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Lunar petrogenesis in a well-stirred magma ocean

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Abstract—When a large number of analyses of low-KREEP highlands rocks, clasts, and lithic fragments are plotted in the quartz–olivine–anorthite pseudoternary phase diagram, three groups or trends can be identified. The most populous group appears to have been established by plagioclase and/or pyroxene crystal fractionation. Rocks in the Si-rich and Si-poor (troctolitic) minor groups can be derived from rocks in the principal group by impact remelting and secondary crystal fractionation.

Chemical trends among the rocks of the principal group violate the Bowen reaction principal, in that the more magnesian and mafic minerals are, the more sodic the coexisting plagioclase tends to be. The present paper postulates that this trend was established during the primary differentiation of the lunar crust, and attempts to rationalize the sense of the trend as the effect of crystallization in a vigorously convecting (well-stirred) system. Under these conditions all plagioclase crystals, all pyroxene crystals, and all of the residual liquid remain fairly uniform in composition until advanced crystallization immobilizes the system. The rock suite then established would vary continuously from anorthositic types at the top, in which early calcic plagioclase crystals coexist with Fe-rich mafics from the (late) intercumulus liquid; to ultramafic types at the bottom, in which early magnesian mafic minerals coexist with sodic plagioclase from the same intercumulus liquid.

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 material. 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 (LSAPT, 1972).

Fractionation on such a large scale would have established certain moon-wide chemical and mineralogical trends in the rocks of the lunar crust. A primary goal of petrologic investigations must be to search for these first-order trends in the lunar highlands samples: insights gained may be broadly applicable to the problem of early planetary differentiation. However, it is essential to recognize that the moon has had a complex geologic and petrologic history since the time of its primary fractionation. Much crustal rock has been remelted by major cratering events, and in some cases secondary fractionation must have occurred in the pools of melt rock. Impact brecciation has mixed earlier-formed lithologies, and in some cases the petrographic evidence of mixing has been obliterated by metamorphism or remelting. These secondary effects are profound, and cannot be ignored (Warner *et al.*, 1974). Chemical and petrologic trends established by the primary fractionation may be difficult or impossible to detect through this veil of secondary effects.

One curious petrologic effect that may have been established by the primary fractionation was noted by Steele and Smith (1972). These authors plotted the

compositions of coexisting olivine and plagioclase in samples that had distinctly igneous textures (Fig. 1), and found a trend opposite to the one predicted by the Bowen reaction principle; i.e. as plagioclase becomes more sodic in highlands rocks, olivine becomes more magnesian. Since samples from three highlands 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 other volatile elements.) This inverted mineralogical trend is difficult to understand on the basis of our experience with terrestrial crystal-fractionated systems. If it was truly established during the primary fractionation of the lunar crust, the Steele and Smith trend places very important constraints on early lunar evolution. The present paper addresses this question.

INTRODUCTION OF A LARGER DATA BASE

Steele and Smith (1972) originally restricted their plot to crystalline igneous rocks, in the belief that these were more likely to represent primary crustal rocks. However, this is a questionable assumption. Truly primary igneous cumulate rocks from a system as vast as the one that separated the lunar crust would be extremely coarse grained, while the great majority of rocks collected in the lunar highlands, including those studied by Steele and Smith, are small grained. The latter are more probably secondary melt rocks, and as such are no more likely than other types of highlands rocks (breccias) to preserve primary petrologic trends. However, when Steele and Smith (1973, Fig. 8) expanded their plot to include a modest amount of data from other research groups and rock types, the trend disappeared.

The question of the reality of the Steele and Smith trend is an important one, and invites reinvestigation. The writer has assembled a data file of analyses of lunar materials from the literature (Wood, 1974) which can serve as the impartial source of a very large number of points in a Steele and Smith-type plot. The data file currently contains (on magnetic tape) analyses of 192 lunar rocks, 661 clasts and lithic fragments from soil samples, and 2714 glass particles from soil samples. Only the first two categories of analyses were drawn on in the present study. Lunar rocks in the data file were analyzed chiefly by X-ray fluorescence, clasts and lithic fragments mostly by the defocused-beam (DBA) microprobe technique. Eighty-five of the lithic fragment analyses were performed in my laboratory; the remainder of the data was taken from the literature.

Several stages of data selection are required in the construction of a plot that searches for chemical trends attributable to primary crystal fractionation in the moon. These deserve careful discussion.

Separation of highlands samples from mare samples

Mare basalt generation was a stage of lunar evolution distinct from and later than the primary differentiation of the lunar crust; it is important to exclude mare basalt analyses from a plot intended to elucidate crust formation. In the case of

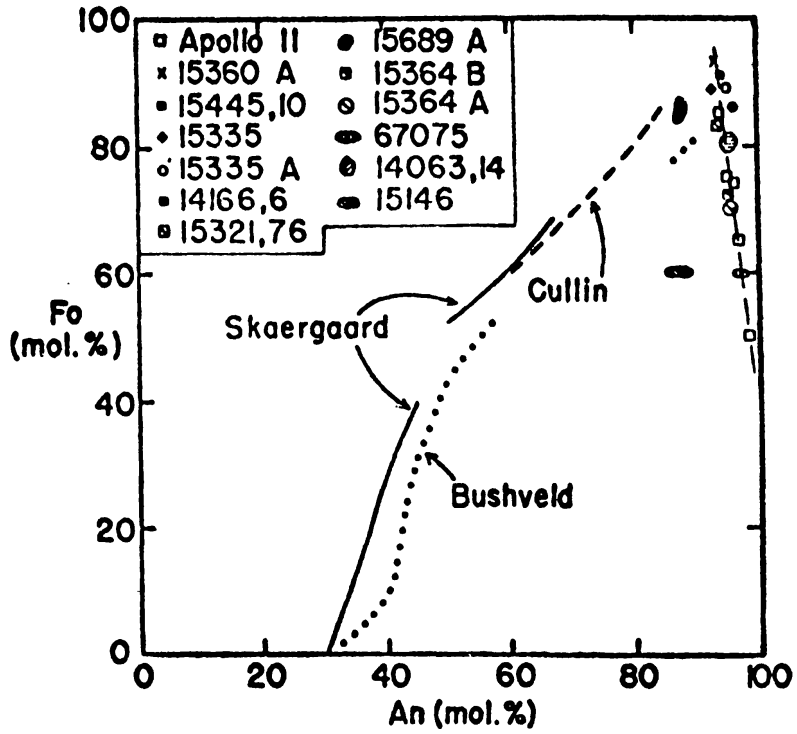

Fig. 1. Compositions of coexisting plagioclase and olivine in terrestrial mafic stratiform bodies, and in low-KREEP lunar highland materials (Steele and Smith, 1972).

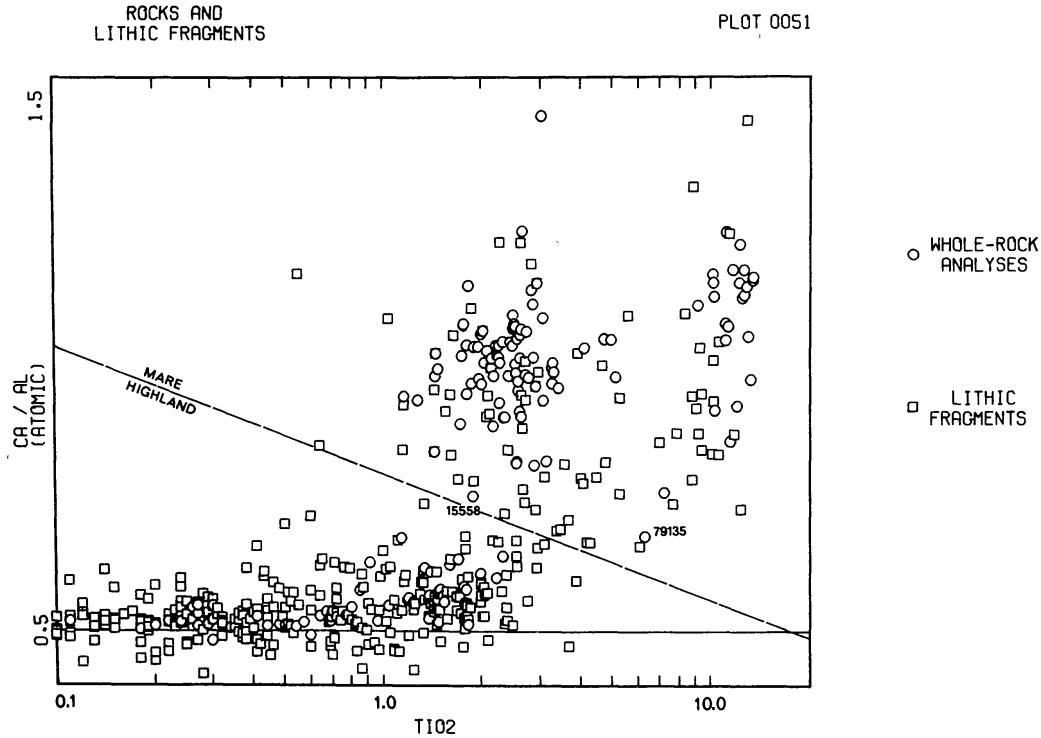

Fig. 2. Points representing all types of lunar samples, in a plot of parameters that tend to differentiate between mare and highland materials. Horizontal line: anorthite stoichiometry (Ca/Al = 0.5). Sloping line: criterion adopted in this paper to separate mare and highland samples.

whole-rock samples, which have been extensively studied and described, it is easy to separate the mare and non-mare specimens. This is not the case for clasts and lithic fragments. In most cases, little or nothing more than the DBA analysis appears in the literature. A purely chemical criterion needs to be developed that separates mare and non-mare materials with a high degree of reliability.

In terms of major elements, mare and non-mare materials differ most strikingly in their content of TiO_2 and the Ca/Al ratio they display. Ca/Al is a useful discriminant because of the systematic difference in character of pyroxenes in the two types of lunar material: mare basalts contain high-Ca diopsidic pyroxenes, while norites and anorthositic rocks from the highlands contain low-Ca orthopyroxenes and pigeonites. Thus virtually all Ca in non-mare rocks occurs in plagioclase, and Ca/Al should be close to the stoichiometic value for anorthite. Abundant calcic pyroxene in the mare rocks gives rise to Ca/Al values substantially in excess of anorthite stoichiometry.

These two parameters are plotted in Fig. 2. The horizontal line represents anorthite stoichiometry (Ca/Al = 0.5). Five hundred analyses, randomly selected from the data file, are entered. These form clusters corresponding to highlands rocks, low-Ti mare basalts, and high-Ti mare basalts. The best separation between mare and highlands rocks is made by the dashed line in Fig. 2; this is confirmed by verification of the character of the rocks and fragments represented by the points in the vicinity of the line. 12038, 14053, 14072, and the great majority of DBAs of high-Al Luna 16 basalts plot above the line. 15558 and 79135 are polymict soil breccias collected near mare–highlands contacts.

The equation of the separating line in Fig. 2 is

$$\mathrm{Ca/Al(atomic)} = (0.786 - 0.229 \log_{10} \mathrm{TiO_2}).$$

This criterion was used to exclude mare basalts from subsequent plots in the present paper.

Separation of high-KREEP from low-KREEP highlands samples

On the basis of melting relationships (Walker *et al.*, 1972) and trace- and minor-element abundances (e.g. Hubbard *et al.*, 1972) it seems clear that KREEP-rich highlands materials were not produced by the primary act of crystal fractionation that separated the lunar crust, but instead were generated by a later, independent partial melting event in the moon. Deep crustal material may have been the parent that was partially melted to yield KREEP-rich norites, but compositions of the latter are irrelevant to the primary crystal fractionation and should be excluded from an investigation of that event on the same grounds that mare basalt compositions are.

Again a chemical criterion is needed to filter out KREEP-rich compositions. Figure 3 is a simple plot of KREEP content (or more accurately the major-element components of KREEP, $K_2O + P_2O_5$) versus normative plagioclase content. Four hundred and eighty-five points, representing all the analyses in the

data file that pass the mare basalt filter, are entered. A rather sharply defined field of low-KREEP samples (beneath B–B′) can be seen, overlain by a more diffuse distribution of higher-KREEP specimens. When the analyses above A–A′ and those beneath B–B′ are entered in "Walker diagrams" (Fig. 4), they produce the expected distribution patterns: compositions controlled by the olivine/plagioclase cotectic in the case of most KREEP-rich samples, and a linear array of compositions controlled by plagioclase accumulation (plus a cluster of troctolitic compositions) in the case of most KREEP-poor samples. (Specimens falling between A–A′ and B–B′ in Fig. 3 were excluded from Fig. 4, on the expectation that they were likely to be polymict breccias involving KREEP-rich and KREEP-poor components.)

The sharpness of the envelope enclosing low-KREEP highlands samples in Fig. 3 is surprising, and suggests that the amount of remixing of earlier differentiates in the lunar crust has been less than we are led to expect by the cratering history of the moon, the highly brecciated character of highlands rocks, and the variety of lithologies present in highlands soils. The persistence of the Imbrium/Procellarum radioactive high (Metzger *et al.*, 1973) as a distinct feature during the cataclysmic phase of basin-forming activity and whatever preceded it point to the same thing. This evidence of the durability of rock compositions encourages the hope that chemical trends established during the primary differentiation of the crust are still present in the lunar highlands rocks.

The equation of line B–B′ in Fig. 3 is

$$(K_2O + P_2O_5) = 0.945 - 0.00893(\%\ \text{normative plagioclase}).$$

This criterion was used to exclude high-KREEP lunar materials from consideration.

It is interesting to note that the low-KREEP triangle in Fig. 4 contains several discrete groups or trends: (1) a "main sequence" of data points extending from the olivine–spinel–plagioclase peritectic toward the plagioclase corner of the diagram; (2) a minor yet apparently separate trend line extending from the olivine–pyroxene–plagioclase peritectic to the anorthite corner (points in this line come from a number of analysts and missions); and (3) a discrete group of troctolitic compositions in the spinel field.

Polymict breccias versus primary rock types

It would appear essential that polymict breccias, mechanical mixtures of two or more discrete lithologies, be excluded from any data set to be used in a search for compositional trends with genetic significance. Steele and Smith (1973) had this in mind when they restricted their plot to igneous rocks. However, this turns out to be very difficult to do. It is easy to establish petrographically that a given rock *is* a polymict breccia, but hard or impossible to establish that it is *not*. All petrographic evidence of an earlier polymict character may have been removed by remelting or recrystallization. The presence or absence of characteristic meteoritic trace elements in a rock is a valuable criterion, but these elements have been

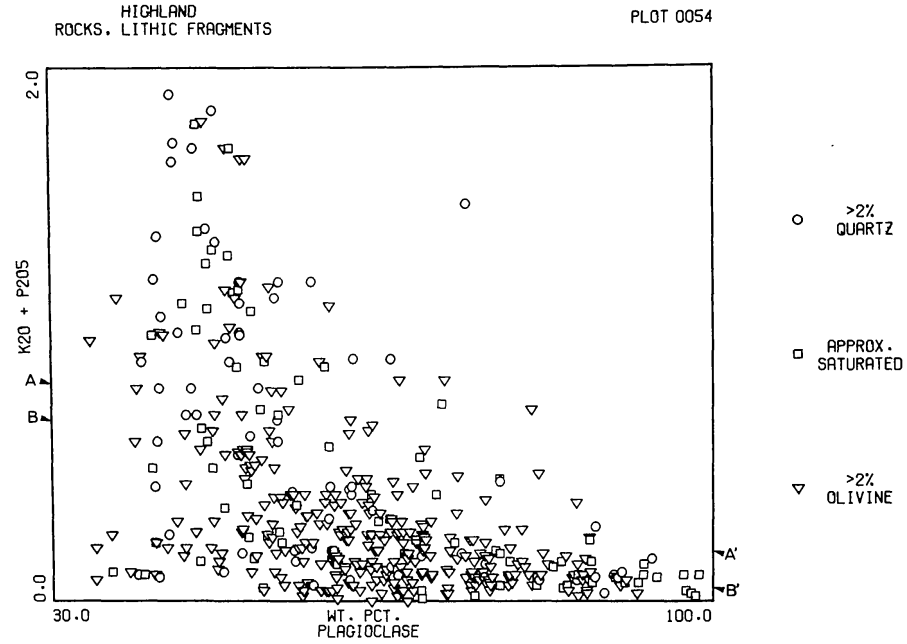

Fig. 3. Points representing highlands samples only. Those below B–B′ are considered to be low-KREEP rocks, products of the original differentiation of the lunar crust. Points above A–A′ are high-KREEP samples, produced by partial melting in the moon. Points between A–A′ and B–B′ are considered especially likely to be polymict breccias.

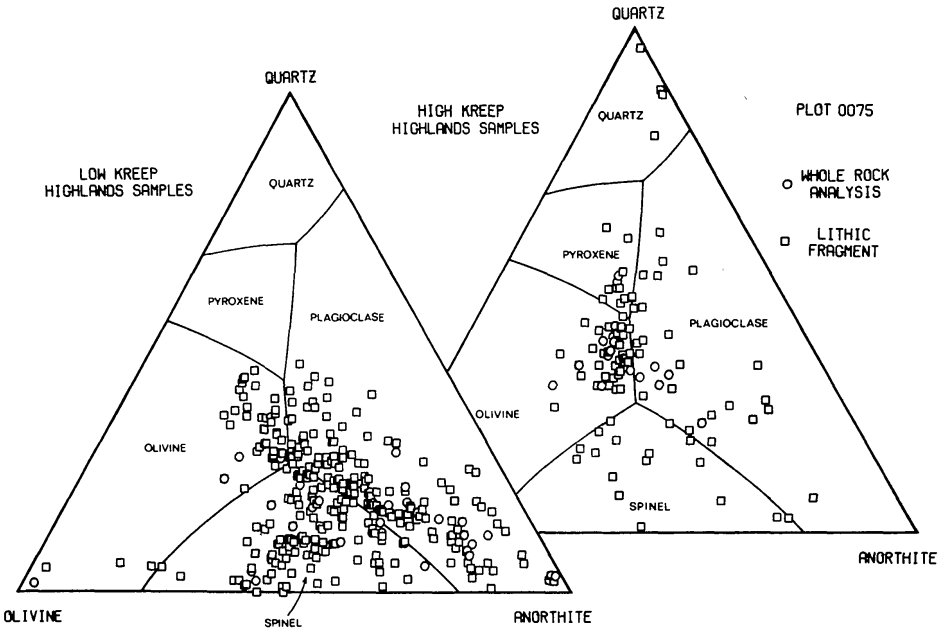

Fig. 4. Points representing highlands samples, plotted in diagrams of the pseudoternary system quartz–olivine–anorthite (Walker *et al.*, 1972). *Left*: analyses that fall beneath B–B′ in Fig. 3. *Right*: analyses that lie above A–A′ in Fig. 3.

determined in relatively few samples; and even where they have been, some uncertainty remains. Thus a primary versus secondary remelted origin is still being debated for one of the most intensively studied of lunar rocks, 14310. The lithic fragments that comprise the bulk of the data base being used in the present study have not been studied or described in detail; in most cases the literature does not provide any reliable basis for weeding out polymict rocks.

Some whole-rock analyses in the data base are of breccias that are unequivocally polymict. These could be removed, but since a judgment cannot be made for most of the analyses in the data file, it seemed preferable to apply a consistent policy and not remove any analyses on the basis of textural inferences. Thus polymict breccias are present in the data base: the usefulness of the latter depends on their relative abundance. I have argued in the subsection above that relatively little mixing seems to have occurred in highlands materials, and will proceed on that basis. Under the worst of circumstances, the data should be capable of defining compositional end-members; only intermediate compositions, which may be mechanical mixtures, are suspect.

Differentiation Parameters in Low-KREEP Highlands Rocks

Three hundred and sixteen lunar analyses, the remainder of the data base after removal of mare basalt and high-KREEP entries, are plotted in Fig. 5. This is a three-dimensional diagram in which three important indices of differentiation in a crystal-fractionating system vary along the axes: content of normative plagioclase; the molar ratio Fe/(Fe + Mg) in the normative mafic minerals; and albite content of the normative plagioclase. There is a distinct trend from high-plagioclase, high-Fe/(Fe + Mg), low-albite points at the right of the volume, to intermediate-plagioclase, low-Fe/(Fe + Mg), higher-albite points at the left of the volume. This appears to confirm the original Steele and Smith trend, and extends it in the sense that (1) a relationship between the Fe and Na parameters originally plotted, and plagioclase content, is found; (2) the relation holds for quartz-normative as well as olivine-normative rocks; and (3) it still holds when all textural types, analyzed by many different groups, are plotted.

When Fig. 5 is decomposed into separate plots (Fig. 6) for the three groups or trends recognized in Fig. 4, the Steele and Smith trend is found to be still present in the most populous group (the "main sequence," Fig. 6a): the trend was not produced artificially by plotting several possibly unrelated analysis groups together.

Compositional Trends in Terrestrial Crystal Fractionations

Formation of the lunar crust by crystal fractionation has often been likened to the differentiation of large mafic intrusive bodies in the earth. A naïve analogy with the terrestrial situation pictures mafic minerals sinking to the floor and plagioclase rising to the surface of the lunar system (Fig. 7). The first products of such a fractionation might reproduce the lunar compositions rather well: early

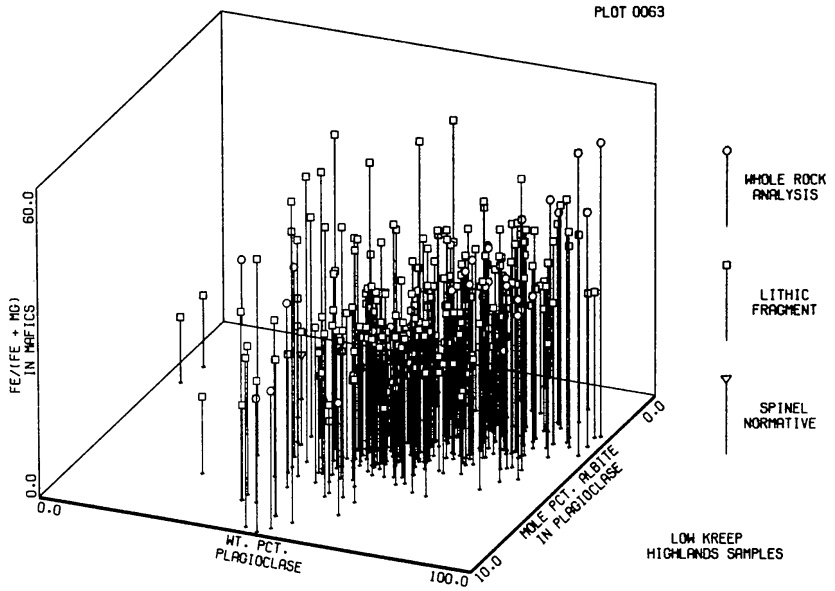

Fig. 5. 435 analyses of low-KREEP highland samples (from beneath B–B′ in Fig. 3), in a plot of three differentiation parameters. References are to normative mineralogy. The dominant trend confirms Steele and Smith's (1972) observation.

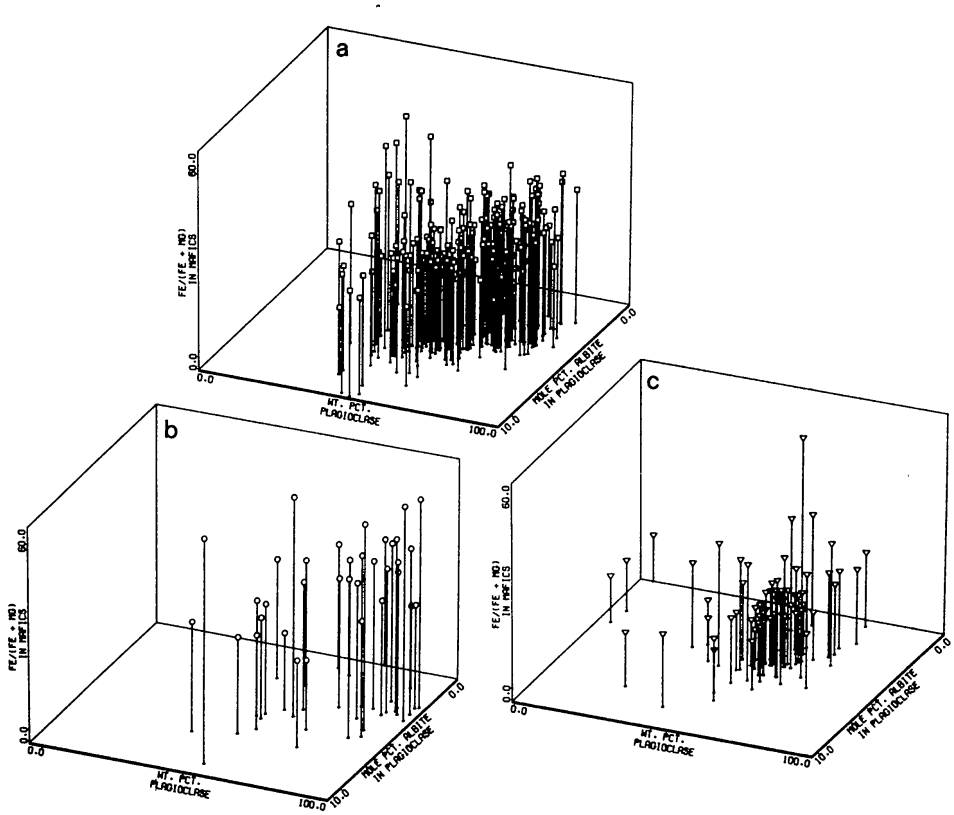

Fig. 6. Decomposition of Fig. 5 into three subplots, based on membership of each point in one of the three clusters in the low-KREEP triangle of Fig. 4. (a) The "main sequence" of points in Fig. 4. (b) Analyses that form the thin line of points extending from the anorthite corner to the olivine–pyroxene–plagioclase peritectic in Fig. 4. (c) The troctolitic cluster in Fig. 4.

floating calcic plagioclase would be coupled with little-fractionated intercumulus liquid with a moderate Fe/(Fe + Mg) ratio (A in Fig. 7); early sunken magnesian mafics would be accompanied by little-fractionated intercumulus liquid with a moderate Na content (D). However, beyond this point crystal fractionation would tend to drive compositions toward B and C, away from the Steele and Smith trend. Rock types containing substantially more of both Na and Fe than A and D would inevitably be produced, and Fig. 5 contains no evidence of a sodic ferrogabbro end-member. Lithologies of this type are largely lacking from the literature of lunar petrography, though isolated occurrences of sodic ferrogabbro are reported by Weiblen and Roedder (1973) and Roedder and Weiblen (1974).

Rocks of this composition are abundant in terrestrial mafic stratiform complexes, as can be seen in Fig. 8, where 500 rock analyses from nine such terrestrial complexes are plotted in the same format as Fig. 5. Here the axes have been expanded to accommodate the higher Na levels and Fe/(Fe + Mg) ratios in terrestrial rocks. The terrestrial plot is dominated by a column of Na- and Fe-rich rocks: granites and ferrogabbros, understood to be late-stage magma compositions residual after extensive crystal fractionation. It is appropriate to object, however, that this plot is not strictly comparable with Fig. 5, since in the lunar case Na-, Fe-rich rocks of this type would have been automatically excluded by the KREEP filter (Fig. 3). The validity of the comparison between Figs. 8 and 5 depends upon the correctness of our interpretation that the nearest lunar equivalents to these terrestrial granites and ferrogabbros are not in fact members of the suite of rocks produced by lunar fractional crystallization. If this premise is granted, then the dissimilarity of Figs. 8 and 5 suggests that processes producing the two rock collections were substantially different.

The fundamental problem in understanding the lunar fractionation is to avoid the creation of a body of late residual liquid, enriched in Na and Fe. A solution is proposed in Fig. 9. 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 ($> \sim 65\%$) 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 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. 9) 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

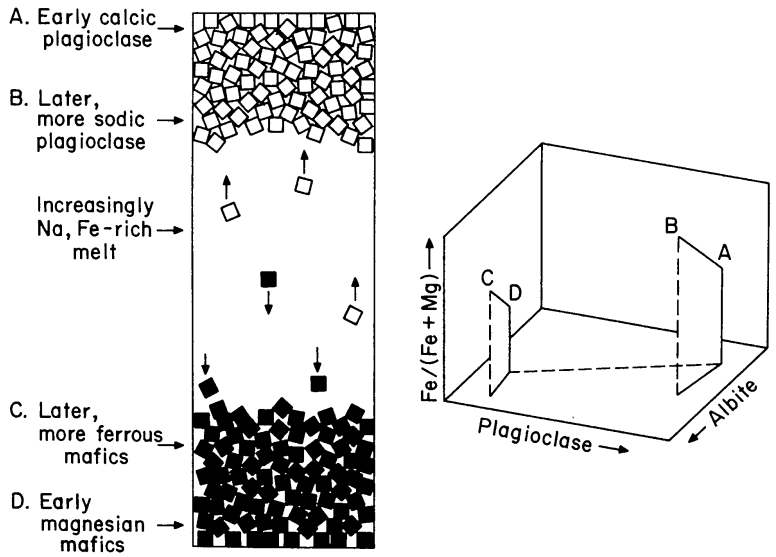

Fig. 7. Idealized representation of crystal fractionation under quiescent conditions, and a plot similar to Fig. 5 of the rock suite produced.

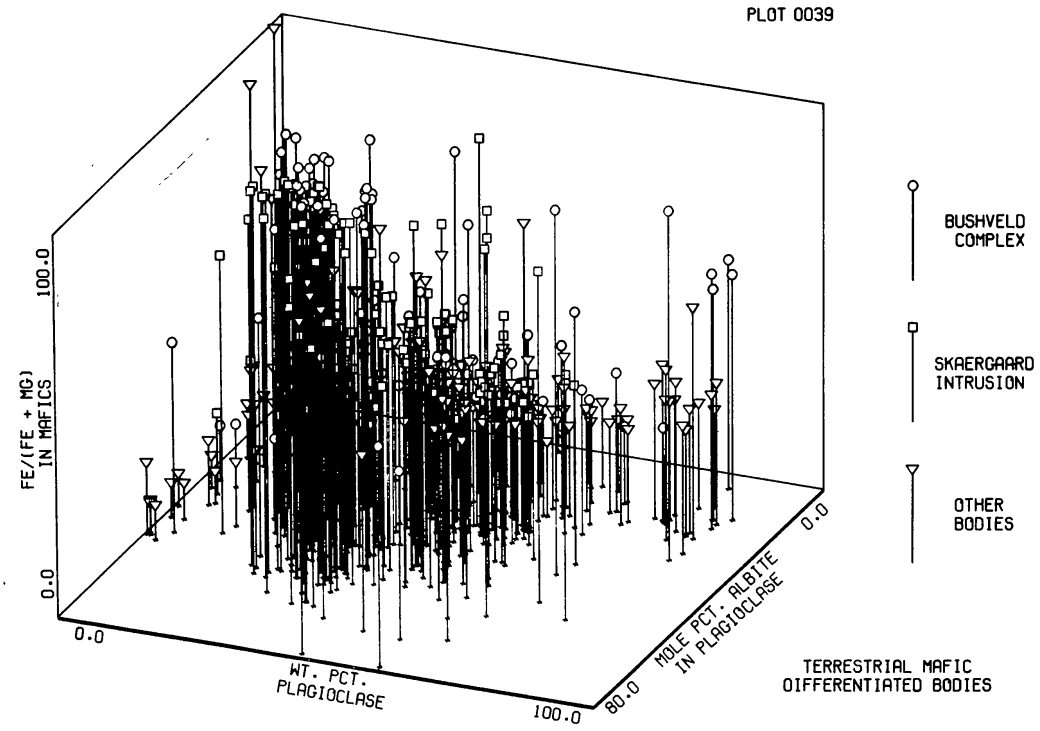

Fig. 8. 500 analyses of rocks from terrestrial mafic stratiform intrusives, plotted as in Fig. 5 (except for expanded scales). "Other bodies" are Stillwater, Rhum, Guadalupe, Duluth, Bay of Islands, Usushwana, and Fethiye. Data are from many sources in the literature, plus unpublished Skaergaard analyses kindly made available by Dr. A. McBirney.

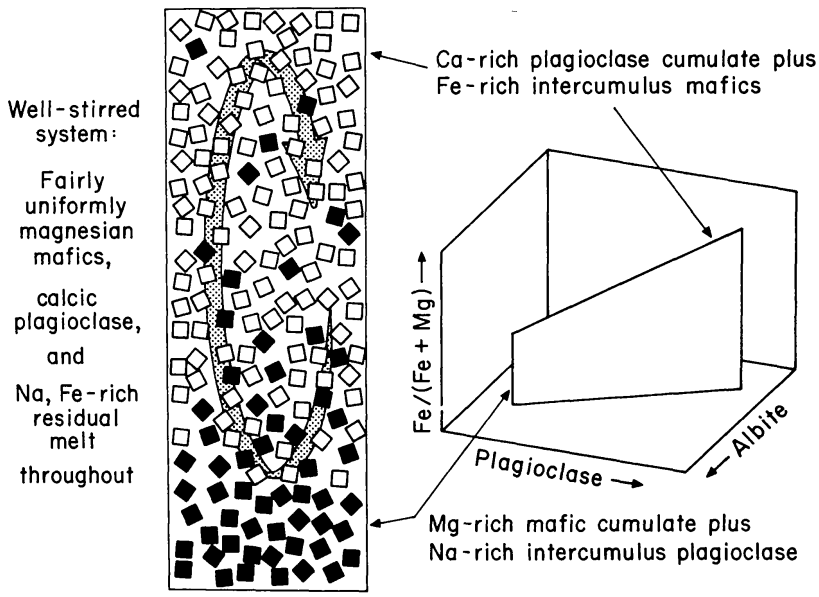

Fig. 9. Crystallization in a well-stirred magma system. Final solidification of the column would produce a compositional trend in the rock suite similar to that observed in low-KREEP highlands materials.

would result from varying proportions of early plagioclase, early mafics, and late liquid.

I propose that such a process, operating on a large scale in an early lunar surface magma system, established the compositional trends in the "main sequence" of anorthositic rocks shown in Figs. 4 and 6a, and that subsequent mechanical mixing and remelting of crustal materials have not erased these primary trends. It is difficult to model crystal and liquid compositions in such a differentiating system accurately or uniquely, but it appears that the trend in Fig. 6a would be reproduced if, at the time of column stabilization, the 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 Fe/(Fe + Mg) ~ 0.14. 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).

Mechanics of Mixing in the Magma Ocean

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.

Walker *et al.* (1975) have pointed out that crystallization would begin at the bottom of a lunar magma ocean, since the melting curve in such a system is less steep than the adiabatic gradient (Fig. 10). This raises the question of whether or not a convecting system of crystals and liquid of large vertical scale can realistically be postulated. It would appear that crystals stable at depth in such a system should dissolve when convected to higher levels.

The concept of an adiabatic gradient is straightforward in the case of a simple fluid or solid, but more difficult to apply to a multicomponent system in the temperature range of crystallization. In the latter case, the net density of the material is related to the proportion of crystals present (which are generally denser than the liquid) as well as the degree of pressure compaction and thermal expansion that the material experiences. The presence of crystals at depth makes the liquid-plus-crystal system denser than overlying pure liquids, hence more thermal expansion is required to convect it upward; this would make the effective adiabatic gradient of the system less steep than the adiabatic gradient of a purely liquid or purely solid system, as suggested in Fig. 10. The latter effect is counteracted to a degree by the fact that minerals release (latent) heat when they crystallize at depth and absorb it when they dissolve at higher levels, but it can be shown that the magnitude of the crystal–liquid density contrast effect is $\sim 4\times$

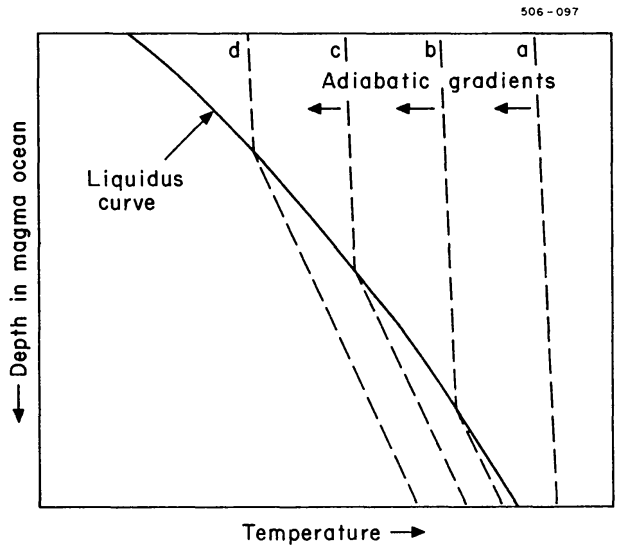

Fig. 10. Relationship of temperature gradient ($\simeq$ effective adiabatic gradient) in a cooling magma ocean to the liquidus curve; schematic. With time the system cools through *a*, *b*, *c*, *d*. Crystallization at depth decreases the effective adiabatic gradient locally (see discussion). Eventually the whole system can consist of a convecting crystal–liquid mixture, though some change in the proportions of crystal and liquid occurs in a unit of the magma as it moves up and down in the system.

greater than the latent heat effect. For this reason, the adiabatic gradient in a cooling magma ocean would eventually accommodate itself rather closely to the melting curve in the ocean. Convection of the multiphase system could occur; the crystal–liquid ratio would remain higher at depth than in the upper reaches of the system, but not by a large factor.

Secondary Differentiation of Crustal Rocks

The largest impacts onto the lunar crust (once it had solidified) must have occasioned extensive remelting; impact melts are commonly associated with the larger terrestrial craters (Dence, 1971). There can be no doubt that a certain amount of crystal fractionation occurred during cooling of the largest bodies of lunar impact melt. Presently observed mineralogic trends in the crustal rocks must have been affected by this secondary differentiation.

(It is unlikely that impacts promoted secondary magmatic fractionation by the mechanism of partial melting, however. Exactly the right amount of energy has to be delivered to a volume of rock to raise its temperature just enough to occasion the small percentage of partial melting that is often called for by particular lunar rock compositions. Hypervelocity impacts do not understand these niceties. They deliver a large amount of energy in a pulse. The likelihood is overwhelming that a given volume of target rock will receive either enough to melt completely, or not enough to melt at all. The probability is very small that just enough energy will be deposited to cause partial melting. This generalization is born out by Grieve's (1975) study of the Mistastin Lake Crater, Labrador; the compositions of melt rocks at this structure are those of bulk-melted mixtures of common country rocks.)

I suggest that the two minor trends or clusters of rock compositions in the low-KREEP triangle of Fig. 4 were generated by the secondary crystal fractionation of impact melts of primary crustal rocks: i.e. rocks having compositions on the most-populated "main sequence" of Fig. 4. In this model, settling of magnesian secondary spinel and olivine crystals gave rise to the troctolitic cluster of points in Figs. 4 and 11.

This cluster corresponds to the Group B troctolites of Weiblen *et al.* (1974); subsequent impact remelting of the troctolitic cumulates postulated by the writer would be required to account for the basaltic textures of the lithic fragments described by Weiblen *et al.* (1974). The Group A spinel troctolites of these authors are probably spinel normative, hence do not appear in Fig. 4. A "main sequence" composition to the left of the olivine–spinel–plagioclase peritectic in Fig. 4 would have to be impact remelted to provide a liquid from which spinel and olivine accumulation might evolve the Group A compositions. A similar parent material was proposed by Weiblen *et al.* (1974).

Crystallizing plagioclase would not have separated as readily as spinel or olivine from secondary melts having "main sequence" compositions, because the density contrast is much smaller. In many cases plagioclase would have remained more or less suspended in residual liquid while early spinel and olivine sank. Thus

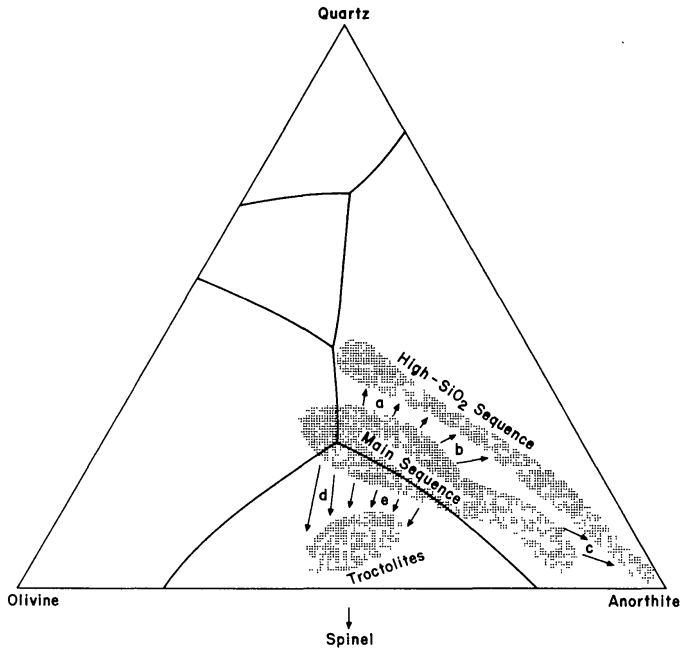

Fig. 11. Secondary differentiation of rocks produced by primary fractionation in the hypothetical magma ocean. Primary rock compositions comprise the "main sequence." *a* represents spinel removal from main sequence liquids; *b*, spinel removal followed by some degree of plagioclase concentration; *c*, plagioclase concentration; *d*, spinel and olivine concentration; and *e*, spinel concentration.

the igneous material complementary to a spinel–olivine cumulate would have been a plagioclase–liquid mixture, more siliceous and having a higher Fe/(Fe + Mg) ratio than the initial melt by virtue of spinel separation. It is suggested that rock compositions in the left half of the high-SiO_2 sequence of Fig. 11 were established in this way. Some concentration of plagioclase crystals in these complementary mixtures, as well as removal of spinel, would be required to account for compositions lower on the high-SiO_2 sequence.

It should be stressed that the rocks and lithic fragments that lie on the high-SiO_2 sequence of Fig. 11 do not have special textural properties which would tend to confirm an origin by crystal fractionation. Most are fine-grained breccias, in common with the majority of highlands rocks.

The most plagioclase-rich compositions among lunar crustal samples, the cataclastic or ferroan anorthosites of Dowty *et al.* (1974) and other authors, plot at the right extreme of the high-SiO_2 sequence in Fig. 10. It is hard to rationalize the formation of these almost monomineralic rocks by large-scale fractionation in the primary magma ocean discussed earlier; in this situation some appreciable amount of intercumulus fluid, containing ~ 50% of normative mafic minerals, would have been incorporated in the cumulate rock finally produced. These rocks are somewhat easier to form by crystal fractionation of impact-remelted rocks from the plagioclase-rich end of the primary "main sequence" (*c*, Fig. 11). Melts of this composition would be low enough in density that plagioclase would tend to segregate from them by sinking. In this case the intercumulus liquid would still be

anorthositic in composition, so the amount of mafic phase that eventually crystallized would be small.

Adcumulus crystallization of the plagioclase might have further diminished the mafic mineral content of these lunar anorthosites. Thin (~ 10 cm) layers of pure plagioclase rock in rhythmically layered terrestrial intrusives appear to have formed in this manner (Wager and Brown, 1967, p. 269). Obviously this mechanism depends upon a small diffusion path length between intercumulus spaces and a reservoir of liquid magma, however, so the process is more likely to have operated in a fractionating body of impact melt than in the hypothetical primary magma ocean.

The formation of the most anorthite-rich rocks by secondary plagioclase fractionation does not account for the very high Fe content of the small amount of mafic minerals present in these rocks (Fig. 6b), however, since their formation is postulated to occur prior to the crystallization or potential fractionation of mafic minerals. Another mechanism appears to have been responsible for the Fe levels in these rocks. Crystallizing plagioclase absorbs Fe and Mg (as minor elements) in different proportions than do mafic minerals crystallizing from the same melt. For melts having compositions in the range of lunar low-KREEP highlands rocks, Fe/(Fe + Mg) is about five times greater in plagioclase that crystallizes than it is in pyroxene (Smith and Steele, 1974). During subsolidus recrystallization, these elements are partly rejected by the plagioclase and absorbed by coexisting mafic minerals. If the amount of the latter in the system is very small, the compositions of the mafics can become dominated by the elements rejected by large amounts of plagioclase. Since more Fe than Mg is available for transfer, the Fe content of the mafic minerals in anorthite-rich rocks would be driven to higher values than they initially had.

The postulated secondary differentiations do not appear to have redistributed the KREEP content of crustal rocks in any regular way. Apart from the most plagioclase-rich crustal rocks, which are consistently KREEP-poor, there does not appear to be any relationship between the KREEP content of the samples considered and their affiliation with one of the three groups recognized in Fig. 11.

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References

Bowen N. L. and Schairer J. F. (1935) The system MgO–FeO–SiO_2. *Amer. J. Sci.* **29**, 151–217.

Dence M. R. (1971) Impact melts. *J. Geophys. Res.* **76**, 5552–5565.

Dowty E., Prinz M., and Keil K. (1974) Ferroan anorthosite: A widespread and distinctive lunar rock type. *Earth Planet. Sci. Lett.* **24**, 15–25.

Grieve R. A. F. (1975) The petrology and chemistry of the impact melt at Mistastin Lake Crater, Labrador. *Bull. Geol. Soc. Amer.* In press.

Hubbard N. J., Gast P. W., Rhodes J. M., Bansal B. M., and Wiesmann H. (1972) Non-mare basalts: Part II. *Proc. Lunar Sci. Conf. 3rd*, p. 1161–1179.

LSAPT (1972) Third Lunar Science Conference. *Science* **176**, 975–981.

Metzger A. E., Trombka J. I., Peterson L. E., Reedy R. C., and Arnold J. R. (1973) Lunar surface radioactivity: Preliminary results of the Apollo 15 and Apollo 16 gamma-ray spectrometer experiments. *Science* **179**, 800–803.

Reid A. M., Warner J., Ridley W. I., Johnston D. A., Harmon R. S., Jakeš P., and Brown R. W. (1972) The major element compositions of lunar rocks as inferred from glass compositions in the lunar soils. *Proc. Lunar Sci. Conf. 3rd*, p. 363–378.

Roedder E. and Weiblen P. W. (1974) Petrology of clasts in lunar breccia 67915. *Proc. Lunar Sci. Conf. 5th*, p. 303–318.

Roscoe R. (1952) The viscosity of suspensions of rigid spheres. *British J. Appl. Phys.* **3**, 267–269.

Smith J. V. and Steele I. M. (1974) Intergrowths in lunar and terrestrial anorthosites with implications for lunar differentiation. *Amer. Mineral.* **59**, 673–680.

Steele I. M. and Smith J. V. (1972) Apollo 15, 16; Luna 20; Mineralogy and petrology (abstract). In *Lunar Science IV*, p. 689–691. The Lunar Science Institute, Houston.

Steele I. M. and Smith J. V. (1973) Mineralogy and petrology of some Apollo 16 rocks and fines: General petrologic model of moon. *Proc. Lunar Sci. Conf. 4th*, p. 519–536.

Tuttle O. F. and Bowen N. L. (1950) High-temperature albite and contiguous feldspars. *J. Geology* **58**, 572–583.

Wager L. R. and Brown G. M. (1967) *Layered Igneous Rocks*. W. H. Freeman, San Francisco. 588 pp.

Walker D., Longhi J., and Hays J. F. (1972) Experimental petrology and origin of Fra Mauro rocks and soil. *Proc. Lunar Sci. Conf. 3rd*, p. 797–817.

Walker D., Longhi J., and Hays J. F. (1975) Differentiation of a very thick magma body (abstract). In *Lunar Science VI*, p. 838. The Lunar Science Institute, Houston.

Warner J. L., Simonds C. H., and Phinney W. C. (1973) Apollo 16 rocks: Classification and petrogenetic model. *Proc. Lunar Sci. Conf. 4th*, p. 481–504.

Weiblen P. W. and Roedder E. (1973) Petrology of melt inclusions in Apollo samples 15598 and 62295, and of clasts in 67915 and several lunar soils. *Proc. Lunar Sci. Conf. 4th*, p. 681–703.

Weiblen P. W., Powell B. N., and Aitken F. K. (1974) Spinel-bearing feldspathic-lithic fragments in Apollo 16 and 17 soil samples: Clues to processes of early lunar crustal evolution. *Proc. Lunar Sci. Conf. 5th*, p. 749–767.

Wood J. A. (1975) A survey of lunar rock types and comparison of the crusts of earth and moon (preprint). *Proc. Soviet–American Conf. Cosmochemistry of the Moon and Planets (Moscow)*. The Lunar Science Institute, Houston.