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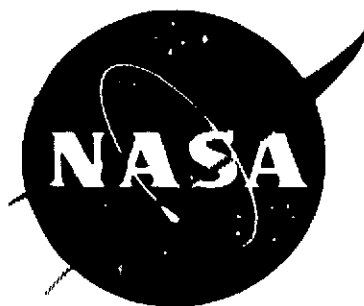
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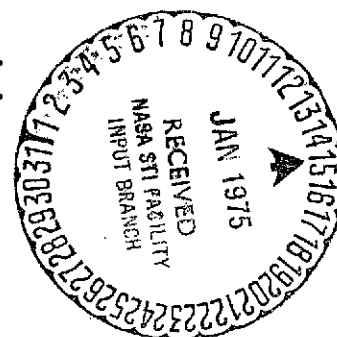
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A CHEMICAL MODEL FOR LUNAR NON-MARE ROCKS

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ABSTRACT

Nearly all rocks returned from the moon are readily divided into three broad categories on the basis of their chemical compositions: 1) mare basalts, 2) non-mare rocks of basaltic composition (KREEP, VHA), and 3) anorthositic rocks. Only mare basalts may unambiguously be considered to have original igneous textures and are widely understood to have an igneous origin. Nearly all other lunar rocks have lost their original textures during metamorphic and impact processes. For these rocks one must work primarily with chemical data in order to recognize and define rock groups and their possible modes of origin. Non-mare rocks of basaltic composition have chemical compositions consistent with an origin by partial melting of the lunar interior. The simplest origin for rocks of anorthositic chemical composition is the crystallization and removal of ferromagnesian minerals. We propose that the rock groups of anorthositic and non-mare basaltic chemical composition could have been generated from a single series of original but not necessarily primitive lunar materials.

INTRODUCTION

Lunar rock samples can be subdivided according to three important types of criteria: 1) the physiographic or geologic province where the sample was collected, 2) the petrographic features of the sample, and 3) its chemical composition. The lunar rocks thus far collected have come from three physiographic regions: 1) mare regions (Apollo 11 and 12), 2) a non-mare area (Apollo 14), and 3) a highland area (Apollo 16). The Apollo 15 and 17 sites were chosen to sample mare boundaries. In the broadest sense, two petrographic types of rocks have been returned: 1) rocks with igneous textures and 2) brecciated and metamorphosed rocks that are often visually polymict. Rocks with igneous textures were collected from all three physiographic regions but are scarce among the samples returned from the non-mare and highland regions. They are common, even characteristic, of the mare regions. Using chemical data, lunar rocks are readily separated into three major groups: 1) mare basalts, including a more aluminous feldspathic subcategory sometimes called "mare-like" basalts (Hubbard et al., 1971), 2) rocks with basaltic chemical composition but distinct from the chemical compositions of mare basalts and characteristicly brecciated, and 3) a group of rocks with broadly anorthositic chemical compositions.

The mare basalts, as the name implies, are typical of mare regions and have not been returned as large rocks from any other regions. In this paper the term "mare basalt" will be used to denote a combination of physiographic or geologic province, chemical composition and basaltic igneous texture, i.e. as commonly used. Mare basalts are not a major

topic in this paper and have been included mainly for contrast and comparison with other lunar rocks of basaltic chemical composition.

Other rocks of basaltic chemical composition have been returned as large rocks from the Apollo 14, 16 and 17 sites and were returned from the Apollo 12 and 15 sites as large fragments (rake fragments and coarse fines). The term non-mare basalt will be used to denote this group of samples because a prominant member of this group, KREEP, is typical of the non-mare Apollo 14 site. This group is identical to the KREEP plus VHA compositions defined earlier (Hubbard and Gast, 1971; Hubbard et al., 1973b). This usage broadens the range of chemical compositions indicated by Hubbard and Gast (1971) when they introduced the term "non-mare basalt" but continues to denote a group of lunar rocks with basaltic chemical composition which we believe records some of the earliest magmatic activity on the moon. The non-mare basaltic group contains three groups of samples that we have kept separate in earlier publications. They are the common Apollo 14 KREEP group at lower Al_2O_3 values, the Apollo 16/17 KREEP group at intermediate Al_2O_3 values and the VHA group at higher Al_2O_3 values. They are grouped together here because the purposes of this general paper are better served by emphasizing the similarities within the non-mare basaltic group of samples and the differences between this group and the mare basalt and anorthositic groups.

Large rocks with anorthositic chemical compositions have been returned from Apollo 15, 16, and 17 and are present as small fragments in the samples returned by Apollo 11, 12, 14 and Luna 20. A predominant subset of this group of rocks will be referred to as the Low-K Anorthositic Series (LKAS) (Hubbard et al., 1974). These rocks may be samples of

the oldest chemical compositions returned from the moon and appear to have been a major component in the lunar crust for at least the last 4.0×10^9 years (Nyquist et al., 1974).

The approach of this paper is to start with the returned rocks and to work backward in an attempt to deduce the chemical composition of the outer part of the moon before these rocks were formed. In doing this no assumptions are made about the material that formed the moon or about an early lunar differentiation.

PRESENTATION OF DATA

The chemical data used in this report were all obtained on samples of large rocks, large breccia clasts or rake samples. Data for soil samples are given in Figures 1, 2, 4 and 5 for comparison. The major element data are largely from X-ray fluorescence analyses and the trace element data are predominantly from stable isotope dilution mass spectro-metric analyses done in our laboratory, and reported in numerous papers by Hubbard and co-authors. Neutron activation and X-ray fluorescence data have been included when needed to fill critical gaps for the elements Eu and Sr.

Quality of Data

The quality of data from a purely analytical standpoint is best assessed using analyses of lunar soils. The chief advantage of this approach is that samples covering a broad range of chemical compositions were analyzed in an analytical environment that was "real" in the sense that these analyses were made in order to supply scientists with chemical

data for research purposes rather than to obtain data on rock standards for the purpose of interlaboratory comparison. The analyses were commonly performed without knowledge of other analyses of the same samples. In Table 1 we list the means and percent relative deviations for one soil sample with three or more chemical analyses from each Apollo mission. This comparison extends over the entire Apollo program and includes results from eight research groups. In an earlier paper (Rhodes and Hubbard, 1973) we documented the degradation of chemical data for mare basalts that resulted from the allocation of excessively small subsamples (commonly only 0.5 gm) of coarse grained Apollo 15 mare basalts. This sampling problem is severe when attempting to use such analyses to interpret the detailed petrogenesis of individual coarse grained mare basalts but less troublesome when studying mare basalts as a chemical group. In contrast, lunar rocks of non-mare and anorthositic chemical compositions contain so many complexities that it has not proven feasible to interrelate individual samples and their study is therefore largely limited to consideration of the chemical groups. The analyses of a large clast in a breccia of different composition is treated as a separate sample. The chemical analyses often reflect the heterogeneities due to the intimate but incomplete mixing of two different rocks with two widely different chemical compositions (61016, for example), and also reflect variability in the plagioclase/ferromagnesian ratio (67075, 14310, 65015, for example).

In order to test the re-producability of our trace element data we recently re-analyzed the very first lunar sample analyzed by us, 10084, and the first Apollo 12 sample analyzed by us, 12070. In all cases the

new values are within 12% of the original values and about 80% of the new values are within 5% of the first values. This comparison covers a four year period and a total change of laboratory, equipment and materials.

In view of the above results, we conclude that the chemical data used in this paper are fully adequate to support detailed study, with due respect for sampling problems, and are free of analytical error for the types of interelement comparisons and correlations made in this study.

The Data

Chemical data for soils are included in some figures for comparison and to demonstrate that lunar soils from the Apollo sites are composed of varying proportions of material, chemically similar or identical to the material found in the local rocks. However, estimates of the relative abundances of these rock types based on soil composition may differ drastically from their relative abundances in the returned sample collection (Rhodes et al., 1974). The three main chemical groups used in this paper have been recognized on several bases, including the chemical one used in this paper. Individual samples that are inconsistent with this broad chemical classification will be noted where considered appropriate.

In Figure 1 we have plotted data for FeO vs. Al_2O_3 which, with the exception of Ti, are the major elements that show the most variance in lunar rocks. The anorthositic rocks have a relatively well-defined inverse variation of FeO and Al_2O_3. Extrapolation of the $FeO-Al_2O_3$

trend seen in these rocks toward the non-mare basaltic rocks shows that the non-mare basaltic rocks generally have less FeO for a given Al_2O_3 value than predicted from the extrapolation, thereby demonstrating that non-mare basaltic rocks and anorthositic rocks are two populations and not simply one population with internal variation in plagioclase abundance. The mare basalts have, on the contrary, more FeO than expected from the extrapolation. In Figure 2 MgO is plotted vs. Al_2O_3, where it is shown that mare basalts have far less MgO than expected by extrapolating from the data for anorthositic rocks. Non-mare basaltic rocks show a wide range in MgO and Al_2O_3 concentrations with their range in MgO concentrations nearly identical to the range in MgO concentrations for mare basalts. Figure 3 shows MgO/FeO ratios vs. Al_2O_3 and demonstrates that anorthositic rocks have the widest range of MgO/FeO ratios of any group of lunar rocks and that the ranges of MgO/FeO ratios for non-mare and mare basalts are similar even though mare basalts have much lower MgO/FeO ratios. The range in MgO/FeO ratios in mare basalts suggests that the similar variations in the non-mare basalt group may also be due to fractional crystallization even though these samples have lost any original igneous textures. Figure 4 illustrates the variation of TiO_2 relative to Al_2O_3. The major features of this diagram are the steady rise in average TiO_2 concentrations in the series anorthositic rocks → non-mare basaltic rocks → Apollo 12 and 15 mare basalts and the three- to four-fold higher TiO_2 concentrations of the Apollo 11 and 17 mare basalts.

Figure 5 shows the variation of Th relative to Al_2O_3 and serves to make the transition between major element and trace element data and to

identify the non-mare basaltic rocks as the group of rocks that have

high concentrations of lithophilic trace elements such as Th, U, REE, .

Ba, Zr, etc.

The data for one set of lithophilic trace elements, the REE and Ba

are summarized in Fig. 6 for a wide range of Apollo 15, 16 and 17 non-

mare basaltic rocks and anorthositic rocks. The data in this diagram

can be divided into two major groups: 1) rocks with deep negative Eu

anomalies and high concentrations of REE and Ba and 2) rocks with almost

no Eu anomalies or positive Eu anomalies and low REE concentrations. Not

surprisingly, the samples in group 2 have anorthositic major element

chemistry and are the anorthositic samples in Figs. 1 thru 5. The

samples in group 1 are the non-mare basaltic rocks (KREEP, VHA) that

cluster together in terms of major element variables (Figs. 1 thru 5).

Taken together, the data in Figs. 1 and 6 amply demonstrate that non-

mare basaltic rocks and anorthositic rocks are two separate chemical

groups.

Rare earth, Ba, U and Sr data are presented in Fig. 7 for anortho-

sitic rocks only. There is a high degree of regularity in the REE, Ba

and U abundance patterns of these rocks, in that the concentrations of

REE, Ba and U generally decrease with increasing Al_2O_3 concentrations,

suggesting that we may be dealing with a series of anorthositic rocks

where the major chemical variations are a function of plagioclase concen-

tration. However, some samples deviate from the simple requirements of

an anorthositic series, in this case a specific correlation of REE

abundance patterns with Al_2O_3 vs. Eu, Sr and Sm (Hubbard et al., 1974).

Further subdivision or reduction to conditional membership in the main

subgroup is made on other chemical parameters such as the slope of the trivalent rare earth abundance patterns, MgO/FeO ratio, and abnormally low or high concentrations of any rock forming element like Si, K, Ti, Cr, etc. On this basis we can immediately reject 63335,36, 15459,38, 61295,34, 68415,10 and 63549,2 from the rest of the samples because 63335,36 has an abnormal Eu anomaly, 15459,38 has too much Eu, Sr and Sm for its Al_2O_3 concentrations, as do 61295,34, 68415,10 and 63549,2. Samples 15418, 67075 and 15445,17 are conditionally retained with the majority of samples. even though sample 15418 has low Sm for its Al_2O_3 value of 26% and also has a flatter trivalent rare earth pattern. Sample 67075,53 also has a flat trivalent rare earth pattern and has the lowest MgO/FeO ratio of anorthositic samples included in this study, and sample 15445,17 has low Al_2O_3, a high MgO/FeO ratio and a high SiO_2 concentration. The white portion of sample 15445 (Taylor et al., 1973) has not been included in the LKAS group because of its high MgO/FeO ratio, low TiO_2, very high Eu concentration and the steep slope of its trivalent rare earth pattern. There are more than 10 samples remaining, after the deletions, with a simple and regular pattern of major and trace element chemical compositions. These have been named the Low-K Anorthositic Series (LKAS). This series has been proposed to be a major subset of anorthositic lunar rocks (Hubbard et al., 1974).

A thorough consideration of the behavior of Eu in lunar rocks requires accurate knowledge of the $Eu^{+3/+2}$ ratio during petrogenesis. Lunar rocks formed in rather reducing conditions, i.e. about 10^{-13} atms.

of oxygen partial pressure at temperatures about 1200°C (Sato et al.,
1973), and it is reasonable to assume, as is commonly done, that Eu
is largely divalent. A plot of Eu vs. Sr (Fig. 8) and the overall rare
earth data shown in Fig. 6 provide fundamental information about the
ratio of $Eu^{+3/+2}$ in the lunar petrogenetic environment for non-mare
and anorthositic rocks. If Eu was entirely divalent during lunar
petrogenesis then Eu should closely follow Sr. Instead, Eu has a much
wider range of concentration than Sr in lunar non-mare and highland
rocks. If one considers that this is due to the presence of substantial
Eu^{+3} then the rare earth data in Fig. 6 allow one to estimate that
the percentage of Eu that is trivalent is 10 to 20% on the assumption
that trivalent Eu is intermediate between trivalent Sm and Gd in its
chemical behavior. Some recent experimental work is directly relevant
to this question. Morris and Haskin (1974) found that for a fixed p_{O_2}
the $Eu^{+3/+2}$ ratio is strongly dependent on the bulk composition for
glasses in the compositional range from anorthite to Ca-Mg pyroxene.
Specifically, the nearer the glass composition to the pyroxene end
member the higher is the $Eu^{+3/+2}$ ratio. Related research by Morris et
al. (1974) found that even in glass of anorthite composition $(CaAl_2Si_2O_8)$
at 1370-1600°C the Eu^{+3} was about 10% of the total Eu at $p_{O_2} = 10^{-12}$ and
about 4% of the total at $p_{O_2} = 10^{-14}$. Thus even a pure anorthite liquid
at lunar p_{O_2} may have a few percent of trivalent Eu. Glass of diopside
composition $(CaMgSi_2O_2)$ at 1450°C at $p_{O_2} = 10^{-14}$ was found to have

$Eu^{+3/+2}$ ~0.5. These experimental data suggest that silicate liquids on the moon of non-mare basaltic composition (KREEP-VHA), i.e. 50% or less pyroxene, will have about 1/4 or less of their Eu in the trivalent oxidation state, thus substantiating the above interpretation of the chemical data for lunar rocks.

THE CHEMICAL MODEL

Introductory Remarks

This model is primarily concerned with the origin of the non-mare basaltic and anorthositic rocks. There will be no attempt to further decipher the genesis of mare basalts. With both the non-mare basaltic and anorthositic rocks there is a fundamental need to directly determine which rocks have had their chemical compositions seriously contaminated by material from non-cogenetic rocks and the nature and extent of such contamination. Typically for current studies of lunar rocks, such data are almost non-existent for the chips of samples used in this study. It is expected that accurate and verifiable knowledge of such contamination will result in a sharper view of the chemical processes described in this paper because the "noise" introduced by contamination will be reduced and seriously contaminated rocks can be excluded from this type of study. Impact related mixing processes are the accepted means of mixing (i.e. contaminating) non-cogenetic lunar rocks, as well as mixing the members of a cogenetic suite of rocks.

There is an apparent paradox in that there is an extensive cratering history in the lunar highlands (Short and Forman, 1972), which is consistent with the brecciated nature of nearly all lunar samples except mare basalts,

and yet the bulk of the chemical data shown in this paper are compatible with igneous processes, suggesting that igneous processes have produced a wide range of chemical compositions. From this we conclude that igneous processes were either more effective or lasted longer than the homogenizing effect of impact processes, or perhaps simply that impact mixing was not adequately efficient to erase the chemical record. This apparaent paradox between the extensive cratering record and the extensive range of chemical compositions seen among the non-mare and highland rocks, as well as the existence of preferred chemical groups, has lead one group of researchers (Warner et al., 1974) to propose that the impacts both homogenize (through mixing) and differentiate (through partial fusion) the material involved in the impact. We find it difficult to accept the hypothesis that impact events can produce the observed abundance of material that has an apparent igneous origin because of a lack of evidence that impact processes cause significantly more igneous differentiation than mixing. Since mixing reverses the processes of differentiation, Warner et al. (1974) are dependent on an unproven efficiency of impact related differentiation.

Mixing processes must operate on existing material and, if mixing processes are of any importance, that material must have initially had at least as wide a range of chemical composition as presently observed because mixing processes will decrease the probable range of chemical compositions available for sampling. The observed range of chemical compositions was either produced on the moon or already existed in the material that accreted to form the outer tens to hundreds of kilometers of the moon or some combination of the two possibilities. At least one

model (Wood and Mitler, 1974) proposes that the moon was made from
partially disrupted pre-existing planetary bodies and thus provides
for lunar material that has a pre-lunar igneous history. In the absence
of unambiguous data to the contrary and for simplicity, we presume that
igneous differentiation on the moon was the cause of the range of
chemical compositions observed in the non-mare basaltic and anorthositic
rocks and, that homogenization due to impact related mixing has been
minimal. We will describe what we consider to be the general features
of that differentiation. We believe that the hypothesis we have chosen
to emphasize has the greatest potential for revealing fundamental internal
lunar processes and evolution. In this paper we will not consider heat
sources that could have caused the inferred igneous differentiation.
If an igneous interpretation of the chemical data is correct then an
adequate heat source must have existed and current interpretations of
the Rb-Sr data (Nyquist et al., 1972, 1973, 1974) suggest that the heat
source was adequate about 4.3×10^9 years ago.

The Model

We will first consider the non-mare basaltic and anorthositic groups
independently and then combine the requirements of these groups in order
to arrive at an overall model. The genesis of mare basalts will not be
discussed below. Interested readers are referred to Hubbard et al.
(1974) and earlier papers where we have presented arguments for the
generation of mare basalts from a different source material than non-
mare basaltic rocks and proposed that much of the inferred chemical
differences were the result of heterogeneous accretion of the outer part

of the moon.

Non-mare basaltic rocks. This group of rocks is identical with the KREEP and VHA rocks described earlier (Hubbard and Gast, 1971; Hubbard et al., 1971, 1972, 1973, 1974). The recent experimental paper of Walker et al. (1973a) provides the clearest insight into the origin of the non-mare basaltic rock types so far as major elements are concerned. Briefly, they are the result of partially melting any of a wide range of rocks having variable amounts of plagioclase, pyroxene, olivine and for the VHA samples sometimes spinel. The deep negative Eu (also Sr) anomalies of these rocks are explained as the result of partially melting plagio-clase bearing source rocks that retain significant plagioclase in the residue after the partial melting episode (Hubbard and Gast, 1971). These samples have a characteristic slope in their trivalent rare earth abundance patterns (chondrite normalized La/Yb $\simeq$ 2.0). This was initially explained (Hubbard and Gast, 1971) as the result of partially melting a plagioclase, clinopyroxene, olivine source rock to a very limited extent (only a few percent liquid generated). This specific partial melting model depended on the combination of clinopyroxene and small amounts of liquid to produce the observed La/Yb slope from material that had the rare earths in absolutely chondritic relative abundances. Even with the enrichments provided by the small amounts of liquid produced, this model requires the source to have about tenfold chondritic concentrations. However, clinopyroxene is absent or of minor importance in both non-mare basaltic and anorthositic rocks, as well as in their probable source materials and their P-T conditions of origin (Walker et al., 1973a, b), thus invalidating partial melting models that depend on clinopyroxene

for fractionation of the La/Yb ratio. Recently Hubbard and Shih (1973, and in preparation) considered partial melting models that are more realistic for lunar non-mare basaltic samples, i.e. no clinopyroxene, and in addition, distribution coefficient data obtained using phenocrysts were preferred to those obtained using high pressure metamorphic mineral pairs. The resulting model, using only plagioclase, olivine and orthopyroxene does very little differentiation of the La/Yb ratio, essentially transmitting the trivalent rare earth abundance pattern of the unmelted source material into the liquid. It is possible to use an orthopyroxene rich source material (Fig. 9) to produce La/Yb ratios approaching the observed ratios from a source material with chondritic relative abundances of the rare earths but, only with the generation of 1% or less liquid. Increasing the plag/opx ratio of the source reduces the La/Yb ratio of the liquid as does the generation of larger percentages of melt. This model requires that the observed La/Yb ratio and the characteristic slope of the trivalent rare earth abundance pattern must have already been in the source material. The deviation from absolutely chondritic relative abundances for the rare earths is not large, in fact only requiring La to be 1.35 X and Yb 0.675 X chondritic. Since the chemical compositions of the returned lunar samples are grossly non-chondritic, this deviation is quite permissible. Partial melting events that produce about 4-5% of liquid (Fig. 9) have about 20 fold more rare earths, etc. in the liquid than in the initial material and can thus produce even the rare earth concentrations in Apollo 14 KREEP if the initial material had 10 fold chondrite concentrations of these elements.

There is an inverse correlation between Al_2O_3 and Eu and the trivalent rare earths within the non-mare basaltic group of rocks for the series VHA through Apollo 16/17 KREEP to Apollo 14 common KREEP (Figs. 1, 6 and 8 and Hubbard et al., 1974). This can be explained by coupling the pseudoternary silica-anorthite-olivine diagram of Walker et al. (1973a) with trace element derived partial melting model calculations. On the pseudoternary diagram the series of compositions from Apollo 14 common KREEP to Apollo 16/17 KREEP to VHA become more aluminous and move toward higher liquidus temperatures. The Eu and trivalent rare earths decrease in this series which, in terms of partial melting models, implies increasing percentages of liquid (melting), which in turn is consistent with the higher liquidus temperatures of the more Al_2O_3 rich compositions. This is not meant to imply that the entire series of chemical compositions within the non-mare basaltic group was generated from a single source material but rather that many of the predictable chemical features are consistent with this concept, even though some allowance must be made for the MgO/FeO ratio differences (Walker et al., 1973a). Schemes that properly combine partial melting models and experimental data require that partial melting models be tuned to produce the observed variations in major element chemical composition and attendant changes in the permissible mineralogical composition of the source material. This is presently very difficult to do for the observed wide range in MgO/FeO ratios but has been taken into consideration for plagioclase/orthopyroxene/ olivine ratios.

The Anorthositic Group

The LKAS subset of the anorthositic samples was anticipated by Hubbard et al. (1971) when they calculated the REE, Ba and Sr concentration in a hypothetical silicate liquid in equilibrium with anorthosite sample 15415. The crystal plus equilibrium liquid model behind those calculations is still the most satisfatory chemical explanation of the internal, plagioclase-related chemical variations. Samples like 77017 and 66095,37 have major and trace element compositions approximating the equilibrium liquid of the model.

It is easier to say, with qualifications, how the group of rocks with anorthositic chemical compositions were not formed than how they were formed. Although the major cause of internal chemical variations is clearly a result of plagioclase control, the anorthositic group itself is probably not the result of plagioclase fractional crystallization because of the consistent lack of negative Eu and Sr anomalies for this group. One could avoid this constraint by assuming a precursor with positive Eu and Sr anomalies, that is, by assuming an even more Al_2O_3 and plagioclase rich precursor and further increasing the difficulty of accounting for these rocks. The consistent lack of negative Eu and Sr anomalies also rules against the production of this group by partial melting because again negative anomalies in the observed rocks and more Al_2O_3 and plagioclase precursors are the predicted result. If the process is to be igneous we are left with either plagioclase accumulation or fractional crystallization of ferromagnesian minerals. Plagioclase accumulation due to flotation of plagioclase has been popular (Wood et al., 1970; Smith et al., 1970) but it remains unproven that plagioclase

will float in feldspathic silicate liquids. On the other hand, ferro-magnesian minerals will almost surely sink unless there is a prohibitive mush of earlier crystallizing plagioclase. A prohibitive mesh of plagioclase crystals is increasingly likely as the Al_2O_3 concentration increases thus progressively reducing the efficiency of this process as more feldspathic compositions are reached. So long as sinking of ferromagnesian minerals is the proposed mechanism for generating the anorthositic group and plagioclase does not move relative to the liquid, and we have no knowledge of the olivine/pyroxene ratio, then the MgO/FeO ratio of the parental material is very poorly defined. Although likely it is not essential that the parent material have plagioclase on the liquidus but it must have had an even higher MgO/FeO ratio than presently found in anorthositic lunar rocks in order to allow removal of ferromagnesian minerals, especially extensive removal. If extensive removal of ortho-pyroxene occurred then the La/Yb ratio would have been increased some-what, but probably no higher than 1.5 times the initial ratio in the source material (Hubbard and Shih, in prep.). Also, if large volumes of material were removed by the fractional crystallization of ferromagnesian minerals then the initial Eu and Sr concentrations would have been lower and the early crystallizing plagioclase crystals would have had to completely re-equilibrate in order to produce the observed consistent minimum concentrations of Eu and Sr. This difficulty decreases as the amount of ferromagnesian minerals removed decreases, after the onset of plagioclase crystallization. In summary we consider the removal of ferro-magnesian minerals to be the most reasonable means of making the anorthositic rocks on the moon, or any other similar planetary body, mainly because

the alternate means considered here are even less probable. An additional
alternative is to provide a precursor that has a chemical composition
very near to or within the field of compositions for anorthositic rocks.

A Common Precursor

The chemical similarities of the parental materials inferred for the
non-mare basaltic and anorthositic chemical groups is suggestive of a
common precursor for these groups. It does not seem possible to describe
material with a single chemical composition because some of the require-
ments of the two groups are mutually inconsistent, in particular the
inferred initial concentrations of rare earths and related lithophile
trace elements. However, definition of a series of closely related
precursors seems appropriate and possible at the present time. The goal
is to define the limits of a probable set of lunar materials that could
have been parental to the chemical groups observed in the returned lunar
samples. The result of this exercise is expected to change, perhaps
radically, as further data are obtained and the approach is further
developed.

First, the materials do not have to be plagioclase rich. Thirty
percent plagioclase is adequate to produce the observed deep negative
Eu and Sr anomalies of the non-mare basaltic group and the ferromagnesian
fractional crystallization deduced for the anorthositic group can produce
the required plagioclase enrichments. Conversely, nothing prohibits a
plagioclase rich material so long as the requirements imposed by large
percentages of plagioclase are not considered prohibitive. The natural
limit on plagioclase enrichment is reached when it becomes prohibitively

difficult to produce an adequate volume of the non-mare basaltic composition liquid, probably around 70% plagioclase.

Second, the pyroxene/olivine ratio is not very well determined and neither is the MgO/FeO ratio, although the MgO/FeO ratio must be greater than about 1.5 in order to produce liquids with MgO/FeO greater than 1.5. Ratios of MgO/FeO increasingly greater than 1.5 are probably compatible with decreasing pyroxene/olivine ratios.

Third, there is no independent way of postulating the trace element concentrations and ratios of these lunar materials unless one adopts a specific model for making the material which was later incorporated into the moon. We have adopted no such model because we are attempting to work backwards from the chemical compositions of analyzed lunar rocks. This approach requires that the parental material for the non-mare basaltic group had REE concentrations at least 10 fold chondritic concentrations for the Apollo 14 type KREEP to perhaps as little as 3-4 fold chondritic concentrations for the VHA compositions, if the rare earth concentrations are to be produced by single stage partial melting and the problems of extracting very small percentages ($\sim$1%) of liquid are to be avoided. A source with 10 fold chondritic concentrations of REE can also be used as the source for the Apollo 16/17 type KREEP and VHA basaltic compositions. The anorthositic rocks require parental material with less than 10 fold chondritic concentration for the LKAS subgroup and similar concentrations for the other samples. Three to five fold lower concentrations are possible if extensive fractional crystallization occurred during the genesis of these rocks.

In summary, the plausible outer bounds for a set of precursors that

could have been parental to the non-mare basaltic group and the anorthositic group are quite far apart. The plagioclase concentration could be as low as about 30% or as high as about 75%, the Al_2O_3 concentration could be as low as about 10% or as high as about 26%. The MgO/FeO ratio can only be constrained to be greater than 1.5 and can be highly variable. Concentrations of lithophile trace elements may be as low as 3-fold chondritic values or as high as more than 10-fold. This wide range in chemical composition is easily converted into a set, or spectrum, of compositions if the realistic assumption is made that the concentration of lithophile trace elements is inversely correlated with plagioclase concentration. However, if the anorthositic rocks require a plagioclase rich source material with nearly 10 fold chondritic concentrations of rare earths, etc. then the series cannot be so simple as just suggested. Although we consider it improbable that the precursor for non-mare lunar rocks was as simple as deduced here, we do consider a precursor consisting of a related series of chemical compositions to be much more reasonable than one with a single chemical composition. The old Rb-Sr model ages of the KREEP rocks and the low initial $Sr^{87/86}$ ratios of some anorthositic samples suggests that this precursor may be original lunar material (Nyquist et al., 1972, 1973, 1974).

If the type of precursor suggested here is basically correct then the hypothesized increase of rare earths, etc. with ferromagnesian content implies that it was not produced by crystal accumulation because the relevant minerals, orthopyroxene, olivine and plagioclase all reject rare earths (except Eu^{+2}) to a very similar extent. We are left with two poorly defined possibilities: 1) the precursor was a residual liquid

produced by extensive differentiation of the moon or 2) the precursor was the material that accumulated to form the outer part of the moon, altered by thermal metamorphism prior to melting. In view of the inferred old ages for the chemical compositions of lunar non-mare rocks (Nyquist et al., 1972, 1973, 1974) this approach may get us as close as any to the chemical composition of original lunar crustal material and is certainly more comprehensive than approaches using individual and unique lunar rocks such as 76535, 72415, or 15415 for example.

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TABLE 1:   PRECISION OF MAJOR ELEMENT DATA FOR LUNAR SOILS.

	10084		12070		14163		15101		66081		72701	
	Mean	Rel. Dev.*	Mean	Rel. Dev.*	Mean	Rel. Dev.*	Mean	Rel. Dev.*	Mean	Rel. Dev.*	Mean	Rel. Dev.*
	N = 9		N = 6		N = 6		N = 4		N = 3		N = 4	
SiO_2	41.98	0.6	45.83	0.2	47.66	0.9	46.21	0.3	44.97	0.9	45.13	0.6
TiO_2	7.49	1.7	2.81	0.7	1.80	2.6	1.31	5.2	0.67	0.9	1.53	2.5
Al_2O_3	13.75	2.1	12.71	1.6	17.45	1.6	17.55	0.7	25.99	0.8	20.64	0.4
FeO	15.83	0.8	16.52	1.2	10.26	1.3	11.61	0.9	5.99	2.5	8.84	1.7
MnO	0.21	3.7	0.22	2.3	0.14	2.9	0.16	0.0	0.08	0.0	0.12	5.3
MgO	7.90	1.6	10.14	3.3	9.29	0.9	10.32	1.9	6.40	0.6	9.95	0.6
CaO	12.02	0.8	10.45	0.4	10.95	2.0	11.63	0.9	15.17	1.1	12.77	0.5
Na_2O	0.44	8.4	0.45	9.7	0.70	9.1	0.40	6.5	0.48	21.5	0.46	10.8
K_2O	0.14	10.4	0.25	6.2	0.57	2.7	0.18	5.4	0.14	8.5	0.16	4.8
P_2O_5	0.10	26.5	0.31	6.9	0.50	4.8	0.16	15.4	0.13	15.4	0.15	4.0
S	0.13	8.4	0.09	29.4	0.09	9.1	0.07	20.8	--	--	0.07	16.4
Cr_2O_3	0.30	7.9	0.41	13.0	0.21	13.5	0.29	21.0	0.13	--	0.22	11.4
Total	100.29		100.19		99.62		99.89		100.15		100.04	

Source of data:

10084: Agrell et al., (1970); Compston et al., (1970); Engel and Engel (1970); LSPET (1972); LSPET (1973b); Maxwell et al., (1970) Willis et al., (1972).

12070: Compston et al., (1971); Cuttita et al., (1971); LSPET (1972); Willis et al., (1971).

14163: Chappell (1972); LSPET (1972); Rose et al., (1972); Schnetzler and Nava (1971); Wiik et al., (1973); Willis et al., (1972).

15101: Carron et al., (1972); LSPET (1972); Scoon (1972); Willis et al., (1972).

66081: Compston et al., (1973); LSPET (1973a); Rose et al., (1973).

72701: Duncan et al., (1974); LSPET (1973b); Rhodes et al., (1974); Scoon (1974).

*Standard deviation (1σ) expressed as a percentage of the mean.

Fig. 1. FeO vs. Al_2O_3 for lunar rocks and soils. Data are from
Compston et al. (1971), Cuttitta et al. (1971), Duncan et al. (1973),
Hubbard et al. (1972, 1973a,1974), LSPET (1972, 1973a, 1973b),
Rhodes and Hubbard (1973), Rhodes et al. (1974), Rose et al.
(1972, 1973) and Willis et al. (1971, 1972).

Fig. 2. MgO vs. Al_2O_3 for lunar rock and soils. Data are from the
same sources as for Fig. 1.

Fig. 3. MgO/FeO ratio vs. Al_2O_3 for lunar rocks. Note that the rocks
with the highest Al_2O_3 concentrations have the widest range in
MgO/FeO ratios. Data are from the same sources as for Fig. 1.

Fig. 4. TiO_2 vs. Al_2O_3 for lunar rocks and soils. Note that only
the Apollo 11 and 17 mare basalts and associated soils have TiO_2
values greater than 6.0%. Data are from the same sources as for
Fig. 1.

Fig. 5. Th vs. Al_2O_3 for lunar rocks and soils. This plot serves to
demonstrate that it is the non-mare basaltic group of rocks that
have high concentrations of lithophile trace elements such as Th,
U, rare earths, Ba, Zr etc. Data are from the same sources as
for Fig. 1 plus numerous other papers published in the Lunar
Science Conf. Volumes.

Fig. 6. Rare earth and Ba data for a large number of Apollo 15, 16 and
17 rocks. The main features of these data are that the rocks with
deep negative Eu anomalies belong to the group of non-mare basaltic
rocks in Figs. 1 thru 5 and the rocks with positive Eu anomalies
belong to the anorthositic group in Fig. 1 thr 5, as do samples
68415 and 61295. All of the data are from publication by Hubbard
and co-workers.

Fig. 7. Rare earth, Ba, U and Sr data for anorthositic rocks from Apollo
15, 16 and 17. Nearly all of the data are from Hubbard et al. (1974)
and the remainder are from earlier publications. In order of increasing
Sm concentrations, the samples plotted are: 61016, plag, 67075,53,
64435,59, 15418,30,03, 66095,37, 15418,30,07A, 76230,4, 63335,36,
61016,3, 77017,2, 15445,17, 78155,2, 67955,56, 76315,62, 68415,10,
63549,2, 15459,38, and 61295.

Fig. 8. Eu vs. Sr for the entire range of non-mare basaltic and anortho-
sitic lunar rocks. If Eu were entirely divalent and the lunar rocks
were formed from a common parent with a single Eu/Sr ratio, then this
Eu vs. Sr plot should be very nearly a single narrow band of data
points. Instead, for a two-fold range in Sr concentration there is
a four-fold range in Eu concentrations. As discussed in the text,
this greater range in Eu concentrations is explained as the result
of 10-20% of the Eu having been in the trivalent oxidation state during
magma genesis.

Fig. 9. Two partial melting models that are capable of producing the range of trivalent rare earth concentrations observed in the non-mare basaltic group of rocks. See Gast (1973) for the most recent version of the old clinopyroxene bearing models. Sr serves to indicate the behavior of Eu^{+2} which is not plotted in order to emphasize the trivalent rare earths.

APOLLO-15 ROCKS

A-15 KREEP
15314,77
15273,4.3
15304,33
15459,38
15445,17
15418,30,03

APOLLO-16 ROCKS

A-16 KREEP
VHA
61295,34
68415
67955,36
66095,37
67075,53

APOLLO-17 ROCKS

A-17 KREEP
72275,2
73235,55M
76315,62
76055,5
78155,2
76230,4
77017,2

CONC. IN SAMPLE/CONC. IN CHONDRITES

300
200
100
70
50
30
20
10
7
5
3
2
1

Ba Ce Nd Eu Dy Er Yb
  La   Sm Gd

Ba Ca Nd Eu Dy Er Yb
  La   Sm Gd

Ba Ce Nd Eu Dy Er Yb
  La   Sm Gd

ANORTHOSITIC ROCKS
A-15, A-16, A-17

15459,38
61295
64435,59
67075,55
61016 PLAG