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THE COMPOSITION AND ORIGIN OF THE MOON

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> "There are more things in heaven and earth, Horatio, than are dreamt of in your philosophy."
>
> Shakespeare:Hamlet

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Abstract

Many of the properties of the moon, including the "enrichment" in Ca, Al, Ti, U, Th, Ba, Sr and the REE and the "depletion" in Fe, Rb, K, Na and other volatiles can be understood if the moon represents a high temperature condensate from the solar nebula. Thermodynamic calculations show that Ca, Al and Ti rich compounds condense first in a cooling nebula. The initial high temperature mineralogy is gehlenite, spinel, perovskite, Ca-Al-rich pyroxenes and anorthite. Inclusions in Type III carbonaceous chondrites such as the Allende meteorite are composed primarily of these minerals and, in addition, are highly enriched in refractories such as REE relative to carbonaceous chondrites. These inclusions can yield basalt and anorthosite in the proportions required to eliminate the europium anomaly, leaving a residual spinel-melilite interior. A high Ca-Al deep interior does <u>not</u> imply an unacceptable mean density or moment of inertia for the moon. The inferred high U content of the lunar interior, both from the Allende analogy and the high heat flow, indicates a high temperature interior. The model is consistent with extensive early melting, shallow melting at 3 A.E., and with presently high deep internal

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temperatures. It is predicted that the outer 250 km is rich in plagioclase and FeO. The low iron content of the interior in this model raises the interior temperatures estimated from electrical conductivity by some 800°C.

1. Introduction

The low iron content of the moon, compared to terrestrial, solar or meteoritic abundances, has lead to many discussions of metal-silicate fractionation mechanisms in the solar nebula and has been used as an argument for both a fission and a capture origin for the moon. The Surveyor and Apollo missions have shown that the composition of the moon is anomalous on other counts. It is depleted in volatiles, as well as iron, and is enriched in refractories. This is true not only for the surface rocks but for their source regions as well and therefore applies to a considerable fraction of the lunar interior. Therefore, it is clear that more than just metal-silicate fractionation is required in order to create a moon from solar or "cosmic" abundances. Although many and diverse proposals have been put forth to explain the bulk and surface chemical properties of the moon, most of them assume that material of chondritic composition was important sometime in the moon's ancestry.

For example, Ringwood [1] proposed that the moon formed primarily from material that vaporized in a massive primitive terrestrial atmosphere. In the terminal stages of accretion of the earth Fe would be selectively retained by the earth but SiO and Mg, along with conventional volatiles, would enter the atmosphere. Magnesium silicate and silica precipitated before the other volatiles and collected into planetesimals. These planetesimals would have been selectively depleted in uranium and thorium because of their lower volatility. It was proposed that the moon accreted cold from a mixture of iron-poor magnesium silicates and planetesimals of primitive origin (Type 1 carbonaceous chondrites). He predicted that iron-free enstatite and quartz would be the most abundant minerals on the moon. Ca and Al, because of their low volatility would be selectively retained, with Fe, by the Earth. The low radioactive content would lead to a permanently cold interior, which would therefore retain the volatile compounds. The hypothesis was modified when it was found that the moon is a refractory rich planet [2]. It was proposed that the less volatile material accreted into chunks and the more volatile material remained as "smoke" which was blown away by a conjectured T-Tauri phase of the sun. In a later paper Ringwood and Green [3] proposed that the interior was carbonaceous and the exterior refractory. We put forth the alternate hypothesis that the bulk of the moon is composed of those elements and compounds that condensed prior to the condensation of iron. Iron, $MgSiO_3$, Mg_2SiO_4 and the volatiles were incorporated into the interior in only minor amounts and, probably, only during the terminal stages of accretion. The outer part, ~ 250 km, of the moon, in our model, is almost identical to that proposed by Gast [4] on geochemical grounds. However, the deep interior is CaO and Al_2O_3 rich and is dominantly diopside, merwinite and spinel. This assemblage has acceptable densities and is stable to higher pressures than the Ringwood-Essene low Ca-Al model lunar pyroxenite.

2. Boundary conditions

Important constraints have been placed on the origin of the moon and the evolution of its crust and mantle from detailed geochemical and geophysical studies:

1. The chemistry of the lunar igneous rocks suggest that they are derived from a feldspathic, refractory element-rich, pyroxene-rich interior [4].
2. The liquids which preceded most lunar rocks were produced by processes that involved extensive separation of igneous liquids and crystalline solids [4].
3. That part of the moon that was involved in the formation of the surface rocks was deficient in volatile elements including Rb, Na and K compared to carbonaceous chondrites.
4. A major fractionation occurred at ~ 4.6 AE which resulted in the creation of a high K, Rb, U, Th and REE crust [5]. The interior initially supplied Fe-poor and Al-rich materials. Later volcanism, 3.0-4.0 billion years ago, supplied very Fe-rich materials.
5. The so-called LIL elements (large ion lithophile) such as K, Rb, Cs, Ba, U, Th, Ree and Sr are enriched in the source region of lunar igneous rocks by a factor of 5-20 times chondritic abundances [4].
6. The composition and temperature of the deep interior must be consistent with the observed mean density and moment of inertia.
7. The outer ~ 200 km of the moon has had some strength for about 3.7×10^9 years in order to explain the persistence of mascons. The stronger constraint of a cold deep interior has been removed by Anderson and Hanks [6].

These constraints can be satisfied with the refractory model discussed in this paper.

3. Composition of the Moon

The enrichment of the moon in refractories and deficiency in volatiles is now well documented [7]. These characteristics are not limited to the surface materials but apply also to their source region which may involve the outer several hundred kilometers or 30% of the moon [4]. The enrichment of refractories is so great, compared to carbonaceous chondritic abundances, that it has been proposed that a refractory rich outer layer, rich in Al and trace element-rich materials, was accreted late in the formation of the moon [3,4,5]. The great thickness (~ 60 km) of the lunar "crust" as measured from the lunar seismic experiment [8] also suggests that a large part of the moon was involved in the differentiation or fractionation process. The degree of partial melting required to produce the Apollo basalts is probably in the range of 3 to 30% [4,9]. If the crust is mostly basalt and anorthosite, very extensive differentiation of most if not all of the moon is required. The high heat flow [10] suggests that the high concentration of U is not just a near surface phenomenon but must extend to a depth at least as great as the thermal diffusion length, ~ 100 - 300 km. Therefore the enrichment of Ca, Al and U and probably the other refractories such as Ba, Sr, and REE occurs for a substantial fraction of the moon and may be a property of the moon as a whole. That is to say the whole moon may be refractory and represent a high temperature condensate from the solar nebula.

Gast [4] and Ringwood [2] have proposed inhomogeneous accretion models in which the interiors of the Earth and the moon were initially more volatile rich than the exteriors. This is the reverse of the accretion-during-condensation sequence proposed by Clark et al. [11] and developed by Anderson [12,13] and Anderson and Hanks [14]. There is abundant evidence that the surface rocks of the moon and their inferred source regions are enriched in refractories and depleted in volatiles but it does not follow, and there is no evidence to support, a volatile rich interior, either initially or at present. Gast and McConnell [15] following Wetherill [16] and Ringwood and Essene [9] believe that the whole moon cannot be rich in Ca and Al because of the presumed inversion to eclogite at modest pressures. They therefore proposed, as have others, that the primitive moon had a more ferromagnesium interior composition that accreted from material that separated from the solar nebula at low temperatures and the interior may approach chondritic composition. We will show that this inference is invalid and that the whole moon may, in fact, have the characteristics determined by Gast [4] to be appropriate for the outer shell.

Element by element comparison of lunar basalts with carbonaceous chondrites have been made by many workers (see for example, the summaries by Mason and Melson [17] and Ganapathy et al. [18]). The basalts are clearly enriched in refractories and depleted in volatiles compared to chondrites. If we quantify the terms "refractory" and "volatile" in terms of condensation temperature from a gas of solar composition the cutoff seems to occur in the vicinity of iron and K-feldspar or ~ 1470°K [for $P_T = 10^{-3}$ atm]. The bulk of the moon is clearly deficient in iron relative to solar or chondritic abundances and, considering that K is probably concentrated toward the surface, the bulk moon is likely also to be depleted in potassium; the K/U, a volatile/refractory pair, ratio is lower than terrestrial or chondritic values.

Figure 1 summarizes the well known basalt-chondrite relations and shows, in addition, that the lunar anorthosites are also enriched in the refractories and depleted in the volatiles. In this figure the circles and the solid lines refer to lunar vs. carbonaceous chondrites. Note that only a few of the data bars - representing the range exhibited by lunar anorthosites and basalts-straddle the 45° line. The triangular data points and the dashed lines are the same lunar data plotted against Ca-Al rich inclusions of the Allende meteorite. We will discuss these inclusions in detail in Section 5. There is a very good agreement between the lunar surface rocks and the Allende inclusions for both the major and the trace element refractories.

4. Properties of the early condensate

The condensation sequence of elements and compounds from a cooling cloud of solar composition has been calculated by Larimer [19], Lord [20] and Grossman [21]. The early condensates (Table 2) are Al, Ca and Ti compounds such as gehlenite ($Ca_2Al_2SiO_7$), spinel ($MgAl_2O_4$) and perovskite ($CaTiO_3$). These compounds all condense before iron. The relative absence of iron in the moon suggests that it may have accreted from these compounds. Under non-equilibrium or lower pressure conditions such compounds as diopside ($CaMgSi_2O_6$), forsterite (Mg_2SiO_4) and anorthite ($CaAl_2Si_2O_8$) also condense before iron. The early condensates will therefore be enriched in Ca, Al and Ti relative to Mg, Si and Fe which are the main constituents of the earth's mantle and chondritic meteorites. They will also probably be enriched in the REE and other refractories which substitute readily for Ca, and may be enriched in Th and U which are relatively refractory. K_2O, S, Na_2O, S, H_2O and other volatiles will be deficient in the early condensate.

The amount and composition of the material that condenses from the solar nebula at high temperature can be estimated in several ways. The average composition of the solar nebula can be estimated from solar and chondritic abundances. Column (1) of Table 1 gives solar abundances recalculated to weight percent oxides. This will presumably be the composition of a fully oxidized planet accreted from the solar nebula. The second column gives the amount of SiO_2, TiO_2, Al_2O_3, MgO and CaO that are involved in the early condensates, $CaTiO_3$, $Ca_2Al_2SiO_7$ and $MgAl_2O_4$. Column (3) gives the composition of a Ca-Al rich inclusion in the Allende meteorite which is taken here as another approximation to the composition of the early condensate. The amount of Fe in the sun is still uncertain so we have also calculated the fraction of the early condensate for an iron free sun to obtain an upper bound on the amount of the high temperature condensate. These condensates account for 3.2 to 7.4% of the total condensable material. This is roughly the fraction of the total condensable material (exclusive of H, C and S) that will condense from a solar nebular prior to the condensation of iron. Trace element refractories will therefore be enriched in this early condensate by a factor of 14 to 31. An alternate method is to assume that carbonaceous chondrites represent the composition of the starting material. In this case, columns (4), (5) and (6), the early condensate fraction is 5.8 to 9.0% and the enrichment factor of the trace element refractories is 11-17 times chondritic. In this regard it is of interest that the refractory trace elements are enriched in the Allende inclusions by a factor of 11 over the whole meteorite and that these inclusions comprise ~ 8% of the meteorite, a C3 chondrite.

Figure 2 gives the chondritic-normalized lunar abundances as a function of condensation temperature of the element or the first condensing compound containing this element. The condensation temperatures of the REE, Ba and Sr are uncertain but their average enrichment, shown by the dashed line, is about the same as the other refractories suggesting that they condense over a similar temperature range. Grossman [21] calculates that U, La, Sm and Eu will condense below 1473°K at 10^{-3} atm. The U/Th ratio therefore may be lower in the early condensates than in chondrites. It is likely however, that solid solution effects will allow the condensation of some refractory trace elements at higher temperature than is the case for pure phases. Perovskite, for instance, could provide lattice sites for the removal of the rare earths and other trace elements [21] at temperatures of 1647°K. Grossman [21] feels that the rare earths will probably condense over the same temperature interval as corundum, perovskite, melilite and spinel. In the lower part of the figure is shown a plot of the fraction of the available material that has condensed as a function of temperature calculated from the results of Grossman [21]. The initiation of condensation of various compounds is indicated by arrows. Note the rapid increase in the fraction of material which has condensed as the temperature drops below the condensation temperature of iron and the magnesium silicates. Conditions in the solar nebula can be expected to drastically change as temperatures drop to this level. When iron starts to condense the opacity of the nebula increases substantially and the cooling rate will decrease. One might therefore expect a discontinuity in the evolution of the solar system at the condensation temperature of iron. If a planet is depleted in iron it is probably also depleted in post iron condensates such as olivine and pyroxene, as well as the more conventional volatiles.

The enrichment factor in Figure 2 is simply the reciprocal of the condensed fraction. It indicates the expected enrichment of the trace refractories in the condensed phases relative to chondritic abundances. Note that the refractories are enriched in the moon to above the level expected in the pre-iron condensates. As the temperature decreases past the condensation temperature of iron the enrichment factor rapidly approaches unity, i.e. chondritic abundances. Everything that condenses after iron is apparently depleted in the moon.

Ir is the main anomaly in Figure 2. It is commonly concentrated in residual high temperature crystals such as chromite and spinel and in sulphide melts [22,23]. Iridium is a siderophile element and may also reside in a metallic phase at depth in the moon.

Table 2 gives the condensation sequence in a cooling nebula of solar composition at a total pressure of 10^{-3} atmospheres [21]. We will show in the next section that the Ca-Al rich inclusions of the Allende meteorite have mineralogies that suggest that they are high temperature condensates. This is supported by their trace element content.

5. The Allende Meteorite

Theoretically, the early condensates from a cooling solar nebula include perovskite, spinel, gehlenite, diopside, anorthite and other Ca, Al and Ti compounds. This assemblage will be enriched in such refractory trace elements as REE, Sr and Ba and, possibly in Th and U, and depleted in such volatiles as K, Rb, S and H_2O. Type II and III carbonaceous chondrites contain Ca-Al rich inclusions which involve these minerals and which are enriched in Ba, Sr and the REE to about the extent predicted in the previous section.

The spectacular meteorite shower near Pueblito de Allende, Mexico in February, 1969 has provided a wealth of data bearing on the nature of the early condensate. Over 2000 kg of this Type III carbonaceous chondritic material has been collected to date. In common with other Type II and Type III carbonaceous chondrites the Allende contains numerous large white aggregates and some chondrules of most unusual chemistry and mineralogy. The bulk chemistry of these inclusions is high in Ca, Al and Ti and low in Fe, Mg and volatiles. We shall refer to these as Ca-Al rich inclusions. The dominant minerals that have been identified in these inclusions include gehlenite ($Ca_2Al_2SiO_7$), spinel ($MgAl_2O_4$), fassaite, an aluminous titanium-rich pyroxene ($Ca(Mg,Al,Ti)(Al,Si)_2O_6$) and anorthite ($CaAl_2Si_2O_8$). Other minerals include perovskite ($CaTiO_3$), diopside ($CaMgSi_2O_6$), ferroaugite ($Ca(Fe,Mg,Al)(Al,Si)_2O_6$), grossular ($Ca_3Al_2Si_3O_{12}$), and corundum (Al_2O_3). They contain no metallic iron or olivine. These aggregates have been studied in detail by Clarke _et al._ [24], Marvin _et al._ [25], Gast [26] and Grossman [21]. The texture and the presence of reaction rims indicate that the inclusions were inserted into the matrix at high temperature. The δO^{18} value of this material is much more negative than any other meteoritic material [27] and in the range to be expected for a primary high-temperature condensate from a nebular gas. Marvin et al. [25] and Clarke et al. [24] have noted the similarity between the composition and mineralogy of the aggregates and the early condensates in a cooling nebula. It is extremely unlikely that the pecularities of these inclusions could be a result of igneous differentiation processes acting on material of solar or chondritic composition. On the basis of their bulk chemistry, mineralogy, texture and oxygen isotope ratios, the Ca-Al rich inclusions apparently represent the highest temperature condensates from a gas of solar composition and are therefore the most primitive solids in the solar system. Grossman [21] has supported this view with detailed thermodynamic calculations. If this interpretation is correct they are extremely sigificant in understanding the origin and composition of the moon [6,12,13,14]. We will show that many properties of the moon, including its overall physical properties, gross layering and the properties of the source region of lunar igneous rocks can be explained if the bulk composition of the moon is similar to that of the Ca-Al rich inclusions. Although the Allende meteorite has provided the greatest amount of material for study, similar inclusions have been observed in numerous C2 and C3 chondrites, for example Kaba [28], Sharps [29], Bali [24], Vigarano [30], Lance [31], Felix [32], Murchison [33], Leoville [34], Grosneja, Orans, and Warrentun [25].

6. Trace elements

The concentrations of the trace element refractories have been determined for the Ca-Al inclusions by Gast et al. [26] and Grossman [21] and for the whole meteorite by Mason and Graham [24] and Wakita and Schmitt [35]. The average enrichment of these elements in the inclusions, which make up ~ 8% of the meteorite, is about a factor of 11, implying that these refractory elements are almost entirely contained in the inclusions, and, by implication in the earliest condensates. Europium is concentrated in the inclusions by ~ 30% more than the average of the other elements. The U content of the whole meteorite is 0.019 ppm. If it is concentrated primarily in the inclusions they will contain ~ 0.2 ppm. A single measurement [21] gives 0.03 for the uranium content of one of the inclusions which suggests that U is not as refractory as the REE, Sr and Ba, or is not as easily incorporated into the lattices of the crystal phases found in the inclusions. For comparison the average U content of the moon has been estimated by Hanks and Anderson [36] to be ~ 0.1 ppm based on thermal history and heat flow considerations.

Table 3 gives concentrations of Ba, La, REE, Sr, Rb, K and U for the Ca-Al rich inclusions of the Allende meteorite, the whole meteorite, carbonaceous chondrites, Apollo 11 basalts and a lunar anorthosite. The abundances in the inclusions are approximately 16 times the chondritic abundances, column (3). In this respect the Ca-Al inclusions are a much more satisfactory source for the lunar igneous material than are carbonaceous chondrites. The first column are abundances in an Allende Ca-Al rich inclusion [26]; the second column are whole meteorite abundances [24].

The anorthosite and basalt have large and opposite europium anomalies. The anomaly can be suppressed by mixing basalt with about 5 times as much anorthosite, columns (6) and (7). The mixture is normalized to carbonaceous chondrites in column (7) and to the Allende inclusions in column (8). The lunar basalts are enriched in refractories by more than an order of magnitude relative to carbonaceous chondrites and a factor of five relative to the Allende inclusions. If the composition of the outer shell of the moon can be accounted for entirely by a mixture of basalt plus anorthosite the absolute abundances can be made comparable to Allende inclusions, as shown in column (9). This mixture, however, still has a small europium anomaly relative to either carbonaceous chondrites or the Ca-Al inclusions.

Table 4 give the chondritic normalized trace element refractory abundances for the Allende inclusion and several combinations of the lunar surface material. Grossman [21] corrected La, Sm, Eu, Sc, Yb and Ir for matrix contamination and concluded that the Ca-Al rich inclusions were enriched in these elements by a factor of 20-25 relative to Type I carbonaceous chondrites. Using different data we obtain, column (1), an enrichment factor of 16. Column (2) is the mixture of basalt and anorthosite required to achieve Allende abundance levels. Column (3) gives the mixture of anorthosite and basalt required to satisfy the Allende Sm/Eu and Eu/Gd ratio. Column (4) is the mixture required to achieve the carbonaceous chondritic ratios. In all cases appreciable Sr, Ba and the REE must be retained in the interior if the moon has the abundances of the Ca-Al rich inclusions. Since the residual crystals in our model amount to ~ 65% of the mass of the moon (see Section 9) the average REE concentration in the interior is 17-19 times chondritic levels. The Eu anomaly, relative to the Ca-Al inclusions, can be eliminated by mixing 0.86 anorthosite and 0.14 basalt, column (9). The exact proportions depend on the choice of materials, but Wakita and Schmitt [37] obtained almost identical values. The lunar interior, for our model (spinel, melilite and perovskite) however, is quite different from those assumed by the above authors. These high temperature crystals are able to retain the large ions much more efficiently than olivines and pyroxenes and these ions will not be as effectively concentrated in the melt. Tables 3 and 4 give strong support to the hypothesis that the lunar differentiates involve a primitive, refractory source region and justifies Gast's [4] conclusions regarding the nature of the source region.

The refractory trace elements support the hypothesis that the Allende inclusions represent the early condensates of the cooling solar nebulae. If the refractory trace elements such as Ba, Sr and the REE condense early they will be concentrated in the early condensate relative to their concentration in the sun or relative to material, such as carbonaceous chondrites, which are presumably representative of the bulk composition of the nebulae. In Table 1 we estimated that the early condensates would be enriched by a factor of 11 to 31 in refractory trace elements, relative to solar or chondritic abundances. Grossman [21] estimated an enrichment factor of 20-25. The average enrichment of Ba, Sr and the REE in the Allende inclusions over carbonaceous chondrites is 16, in the range of that predicted.

This study attaches profound significance to the Type III carbonaceous chondrites. To date this class includes 12 falls and 3 finds totalling in excess of 2400 kilograms. For comparison, the Type I carbonaceous chondrites, upon which several cosmologies have been constructed, have 4 members and a total recovered weight of 16 kilograms. While it is clear that the Type I carbonaceous chondrites are primitive objects and are relatively unmodified they have few of the characteristics required for the moon.

7. Major elements

Table 5 gives the major oxide composition of lunar surface material and the Ca-Al rich inclusion and, for comparison, a theoretical estimate of the composition of the early condensate. Columns (3) and (4) are two estimates of the mean composition of the lunar crust based on trace element concentrations. Column (3) is the basalt-anorthosite mixture which is required to give Allende inclusion trace element refractory levels. Column (4) is the mixture which gives the Allende inclusion Sm/Eu ratio.

There is little difference as far as the major elements are concerned. In the CaO-MgO-Al_2O_3-SiO_2 system with this composition, pyroxene melts at 1235°C, anorthite at 1250°C and gehlenite at about 1400°C. Spinel remains as a solid until 1550°C. The first melt will therefore be rich in pyroxene and, as melting proceeds, will become more anorthositic. Column (5) gives the composition of the early, $T < 1250°C$, melt and also the late condensate and can be compared with columns (3) and (4). The amount of this material in the inclusion corresponds to a thickness of ~ 270 km on the moon.

Column (6) gives the composition of the inclusion as determined by Clarke et al. [24]. The FeO, K_2O and Na_2O contents of the Ca-Al rich inclusions are highly variable and may represent contamination from the matrix [21]. The pure inclusions contain less than 1.4 percent Fe [21]. Column (7) gives the composition of the high temperature crystals in the Allende inclusion, a possible composition of the deep, > 270 km, interior. It would perhaps be surprising if the single Allende aggregate that has been analyzed were completely representative of the early condensate. An alternate approach is to consider the mineralogy of the early condensate predicted from thermodynamic calculations. Column (8) gives the composition of the condensate prior to the condensation of iron, olivine and enstatite. The major difference between the theoretical composition and the Allende aggregate composition is the MgO content. This is probably because the Allende inclusion was armored from complete reaction with MgO(g) therefore keeping the akermanite content of the melilite below equilibrium levels.

poor assemblage. The high pressure phases have theoretical densities of the order of 3.5 g/cm^3 but this theoretical density is only reached gradually as the pyroxenes react with the garnet. Ito and Kennedy [38], Green [39] and Boettcher [40] have all emphasized the two-stage nature of the density increase.

It should be noted that, for the temperature profile shown, the intermediate density assemblage is also stable above some 100 km which is interesting in that high seismic velocities are found in the lunar "upper mantle"[8]. If the outer several hundred km of the moon represent a uniform composition the 70 km discontinuity would represent a kinetic boundary (the temperature at this depth is almost certainly less than 300°C). A substantial decrease in both compressional velocity and density is predicted below some 100 km.

The precipitious drop in electrical conductivity found by Sonnett _et al_. [41] starting at 250 km has been attributed [6] to a decrease in the FeO content below this level. This can be interpreted in two ways, both of which are consistent with the present hypothesis. First, iron starts to condense and react with previously condensed silicates after the bulk of the Ca-Al rich silicates have already condensed. The iron rich layer may therefore be a relic of an initial inhomogeneous accretion [6]. More reasonable, however, is the view that the outer layers of the moon are differentiates of the bulk of the moon. In a solidifying magma, iron is strongly concentrated in the residual melt. For example, in the Skaergaard intrusion of east Greenland the FeO content of the last solidifying layers

It appears that the Allende inclusion is capable, in principal, of satisfying the major element and trace element requirements placed on the interior by the lunar igneous rocks. We will show that it is also capable of explaining the geophysical data.

8. A Ca-Al rich Deep Interior

Ringwood and Essene [9] have ruled out a Ca-Al rich interior for the moon on the basis of the mean density and moment of inertia. They suggest that the coefficient of moment of inertia implies that important phase transitions to much denser states do not occur within the outer 700 km or so of the moon. They conclude that the Al_2O_3 and CaO contents of the moon are less than 6 and 5 percent respectively. This has been adopted as a boundary condition by Gast [4] and others leading to the suggestion that the moon has a Ca-Al rich outer shell. While it is true that garnet, the principle high density phase, is stable at relatively low pressures in high Al assemblages, it is not the dominate phase until plagioclase or spinel disappear, which occurs at much higher pressures. This is illustrated in Figure 3 which shows the stability fields of three high Ca-Al materials. The compositions of these assemblages are given in Table 6. Also shown is a temperature depth curve from Hanks and Anderson [36]. For this temperature profile pyroxene and/or plagioclase are the dominant stable phases until $\sim$ 35 kilobars, which corresponds to depths of $\sim$ 800 km. The densities of the assemblages down to this depth are the order of 3.3-3.4 g/cm^3, similar to those in the Ringwood-Essene model lunar pyroxenite, a hypothetical Ca-Al is almost 3 times the inferred FeO content of the original liquid [42]. If the lunar basalts and anorthosites are the result of fractional crystallization, as proposed by Wood et al. [43], Smith et al. [44], and others, the outer 250 km (35 wt% of the moon) would represent the residual melt. With the bulk composition of the moon proposed in this paper the near liquidus phases would be melilite or merwinite and spinel, all of which are denser than the residual liquid. Spinel and melilite crystallize between 1400 and 1550°C at $P \sim 0$ [46]. Once the melilite and spinel are removed the remaining liquid is 34.6% of the mass of the original melt, in agreement with the above calculation.

The density of the low pressure assemblage of the residual crystals in the interior is about 3.2 g/cm^3 (spinel plus melilite). Akermanite, a major component of melilite, breaks down at moderate pressure, to merwinite plus diopside [45]. At lunar temperatures this would occur at about 200 km. The spinel + merwinite + diopside assemblage has a density of 3.4 g/cm^3.

9. Possible fractionation of an Allende-like moon

The composition of the Allende inclusion, as reported by Clarke et al. [24] has been recast into a mineral assemblage with the following results (in weight percent); feldspar 28.4%, melilite 39.7%, spinel 25.7%, perovskite 2.3% and diopside 3.9%. The near liquidus phases in a similar assemblage studied by Prince [46] are spinel and melilite. The crystalline sequence is spinel at about 1550°C followed by melilite at 1400°C, anorthite at 1250°C followed shortly by pyroxene at 1235°C. Fractional crystallization would give a spinel-melilite or spinel-merwinite-diopside interior and a feldspathic pyroxenitic surface layer. The refractory interior would comprise approximately 65% of the mass of the moon. The residual liquid would be enriched in Fe and any trace elements that are incompatible with the spinel and melilite lattices and would comprise the outer 250 km of the moon. The basalts and anorthosites could be derived from this layer either by further crystal fractionation involving plagioclase floatation, or by partial melting after solidification. The high U and Th contents of the surface layer are adequate to remelt the lower portions within several hundred million years after solidification [36].

The composition of the outer layer of the moon, obtained by removing the near liquidus crystals is given in column (1) of Table 7. For comparison, column (2) gives a previous "average" crustal composition of the moon. The similarity is remarkable. Column (3) gives the hypothetical parent liquid calculated by Gast et al. [47] on the basis of trace element distributions and a fractional crystallization model. The MgO in column (3) is arbitrary because of lack of information regarding the extent to which olivine is involved in the source region. On the other hand the MgO content of the early condensates is also uncertain; it increases with falling temperature due to the increasing akermanite content of the melilite and rises rapidly once olivine and enstatite start condensing. The moon may have accreted from material that condensed over a slightly broader temperature range than the Allende inclusion. Column (4) is a hypothetical parent liquid derived from a partial melt model. The agreement with this model is not as good as the fractional crystallization model but the inferred Al_2O_3 and CaO content is still considerably greater than models such as Ringwood and Essene [9]. Column (5) is the inferred deep interior (> 250 km) composition (spinel + melilite). For comparison column (6) gives Gast's [4] deep interior composition which is based on the (invalid) Ringwood [2] constraint on total CaO and Al_2O_3. The density of the spinel-melilite assemblage is 3.2 g/cm^3, about the same as the mean density of the Allende inclusions but ~ 10% greater than the density of the residual melt. At high pressure akermanite breaks down to merwinite plus diopside with a density of 3.29 g/cm^3; a similar reaction presumably occurs for gehlinite. The assemblage spinel + merwinite + diopside is probably stable through most of the bulk of the moon. This assemblage has a density of 3.40 g/cm^3.

The density variation in the moon is likely to be complex. The Apollo seismic experiment showed that large velocity jumps occurred at 25 and 65 km [8]. The very low velocities in the upper 25 km suggest that this region is porous or fractured and the density may be as low as 2 g/cm^3. The lower crust, 25-65 km, has velocities consistent with gabbroic anorthosite and densities may range from 2.7 - 3.0 g/cm^3 in this region. The velocities from 65-120 km [8] are high and may indicate the transformation to a garnet bearing assemblage with densities from 3.3 to 3.7 g/cm^3 [48]. A garnet bearing assemblage in the lunar upper mantle is consistent with the phase diagrams presented in Ringwood and Essene [9] and Figure 6. At slightly greater depth the garnet will become unstable because of the rapid rise in lunar temperatures (see Figure 6) and lower densities, comparable to those in the lower crust, may prevail until ~ 300 km, at which depth we again cross the garnet-in curve for Ca-Al rich assemblages. However, we have inferred a compositional change near $\sim$ 250 km to a spinel-merwinite-diopside assemblage with $\rho \sim 3.4$ g/cm^3. There is abundant flexibility to satisfy the mean density and the moment of inertia.

10. Formation and differentiation of the moon

The derivation of the lunar surface rocks could proceed from our assumed composition for the moon in several ways. The following is one possible scenario:

1) The moon accreted from the material that condensed from a cooling solar nebula prior to the condensation of significant amounts of iron. The uncondensed material in the vicinity of the accreting moon, including most of the iron and the volatiles were removed by an intense solar wind or were swept up by the more massive and more favorably disposed Earth. From cooling rate and other considerations, the accumulation of the moon occurred very rapidly.

2) The whole moon was enriched in Ca, Al, Ti, U, Th and the REE by approximately the ratio of the fraction of the material that condenses before iron relative to chondritic or solar non-volatile abundances. It was depleted in Fe, Na, Rb, K and the more volatile elements.

3) The initial mineralogy of the moon was primarily melilite (solid solution of akermanite and gehlinite), aluminous clinopyroxene, diopside, spinel, anorthite and perovskite.

4) The rapid accretion, the high initial temperatures which are a consequence of the accretion-during-condensation hypothesis and the high U and Th abundances (10-16 times chondritic) lead to early and extensive, and perhaps complete, melting.

5) The near liquidus phases, spinel and merwinite, settle to the interior. These crystals constitute approximately 65% of the mass of the moon which corresponds to the volume below some 250 km. The REE, Ba and Sr are not necessarily strongly fractionated at this stage between crystals and melts. The melt, in fact, may be slightly depleted.

6) The residual liquid is approximately 80% anorthosite and yields anorthosite, upon further cooling, which presumably formed the protocrust and the highlands, and then pyroxenes from which the basalts were derived either directly or by partial melting after solidification. An alternate scheme could involve the complete crystallization of the outer shell followed by remelting and separation of the basalt liquid. The high U and Th content of the outer shell permits this possibility [36].

7) The small initial FeO content of the moon was strongly concentrated in the residual melts and therefore concentrated in the outer 250 km of the moon.

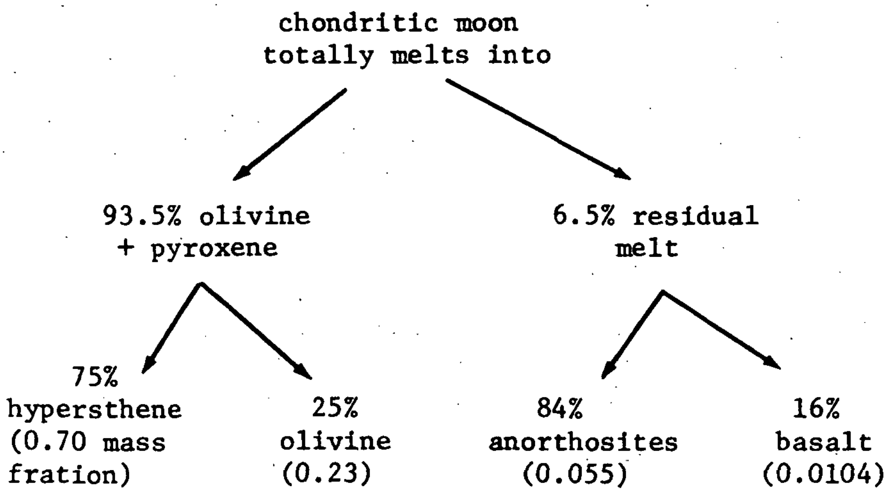
8) The basalts and anorthosites could be derived either by partial melting or by fractional crystallization, or both, of the outer 250 km of the moon. The composition of this shell is similar to that inferred by Gast [4].

Gast [4] has ruled out fractional crystallization on the basis that parent liquids with more than 80% anorthite were implausible. Anorthite contents of the order of 80% are a feature of our model and a similar model for the outer layers of the moon of Wakita and Schmitt [37]. These estimates are based on the mixing required to remove the europium anomaly. If KREEP basalts are an important component of the lunar crust even higher anorthosite contents are required. A further difficulty pointed out by Gast with the fractional crystallization model is that the abundance of such elements as Br, Sr and REE in the source region must be 15-20 times that of the average chondrite. These high abundances are also an intrisic feature of our model. Independently, Smith et al. [44] concluded that the Apollo 11 basalts represent a residual fraction after crystallization of more than 80 percent of a parent magma.

The lunar igneous rocks could be either the result of a single stage extensive fractional crystallization or partial melting process, or could result from a multiple stage process involving both. The variation in the properties of the lunar basalts suggest that secondary processes may have operated. Some of the basalts may have crystallized from the residual melt after the higher temperature crystals were removed by sinking and floatation and others may have formed by partial melting at depth after crystallization of the liquid residiuum.

In order to facilitate comparison with previous models, we will briefly discuss the model of Wakita and Schmitt [37]. It has many elements in common with the proposals of Smith et al. [44] and Wood et al. [43]. They assumed as have most previous investigators that the total moon accreted from material similar to that of ordinary chondritic meteorites. Although their models are quite different, Gast [4] and Ringwood and Green [3] also propose that the bulk of the moon's interior is chondritic. Wakita and Schmitt [37] considered [on the basis of a personal communication from Anders] the use of "chondrules from carbonaceous meteorites that are significantly depleted in alkalies and are deficient in metal" but did not pursue this suggestion because of the lack of sufficient data on the abundances of REE and other elements in chondrules.

They proposed that the moon was completely molten early in its history and, after formation of a small Fe core, fractional crystallization of the high-temperature minerals (in a chondritic assemblage) olivine and orthopyroxene, took place. The light residual magma floated to the surface from which anorthosites and basalts separated, the light anorthosite floating on the denser basalt. During this fractional crystallization process the REE concentration in the residual magma increases with the crystallization of olivine and pyroxene minerals since these can accommodate very little of the large REE ions. About 93 percent of the mixed olivine plus hypersthene minerals crystallized from the initial melt leaving ~ 7 percent residual melt with a thickness of ~ 35 km. From this residual melt 84 percent separated as anorthosites and 16 percent remained as basalts. Although not stated by them, a feature of the model is progressive enrichment of the melt in FeO and, probably TiO_2. The flow chart below illustrates their proposed process.



A basically similar scheme can be proposed if the original composition of the moon is Ca-Al rich throughout. The high temperature minerals, in this case, however, are gehlinite-akermanite solid solutions (at low pressure), spinel and perovskite and the thickness of the residual is ~ 230 km of which ~ 30 km is potentially basaltic. The fractionation of iron into the residual melt provides a high conductivity outer shell. The lattices of the high temperature minerals, in this model <u>can</u> accommodate the large REE and other ions although information is unavailable on the distribution coefficients. The fact that the REE ions substitute readily for Ca^{++} suggests that they may be retained by gehlinite and perovskite. If the initial concentration of the REE in the Allende inclusion is appropriate for the bulk moon and if the anorthosite-basalt mix discussed previously is appropriate for the outer shell of the moon (Table 4) it follows that the melt, the parent liquid of the lunar basalts and anorthosites, is slightly depleted in REE, relative to the bulk moon, rather than enriched as is the case when olivine and orthopyroxenes are the high temperature phases.

Smith *et al*. [44] propose that the moon was formed from iron and volatile depleted chondritic material, after which it was completely melted. The entire interior was subjected to crystallization differentiation and the basalts are regarded as the residuum. This hypothesis is the antithesis of the one presented by Ringwood and Essene [9]. Ringwood [49] has vigorously objected to this model, primarily on thermal grounds. Although the interior of the moon in the Smith *et al*. model is formed of concentric layers of Fe-Ni, olivine and pyroxene rather than melilite and spinel it has some attractive features, mainly the concentration of Fe and Ti in the residual liquid and upward floatation of plagioclase (see also Wood et al. [43] which are in common with the present model. Ringwood's objections would also be directed to our model. His first concern is with the mechanism that caused complete melting of the moon. In our model complete melting is not necessary but we see no particular difficulty in this regard. The high initial temperature of the material that accretes on the moon (~ condensation temperature), the rapid accretion time proposed by Opik [50] and Mizutani [51] and high U and Th contents (~ 16 times chondritic) all lead to extremely high initial temperatures. Ringwood [49] considers the evidence for igneous activity 10^9 years after solidification of the moon has commenced to be a fatal difficulty with the Smith *et al*. hypothesis. However, the thermal history calculations of Hanks and Anderson [36] show that the moon, even with strong upward concentration of the heat producing elements (adjusted so that the present day heat flow is satisfied) will be above the solidus of lunar basalts, at 3.7 A.E. in the depth interval 50-400 km. The later lunar basalts were probably formed somewhere in this interval and extruded where the lithosphere was thin enough or weak enough that they could make their way to the surface. While it is true that the thermal time constant of the solid outer shell is short the thermal history models show that the temperature between about 70 and 400 km increases during the first 1.5 b.y. of the moon's life because of the high radioactivity content in the upper layers. The other objections of Ringwood [49] are directed toward the chondritic nature of the Smith *et al*. model and are not relevant here.

11. Depth of Origin

The considerations in this paper and in two previous papers [6,12] reopen the questions of partial melting and fractional crystallization, as discussed in the previous section, and the depth of origin of the lunar basalts.

Ringwood [49] marshalls a series of arguments in support of his belief that, the Apollo 11 basalts at least, were derived from a depth greater than 200 km:

1) The cooling of the moon is too rapid to permit melting to occur at shallower depths 1 x 10^9 years after the birth of the moon. Hanks and Anderson [36], however, showed that melts could exist below 50 km at the appropriate time for generating the younger basalts.

2) The persistence of mascons for $\sim$ 3.7 b.y. implies an underlying lithosphere of substantial long-term strength; preservation of mascons would not be explicable, if partial melting occurred in the lithosphere. Anderson and Hanks [6] showed that substantially higher stresses can be maintained by the lunar lithosphere than are now indicated and that considerable stress relaxation could have occurred in the early history of the moon. A thin outer shell can support both the non-hydrostatic shape of the moon and the mascons.

3) Extensive fractionation of a considerable portion of the moon is required in order to obtain the high levels of the trace element refractories; near surface melting processes are inadequate. This argument is based on presumed chondritic abundance patterns and not on the more plausible 16x chondritic lunar abundances.

The other arguments are also based on presumed chondritic abundances or on melting experiments which allow the basalts to be derived from depths as shallow as 100 km.

The present model is consistent with basalt origin below 200 km but the small amount of melt and the great thickness and strength of the lithosphere in the Ringwood [49] model seem incompatible. In one of the alternates discussed in Section 10 the later lunar basalts formed by complete melting of the region between 200 and 230 km. In the other extreme case they formed by $\sim$ 20% melting of the outer 230 km.

Inhomogeneous accretion of the moon

As mentioned previously, it has been suggested several times that the moon accreted inhomogeneously. However, the motivation has been to enrich the outer layer, in particular, the source regions of the lunar igneous rocks in Ca, Al, U, Th, Ba, REE and MgO/(FeO + MgO). It has been considered unlikely that the whole moon could exhibit these properties. However, we have shown that the early condensates in general, and the Allende inclusions, in particular provide the necessary characteristics of the source region and do not violate the inferred properties of the deeper interior. No primitive layering is required by the geochemical and geophysical data but chemical zonation as implied by the inhomogeneous accretion hypothesis [11] is a distinct possibility.

The chemical zoning that has been proposed has the interior enriched in FeO, MgO, SiO_2 and the volatiles relative to the exterior, which is enriched in CaO, Al_2O_3, U, Th and the REE. This is contrary to expectations based on inhomogeneous accretion directly within a condensing solar nebulae. In this case, the CaO and Al_2O_3 would increase with depth and SiO_2, MgO and FeO would decrease with depth. The initial distribution of the refractory trace elements, such as Ba, U, Th and the REE depends on the phases in which they concentrate upon condensation. If they occur primarily in the gehlenite, perovskite and spinel they can be expected to be concentrated initially in the center of the moon. If they are concentrated in the pyroxenes they can be expected to be brought in with the upper layers. If the moon partially or totally melts upon or after accretion they will be redistributed according to distribution coefficients between the melt and the liquidus phases - gehlenite and spinel. A detailed study of the trace element refractory distribution among phases in the Allende inclusion would help resolve this question.

The present day gross chemical layering in the Moon would be about the same whether it resulted from inhomogeneous accretion or homogeneous accretion followed by fractional crystallization or partial melting. In the inhomogeneous accretion model the phases in the deep interior would be merwinite, diopside spinel and, possibly, perovskite and corundum, the early condensing phases or reaction products. If the moon were ever totally molten the interior would also be melilite, or merwinite, these are the near liquidus phases and are denser than the residual melt. In the partial melt model the low melting point and low density phases are pyroxenes and anorthite, which would rise to the surface to form the source region for the lunar basalts and anorthosites.

A critical test of the alternates involves the distribution of FeO. In the inhomogeneous accretion model the FeO would be concentrated near the surface because of the late condensation of iron. In the fractional crystallization model the residual melt, and hence the surface layers, would also be strongly enriched in FeO. In the homogeneous accretion, partial melt model the melt would be only slightly enriched in FeO. The main evidence bearing on this point, although controversial, is the conductivity profile of Sonett _et_ _al_. [41]. They found a three orders of magnitude drop in electrical conductivity between 250 and 350 km depth, although other interpretations are possible. This has been interpreted [6] in terms of a dramatic decrease in the FeO content at this depth. The mass fraction of the moon below 250 km is 0.6 which is also the amount of gehlenite and spinel (the early condensates and also the near liquidus phases) in the Allende inclusions. Thus the inhomogeneous accretion and fractional crystallization models satisfactorily account for the gross layering as interpreted by Sonett et al. [41] and Anderson and Hanks [6]. The outer 250 km in either of these models would be the source region from which the lunar igneous rocks are subsequently derived by partial melting or fractional crystallization. This source region must be enriched in U, Sr and the REE, relative to chondrites. If these are concentrated in the early condensates the deep interior must have been involved in the early and extensive differentiation and this would favor fractional crystallization on the grand scale envisaged by Wood et al. [43]. If these trace refractories are concentrated in the later condensates the interior need not be involved in a major way in the subsequent evolution of the moon. In liu of measurements on the Allende inclusions our only recourse is to theoretical thermodynamic calculations. According to Grossman [21], ThO_2 condenses between the condensation temperature of spinel and gehlenite. Thorium is enriched in the moon to about the same degree as the higher temperature condensates such as Hf, Y, N, Ta and Sc. U and the REE also have similar enrichment factors. This suggests that the trace refractories are in the early condensates and that the whole moon has been involved in the early differentiation event. The present chemical zonation of the moon, therefore, is not necessarily primitive; the moon could initially have been a homogeneous mixture of the, primarily pre-iron, condensates. However, since the Ca-Al rich inclusions in C2 and C3 chondrites commonly exhibit a zonation it is of interest to discuss a possible primitive zonation in the moon.

There are two possible variants of the direct heterogeneous accretion hypothesis. If accretion is rapid and completely efficient in the sense that it keeps up with the condensation the moon will grow as a chemically zoned body with successive condensates shielding the early condensates from further reaction with the gas. One would obtain a moon composed of a corundum nucleus overlain by perovskite, melilite and diopside shells. More likely some of the early condensate will be available for later reaction with the gas either before accretion or at the lunar surface. In this case the moon will be composed of diffuse shells grading from a primarily corundum, pervoskite, melilite interior to a spinel rich shell overlain by diopside. The diopside and the spinel can react to form anorthite. The moon is unlikely to be perfectly prompt or efficient in accreting material that has condensed in its vicinity and it may therefore be initially a relatively homogeneous mixture of, primarily, perovskite, melilite, spinel and diopside, with, if temperatures fell low enough, some olivine. The amount of olivine is constrained to be small since its condensation interval overlaps iron and only a small fraction of the available (solar) iron has been incorporated into the moon. For example, in a cooling gas of solar composition at 10^{-3} atm total pressure, 46 percent of the iron had condensed before forsterite appears [21]. More olivine may be incorporated into the interior if the condensation of iron is delayed by the non-equilibrium considerations of Blander and Katz [52]. As discussed previously, the melilite will break down to pyroxene plus merwinite at high pressure.

13. Other considerations

Since the moon is clearly depleted in iron it is hard to see why it should not also be depleted in compounds more volatile than iron, as the surface rocks clearly are. There is no evidence that the interior approaches chondritic composition.

If the moon is comprised primarily of high temperature condensates, the interior, as well as the surface rocks, will be enriched in Ca, Al, Ti, U, Th and the REE relative to carbonaceous chondrites, the Earth or solar abundances. Similarly, it should be depleted in Fe, K, Na, Rb, S and H_2O. A Ca-Al rich interior has been dismissed by Wetherhill [16], Ringwood and Essene [9] and O'Hara et al [53] because it was believed that the high pressure phases of Ca-Al rich compounds would lead to densities which would violate the lunar mean density and moment of inertia. Although this is true for some assemblages, such as the Apollo 11 basalts, it is not a general characteristic of all Ca-Al rich assemblages. Similarly, a high concentration of U in the interior has been ruled out because this would lead to temperatures which has been considered to be too high. The low iron content of the early condensate, and inferred for the lunar interior, leads to a low intrinsic electrical conductivity. The interior temperature must be some 800°C greater than inferred previously from the lunar electrical conductivity experiment and measurements on iron rich rocks [6]. These measurements have provided some of the main arguments for a cold moon. The other main agrument for a cold moon is based on its non-equilibrium shape and the persistance of mascons. However, when scaled properly for gravity the moon is much closer to hydrostatic equilibrium than is the Earth or Mars, and the stresses being supported by the lunar lithosphere are modest by terrestrial and laboratory standards [6]. The geophysical data does not require a cold, strong deep interior. The long persistence of lunar igneous activity also strongly suggests that the source region of the lunar basalts at least was strongly enriched in uranium. It must be at least high enough to counteract the effects of conduction through the outer shell in the first 10^9 years of lunar existence.

The observations presented in this paper suggest that the moon accreted from high temperature condensates, in particular, material that condensed out of the cooling solar nebula before Fe. This would lead to a moon that is enriched in refractories and depleted in volatiles relative to the average composition of the inner solar system. This can be accomplished if the moon accreted during condensation and was competing with a more massive or more favorable disposed body, such as the earth. The accretion process is only vaguely understood at best but it seems clear that the initial stages of accretion will take place most readily by the coalescence of hot particles orbiting in a dense, viscous cloud, i.e. during the early stages of condensation. This will certainly be true when the gravitational cross section of the protoplanet is small.

14. The Origin of the Moon

If the bulk of the moon does represent a high temperature condensate the question arises, why did the moon not accrete substantial quantities of material that condensed at lower temperatures? There are several possibilities.

The temperature at which an element or compound condenses out of a cooling nebula depends both on the composition and the pressure of the gas. The temperature of the nebula [55] dies off rapidly away from the sun and slowly with distance from the median plane. Pressure dies off with distance from the sun and rapidly with height above the plane. At any given time the composition of the condensed material, prior to complete condensation, is a function of location in the nebula. If the uncondensed gas is removed at some stage, the planets and meteorites will differ in composition.

The difference in mass and composition of the Earth and the moon can be explained if:

a) The Earth was accreting in a dense part of the nebula, i.e. the median plane, and the moon was accreting, on the average in a less dense part of the nebula. This could happen, even if the moon were always at 1 A.U., if it were in a highly inclined orbit - the orbit would eventually settle down to its present configuration by gas drag, collision and tidal friction. The tendency of the moon to grow slower than the Earth, and to get less of the later condensates, would be ever more pronounced by the lower temperatures required to condense material at the lower pressures encountered away from the ecliptic and the high encounter velocities due to the highly inclined orbit.

b) Even if the moon was always in a low inclination orbit, the fact that it is orbiting the earth makes its encounter velocity with solar orbiting gains higher than the earth's and therefore its capture probability less [56].

c) If the earth started accreting sooner than the moon, or for some other reason got a head start, it would always have a larger capture cross section than the moon. When it became large enough to retain a atmosphere or, equivalently, to make a significant perturbation in the pressure of its surrounding gas envelope it would retain infalling material more efficiently and material would condense in its vicinity at higher temperatures.

The observational fact that the earth is bigger than the moon and is enriched in iron and the volatiles compared to the moon suggests that the Earth was more favorably disposed to collect the later condensates, and was possibly more favorably disposed throughout its accretional history. This is possibly related to its central position in the disc. If the moon's orbit was initially highly inclined it would be accreting, on the average, in a less dense part of the nebulae, even though it was accreting at the same distance from the sun as the Earth. The Earth would be continuously sweeping up the material in the median plane while the protomoon only crossed it twice a year. An even more important effect is the pressure dependence of the condensation temperature. Condensation occurs first, in a cooling nebula at the median plane, i.e. the high pressure region. Condensation occurs at lower temperatures and later times away from the plane. This leads to a delayed start for the moon and gives the Earth a head start on sweeping up material near the central plane. The scenerio leads naturally to a moon that is smaller than the earth and that is enriched in the early condensates and depleted in the later condensates.

Condensation temperatures depend on pressure as shown in Figure 4. The mean pressure in the nebula is usually taken as 10^{-3} to 10^{-4} atmospheres, but the pressure varies with distance from the Sun and with height above the median plane. Note that the condensation intervals of the refractories, forsterite, and iron overlap at high pressures but diverge at low pressures. The vertical line labeled 1 AU is the temperature in the vicinity of the Earth's orbit during the high luminosity phase of the Sun [57]. If the Earth were accreting in a dense, high pressure part of the nebula, such as the median plane, it would have iron and the magnesium silicates available for incorporation into its interior as well as the early condensing refractories. As it grows, it perturbs the gas pressure in its vicinity, or, equivalently, develops a massive atmosphere and the effective pressure in its vicinity will increase, which enhances condensation in its vicinity. The atmosphere will also make it a more efficient collector of the condensed material [58]. Away from the median plane the temperature remains almost constant [55] but the gas pressure decreases rapidly. Condensation, therefore, occurs at lower temperatures, and in a cooling gas, at later times. As drawn in Figure 4 the Earth will be more than 50% assembled before the Moon starts. If the cooling rate is constant, the Earth will have spent three times as much time accreting as the Moon. By the time the Moon nucleates, the Earth will have swept up most of the iron. Even after the Moon starts to form, the Earth will get most of the remaining iron and other later condensates, since it is spending all of its time in the median plane while the Moon only crosses it twice a year and does so with high encounter velocities and a relatively small capture cross-section.

15. Summary

The enrichment of refractories in the moon such as Ca, Al, Ti, Ba, Sr, REE and U and the depletion of "volatiles" such as Fe, Rb, K, S and H_2O relative to solar or carbonaceous chondritic abundances can be understood if the moon represents a high temperature (pre-iron) condensate. The pre-iron condensates represent about 6% of the total condensables (exclusive of H, S and C) and will therefore be enriched in the refractory trace elements (such as Ba, Sr, REE, U and Th) by a factor of about 16, relative to carbonaceous chondrites. This is close to the average enrichment observed in the lunar surface material and in the Ca-Al rich inclusions of Type II and III carbonaceous chondrites. The bulk surface chemistry of the moon is consistent with the composition of the low-melting fraction of the early condensables. Trace elements, seismic and heat flow data are consistent with "enrichment" of Ca, Al and U at the surface and in the interior of the moon. A Ca-Al rich deep interior does not imply an unacceptably large mean density. Most of the moon's complement of volatiles may be brought in by chondritic material in the terminal stages of accretion.

The differences between the earth and the moon and the terrestrial planets can be understood if accretion occurred during condensation.

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References

[1] A. E. Ringwood, Geochim. Cosmochim. Acta 30 (1966) 41.

[2] A. E. Ringwood, Earth Planet. Sci. Lett. 8 (1970) 131.

[3] A. E. Ringwood and D. H. Green, Proc. 3rd Lunar Science Conf. (1972) 573.

[4] P. W. Gast, The chemical composition and structure of the moon (in press).

[5] D. A. Papanastassiou and G. V. Wasserburg, Earth Planet. Sci. Lett. 11 (1971) 37.

[6] D. L. Anderson and T. Hanks, Science (in press).

[7] A. A. Levinson and S. R. Taylor, Moon Rocks and Minerals, Pergamon Press (1971).

[8] M. N. Toksoz, F. Press, K. Anderson, A. Dainty, G. Latham, M. Ewing, J. Dorman, D. Lammlein, G. Sutton, F. Duennebier and Y. Nakamura, Science 176 (1972 1012.

[9] A. E. Ringwood and E. Essene, Science 167 (1970) 607.

[10] M. Langseth, S. P. Clark, J. Chute and S. Keihm, Proc. 3rd Lunar Science Conf. (1972) 422.

[11] S. P. Clark, K. K. Tunekian and L. Grossman, in the Nature of the Solid Earth, E. C. Robertson, ed., McGraw-Hill (1972) 3-18.

[12] Don L. Anderson, Nature (in press).

[13] Don L. Anderson, Comments on Earth Sciences: Geophysics 2 (1972) 93.

[14] Don L. Anderson and T. Hanks, Nature

[15] P. W. Gast and R. K. McConnell, Proc. 3rd Lunar Science Conf. (1972) 257.

[16] G. W. Wetherill, Science 160 (1968) 1256.

[17] B. Mason and W. Melson, The lunar rocks, Wiley-Interscience (1970) 179 pp.

[18] R. Ganapathy, R. Keays, J. Laul and E. Anders, Geochim. Cosmochim. Acta, Suppl. 1, (1970).1117.

[19] J. Larimer, *Geochim. Cosmochim. Acta 31* (1967) 1215.

[20] H. C. Lord III, *Icarus 4* (1965) 279.

[21] L. Grossman, Condensation, chondrites and planets, Ph.D. Thesis, Yale University (1972) 97 pp.

[22] L. P. Greenland, *Geochim. Cosmochim. Acta 35* (1971) 319.

[23] L. V. Razin, V. P. Khvostov and V. A. Novikov, Geochimistry International 2 (1965) 118.

[24] R. Clarke, E. Jarosewich, B. Mason, J. Nelen, M. Gomez and J. R. Hyde, Smithsonian Contrib. Earth Sci. No. 5 (1970).

[25] V. Marvin, J. Wood, J. Dickey, *Earth Planet. Sci. Lett. 7* (1970) 346.

[26] P. Gast, N. Hubbard and H. Weismann, *Geochim.et Cosmochim. Acta*, Suppl. 1 (1970) 1143.

[27] Onuma et al.

[28] K. Sztrokay, V. Tolnay and M. Foldvari-Vogl, *Acta Geologica, 7* (1961) 57.

[29] K. Fredriksson and A. Reid, Researches in Geochemistry, P. Abelson, ed., Vol. II, Wiley (1967) 143.

[30] M. Christophe, *Bull. Soc. Fr. Mineral. Cristallogr. 91* (1968) 212.

[31] G. Kurat, *Earth Planet. Sci. Lett. 9* (1970) 225.

[32] M. Christophe, in *Meteorite Research*, P. Millman, ed. (1969) 492.

[33] L. H. Fuchs, *Am. Mineralogist 54* (1969) 1645.

[34] K. Keil and L. Fuchs, *Earth Planet. Sci. Lett. 12* (1971) 184.

[35] H. Wakita and R. Schmitt, *Nature 227* (1970) 478.

[36] T. Hanks and Don L. Anderson, *Phys. Earth Planet. Interiors* (in press).

[37] H. Wakita and R. Schmitt, *Science 170* (1970) 969.

[38] K. Ito, and G. Kennedy in The Structure and Physical Properties of the Earth's Crust, J. Heacock, ed., Am. Geophys. U., Geophys. Mono. 14 (1971) 303.

[39] T. Green, Phys. Earth Planet. Interiors 3 (1970) 441.

[40] A. Boettcher in The Structure and Physical Properties of the Earth's Crust, J. Heacock, ed., Am. Geophys. U. Geophys. Mono. 14 (1971) 261.

[41] G. Sonett, G. Shubert, B. Smith, K. Schwartz and D. Colburn, Proc. Apollo 12 Lunar Science Conf., The MIT Press (1971).

[42] F. J. Turner and J. Verhoogen, Igneous and Metamorphic Petrology, McGraw-Hill (1951) 602 pp.

[43] J. Wood, J. Dickey, U. Marvin and B. Powell, Proc. Apollo 11 Lunar Sci. Conf. 1 (1970) 965.

[44] J. Smith, A. Anderson, R. Newton, E. Olsen and P. Wyllie, J. Geol. 78, (1970) 381.

[45] I. Kushiro, Carnegie Institution of Washington Yearbook 63 (1964) 84.

[46] A. Prince, Am. Ceramic Soc. J. 37 (1954) 402.

[47] N. Hubbard, C. Meyer and P. Gast, Earth Planet. Sci. Lett. 10 (1971) 341.

[48] Don L. Anderson and R. Kovach, Phys. Earth Planet. Interiors (in press).

[49] A. Ringwood, J. Geophys. Res. 75 (1970) 6453.

[50] E. Opik, Astron. J. 66 [1961] 60.

[51] H. Mizutani, Moon (in press).

[52] M. Blander and J. Katz, Geochim. et Cosmochim. Acta 31 (1967) 1025.

[53] M. O'Hara, G. Biggar and S. Richardson, Science, 167 (1970) 605.

[54] J. Hays, Carnegie Institution of Washington, Year Book 65 (1966) 234.

[55] A.G.W. Cameron, to be published (1972).

[56] R. Ganapathy, R. Keays, J. C. Laul and E. Anders, Geochim. et Cosmochim Acta, Suppl. 1 (1970) 1117.

[57] F. Hoyle and N. Wickramasinghe, Nature, 217 (1968) 415.

[58] J. Wasson, Earth Planet. Sci. Letters, 11 (1971) 219.

[59] J. Laul, J. Morgan, R. Ganapathy and E. Anders, Proc. 2nd Lunar Science Conf., 2 (1971) 1159 .

[60] N. Hubbard, P. Gast, C. Meyer, L. Nyquist, C. Shih and H. Wiesmann, Earth Planet.Science Letter, 13 (1971) 71.

Table 1

Estimates of the Composition of the Early Condensate

	(1)	(2)	(3)	(4)	(5)	(6)
SiO_2	37.4	0.6	1.4	33.3	1.1	3.1
TiO_2	0.1	0.1	.05	----	---	---
Al_2O_3	1.3	1.3	1.1	2.4	2.4	2.4
FeO	43.0 (0)*	---	0.1	35.5	---	0.2
MgO	15.6	0.3	0.6	23.5	0.6	1.3
CaO	0.9	0.9	0.9	2.3	1.7	2.0
Total	98.3%	3.2% (5.6%)*	4.2% (7.4%)*	97.0	5.8%	9.0%
Enrichment Factor		31x (18x)*	24x (14x)*		17x	11x

(1) Solar abundances recalculated to weight percent of the major oxides

(2) Solar "refractory" composition (Ca, Al and Ti compounds); all Ti in $CaTiO_3$, remaining CaO in $Ca_2Al_2SiO_7$, remaining Al_2O_3 in $MgAl_2O_4$

(3) Allende Ca-Al rich inclusions scaled to solar CaO [24]

(4) Carbonaceous chondrites [17]

(5) Early condensate assemblage scaled to chondritic Al_2O_3

(6) Allende inclusions scaled to chondritic Al_2O_3

*Ignoring FeO

Table 2

Stability Fields of Equilibrium Condensates at 10^{-3} Atmospheres Total Pressure [21]

Phase		Condensation Temperature (°K)
Trace refractories (1)		1931-1768
Corundum	Al_2O_3	1758
	HfO_2	1744
	Mo	1698
Perovskite	$CaTiO_3$	1647
	Ru	1634
Melilite		
Gehlenite	$Ca_2Al_2SiO_7$	1625
Akermanite	$Ca_2MgSi_2O_7$	
	ThO_2	1517
Spinel	$MgAl_2O_4$	1513
Merwinite	$Ca_3MgSi_2O_8$	1475
Metallic Iron	(Fe, Ni)	1473 (2)
Diopside	$CaMgSi_2O_6$	1450
Forsterite	Mg_2SiO_4	1444
	Ti_3O_5	1393
Anorthite	$CaAl_2Si_2O_8$	1362
Enstatite	$MgSiO_3$	1349
Eskolaite	Cr_2O_3	1294
Rutile	TiO_2	1125

Table 2 (Cont'd)

(1) Os, Sc_2O_3, Te, Ta, ZrO_2, W, Nb, Y_2O_3

(2) The relative location of Fe-Ni in the condensation sequence depends critically on pressures in the nebula and on departures from equilibrium, i.e., the nebula may be supersaturated in iron vapor before condensation ensues. Iron condenses after forsterite, and presumably diopside, at pressures less than 10^{-4} atmospheres.

Table 3

Trace Elements in Allende Meteorite, Carbonaceous Chondrites and the Moon

	Meteorites			Moon				Moon/Meteorite	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Refractories									
Ba	47.3	5	3.6	200	6.28	48.9	33.4	13.6	1.03
La	4.63	0.44	(.28)	18	0.12	4.5	2.62	14.5	0.87
Ce	11.5	1.25	.787	54	0.35	12.2	7.86	15.5	1.06
Nd	8.40	0.91	.652	46	0.18	10.3	6.59	15.8	1.23
Sm	2.82	0.29	.208	15	0.05	3.4	2.14	16.2	1.21
Eu	1.30	0.11	.071	2	0.81	1.1	.96	14.8	0.81
Gd	3.87	0.43	.256	20	0.05	4.4	2.84	17.2	1.14
Dy	4.90	0.42	.303	25	0.04	5.5	3.53	18.2	1.12
Er	3.44	0.31	.182	14	0.02	3.1	1.97	17.0	0.90
Yb	3.96	0.32	.188	13	0.04	2.9	1.85	15.4	0.73
Sm/Eu	2.17	2.64	2.93	7.89	0.06	3.24			
U	(0.2) 0.03	.019	0.01	0.5	0.015	0.12	.083	12.	0.60-4.00
Sr	180	13	11	170	178	176	177	16.0	0.98
Volatiles									
Rb	3.5	1.3	3.0	3.4	0.15	.87	0.61	0.29	0.24
K	96-415	250	1000	1400	120	402	299	0.40	4.17-0.97

Table 3 (Cont'd)

	Meteorites			Moon				Moon/Meteorite	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
K/U	500-10,000	1.3×10^4	10^5	2800	9500	3350			
K/Ba	2 - 9	50	278	7	19	8			
K/Rb	30-120	192	330	412	800	462			
Rb/Sr	.019	0.10	3.67	0.02	.0008	.0049			

(1) Allende Ca-rich inclusions (Gast, et al, 1970); U = (0.2) estimated from 10x whole meteorite and 16x Cl chondrites; U = 0.03 from Grossman (1972)

(2) Allende - whole meteorite (Clarke, et al, 1970)

(3) Carbonaceous chondrites

(4) Apollo 11 basalt-mean (Mason and Melson, 1970)

(5) Lunar anorthosite - 15415, 11 (Hubbard et al, 1971)

(6) 0.22 basalt + 0.78 anorthosite

(7) 0.14 basalt + 0.86 anorthosite

(8) Column 6 normalized to carbonaceous chondrites

(9) Column 6 normalized to Allende Ca-rich inclusions

Table 4

Enrichment of Refractories

Allende inclusions/carbonaceous chondrites and

Lunar surface/carbonaceous chondrites

	(1)	(2)	(3)	(4)
Ba	13.1	13.6	9.3	12.1
La	16.5	14.5	9.4	12.6
Ce	14.6	15.5	10.0	13.4
Nd	12.9	15.8	10.1	13.6
Sm	13.6	16.3	10.3	13.9
Eu	18.3	14.8	13.5	14.3
Gd	15.1	17.2	11.1	15.0
Dy	16.2	18.2	11.7	15.8
Er	18.9	17.0	10.8	14.7
Yb	21.1	15.4	9.8	13.3
Sr	16.4	16.0	16.1	16.0
Average	16.1	15.8	11.1	14.1

(1) Allende Ca-Al rich inclusions

(2) .22 basalt + .78 anorthosite

(3) .14 basalt + .86 anorthosite (to eliminate Eu anomaly relative to Allende inclusion)

(4) .19 basalt + .81 anorthosite (to eliminate Eu anomaly relative to carbonaceous chondrite)

Table 5

Composition of lunar and Allende Materials

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
SiO_2	40.4	45.7	44.5	45.0	41.4	33.7	30.8	29.5
Al_2O_3	9.4	30.6	25.9	27.6	25.5	26.6	27.6	30.0
FeO	19.3	4.5	7.7	6.6	7.5	2.3	0	---
MgO	7.2	4.8	5.3	5.1	3.3	13.1	17.8	19.7
CaO	11.1	15.8	14.7	15.1	21.3	21.6	22.2	20.7
TiO_2	10.9	0.2	2.5	1.7	0.8	1.3	1.6	---
Na_2O	0.5	0.3	---	---	---	1.1	---	---
K_2O	0.2	---	---	---	---	0.1	---	---
Cr_2O_3	0.3	0.1	---	---	---	0.1	---	---
MnO	0.3	0.1	---	---	---	0.0	---	---

(1) Apollo 11 basalt-mean

(2) Lunar anorthosite

(3) 0.22 basalt + 0.78 anorthosite (based on trace elements)

(4) 0.14 basalt + 0.86 anorthosite (based on trace elements)

(5) Low melting fraction of Allende inclusions; pyroxene + anorthite (40%)

(6) Allende Ca-Al rich inclusion

(7) Allende inclusion with low melting fraction removed - i.e. implied composition of the lunar interior if the moon is composed of the high temperature condensates

(8) Composition of early condensate ($T > 1450^\circ K$, $P_T = 10^{-3}$atm) (Grossman, 1972)

Table 6

Composition and Transformation Pressures of High Ca and Al Assemblages

	(1)	(2)	(3)	(4)	(5)	(6)
SiO_2	49.9	59.9	53.5	27.5	47.6	53.1
Al_2O_3	16.8	17.3	22.5	46.8	20.7	5.0
FeO	11.4	6.3	4.7	---	8.2	13.5
MnO	0.2	---	0.1	---	0.1	0.4
MgO	7.6	3.4	2.1	---	7.6	22.5
CaO	9.3	7.1	9.9	25.7	12.5	4.0
Na_2O	2.5	3.7	3.7	---	0.7	0.1
TiO_2	1.3	0.7	1.0	---	1.2	1.0
Pressure*	11.	15.	15.	(14)†	9.	10.
range(kb)	28.	28.	31.	(27)†	21.	25.

(1) Olivine tholeiite, NM5, Cohen *et al*, 1967

(2) Diorite, Green, 1970

(3) Gabbroic anorthosite, Green, 1970

(4) Anorthite + Gehlenite + Corundum; Hays, 1966

(5) Plagioclase rich lunar basalt 14310; Ringwood and Green, 1972

(6) Model lunar pyroxenite; Ringwood and Essene, 1970

*Pressure range for intermediate density ($\rho \sim 3.3\text{-}3.4\ g/cm^3$) phases. In general, the lower pressure is the first appearance of garnet and the higher pressure is for the disappearance of plagioclase, both at 1200°C. (1100°C for column 5).

In the moon 27 kb corresponds to approximately 600 km depth.

Table 6 (Cont'd)

† In column (4) the pressures correspond to

$$\underset{\text{anorthite}}{CaAl_2Si_2O_8} + \underset{\text{gehlenite}}{Ca_2Al_2SiO_7} + \underset{\text{corundum}}{Al_2O_3} \rightarrow + \underset{\text{pyroxene}}{3CaAl_2SiO_6} \quad (\rho = 3.43\ g/cm^3)$$

and

$$\underset{\text{pyroxene}}{3CaAl_2SiO_6} \rightarrow \underset{\text{grossular}}{Ca_3Al_2Si_3O_{12}} + \underset{\text{corundum}}{2Al_2O_3}$$

both at 1400°C.

Table 7

Model Compositions of Lunar Interior

	(1)	(2)	(3)	(4)	(5)	(6)
SiO_2	48.8	47.7	47.1	52.9	26.7	61.0
TiO_2	3.8	2.7	3.2	0.9	--	0.6
Al_2O_3	25.3	27.8	27.3	17.6	28.3	7.4
MgO	2.1	5.7	6.8	15.4	19.7	24.3
CaO	16.6	15.8	15.6	13.2	25.2	6.5

(1) Allende inclusion with near liquidus phases removed (spinel and melilite); this is the inferred parent liquid for the lunar basalts and anorthosites (this paper)

(2) Average crustal composition derived by mixing basalt and anorthosite in the proportions 22% basalt, 78% anorthosite

(3) Hypothetical parent liquid for Apollo 11 igneous rocks derived from fractional crystallization model (Case 1 of Gast *et al*, 1970 renormalized)

(4) Hypothetical parent liquid for partial fusion model (Gast, 1972), renormalized

(5) Deep interior (near liquidus crystals); Allende inclusions minus column (1) (this paper)

(6) Deep interior, partial melt model (Gast, 1972); assumptions a) CaO and Al_2O_3 contents must be low and b) lunar basalts are derived from great depth in a single stage process

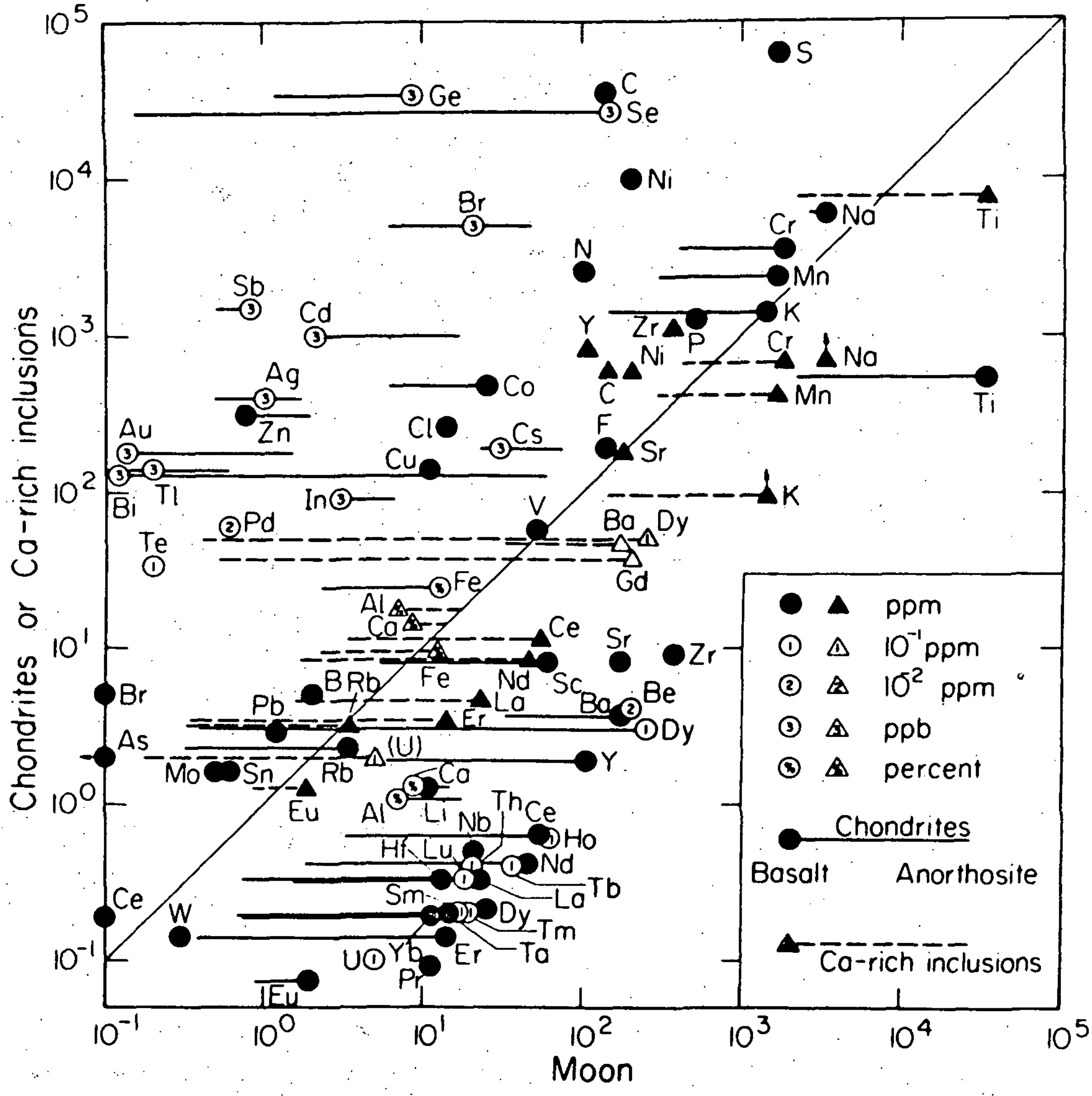
FIGURE CAPTIONS

Figure 1. Composition of lunar basalt [17] and anorthosite [35,59,60] versus carbonaceous chondrites (circles and solid lines) and versus Allende Ca-Al rich inclusions (triangles and dashed lines) [26].

Figure 2. Chondritic normalized lunar abundances versus condensation temperature. The lower curves is the fraction of the total material that has condensed as a function of temperature. The upper curve is the enrichment factor of trace element refractories in the early condensate.

Figure 3. Equilibrium fields in Ca-Al rich assemblages. Basalt is from Ito and Kennedy [38]; gabbroic anorthosite from T. Green [39] and anorthite + gehlenite + corundum from Hays [54]. The transformation akermanite → merwinite + spinel ($\rho = 3.29$ g/cm^3) occurs close to the anorthite + gehlinite + corundum → pyroxene boundary and its downward projection [45].

Figure 4. Condensation temperature versus total pressure in the solar nebula. The temperature at 1 A.U. is from [57]. The Earth and the Moon are placed on this line in such a position to explain their bulk compositions assuming they accreted only from material that condensed at this and higher temperatures. The other terrestrial planets can be placed on this diagram in such a way to explain their size, composition and presence or absence of satellites.



Chondrites or Ca-rich inclusions
Moon
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
S
C
Ge
Se
Ni
Br
Na
Ti
Cr
N
Mn
Sb
Cd
K
Y
Zr
P
Ni
Cr
Na
C
Ag
Co
Mn
Ti
Zn
Cl
Cs
Au
F
Sr
Cu
Bi
Tl
In
K
Pd
V
Ba
Dy
Te
Gd
Fe
Al
Ca
Ce
Sr
Zr
Fe
Nd
Sc
B
Rb
La
Br
Pb
Ba
Be
Er
Dy
As
(U)
Y
Mo
Sn
Rb
Ca
Eu
Al
Li
Th
Ce
Nb
Ho
Hf
Lu
Nd
Tb
La
Sm
Dy
Tm
Ce
W
Ta
Er
U
Yb
Pr
Eu
ppm
10^{-1}ppm
10^{-2} ppm
ppb
percent
Chondrites
Basalt
Anorthosite
Ca-rich inclusions

Fig. 1

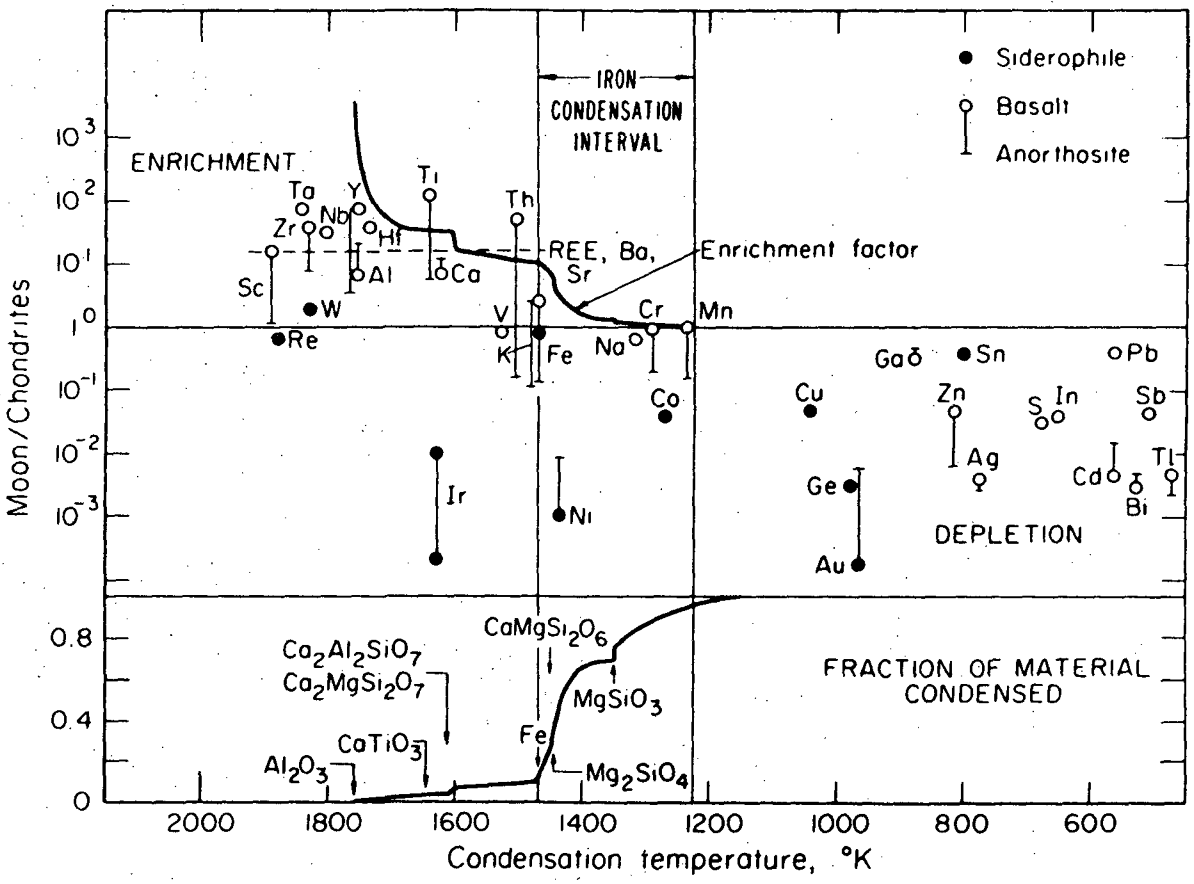
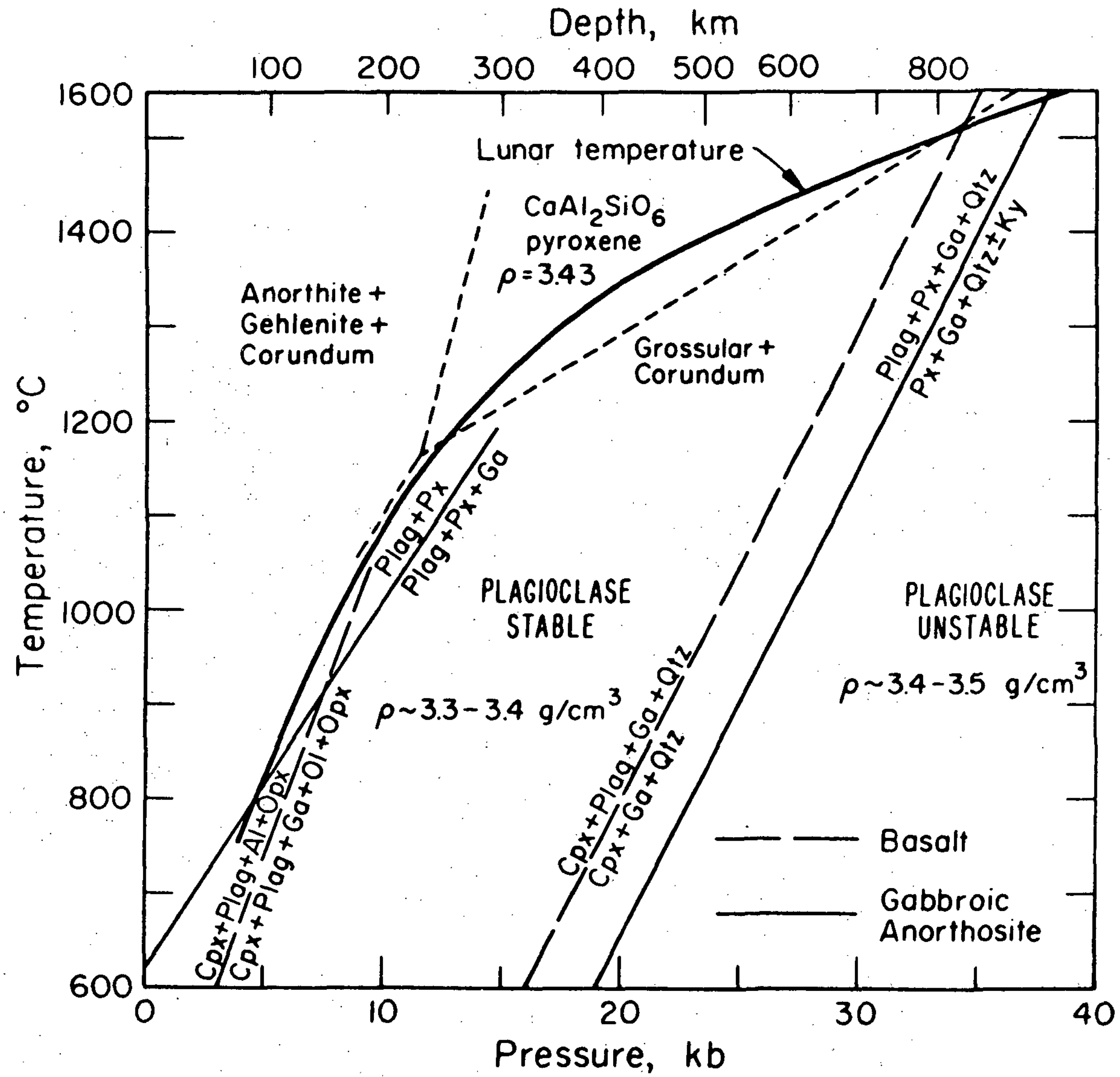

● Siderophile
○ Basalt
Anorthosite
IRON CONDENSATION INTERVAL
ENRICHMENT
DEPLETION
Enrichment factor
REE, Ba, Sr
Ta
Zr
Nb
Y
Hf
Ti
Th
Sc
Al
Ca
W
Re
V
K
Fe
Na
Cr
Mn
Co
Cu
Ga
Sn
Pb
Zn
S
In
Sb
Ag
Cd
Bi
Tl
Ge
Au
Ir
Ni
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
Moon/Chondrites
0.8
0.4
0
FRACTION OF MATERIAL CONDENSED
$CaMgSi_2O_6$
$Ca_2Al_2SiO_7$
$Ca_2MgSi_2O_7$
$MgSiO_3$
$CaTiO_3$
Al_2O_3
Fe
Mg_2SiO_4
2000
1800
1600
1400
1200
1000
800
600
Condensation temperature, °K

Figure 2.



Depth, km
100
200
300
400
500
600
800
1600
1400
1200
1000
800
600
Temperature, °C
0
10
20
30
40
Pressure, kb
Lunar temperature
CaAl$_2$SiO$_6$ pyroxene ρ=3.43
Anorthite + Gehlenite + Corundum
Grossular + Corundum
Plag+Px / Plag+Px+Ga
PLAGIOCLASE STABLE
ρ~3.3-3.4 g/cm^3
PLAGIOCLASE UNSTABLE
ρ~3.4-3.5 g/cm^3
Plag+Px+Ga+Qtz / Px+Ga+Qtz±Ky
Cpx+Plag+Al+Opx / Cpx+Plag+Ga+Ol+Opx
Cpx+Plag+Ga+Qtz / Cpx+Ga+Qtz
Basalt
Gabbroic Anorthosite

Figure 3.

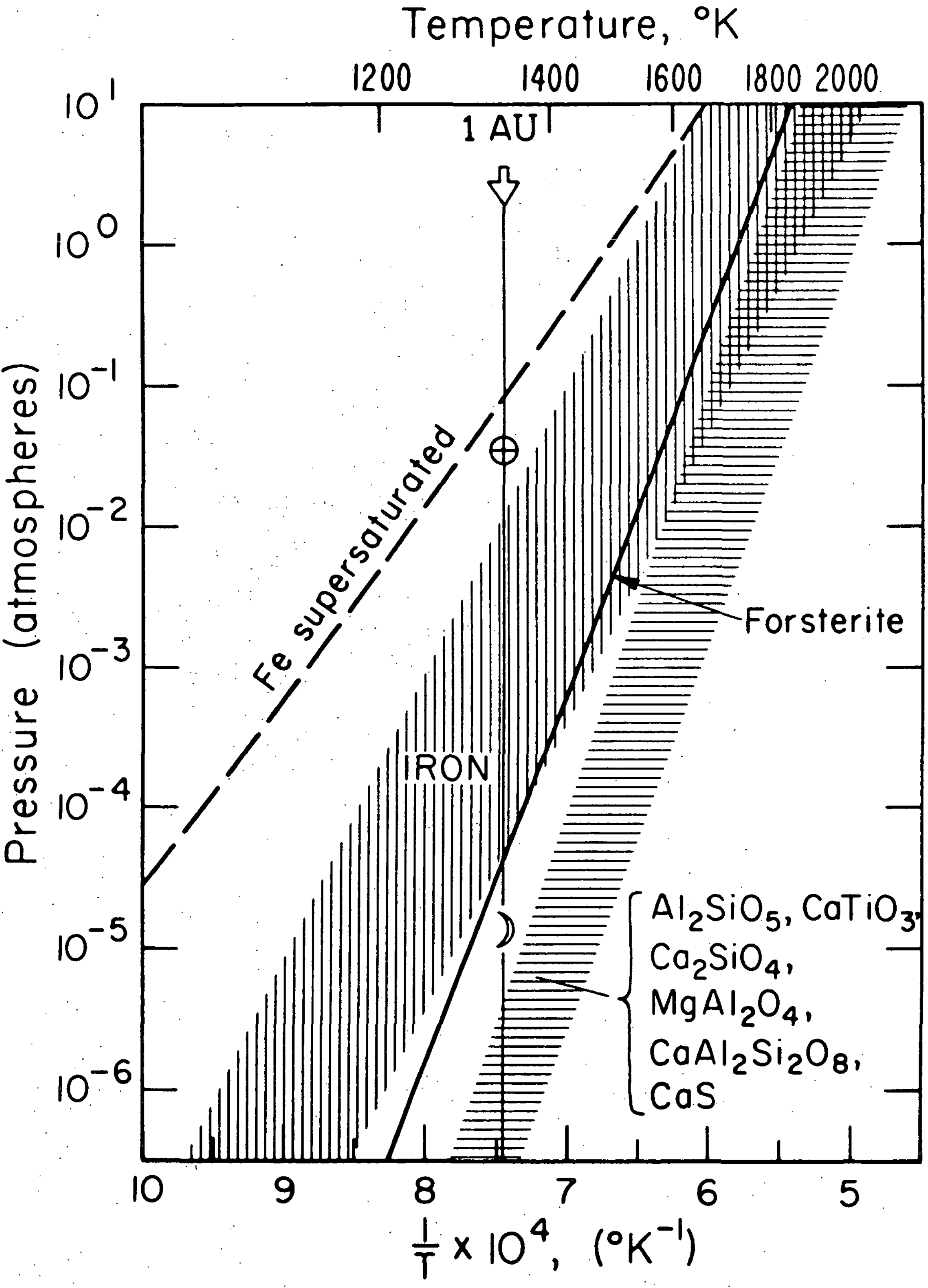

Temperature, °K
1200
1400
1600
1800
2000
1 AU
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
Pressure (atmospheres)
Fe supersaturated
⊕
IRON
Forsterite
☽
Al_2SiO_5, $CaTiO_3$,
Ca_2SiO_4,
$MgAl_2O_4$,
$CaAl_2Si_2O_8$,
CaS
10
9
8
7
6
5
$\frac{1}{T} \times 10^4$, (°K^{-1})

Figure 4.