A Survey of Lunar Rock Types and Comparison of the Crusts of Earth and Moon

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The principal known types of lunar rocks are briefly reviewed, and their chemical relationships discussed.

In the suite of low-KREEP highland rocks, Fe/(Fe + Mg) in the normative mafic minerals increases and the albite content of normative plagioclase decreases as the total amount of normative plagioclase increases, the opposite of the trend predicted by the Bowen reaction principle. Lunar highland samples analyzed are uniformly distributed in this sequence, in which normative plagioclase contents range from ~ 40 percent to ~ 100 percent. The distribution of compositions of rocks from terrestrial layered mafic intrusives is substantially different: here the analyses fall in several discrete clusters (anorthositic rocks, norites, granophyres and ferrogabbros, ultramafics), and the chemical trends noted above are not reproduced.

It is suggested that the observed trends in lunar highland rocks could be produced by crystal fractionation in a deep global surface magma system if (1) plagioclase tended to float, upon crystallization, and (2) the magma was kept agitated and well mixed (probably by thermal convection) until crystallization was far advanced and relatively little residual liquid was left. When such a system was finally immobilized, the Fe-, Na-rich residual liquid would produce Fe-rich mafic minerals in the upper levels of the system, but could not much alter the composition of abundant calcic plagioclase. Conversely, the same liquid would produce sodic plagioclase deep in the sequence, but could not much alter the composition of abundant magnesian mafic minerals.

After the crustal system solidified, but before extensive cooling had developed a thick, strong lithosphere, mantle convection was able to draw portions of the lunar anorthositic crust down into the mantle in a manner analogous to the present-day behavior of the terrestrial mantle and crust. At depth, the crustal material was heated; KREEP-rich norite was extracted by partial melting and erupted at the surface as a lava, analogous to terrestrial andesite eruptions.

Five years have passed since Eagle, the Lunar Module of the Apollo 11 mission, landed at Tranquillity Base. In the time since, samples of lunar material returned by six Apollo and two Luna missions to the Moon have been studied intensively, and thousands of pages of descriptive material have been published. The samples collected at the eight sites are not totally different from one another: in many cases, essentially the same rock type has been observed among the collections returned from two or more sites. The tendency for certain rock types to occur at several widely separated points on the Moon is sufficiently great to make us confident that we have obtained a fairly good sampling of the surface layers of the lunar nearside.

In reading the literature, it is not easy to gain an impression of the total range of compositions of lunar materials encountered, or their frequency of occurrence in the samples returned. Papers descriptive of lunar samples

are typically specialized and detailed, and present only the results from a single laboratory, employing a single technique of analysis. Sometimes data from the samples of other missions, or data obtained by other workers, are shown for comparison, but the body of data included for comparison tends to be small and highly selective. The need exists for a broad comparison of the properties of all lunar materials studied to date.

The chemical composition of its major element is the most fundamental property of a lunar rock, and the one most useful for separating categories of lunar rocks and understanding the relationship of the various categories to one another. Petrographic textural information is, in my opinion, of secondary importance. In the case of highland rocks, textures record a history of relatively superficial processes (brecciation, mixing, thermal recrystallization) that are less important than the large-scale internal geochemical processes that largely determined the chemical compositions of the lunar rocks. It might be argued that textural information is essential in order to distinguish between pristine igneous rocks and polymict breccias in which several rock types with different chemical compositions have been mixed; but, unfortunately, major impacts are capable of remelting complex breccias on the Moon and giving them igneous textures. For few, if any, crystalline igneous rocks from the lunar

highlands can one exclude, on petrographic grounds, the possibility of derivation from an impact melt, in which the parent material melted was a complex mixture of earlier rock types.

There are three major categories of lunar samples, the analyses of which might be expected to inform us of the major lunar rock types. The first of these is lunar rocks of hand specimen size, which are usually analyzed by traditional wet-chemical or X-ray fluorescence techniques. The second is smaller lithic fragments from soil samples and discrete clasts from complex breccias. These can be analyzed by a variety of techniques, including neutron activation analysis and electron-microprobe analysis of fused beads; but the great majority of lithic fragment and clast analyses reported in the literature were obtained by using an electron microprobe with a broad (defocused) beam to analyze a large number of spots on a polished section surface. The third category consists of fragments or globules of glass from the lunar soil samples, which are analyzed individually by the traditional electron-microprobe method.

Each of these three categories of material, including its method of analysis, has its own strengths and weaknesses, which are summarized in table 1. Here the comment that studies of lithic fragments from soils (and clasts) are least accurate alludes to the fact that most such analyses reported in the liter-

Table 1.—*Sources of Information About Lunar Rock Compositions*

	Advantages	Disadvantages	No. of Analyses in SAO Library
Large Rocks	Most accurate Representative (?) Petrography, other properties known	Small number of samples analyzed Integrates polymict breccias	156
Lithic Fragments From Soils	Petrography known Large number analyzed	Least accurate Poorly representative (?)	530
Glass Particles From Soils	Accurate Probably very representative (well-mixed) Large number analyzed	Petrography not known; parent may be polymict	2389

ature were made by the defocused-beam technique. The traditional procedure for reducing and correcting electron-microprobe analyses assumes a homogeneous target volume and is not strictly applicable when the microprobe beam is enlarged to embrace many mineral grains of differing compositions simultaneously. For this reason, it is recognized that defocused-beam analyses (DBA) provide no more than an approximation of the true composition of the material analyzed, although the approximation can be a very good one, if the data reduction is carried out thoughtfully.

In table 1, the question of which type of sample is most representative of its parent rock is not so straightforward as it might seem. Clearly, a large rock can be sampled and analyzed in a much more representative way than a 1-mm lithic fragment, especially when only a section surface through the lithic fragment is accessible for DBA sampling. However, this assumes that the large rock, or a substantial fraction of it, was homogenized and properly sampled to obtain an aliquot for chemical analysis. In fact, with a handful of exceptions, this procedure was not carried out for lunar hand specimens because of the wish to consume as little of them as possible, retaining the great bulk of each specimen intact and uncontaminated for study by future generations of scientists. Typically, rock in the amount of 0.5 g was allocated to an investigator for major element chemical analysis, and this was delivered in the form of a single chip, rather than as a powder representative of a much larger mass of material. If the rock was coarse grained or otherwise heterogeneous on a large scale, the sample analyzed may have been a poor representative of the whole.

In the case of lithic fragments, the volume sampled is undeniably smaller by a large factor; yet for very fine grained rocks, the sample volume may be adequate. Many of the lunar highland rocks are, in fact, fine grained; presumably responsible investigators would not report or attempt analyses of lithic fragments in which the grain size is too coarse to permit adequate sampling. The

DBA technique has an advantage that should be weighed against the disadvantage of the small volume sampled, i.e., the fact that lithic fragments can be assessed petrographically, in thin section, at the time the analysis is performed. Thus, materials that are obviously polymict in character can be avoided, and analyses can be limited to fragments or clasts of uniform lithology.

During the past year, my group has assembled from the literature a library of chemical analyses of lunar materials from all three categories. The current number of entries is shown in table 1. These come from many different sources, too many for each to be referenced explicitly. The library includes all analyses reported in the *Proceedings* of the first through fourth Lunar Science Conferences, in *Lunar Science I* through *IV*, and in the Apollo 15, 16, and 17 Preliminary Science Reports. The largest contributors to the library were the group headed by K. Keil (DBA's of lithic fragments and point microprobe analyses of glass particles) and the Apollo Soil Survey (A. M. Reid and coworkers; point analyses of glass particles from soil samples). No analyses of bulk soil samples were included in the library.

My objective was to plot large bodies of lunar data in a number of types of chemical and mineralogical variation diagrams, and to seek broad trends and clusterings of compositions. A conscious effort was made to escape the detailed relationships between individual analyses that have dominated lunar science, and to try to see "the forest instead of the trees." A computer plotting routine was developed that samples the library and enters the appropriate analyses in a three-variable orthogonal reference frame, the axes of which can be made to correspond to three chosen variables. An orthographically projected view of the reference frame and up to 500 plotted data points are drawn by a CalComp plotter. Each data point is represented as the head of a pin, the shaft of which projects down to the plane defined by the two horizontal axes of the reference frame. This intersection of the "pin" with the base of the reference frame gives the

viewer an impression of its depth in the three-dimensional volume portrayed. The assembly of a single plot takes about 1 minute of central processor time on a CDC 6400 computer, and the plot is drafted in approximately 1 hour by a CalComp model 564.

It should be stressed that when the content or composition of minerals is plotted in these diagrams, the reference is to normative mineralogy, computed from major element chemical compositions. Actual modal mineralogies and compositions are not stored in the analysis library.

Use of the data library and plotting routine is illustrated in figure 1, a plot of three chemical parameters that might be expected to discriminate effectively between lunar mare basalts and highland samples. The library of analyses was sampled randomly, in such a way as to provide approximately equal numbers of data points from the three categories of analyses discussed above. Included are 152 whole-rock analyses, 177 analyses of lithic fragments, and 171 analyses of glass particles. The plot distinguishes fairly cleanly between mare and highland materials. However, it also illustrates some of the shortcomings of lithic fragment and glass analyses alluded to in table 1. The highland data points form an extremely compact and well-defined grouping, except for a number of DBA stragglers, which seem to contain anomalously high levels of Al_2O_3 and/or $K_2O + P_2O_5$ (D, figure 1). The "stragglers" appear only on the high Al_2O_3 side of the highland grouping. It is likely that their position is false; the DBA technique systematically overreports Al and P, unless special corrections are
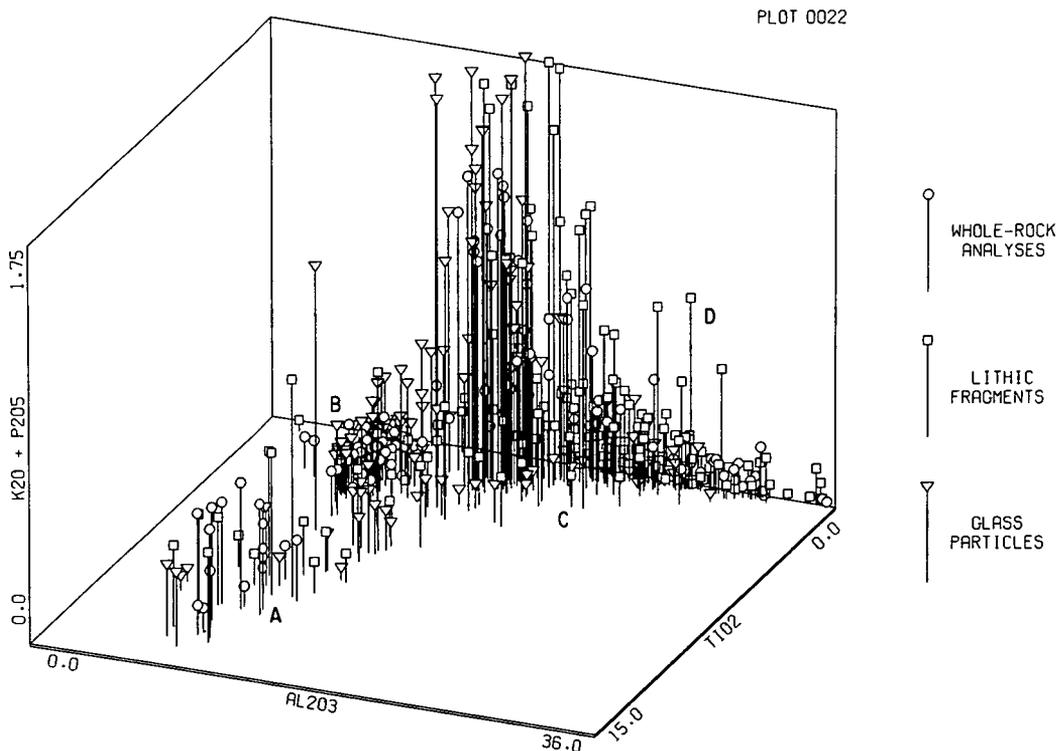

Figure 1.—*Approximately equal numbers of lunar whole-rock, lithic fragment, and glass analyses, in a type of plot that attempts to discriminate clearly between mare and highland samples. A: high-Ti mare basalts from the Apollo 11 and 17 missions. B: Apollo 12 and 15 basalts and green glasses (chiefly from Apollo 15). C: highland materials. D: defocused-beam analyses of highland materials, probably reporting spuriously high levels of Al_2O_3 and/or KREEP.*

made. Again, there is an almost continuous row of data points representing glass analyses extending from A (mare basalts) to C (highland compositions). This does not represent a spectrum of real lunar lithic types; it is undoubtedly a mixing line. These glasses were derived from soil or breccia parent materials that contained a mechanical mixture of mare and highland rock types. The crucial distinction between mare and highland rock types is blurred here, and also in the gap between cluster B and the main body of highland rock compositions, by glass analyses. Because of this obscuring effect of the glass data, I have omitted glass analyses from most of the other plots in this paper. Possibly this is an overreaction to the deficiencies of the glass data; the consideration of plots of large numbers of glass particle compositions

has led to the appreciation of several important lunar rock types (ref. 1), and it is also the case that several important lunar materials (the green and orange glasses) have no known crystalline equivalents.

Figure 2 is a replot of figure 1, containing 156 whole-rock analyses and 348 lithic fragment analyses. Here and in most other plots of this paper, shapes of pinheads are no longer used to identify the categories of lunar samples plotted, but rather their sources on the Moon. The distinction between mare and highland rock compositions can be drawn somewhat more clearly in this figure than in figure 1. Two entries that occupy an equivocal position between the mare and highland groupings of analyses are identified in the caption of figure 2. The "highland/mare" boundary drawn on the floor of the plot illus-
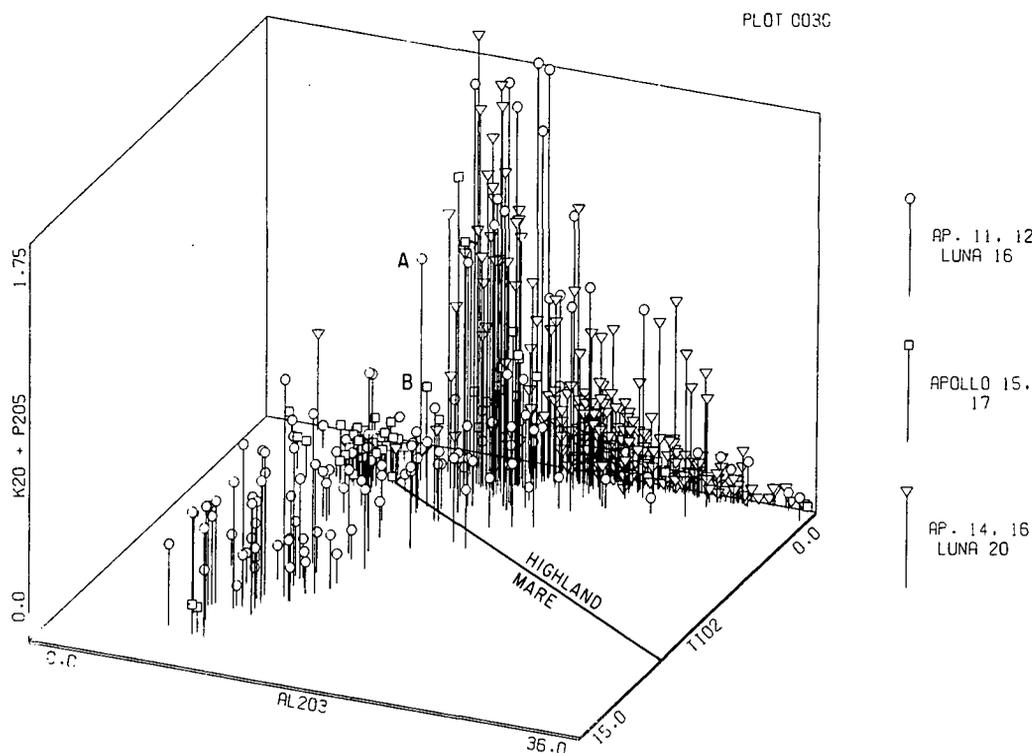

Figure 2.—*Plot similar to figure 1, except that glass analyses have been eliminated; pinhead shapes now denote sources of samples on the Moon. "Highland/Mare" boundary drawn on floor illustrates chemical criteria used to separate these two classes of lunar rocks in succeeding plots. The separation is generally clean; A and B occupy equivocal positions. A is a DBA of an "igneous" lithic fragment from soil 12057 (Bunch et al., ref 2); B is soil breccia 15558, which contains both mare and highland components.*

trates the chemical criteria used elsewhere in this paper to arbitrarily separate mare from highland samples. The rule adopted was that if

$$Al_2O_3 > 11\% \text{ and } (0.3 \times Al_2O_3 - 1.1) > TiO_2,$$

a sample was considered to be a highland rock type.

The two discrete categories of lunar rocks —mare basalts and highland rocks of various types—will be discussed separately below.

Mare Basalts

Crystalline mare materials can be separated into four categories—three major and one minor—by plotting TiO_2 against K_2O (fig. 3). The plot also displays the proportion of olivine among normative mafic minerals, a measure of the degree of undersaturation of the rock. Categories C, D, E, and F of figure 3 have been further subdivided petrographically, as follows.

Group C consists of Apollo 12 and 15 basalts. James and Wright (ref. 3) subdivide the Apollo 12 basalts into three categories: olivine-pigeonite basalts and gabbros, ilmenite-bearing basalts and gabbros, and feldspathic basalts. Brown et al. (ref. 4) subdivide the Apollo 15 mare basalts into three additional groups: pyroxene-rich tridymite gabbros, porphyritic vitrophyres, and olivine basalts.
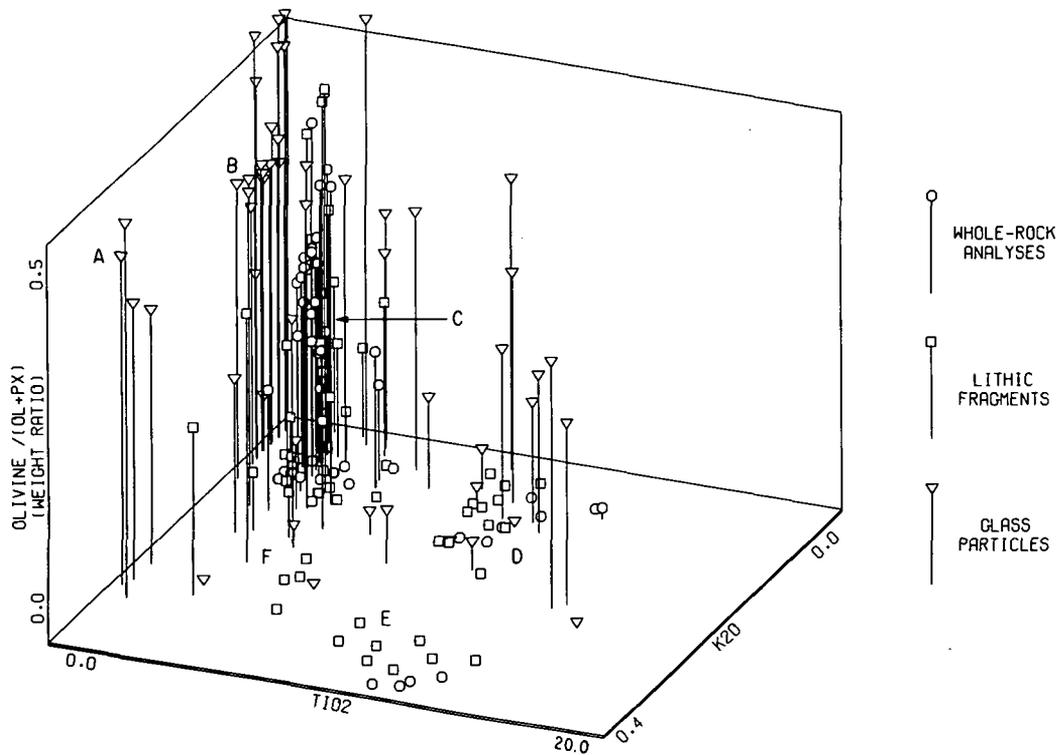
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Figure 3.—*Plot of parameters that tend to separate the recognized categories of lunar mare basalts. The criteria of figure 2 were used to reject highland materials from the plot, but the separation is not perfect; points at A (Apollo 14 and 15 glasses) are unlikely to be pure rock types. The array of low-TiO₂ entries at B is composed of green glasses, mostly from Apollo 15. C is a column of Apollo 21 and 15 mare basalts; both missions are represented along the entire sequence of olivine contents. D represents Apollo 11 and 17 low-K basalts; E, Apollo 11 high-K basalts. At F, several of the entries are Luna 16 basalts, which tend to span the gap between E and C.*

Group D comprises the Apollo 11 ophitic ilmenite basalts (low-K basalts) recognized by James and Wright (ref. 3) and others, and all the Apollo 17 mare basalts. Brown et al. (ref. 5) subdivide the latter into three categories: olivine basalts, ferrobasalts, and basalts transitional between these two.

Group E consists of the Apollo 11 intersertal ilmenite basalts (high-K basalts) recognized by James and Wright (ref. 3) and other authors.

The ophitic pigeonite basalt fragments from the Luna 16 soil sample appear in group C. In terms of the parameters plotted, the Luna 16 basalt is intermediate in character between groups C and E; however, in other respects, including its content of trace elements (e.g., ref. 6), the Luna 16 basalt cannot be regarded as a simple mixture of the two end members indicated.

Chemical compositions of representatives of most of the mare basalt subcategories discussed are presented in table 2.

Highland Rocks

The frequency of occurrence of different types of highland rock is highly variable in figure 2. In this figure, a dense mass of entries occurs in the interval of Al_2O_3 content between 21 and 32 percent. These are the anorthositic rocks of the lunar highlands; they are anorthositic gabbros and gabbroic anorthosites according to traditional terrestrial nomenclature. The KREEP content of this group of rocks is probably extremely sharply bounded; as previously noted, the half-dozen entries that rise to KREEP contents substantially higher than those of the great mass of lunar anorthositic rocks are probably the result of inaccurate defocused-beam analyses. The density of entries seems to fall off very sharply above 32 percent Al_2O_3.

The central column of "pins" in figure 2 represents the lunar norites. This cluster of entries appears discontinuous with the low-plagioclase end of the anorthositic distribution. This may signify that the two families of highland rocks formed by fundamentally

different processes, a conclusion that has gained wide currency in the lunar science community for other reasons; but it is important to recognize that the exceptional density of data points in the Al_2O_3 range from 21 to 32 percent in figure 2 is largely due to the heroic project of defocused-beam analysis of lithic fragments from the Luna 20 sample carried out by Conrad et al. (ref. 15). Thus, the apparent discontinuity between abundances of noritic and anorthositic gabbro compositions may occur only in the vicinity of Mare Crisium, and may not be a property of the lunar highlands as a whole.

Entries appear to be unevenly distributed along the vertical extent of the norite column. When the entries in this column are plotted in a simple histogram, three peaks appear: a low-KREEP peak centered about 0.3 percent $K_2O + P_2O_5$; a high-KREEP peak centered on 1 percent $K_2O + P_2O_5$; and a smaller extra-high-KREEP peak at 1.6 percent $K_2O + P_2O_5$. The extra-high-KREEP cluster consists entirely of DBA's of lithic fragments from Apollo 12 and 14 soil samples; several were reported by my own group. It now appears that these analyses systematically overreported P_2O_5, so it is likely that the extra-high-KREEP group is spurious. Unfortunately, the total number of high- and low-KREEP points plotted is not large enough to resolve with confidence the important question of whether the distribution of KREEP contents is continuous or bimodal.

Table 3 presents analyses of lunar highland rocks representative of the major classes discussed above. One other minor but potentially important rock class, the spinel troctolites, is also represented. Spinel troctolite entries in figure 2 would be hidden behind the mare basalt cluster beneath B. They are excluded from plots containing highland samples only, by the chemical criteria that separate out mare basalt analyses.

In figure 4, 156 whole-rock analyses and 530 lithic fragment analyses of highland materials are plotted against three indices of igneous fractionation. The assemblage of "pins" falls into two distinct groups. At the left of the plot (A–B), a group of entries

Table 2.—*Chemical Compositions of Mare Basalts Representative of of Major Recognized Classes*

Group	C					D			E	F
	Apollo 12			Apollo 15		Apollo 11	Apollo 17		Apollo 11	Luna 16
Petro-graphic Type	Olivine-Pigeonite Basalt	Ilmenite-bearing Basalt	Feldspathic Basalt	Pyroxene-rich Tridymite Gabbro	Olivine Basalt	Ophitic Ilmenite Basalt	Olivine Basalt	Olivine Ferro-basalt	Intersertal Ilmenite Basalt	Ophitic Pigeonite Basalt
Example	12009[a]	12022[b]	12038[c]	15058[d]	15016[e]	10020[f]	70215[g]	70017[g]	10072[f]	21012, B-1[h]
SiO_2	45.03	43.20	47.1	47.81	44.30	41.00	37.91	38.37	40.20	45.50
Al_2O_3	8.59	9.04	12.8	8.87	8.39	9.83	8.86	8.78	7.78	13.95
TiO_2	2.90	5.16	3.17	1.77	2.27	10.28	13.08	12.83	12.28	4.04
MgO	11.55	10.43	6.80	9.01	11.65	7.77	7.99	9.41	8.06	5.95
FeO	21.03	21.44	17.4	19.97	22.95	19.03	19.96	18.71	19.77	17.77
MnO	0.28	0.25	0.24	0.28	0.29	0.27	0.26	0.25	0.22	0.26
CaO	9.42	9.56	11.4	10.32	9.20	11.96	10.77	10.43	10.27	11.96
Na_2O	0.23	0.47	0.64	0.28	0.32	0.37	0.38	0.43	0.52	0.63
K_2O	0.06	0.07	0.07	0.03	0.05	0.05	0.04	0.05	0.29	0.21
P_2O_5	0.07	0.13	0.17	0.08	0.06	0.07	0.11	0.05	0.18	0.15
SUM	99.16	99.75	99.79	98.42	99.48	100.63	99.36	99.31	99.57	100.42

NOTES: [a] Compston et al. (ref. 7).
[b] Engel et al. (ref. 8).
[c] Cuttitta et al. (ref. 9).
[d] Rhodes and Hubbard (ref. 10).
[e] Cuttitta et al. (ref. 11).
[f] Maxwell et al. (ref. 12).
[g] Duncan et al. (ref. 13).
[h] Albee et al. (ref. 14).

Table 3.—*Compositions of Highland Rocks Representative of Major Chemical Classes*

	Anorthositic Gabbro	Gabbroic Anorthosite	Anorthosite (cataclastic)	Low-KREEP Norite	High-KREEP Norite	Spinel Troctolite
Example	60335[a]	68415[a]	60015[b]	76055[c]	14303[d]	62295[e]
SiO_2	46.33	45.30	43.97	45.7	47.90	45.16
Al_2O_3	25.01	28.70	35.83	15.84	15.6	20.05
TiO_2	0.57	0.29	0.02	1.38	1.80	0.70
MgO	7.70	4.35	0.25	17.89	10.93	14.85
FeO	4.60	4.12	0.36	9.27	10.74	6.40
MnO	0.08	0.05	0.00	0.12	0.15	0.09
CaO	14.23	16.24	18.95	9.13	9.90	11.85
Na_2O	0.62	0.50	0.34	0.55	0.78	0.48
K_2O	0.27	0.09	0.01	0.22	0.52	0.11
P_2O_5	0.21	0.06	—	0.22	0.60	0.15
SUM	99.62	99.70	99.73	100.32	98.92	99.84

NOTES: [a] Rose et al. (ref. 16).
[b] Juan et al. (ref. 17).
[c] Nava (ref. 18).
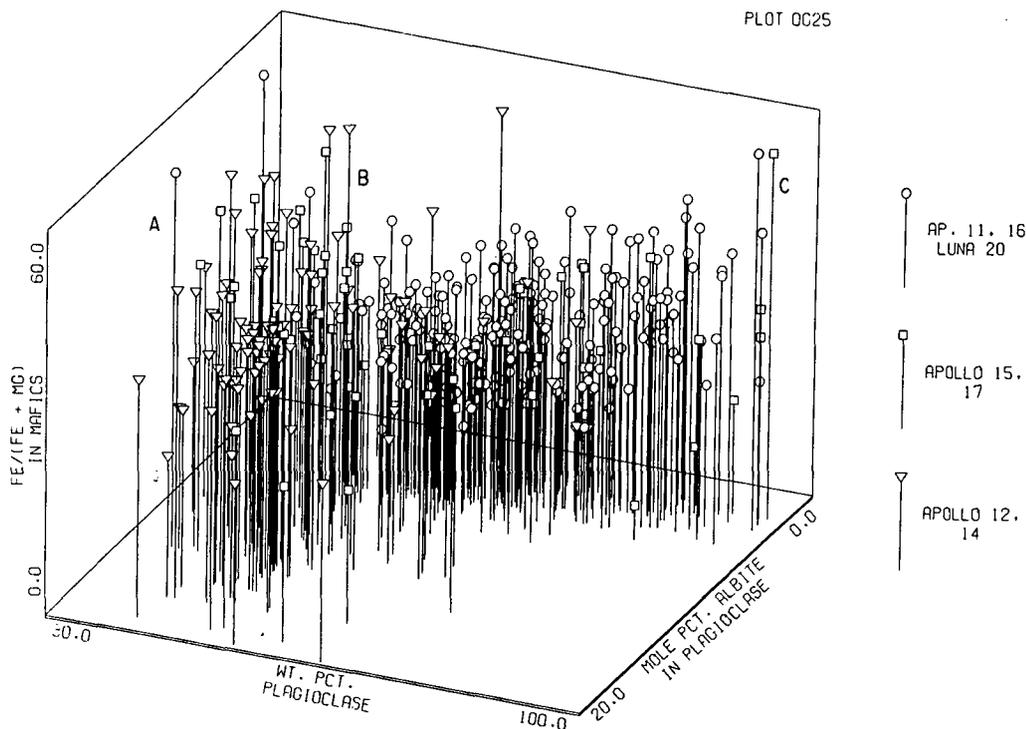[d] Wiik et al. (ref. 19).
[e] Rose et al. (ref. 20).

Figure 4.—*Lunar highland samples only (whole-rock and lithic fragments analyses), plotted against three indicators of the degree of differentiation. Group between A and B: noritic materials; B through C: sequence ranging from anorthositic gabbro to anorthosite.*

has an approximately constant (40- to 50-percent) content of normative plagioclase, but the plagioclase has variable albite content; these are the lunar norites. It is not possible in this figure to discriminate between high- and low-KREEP norites. The other group of "pins" (B–C) is the anorthositic sequence, ranging from anorthositic gabbro near B to anorthosites proper at C. Here, the albite content of the plagioclase varies very little, while the content of normative plagioclase ranges from 50 percent to almost 100 percent.

This plot provides an opportunity to test the observation of Steele and Smith (ref. 21), that the relationship between the fayalite content of olivine and the albite content of coexisting plagioclase in highland rocks is the inverse of that predicted by the Bowen reaction principle; i.e., as the plagioclase content of highland materials increases, the albite content of plagioclase decreases, but $Fe/(Fe + Mg)$ in olivine (and presumably also in pyroxene) increases. Figure 4 confirms this relationship, although the variation of the albite content of plagioclase is extremely small compared with the general scatter of albite content plotted for anorthositic samples. (The small range of Ab content compared with that of Fo in coexisting olivines was also noted by Steele and Smith (ref. 21).)

Comparison of the Crusts of Earth and Moon

It would appear interesting to draw a direct comparison between the crustal materials of the Earth and Moon. However, we are conscious by now that the crusts of the two bodies are the products of very different processes. Because of the thinness of the Earth's lithosphere and the thermal and convective activity of its interior, the crust of the Earth is continually being drawn down into its mantle (fig. 5). In the process, certain easily meltable and low-density constituents are selectively removed from the descending crustal material and sent back to the surface
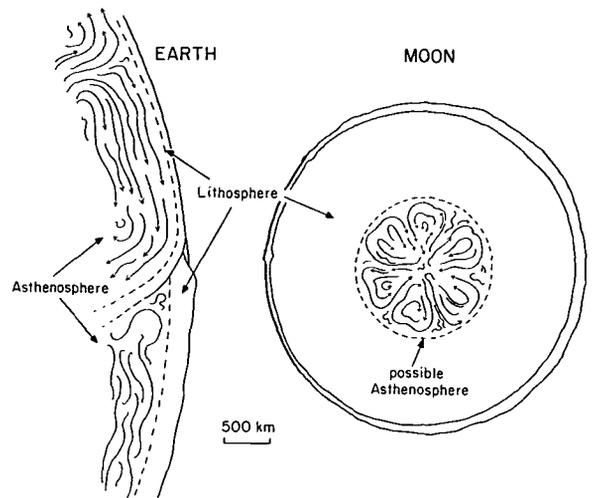

Figure 5.—*Differences in thickness of lithospheres of the Earth and Moon; to scale. Because Earth's lithosphere is less than 100 km thick beneath ocean basins, it is not strong enough to resist being moved and subducted by mantle convection. The Moon's lithosphere is 1000 km thick and highly stable. A weaker zone (attenuating seismic S-waves), which may or may not be in convective motion, exists beneath 1000 km.*

in the form of volcanic rocks. These low-temperature, low-density constituents have, in this way, become concentrated near the surface of the Earth over the course of geologic time and have come to dominate the composition of Earth's crust. The Moon has a very much thicker lithosphere than does the Earth, for two reasons. First, the temperature increase with depth is smaller in the Moon than in the Earth, because of the Moon's greater surface-to-volume ratio, which compromises its ability to conserve internal heat; and, second, the water content of the Moon is effectively zero, and the plasticity of mantle rocks at a given temperature is greatly enhanced by the presence of water. Because of the thickness and rigidity of the Moon's lithosphere, internal mantle convection (if it occurs at all) does not act to draw lunar crustal material down into the depths of the Moon and selectively recycle its easily meltable constituents. The pre-mare crust of the Moon is generally felt to be the product of a great cycle of geochemical differentiation that affected the outermost hundreds of
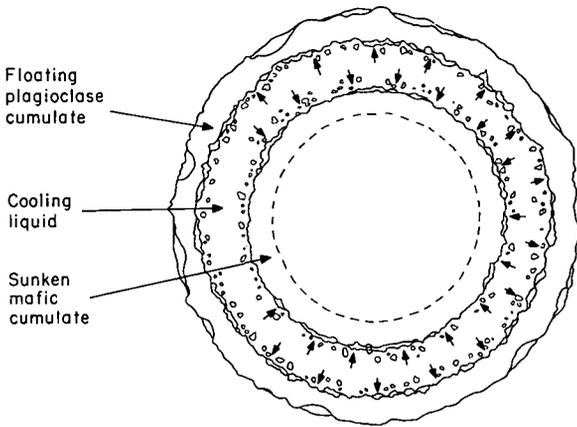
Figure 6.—*Model for early large-scale differentiation of the Moon's outer layers (schematic; radial scale exaggerated). Accretional heating melted the primordial lunar material to a depth suggested by the dashed line. During subsequent cooling and crystallization, dense mafic minerals sank and plagioclase floated to form an anorthositic crust.*

kilometers of the Moon immediately after its formation (fig. 6).

Because of these fundamental differences, there is little point in making a straightforward chemical comparison between the lithic constituents of the crusts of Earth and Moon. It is more profitable to draw a comparison between lunar rocks and selected terrestrial rock systems in which the processes of geochemical fractionation that have operated are similar to those believed to have affected the lunar crust. The Earth's crust contains a number of layered mafic intrusives, in which gravity crystal fractionation has produced a range of different rock types from a (presumably) homogeneous parent magma. This is the process that, on a much larger scale, is believed to have differentiated the premare crust of the Moon. It is interesting to compare the array of rock types found in terrestrial mafic layered intrusives with those from the lunar crustal system. To com-
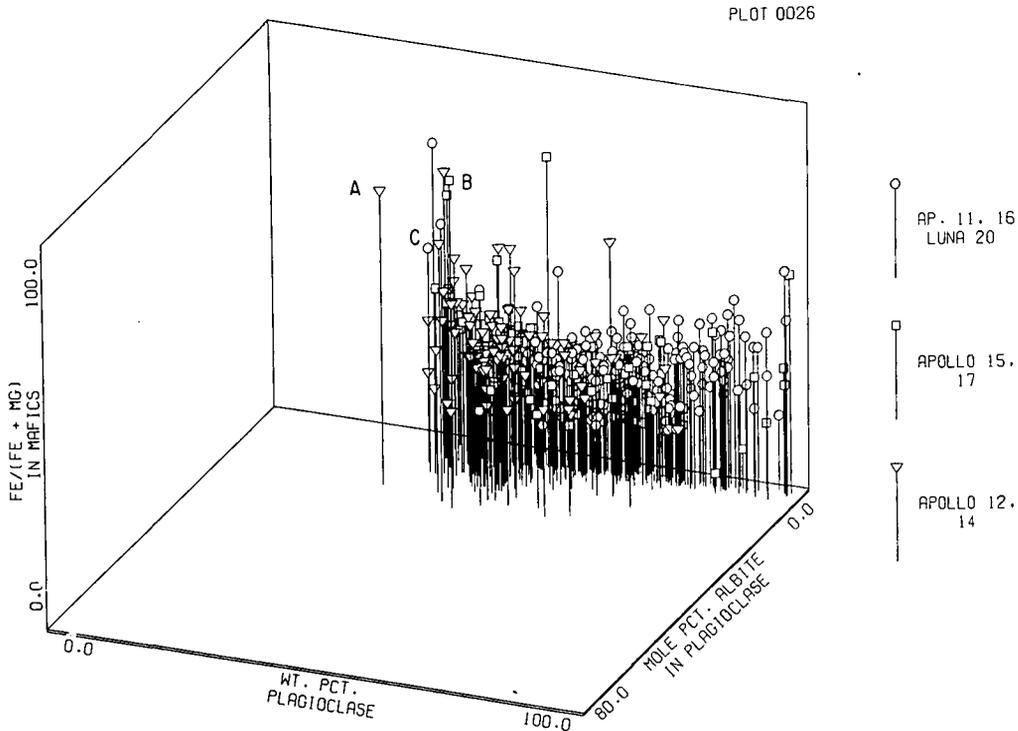

Figure 7.—*Data of figure 4, plotted on an expanded scale. Entries with highest Fe/(Fe+Mg) and low plagioclase (A, B, C) are not actually highland materials, reflecting the limitations of the arbitrary criteria for discrimination shown in figure 2.*

pare the data of figure 4 with terrestrial systems, the scale of the axes must be expanded to accommodate the greater range of rock compositions found in terrestrial systems. This is done in figure 7, where the data of figure 4 are replotted. Emphasis in this figure is upon the tendency of the total array of data to reach minimum Fe/(Fe + Mg) values for mafic minerals at intermediate contents of plagioclase, and to rise to higher values of mafic Fe/(Fe + Mg) at the low-plagioclase and high-plagioclase ends of the array. (The entries displaying the highest values of Fe/ (Fe + Mg) at the low-plagioclase end of the array are probably not highland rocks; but the general tendency of the array to rise to higher values of Fe/ (Fe + Mg) below the letter C in the diagram is definitely attributable to non-mare samples.)

Analyses of 317 rock samples from nine terrestrial mafic layered intrusives are plotted in figure 8. To jumble analyses of rocks from three widely separated and petrologically unrelated intrusives on the Earth in this fashion, and to lose sight of the known spatial relationships between the rocks analyzed, might be deplored; however, precisely such a situation exists for the collection of lunar highland samples we have access to, so a similarly indiscriminate mixture of terrestrial analyses (of rocks from appropriate geologic structures) provides the most valid basis for a comparison between the Earth and the Moon available to us.

Figures 7 and 8 appear totally dissimilar. To make a fair comparison, however, allowance must be made for several things. First, it is well known by now that the Moon is depleted in Na, along with all the other volatile elements, relative to Earth. For this reason, the plagioclase in terrestrial rocks of all types should contain a greater albite component than do their lunar equivalents. Consequently, the "pins" of figure 8 stand
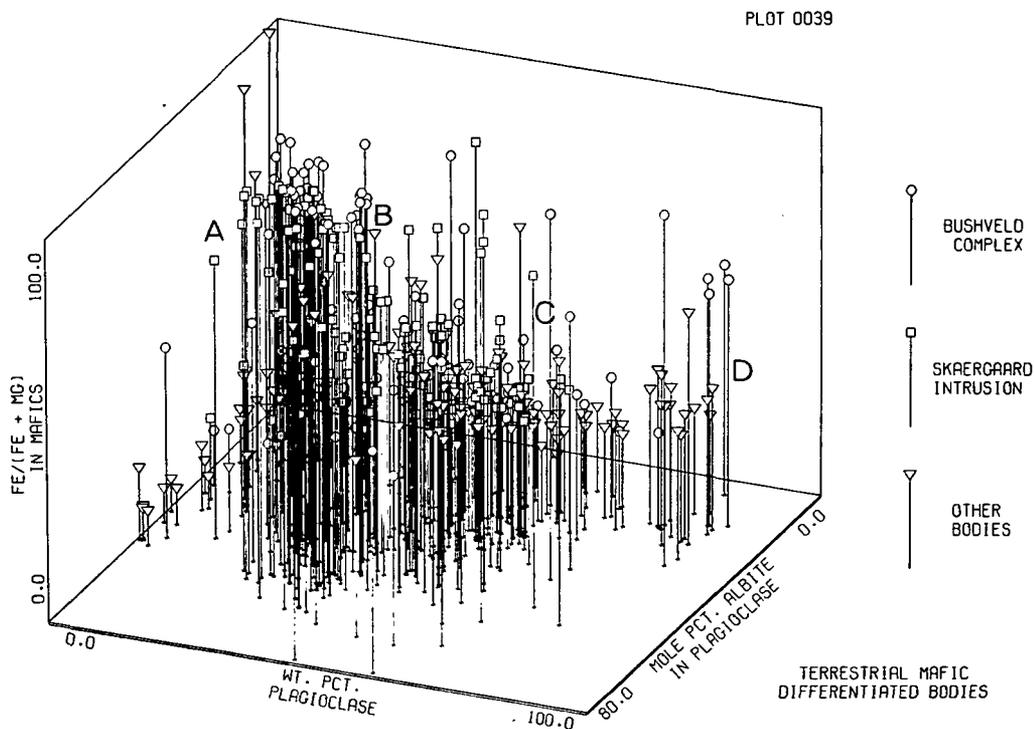

Figure 8.—*Rock analyses from nine terrestrial differentiated mafic igneous bodies, plotted on the same base as figure 7. Group between A and B: chiefly ferrogabbros and granophyres. Between B and C: norites and gabbroic rocks. C and D: anorthositic sequence. Analyses of samples from the Stillwater, Rhum, Guadalupe, Duluth, Bay of Islands, Usushwana, and Fethiye complexes are lumped under "other bodies."*

farther forward in the plot than do those of figure 7. Second, a number of the entries in figure 8 are ultramafic cumulates. (Most of these occur near the origin of the plot, largely hidden behind the major cluster of "pins" between A and B.) Ultramafic rocks are rare among the lunar samples (but not absent), presumably because we have access only to the uppermost layers of the great differentiated sequence that composes the crust of the Moon, and ultramafic cumulates would be expected to occur near its base. Such ultramafic rocks as do occur in our library of analyses were excluded from figure 7 by the chemical criteria that were used to separate highland from mare rocks. Third, figure 8 contains a massive cluster of entries displaying very high values of $Fe/(Fe + Mg)$, between A and B, which has no equivalent in figure 7. These represent the ferrogabbros and granophyres that are abundant in terrestrial mafic layered intrusives and that appear to comprise the late-stage residua after extensive crystal fractionation has removed other components from the melt. Rocks of this type are also rare on the Moon but not nonexistent, although our analysis library has not incorporated any. Fragments of granophyric material in which $Fe/(Fe + Mg)$ for the mafics present is very high have been found in soils and breccias by a number of authors (e.g., refs. 22 and 23). If plotted in figure 7, they would occupy a position analogous to the A–B grouping in figure 8, although the density of the cluster in figure 8 could not be matched. After allowance is made for these discrepancies, the entries corresponding to noritic and anorthositic rock types (B–C–D) form an array somewhat similar to that of figure 7, in that the $Fe/(Fe + Mg)$ content of mafic minerals reaches a minimum value of approximately 0.3 in the intermediate or anorthositic gabbro range of plagioclase contents while higher values (approximately 0.5) obtain for rock types that contain greater and lesser amounts of plagioclase.

In an earlier version of the present article that was distributed as a preprint, I attached importance to this similarity and suggested that the suite of lunar feldspathic rocks was formed by processes analogous to those that operate in terrestrial mafic intrusives, including the tendency of plagioclase to sink rather than float. However, further investigation of the compositional trends among lunar rocks has diminished the apparent similarity of the two rock types.

In particular, it is widely believed for both petrologic and geochemical reasons (refs. 24 and 25) that KREEP-rich lunar norites do not sample the liquid residuum after separation of anorthositic rocks, nor do they represent differentiates complementary to the anorthosites; instead, they appear to be products of a different magma system that was produced by remelting of some suitable parent rock, which may have been the anorthositic sequence itself. In the terrestrial systems plotted, on the other hand, it is clear from field relationships that the noritic rocks are part of the same differentiation sequence that contains the anorthositic members, and have not been introduced to the sequence by some late act of magma generation. Thus, the KREEP-rich norites would need to be excluded from figure 7 in order to reveal trends attributable solely to those lunar differentiation processes thought to be analogous to processes operating in terrestrial layered mafic intrusives. When this is done (by excluding all analyses for which $K_2O + P_2O_5 > 0.5$ percent), the high-Fe/ $(Fe + Mg)$ peak at the left end of the sequence in figures 4 and 7 disappears (ref. 26). Low-KREEP norites are still present in the sequence, but $Fe/(Fe + Mg)$ in their mafic minerals is small, ~ 0.25. The overall trend among low-KREEP lunar crustal rocks is for $Fe/(Fe + Mg)$ to increase monotonically, and for the albite content of plagioclase to decrease monotonically, with increasing content of plagioclase. This is still consistent with the trend noted by Steele and Smith (ref. 21), but it bears very little resemblance to trends in terrestrial mafic intrusives.

For crystal fractionation to produce a suite of rocks that appear to violate the Bowen reaction principle, it is necessary for the two principal mineral groups to move in

opposite directions (i.e., if mafic minerals sink, feldspar must float). In a magma where plagioclase floats, early-formed calcic plagioclase will accumulate at the top of the system in company with relatively unfractionated intercumulus liquid, which will crystallize mafic minerals of intermediate $Fe/(Fe + Mg)$. Early-formed magnesian mafic minerals will accumulate on the floor of the system in company with relatively unfractionated intercumulus liquid, which will crystallize plagioclase of intermediate composition. Thus, at the top and bottom of the system, compositions are qualitatively similar to those found at the right and left ends of the trend shown in figure 4.

The difficulty lies in what occurs between the end members. Straightforward application of principles of phase equilibrium indicates that both $Fe/(Fe + Mg)$ in mafic minerals and albite in plagioclase should increase downward in the floating anorthositic layer, and upward in the sunken mafic layer. These trends are not reflected by figure 4. Further, it is unlikely that bulk plagioclase content would decrease smoothly with depth in the anorthositic and mafic layers, as is suggested by the even distribution of entries in the sequence of figure 4. Terrestrial experience suggests that units of mafic-poor anorthosite and plagioclase-poor ultramafic rock would be produced, probably separated by a residual magma rich in Fe and Na. (Note the clusters of "pins" corresponding to these three compositions in figure 8). These discontinuities of composition are not apparent among the lunar rocks, and there are no samples corresponding to an Fe-, Na-rich residual liquid. (It might appear that the KREEP-rich norites fill this role; but, as already noted, there are compelling reasons for believing that this class of rocks was formed by partial melting, not as a residuum after crystal fractionation. In the simplest terms, degrees of enhancement of $Fe/(Fe + Mg)$ and enrichment of large-ion-lithophile (LIL) elements are incongruous if the rock type was formed by crystal fractionation. The ratio $Fe/(Fe + Mg)$ reflects only a modest degree of frac-

tionation, while a very large percentage of the original magma would have to be removed as crystals to effect the observed enrichment of LIL elements.)

The seriousness of the difficulty just noted depends upon the mechanics of crystal fractionation. The problem is at its worst if the lunar surface magma system was quiescent and cooled slowly. Under these circumstances, thick units of anorthositic and ultramafic cumulate rocks could be expected to form, and the crystals added last to these units should be richer in Fe and Na than the first-formed crystals. On the other hand, the problem diminishes if we contemplate a dynamically active system in which magma motions kept crystals well stirred until crystallization was far advanced. As magma motions slowed and the solidifying system approached stability, some degree of gravitational separation of the crystals would occur, but clean separation of plagioclase from mafic minerals would be impossible (except at the extremities of the system) because of the crowding of crystals in the magma. The rocks of the sequence would be left with a continuous spectrum of plagioclase contents. The suspended minerals would be relatively uniform in composition at the time when the system immobilized, because of stirring during the previous period when they crystallized. Subsequent crystallization of the Fe-, Na-rich intercumulus liquid in the upper, plagioclase-rich levels of the system would increase the mean value of $Fe/(Fe + Mg)$ in the mafic minerals substantially, since few early-crystallized Mg-rich crystals would be present to lower $Fe/(Fe + Mg)$; on the other hand, the amount of early-formed calcic plagioclase present would be so great that the contribution of Na from the intercumulus liquid could do little to enhance the mean value of albite content of the plagioclase.

Conversely, crystallization of the same Fe-, Na-rich intercumulus liquid in a mafic-rich cumulate deep in the system would effect a great increase in the mean albite content of the small amount of plagioclase present, but could not importantly increase Fe/

(Fe + Mg) in the abundant mafic minerals. The process should operate to intermediate degrees at intermediate positions in the differentiated sequence, and continuous compositional trends similar to those of figure 4 would be produced.

Is it reasonable to suppose that the lunar surface magma system was more dynamically active than terrestrial mafic intrusives during the first phase of its cooling history? There are several reasons for thinking so.

1. The outer surface of the lunar magma system was exposed to space; hence, heat losses at this surface were vastly greater than at the walls of a terrestrial plutonic intrusive. The steep thermal gradient established in the lunar case would be more likely to promote convective motion, which would act to stir the magma. Surface heat losses would be cut when the system began to crust over, as in the case of a lava flow, but it is likely that the intensity of the early meteoroid bombardment of the Moon thwarted formation of a crust for some time.

2. Because of the Moon's small mass, the pressure gradient in the Moon is only one-sixth as steep as the terrestrial pressure gradient. As a consequence, the vertical thermal gradient in a magma system needed to produce convective motion would only need to be one-sixth as steep on the Moon as on Earth.

3. Because of the small value of lunar gravity, crystals are less rapidly separated from a lunar magma by specific gravity differences, and hence would be more readily held suspended by a convecting magma, than would be the case on Earth. (The small value of lunar gravity also works against this model, however, by providing less energy for a convecting system to use to overcome viscous drag.)

4. Plagioclase crystals, in particular, could be kept well mixed with the lunar magma even by sluggish convective motions, since the specific gravity contrast between calcic plagioclase and a residual magma of reasonable composition is extremely small. Plagioclase crystallization would act principally to increase the effective viscosity of the cooling system, until the latter stabilized.

The question of the origin of high-KREEP norite has tormented lunar petrologists since this lithology was recognized. Its content of large-ion-lithophile elements and its position in the quartz-olivine-anorthite pseudo-ternary phase diagram seem to require that it was generated by partial melting of a parent similar to lunar anorthositic rocks. An objection I have raised to this interpretation (ref. 27) is that once the surface layers of the Moon had solidified and their content of heat-generating radionuclides had been immobilized, this part of the system would have cooled monotonically. Temperatures in a subcrustal layer or zone should not rise again (as is required in order to remelt the material) unless some new external source of energy were involved. The question of a source of heat to effect remelting of KREEP norite has been a serious one.

One possible resolution of this problem has been overlooked, however. Earlier in this paper it was remarked that the Moon's thick lithosphere prevents interior convection from subducting crustal material into its mantle. But this was not necessarily always the case. If the initially hot outer layers of the Moon cooled from the surface inward, there must have been a time, after the crustal magma system had completely solidified, when the lunar lithosphere was still thin and weak. If mantle convective motion occurred during this early and transient phase of lunar history, it is possible that the primordial anorthositic crustal material was dragged down into the lunar mantle. There, higher temperatures would have occasioned partial melting of the crustal material, producing a melt having many of the properties of KREEP-rich norite, which would have
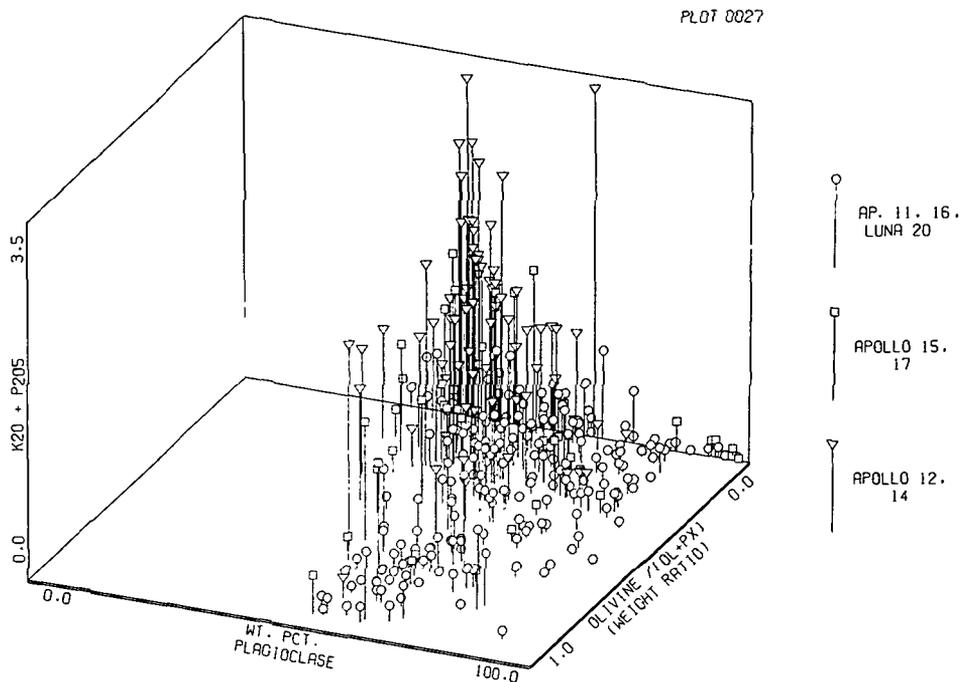
Figure 9.—*Lunar highland samples only (whole-rock and lithic fragment analyses), plotted against KREEP content ($K_2O + P_2O_5$) and degree of silica saturation (expressed as normative olivine/(ol + px)).*
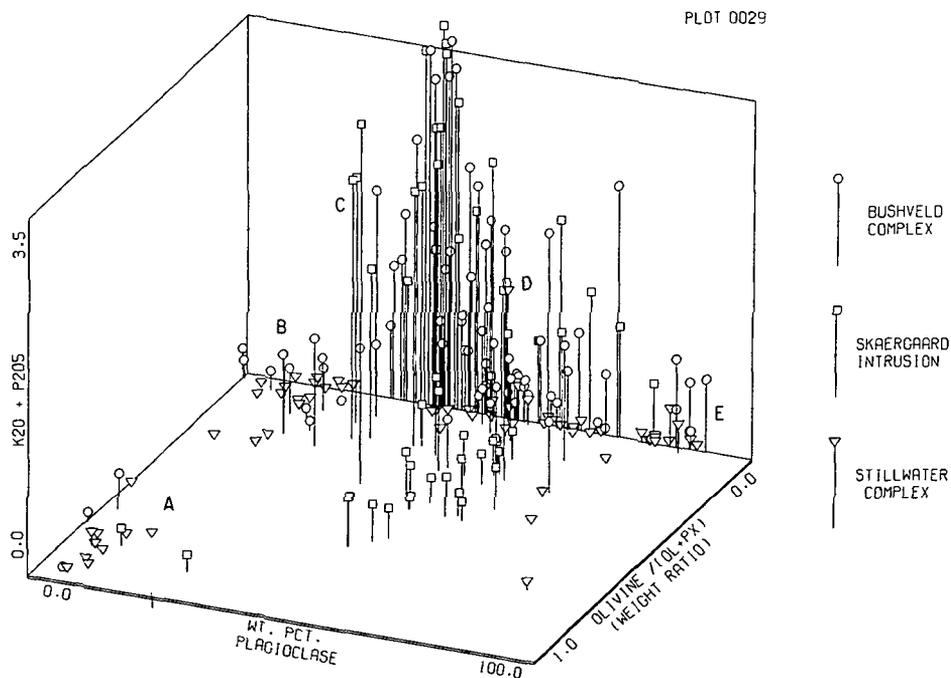

Figure 10.—*Rock analyses from three classic terrestrial differentiated mafic igneous bodies, plotted on the same base as figure 9. A: peridotites, dunites; B: pyroxenites. Olivine-free rocks range from ferrogabbros at C through norites and gabbros near D, to anorthosites at E.*

erupted to the surface as a lava. In this case, the KREEP-rich norites could be regarded as the lunar equivalents of terrestrial andesites.

In figures 9 and 10, a comparison is drawn between the lunar highland rocks and samples from the three classic terrestrial basic differentiated bodies, for several other parameters of petrologic interest. Entries representing granophyric rocks are largely missing from figure 10, because their content of K_2O is too great to be accommodated by the axes defined. Of greatest interest is the difference in olivine content of the rocks of the two series. Lunar highland rocks, especially those of the anorthositic series, are often troctolitic in character. The terrestrial differentiates are much less likely to contain olivine.

The difference may be due to the fundamentally dissimilar modes of origin of the parent magmas of the two systems. The terrestrial gabbroic magmas were presumably generated by a small degree of melting in the mantle of the Earth and escaped from their source before the temperature of the system had risen high enough to melt substantial amounts of any olivine present in the source region. If the lunar surface magma system was melted by accretional energy during the assembly of the Moon, on the other hand, this control on melt composition would not have existed. The injection of large amounts of energy during accretional impact would have tended to melt the primordial material of the Moon completely. Presumably this primordial material included a substantial component of chondrite-like material (refs. 28 and 29); chondritic meteorites are substantially undersaturated and contain a large proportion of normative olivine, all of which would have been included in magmas formed by the total melting of primordial lunar material.

In conclusion, while no valid comparison can be drawn between the properties of the lunar crust and the present terrestrial crust, it is possible that the Moon preserves an accurate and informative record of the properties of the crust that *initially* formed on the Earth. If the Earth began its existence with a plagioclase-rich crust analogous to the Moon's, formed by crystal flotation in an extensive early global magma system, this crust would not have been thicker than the Moon's in proportion to the greater size of the Earth. Paradoxically, it may have been thinner. Since the acceleration due to gravity is six times greater on the Earth than on the Moon, the pressure gradient inside the Earth is six times steeper (fig. 11). Plagioclase is unstable in mafic rock systems at pressures in excess of approximately 12 kb. In the Moon, plagioclase could have crystallized stably from a cooling mafic magma system to depths in excess of 200 km. For magmas of reasonable composition, this volume of magma could have crystallized enough plagioclase to form a crustal cumulate up to 100 km thick. In the case of the Earth, plagioclase instability begins at less than a 50-km depth. A layer thicker than this could not have formed.
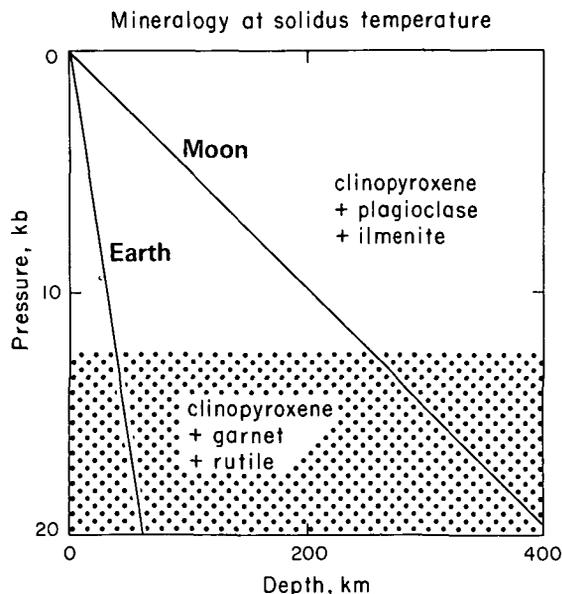

Figure 11.—*Relationship between depth and pressure in Earth and Moon. At greater than ~ 12 kb of pressure, plagioclase in crystallizing mafic rocks is unstable relative to denser garnet-bearing assemblages (Ringwood and Essene, reference 30).*

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