeonite, spinel, and ilmenite plus variable amounts of the crystallization products of trapped residual liquids (plagioclase-saturated and rich in incompatible trace elements) would produce most of the observed characteristics of the titaniferous mare basalt suite (ref. 22).

Speculations on Magmatic Time Sequence and Implied Lunar Thermal History

The inferred source depths for magma generation reported here show an inverse correlation with radiometric age of the resulting crystalline rocks. It is tempting to speculate on a model for lunar structure and history that would be consistent with the observed sequence of magmatic activity.

We recognize the difficulty of accounting for a heat source adequate to remelt refractory cumulates once crystallized. We are also aware of telescopic observations suggesting the presence on the lunar surface of young (2.5 Gy?), titanium-rich mare basalts that have not yet been recognized among the returned lunar samples. Despite these reservations, we present the following highly speculative model compatible with studies of lunar igneous rocks.

The Moon now has a crust consisting of a (floating) cumulus of plagioclase with entrapped olivine, low-calcium pyroxene, and MgAl-rich spinel. It overlies a (sinking) layered cumulus of olivine, low- and high-Ca pyroxene, and FeCr-rich spinel, with an intermediate zone rich in FeTi-oxide and fractionated residual liquid or its crystallization product. From 4.7 to 3.8 Gy, lunar petrologic history was dominated by impact brecciation and metamorphism and intracrustal

melting (< 60 km). In the interval from 3.8 to 3.6 Gy, titaniferous mare basalts were produced by partial melting in the sub-crustal Ti-rich zone (~ 100 km). From 3.4 to 3.1 Gy, low-titanium mare basalts, produced by deep melting (200–400 km) reached the surface after varying degrees of en route crystallization. Present-day lunar melting is limited to depths below 1000 km, and lavas produced in the interval from 3 Gy to the present have not yet been identified among the lunar samples.

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