THE MOON AS A HIGH TEMPERATURE CONDENSATE*

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Abstract

The accretion during condensation mechanism, if it occurs during the early over-luminous stage of the sun, can explain the differences in composition of the terrestrial planets and the moon. An important factor is the variation of pressure and temperature with distance from the sun, and in the case of the moon and captured satellites of other planets, with distance from the median plane. Current estimates of the temperature and pressure in the solar nebula suggest that condensation will not be complete in the vicinity of the terrestrial planets, and that depending on location, iron, magnesium silicates and the volatiles will be at least partially held in the gaseous phase and subject to separation from the dust by solar wind and magnetic effects associated with the transfer of angular momentum just before the sun joins the main sequence.

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 high temperature mineralogy is gehlenite, spinel, perovskite, Ca-Al-rich pyroxenes and anorthite. The model is consistent with extensive early melting, shallow melting at 3 A.E. and with presently high deep internal 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. The lunar crust is 80% gabbroic anorthosite, 20% basalt and is about 250-270 km thick. The lunar mantle is probably composed of spinel, merwinite and diopside with a density of 3.4 g/cm^3.

Introduction

The inhomogeneous accretion hypothesis has recently been revived by Clark, Turekian and Grossman (1972) to explain the gross layering in the earth and the differences in composition of the terrestrial planets. Larimer (1967) and Grossman (1972) computed the condensation sequence of elements and compounds in a cooling solar nebula and have applied these calculations to the problem of differences in the composition of meteorites. Earlier, Hoyle and Wickramasinghe (1968) proposed that the solid material in the solar system condensed and accreted during the early over-luminous phase of the contracting sun, during the short period of time that the sun was rotationally unstable and transferrring angular momentum to the planetary material, and before the slight increase in luminosity that occurred just before the sun joined the main sequence. They revived the old idea that the planets formed hot. Most current theories of the origin of the planets assume that they accreted cold from either a mixture of iron and silicates or from material of chondritic composition which was chemically reduced in the terminal stages of accretion to yield free iron. In the former case radioactive heating is invoked to melt and separate the earth's molten core. In the latter case, the gravitational potential energy of the accreting planet is used both to reduce the iron and to melt it so it can drain to the interior. There are serious time scale and compositional difficulties with both of these hypotheses. The accretion during condensation hypothesis, while the sun is still in the over-luminous stage, can avoid these difficulties and can explain the differences in the bulk composition of the planets. It also provides a clue to the anomalous situation of the moon.

In particular, if it is assumed that condensation and accretion occurred before the dissipation of the solar nebula and that the nebula contained uncondensed silicates and volatiles in the vicinity of the terrestrial planets, it is fairly easy to understand the differences in bulk chemistry of the terrestrial planets, the moon and the meteorites. The bulk chemistry of the various bodies will reflect the temperatures prevailing in their vicinity just prior to dissipation, in particular, the composition of the material that has condensed at this temperature.

Condensation

The condensation sequence of elements and compounds from a cooling cloud of solar composition has been calculated by Larimer (1967), Lord (1965) and Grossman (1972). The early condensates 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 condensate will 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, H_2O and other volatiles will be deficient in the early condensate.

The condensation sequence of the compounds and elements in a cloud of solar composition is shown in Table 1. The Ca, Al and Ti rich compounds will provide the nucleus for later condensates such as iron and the magnesium-rich silicates. We will refer to the Ca, Al and Ti rich compounds as the early condensates or the refractories.

Figure 1 gives the condensation temperature as a function of pressure in the nebula and also the temperature in the vicinity of the earth during the over-luminous phase of the sun. As drawn, the earth will be composed of the early condensates plus iron and the magnesium silicates in solar or cosmic proportions. The placement of the moon anticipates our later conclusion that the moon is composed of refractories and consists of material that condensed in a lower pressure part of the nebula - for example, off the median plane. The other terrestrial planets can also be placed on this diagram. For example, Mercury will be in a higher pressure and higher temperature part of the nebula. In order to explain its high mean density we can assume that it is composed primarily of the refractories and iron and that it has not received a full complement of magnesium silicates such as olivine and pyroxene. Venus is slightly lighter than the earth and, therefore, probably did not incorporate as much iron into its interior. This suggests that the nebula was dissipated before iron had finished condensing in the vicinity of Venus. Mars was in a much cooler part of the nebula and incorporated volatiles as well as the refractories, iron and the magnesium silicates into its interior. The carbonaceous chondrites are presumably even more volatile rich than Mars if they formed beyond the orbit of Mars.

Figures 2 and 3 indicate in a schematic fashion how the composition of a planet changes as the temperatures in the nebula decreases. At high temperatures only the refractories have condensed. The composition of the solid material in the solar system at this point, will be dominated by Ca, Al and Ti rich minerals and will be enriched in the refractory trace elements such as Ba, Sr, Th and the rare earth elements. Inclusions in Type II and Type III carbonaceous chondrites have these characteristics and, in addition, have textures and oxygen isotope ratios that indicate that they are high temperature condensates. The moon also has chemical and physical properties that indicate it is composed of the high temperature condensates.

Iron condenses at lower temperatures and, along with the refractories, forms the protocore of a planet. Mercury may represent a planet that has not proceeded much beyond this stage. The bulk of Venus, Earth, and Mars are composed of the ferromagnesium silicates which condense during and after iron. Minerals such as olivine, pyroxene and garnet form the major part of the mantle of a fully assembled terrestrial planet. Prior to the condensation of iron the mineralogy of a planet is dominated by such exotic minerals as perovskite, akermanite, gehlenite, spinel and merwinite.

The Moon

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.

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, $MgSiO_3$, $MgSiO_4$ 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 (1972) 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 (1970) low Ca-Al model lunar pyroxenite.

The enrichment of the moon in refractories and its depletion in volatiles is now well documented. Figure 4 gives lunar versus meteoritic abundances. Note that carbonaceous chondrites are a very poor approximation to the composition of the lunar surface rocks. The lunar rocks are fairly uniformly enriched in refractories and strongly depleted in volatiles. However, the Ca-Al rich inclusions in the Allende meteorite provide an excellent match to the lunar surface composition.

The early condensate amounts to 5.8 to 9.0% of the total 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 5 shows lunar abundances, normalized to carbonaceous chondrites, plotted as a function of condensation temperature. The amount of material that has condensed and the predicted enrichment factor of the trace element refractories is also shown. Note that the lunar surface material is enriched by about the predicted amount for the pre-iron condensate. Note also the very rapid increase in the condensed fraction that occurs when iron and olivine start to condense. Conditions in the solar nebula, such as opacity and cooling rate, can be expected to change markedly as temperatures drop to this level.

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 (1972) 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 the pure phases. Perovskite, for instance, could provide lattice sites for the removal of the rare earth and other trace elements at temperatures of 1647°K. The rare earth elements will probably condense over the same temperature interval as corundum, perovskite, melilite and spinel. Ir is the main anomaly in Figure 5. It is commonly concentrated in residual high temperature crystals such as chromite and spinel. It may, therefore, reside in a dense phase in the interior of the moon or, because it is siderophile, it may never have entered the moon in quantity.

The refractory properties of the moon apply not only to the surface rocks, but also to the inferred source region of these rocks, which extends at least 100 km and possibly 400 km into the interior. This has been eloquently demonstrated by Paul Gast and his coworkers. In any event, a substantial fraction of the moon seems to be enriched in Ca and Al and the trace refractories such as Ba, Sr and the REE. Of course, the mean density and the moment of inertia of the moon require that the whole moon be deficient in iron relative to solar, terrestrial or chondritic abundances. We have previously suggested that the whole moon may also be deficient in those elements and compounds that condense after iron. It has been suggested by many authors, however, that the deep interior of the moon may be chondritic in composition. This suggestion is based on the argument of Ringwood and Essene (1970) that both CaO and Al_2O_3 must be less than about 6% if the mean density of the moon is to be satisfied. This constraint is not valid and there is no support for the suggestion that the interior of the moon must be more volatile-rich and less refractory than the outer shell.

For example, Figure 6 gives the stability fields of a CaO-Al_2O_3 rich peridotite and the "model lunar pyroxenite" of Ringwood and Essene (1970). Note that the intermediate density field for the peridotite is broader than the corresponding field for the CaO-Al_2O_3 poor pyroxenite and the density in this field closely corresponds to the mean density of the moon. The composition of this peridotite is close to that of the composition of the early condensate with the low melting fraction removed. To put it another way the composition of this material is similar to the near liquidus crystals of the Allende inclusions.

Figure 7 gives the equilibrium fields in a simplified peridotite as a function of CaO content. At low CaO-Al_2O_3 contents the high density garnet rich assemblage occurs at shallower depths as the CaO content increases. However, at high CaO contents the intermediate density field broadens rapidly. Therefore, there is no difficulty in having the bulk of the moon composed of the Ca-Al rich refractories.

Likewise, a thick CaO-Al_2O_3 and plagioclase rich outer shell is permitted by the mean density of the moon. Figure 8 shows the stability fields of several high Ca-Al plagioclase bearing assemblages. The intermediate density field is stable throughout most of the lunar crust and mantle. Increasing the Al_2O_3 content,in fact, increases the pressure of the gabbro-eclogite phase change, Figure 9.

All of the geophysical and geochemical data suggest, or at least are consistent with, the idea that the bulk of the moon is composed of material that condensed from the solar nebula prior to the condensation of appreciable amounts of iron.

The following is one possible scenario for the formation and subsequent evolution of the moon: The moon started to accrete during or shortly after the initiation of condensation in the solar nebula. Temperatures in its vicinity never fell far below the condensation temperature of iron before the uncondensed portion of the solar nebula was removed. It is, therefore, composed of corundum, perovskite, melilite (a solid solution of gehlenite and akermanite), spinel and possibly, diopside and anorthite. Its composition is similar to the Ca-Al rich inclusions in the Allende meteorite, and it is enriched in the trace element refractories such as Ba, Sr, REE, U and Th. Because of the high initial temperatures (i.e., condensation temperature), the rapid accretion rate and the high content of U and Th, it melts, either partially or totally, during or shortly after accretion. The near liquidus crystals, spinel, melilite and perovskite, which represent about 65% of the early condensate settle to the interior. The remainder constitutes the outer 250 km of the moon and is the source region for the lunar basalts and anorthosites. Both the interior and the outer shell are enriched in Ca and Al and Ti. The outer shell will be enriched in U, Th, Fe and Ti which are rejected by the early crystallizing solids. Anorthite crystallizes from the residual melt before pyroxene and, being lighter than the remaining melt, floats to the surface to form the lunar protocrust, in particular, the highlands. The early condensate has the potential to yield a layer about 200 km thick of anorthosite. The lunar basalts are the result of further fractional crystallization or later partial melting processes. The basalts represent about 20% of the outer shell. With this model the outer 250 km contains most of the iron of the moon and the interior is essentially iron free. This requires a reinterpretation of the lunar electrical conductivity profiles. Figure 10 gives the lunar conductivities as inferred by Sonnet _et_ _al_.,(1971) and temperatures inferred from iron poor refractories. Temperatures are some 800°C higher than inferred for an iron rich interior.

Figure 11 gives thermal history calculations which indicate, in agreement with the previous figure, that the interior of the moon is presently hot and was hot enough in its early history to supply basalts for some 10^9 years after initial melting from depths greater than about 150 km. The thickness of the solid "lithosphere" increases with time.

With this model the lunar interior, below 250 km, is merwinite, diopside, spinel and perovskite with a zero-pressure density of about 3.4 g/cm^3. Merwinite and diopside are the high pressure equivalents of akermanite. The mean composition of the outer shell or crust, is gabbroic anorthosite, and it is enriched in the trace element refractories by a factor of about 16 times chondritic.

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, 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 bulk chemistry of these inclusions in the Allende meteorite is high in Ca, Al and Ti and low in Fe, Mg and volatiles. The dominant minerals 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). The inclusions contain no metallic iron or olivine. These aggregates have been studied in detail by Clark _et_ _al_. (1970), Marvin _et_ _al_. (1970), Gast _et_ _al_. (1970) and Grossman (1972). The texture and the presence of reaction rims indicate that the inclusions were inserted into the matrix at high temperature. The O^{18}

value of this material is much more negative than any other meteoritic material Onuma et al. (1972) and in the range to be expected for a primary high-temperature condensate from a nebular gas. Marvin et al. (1970) and Clarke et al. (1970) 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 (1972) has supported this view with detailed thermodynamic calculations. If this interpretation is correct they are extremely significant in understanding the origin and composition of the moon. 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.

Trace elements

The concentrations of the trace element refractories have been determined for the Ca-Al inclusions of the Allende chondrite by Gast et al. (1970) and Grossman (1972) and for the whole meteorite by Clarke et al. (1970) and Wakita and Schmitt (1970). 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.

Table 2 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; the second column are whole meteorite abundances. The anorthosite and basalt have large and opposite europium anomalies. The anomalies can be suppressed by mixing basalt with about five times as much anorthosite, columns (6) and (7). This is also shown in Figure 12. The mixture is normalized to carbonacous 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.

[illegible] gives the chondritic normalized trace element refractory abunda[illegible] Allende inclusion and several combinations of the lunar surface material. 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, 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 (1970) 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 2 and 3 give strong support to the hypothesis that the lunar differentiates involve a primitive, refractory source region and are consistant with Gast's (1972) 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. Previously, we estimated that the early condensates would be enriched by a factor of 11 to 17 in refractory trace elements, relative to solar or chondritic abundances.

Major elements

Table 4 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. (1970). 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.

It appears that the early condensate is capable, in principal, of satisfying the major element and trace element requirements placed on the interior by the lunar igneous rocks. It is also capable of explaining the geophysical data.

Possible fractionation of an Allende-like moon

The composition of the Allende inclusion, as reported by Clarke et al. (1970) 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 (1954) 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 (Hanks and Anderson, 1972).

The composition of the outer layer of the moon, obtained by removing the near liquidus crystals, is given in column (1) of Table 5. 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 Hubbard _et al_. (1972) 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 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 (1970). Column (5) is the inferred deep interior (> 250 km) composition (spinel + melilite). For comparison column (6) gives Gast's (1970) deep interior composition which is based on the (invalid) 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.

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 sequence:

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.

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.

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 (1972).

Gast (1972) 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, however, a natural feature of our model. A further difficulty pointed out by Gast with the fractional crystallization model is that the abundance of such elements as Ba, 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.

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 several 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.

The high temperature minerals in this model are gehlinite-akermanite solid solutions (at low pressure), spinel and perovskite. The thickness of the residual melt 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 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.

Inhomogeneous accretion of the moon

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 and the REE. 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 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 interior 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.

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. (1971). They found a three orders of magnitude drop in electrical conductivity between 250 and 350 km depth, although other interpretations are possible. This can be interpreted in terms of a 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. 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_. (1970). 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.

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, perovskite, 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 % of the iron had condensed before forsterite appears (Grossman, 1972). More olivine may be incorporated into the interior if the condensation of iron is delayed by the non-equilibrium considerations of Blander and Katz (1967). As discussed previously, the melilite will break down to pyroxene plus merwinite at high pressure.

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 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 accreted in a dense part of the nebula, i.e. the median plane, and the moon accreted, 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 even more pronounced by the lower temperatures required to condense material at the lower pressures encountered away from the ecliptic and the higher encounter velocities due to the inclined orbit.

b) The moon was always in a low inclination orbit around the sun and orbiting the earth as well. Its encounter velocity with solar orbiting gains is higher than the earth's and, therefore, it has a lower collection efficiency (Ganapathy _et_ _al_. 1970).

c) The earth started accreting sooner than the moon, or for some other reason got a head start. It would therefore have a larger capture cross section than the moon. When it became large enough to retain an 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. Assembly of the Moon from material condensing off the median phase leads naturally to a Moon of initial high inclination.

If the Moon's orbit was initially highly inclined it would accrete 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 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.

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 low melting fraction of the Ca-Al rich inclusions in the Allende meteorite provide a source region some 250 km thick which has the properties inferred by Gast (1972) to be appropriate for the source region of lunar basalts. The mantle, in this model, is primarily merwinite, diopside and spinel with a zero-pressure density of ~ 3.4 g/cm^3. The moon in no way resembles a carbonaceous chondrite. One specific prediction of the model which can be tested by geophysical techniques is the gross layering, namely, a 250 km thick FeO rich crust overlying an iron poor mantle having a density of about 3.4 g/cm^3. The thermal and seismic aspects of this hypothesis are discussed by Anderson and Kovach (1972), Hanks and Anderson (1972), Anderson and Hanks (1972) and Anderson (1972).

The seismic profile is likely to be complex. The crust will be $\sim$ 250 km thick but it may contain a layer, above $\sim$ 90 km, which is in the garnet stability field and will therefore have higher density and velocity that the deeper and shallower parts of the crust (see Fig. 6). Below 90 km the lunar temperature crosses the "garnet in" curve and lower part of the crust (90-250 km) should have relatively low seismic velocities. The velocities in the mantle should be high, around 8.5-9 km-sec, as long as temperatures are below the solidus. Thermal history calculations (Hanks and Anderson, 1972)

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indicate that the deep interior may be above the solidus and therefore at least partially molten. This can occur anywhere below about 200 km and not be inconsistent with the shape of the Moon or the presence of mascons (Anderson and Hanks, 1972). The electrical conductivity profile suggests that partial melting, if it occurs, starts below 250 km. Seismic velocities decrease abruptly upon partial melting and attenuation, particularly for shear waves, increases.

Cameron's Objections

Cameron (1973) has objected to various cosmological implications of accreting a Moon from material that condensed off the plane of the ecloptic. In particular he feels that the pressures inferred for the formation of the Earth (Fig. 1) implies large densities at midplane and therefore considerable damping for objects in inclined orbits which must pass through this plane twice per orbital period. He also believes that, at midplane the objects will pick up iron.

First, the inferred pressure for the Earth's formation is not the ambient pressure at midplane. A massive body will perturb the gas pressure in its vicinity. For a body the size of the Earth the gas pressure at the surface will be above three orders of magnitude greater than ambient pressure. In addition, there are pressure fluctuations around the body due to aerodynamic forces. Finally, a large body will be outgassing trapped volatiles and have a transient increment to the atmosphere by each new impact.

The effective pressure in the vicinity of a large planet is greater than the ambient pressure. The passage of such a body through a gas will therefore trigger condensation in its vicinity. The presence of an atmosphere also makes a planet more efficient at scavenging and retaining already condensed material along its orbit. A late forming Moon whether in or out of the plane will be composed of only the earliest condensates. Material in the median plane is incorporated into the massive body before condensation occurs under ambient conditions of temperature and pressure. The Moon never had a chance!

The hypothesis that the Moon formed from material that condensed off the plane in no way regroves that the Moon itself was fully assembled off the plane. Therefore, Cameron's objections are not relevant. However, the above considerations permit a three order of magnitude decrease in the mass of the body which will not be affected by gas drag and which must be assembled in half an orbital period, according to Cameron.

Forming the Moon from material originating off the plane has the advantage that it delays the start of the Moon, relative to the Earth, in a straight forward manner. It also explains, in a natural way, the initial high inclination of the lunar orbit suggested by orbital evalution calculations. Capture from an Earth-orbit crossing trajectory is certainly more appealing than the double perturvation that is required if the Moon formed inside the orbit of Mercury.

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Table 1

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

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 1 (Cont'd)

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

(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.

*After Grossman, 1972

Table 2

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	1[illegible].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 2 (Cont'd)

	Meteorites			Moon				Moon/Meteorite	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
K/U	500-10,000	$1.3\text{x}10^4$	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 C1 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 3

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)/carbonaceous chondrites

(2) (.22 basalt + .78 anorthosite)/carbonaceous chondrite

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

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

Table 4

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	---

(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 5

Model Compositions of Lunar Interior

	CRUST				MANTLE	
	(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. Compare with Column (1).

(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. Condensation temperature vs. pressure in the nebula.

Figure 2. Development of a planet according to the accretion during condensation hypothesis.

Figure 3. Development of a planet, continued.

Figure 4. Lunas vs. meteoritic abundances.

Figure 5. Chondritic normalized lunar abundances (above) and fraction of condensed material (below) as a function of temperature in the nebula.

Figure 6. Stability fields of plagioclase in plagioclase rich systems (Anderson, 1972d).

Figure 7. Phase relations in a simplified periotite (Anderson, 1972d).

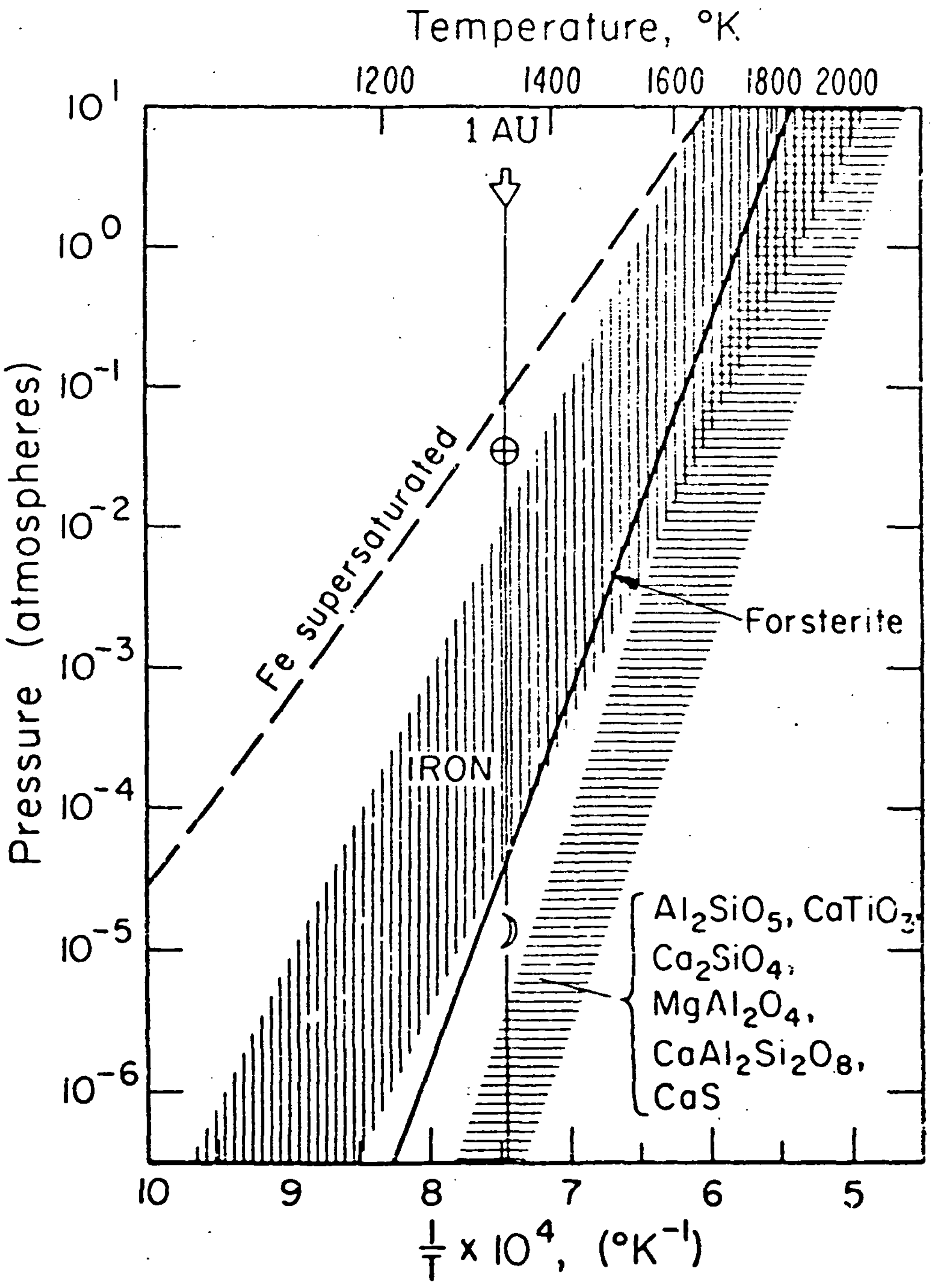
Figure 8. Stability fields for two lunar interior models (Anderson, 1972d).

Figure 9. Gabbro-eclogite boundary as a function of iron content (Anderson, 1972d).

Figure 10. Electrical conductivities of MgO, Al_2O_3, forsterite (Mg_2SiO_4) and olivines of varying fayalite (Fe_2SiO_4) content (left). Electrical conductivity of the moon (lower right) and inferred temperatures (upper right).

Figure 11. Thermal history calculations (Hands and Anderson, 1972).

Figure 12. Trace element refractory abundances in the moon and the Allende meteorite (Anderson, 1972c).


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})

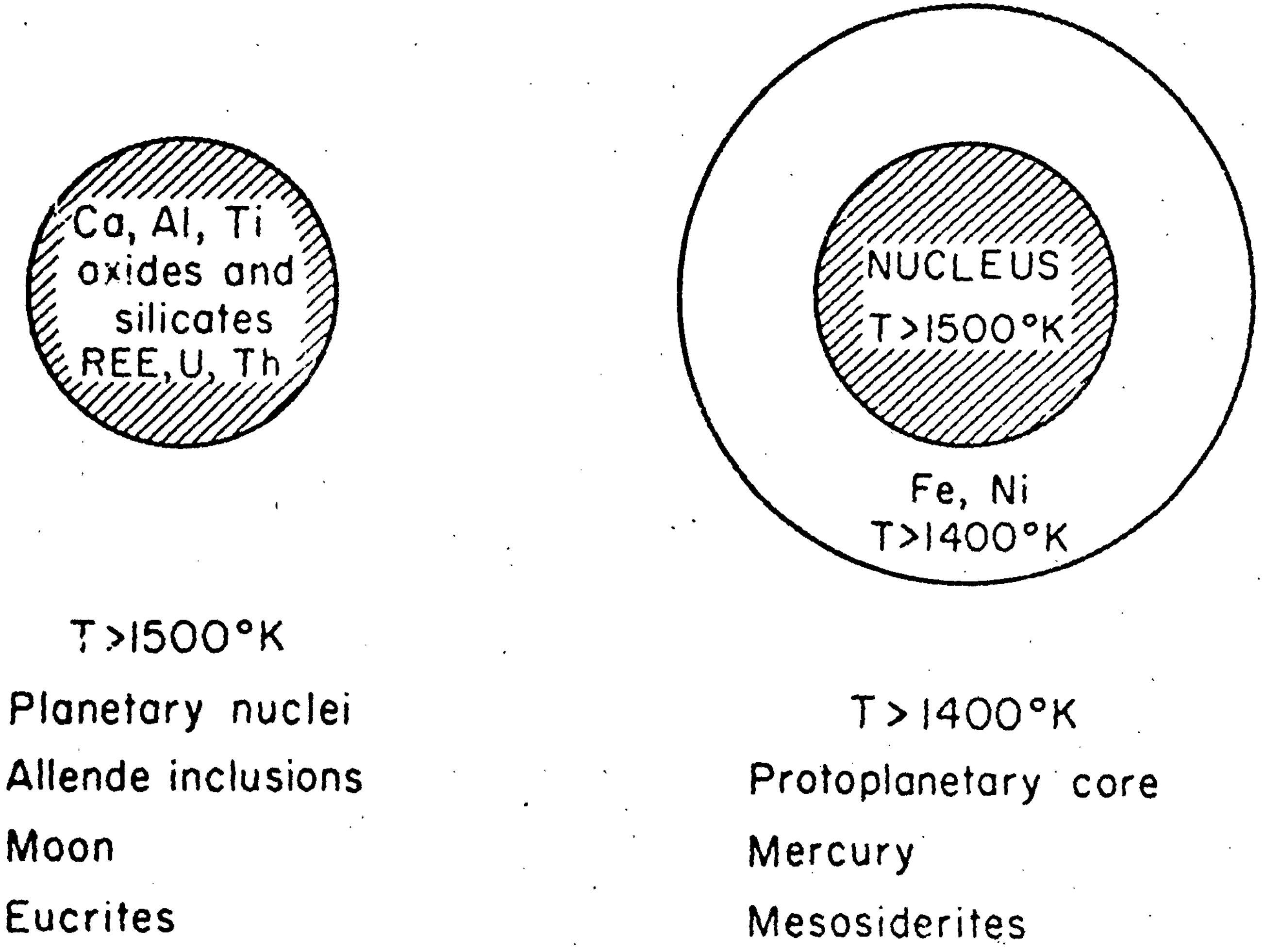
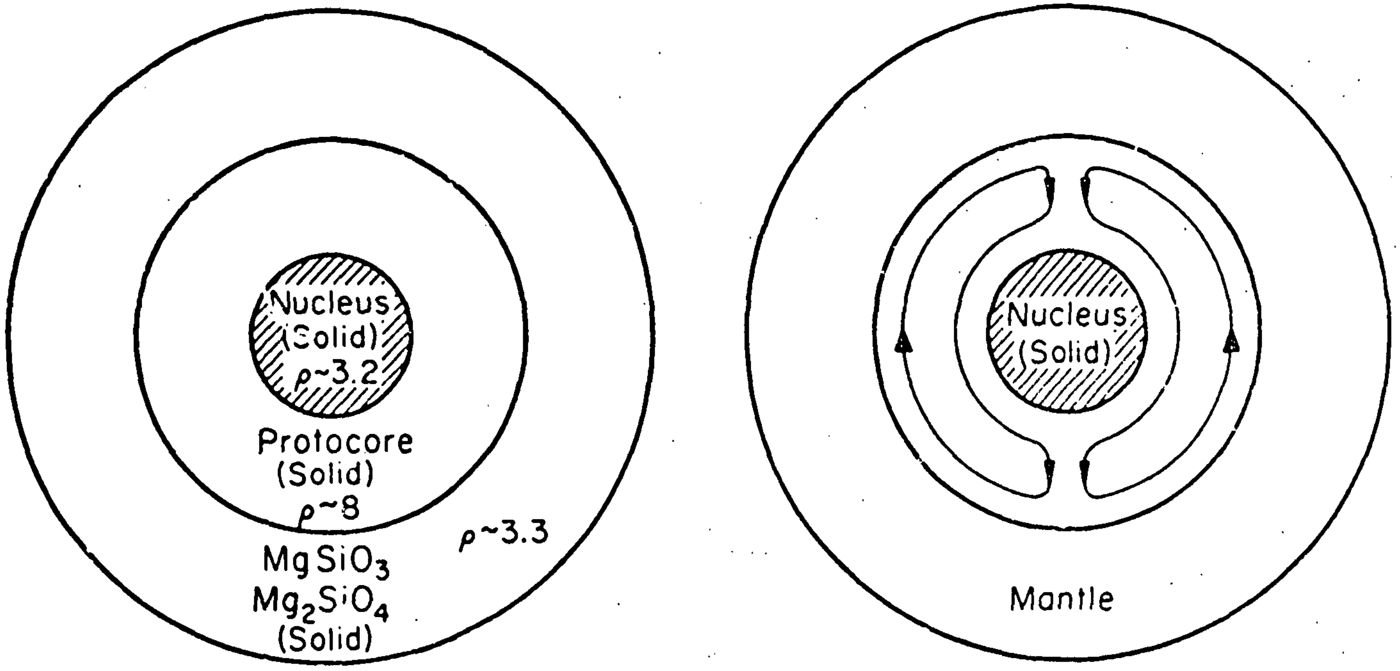

Ca, Al, Ti
oxides and
silicates
REE, U, Th
NUCLEUS
T>1500°K
Fe, Ni
T>1400°K
T>1500°K
Planetary nuclei
Allende inclusions
Moon
Eucrites
T>1400°K
Protoplanetary core
Mercury
Mesosiderites

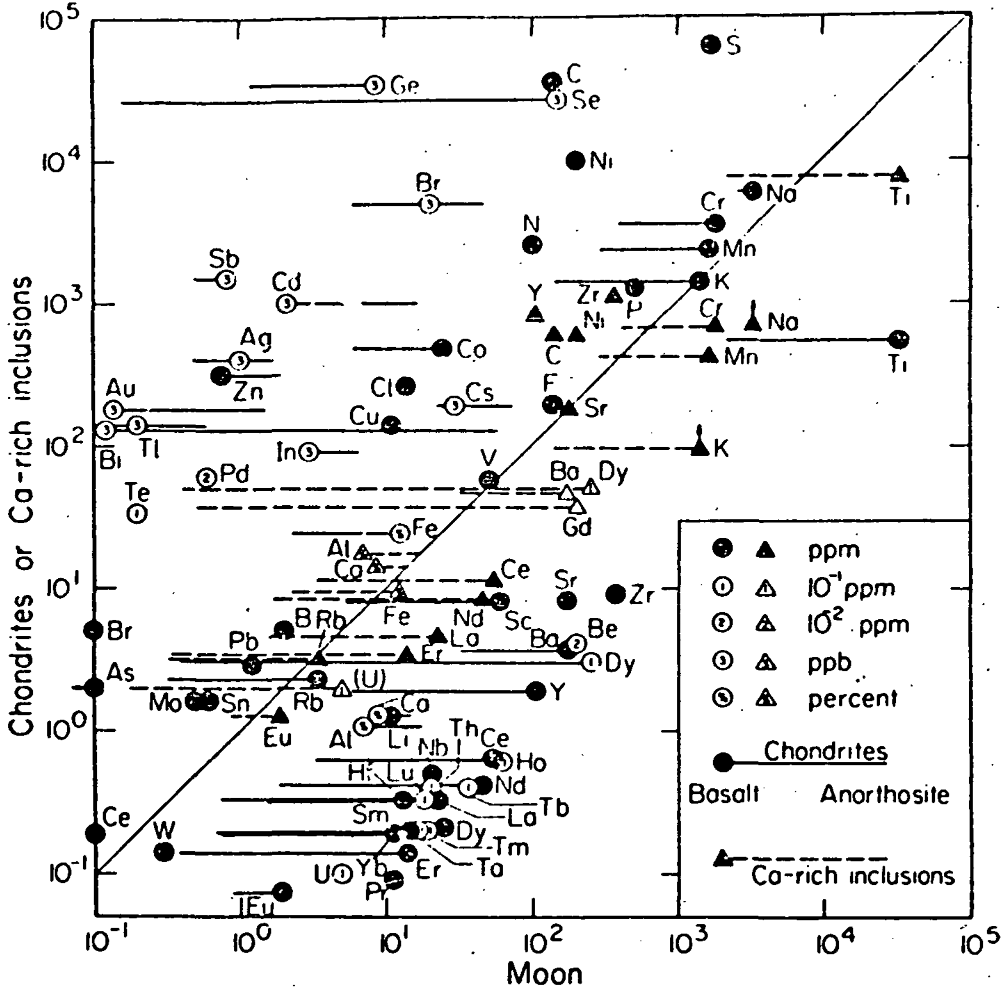
Fig. 2



+ volatiles = Earth, Venus
+ more volatiles = Mars
$t \sim 10^4$ years

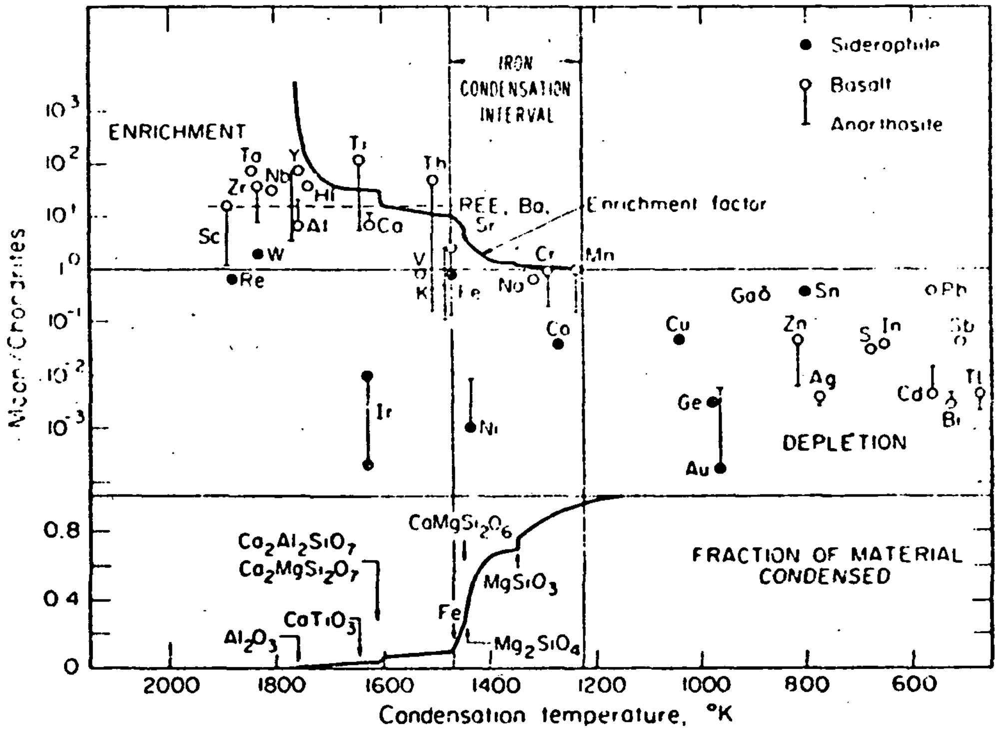
$t \sim 0.3 \times 10^9$ years
melting in protocore;
core instability sets in

Fig. 3



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

Fig. 4



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

Fig. 5

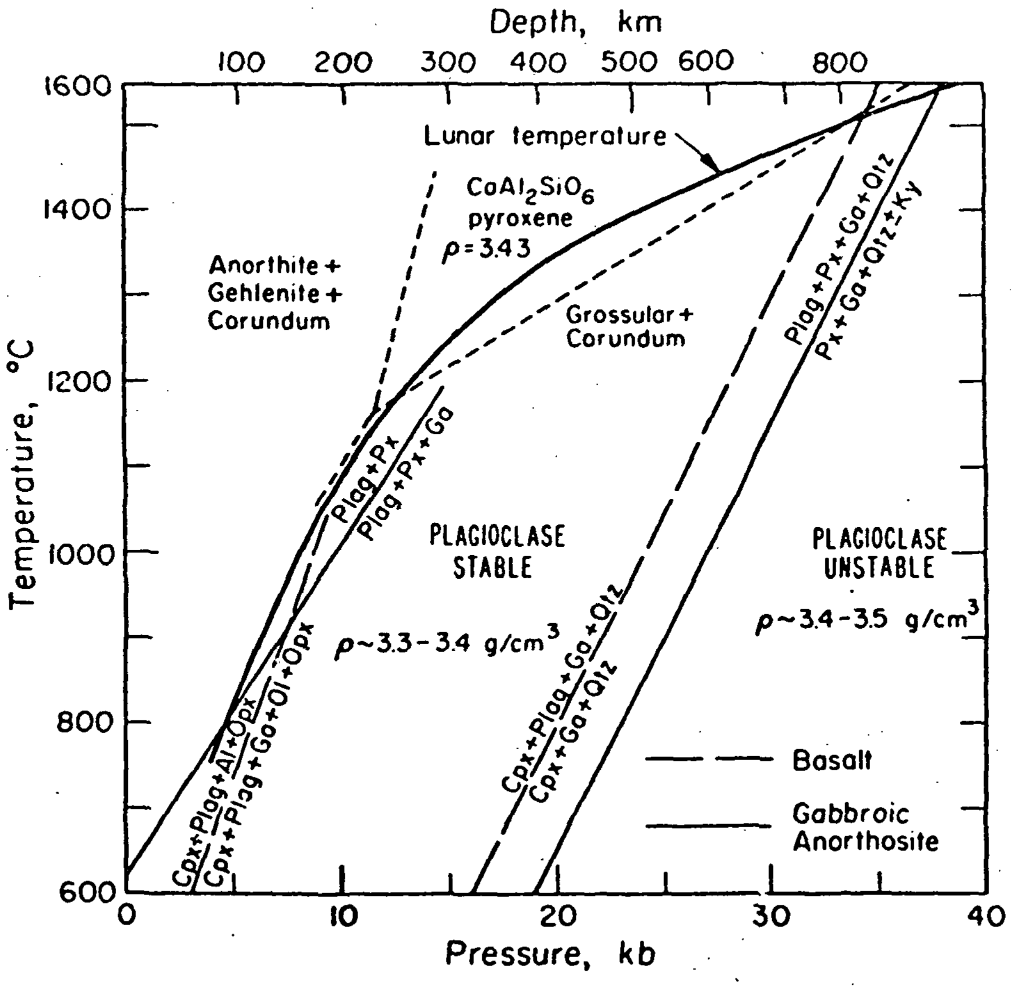
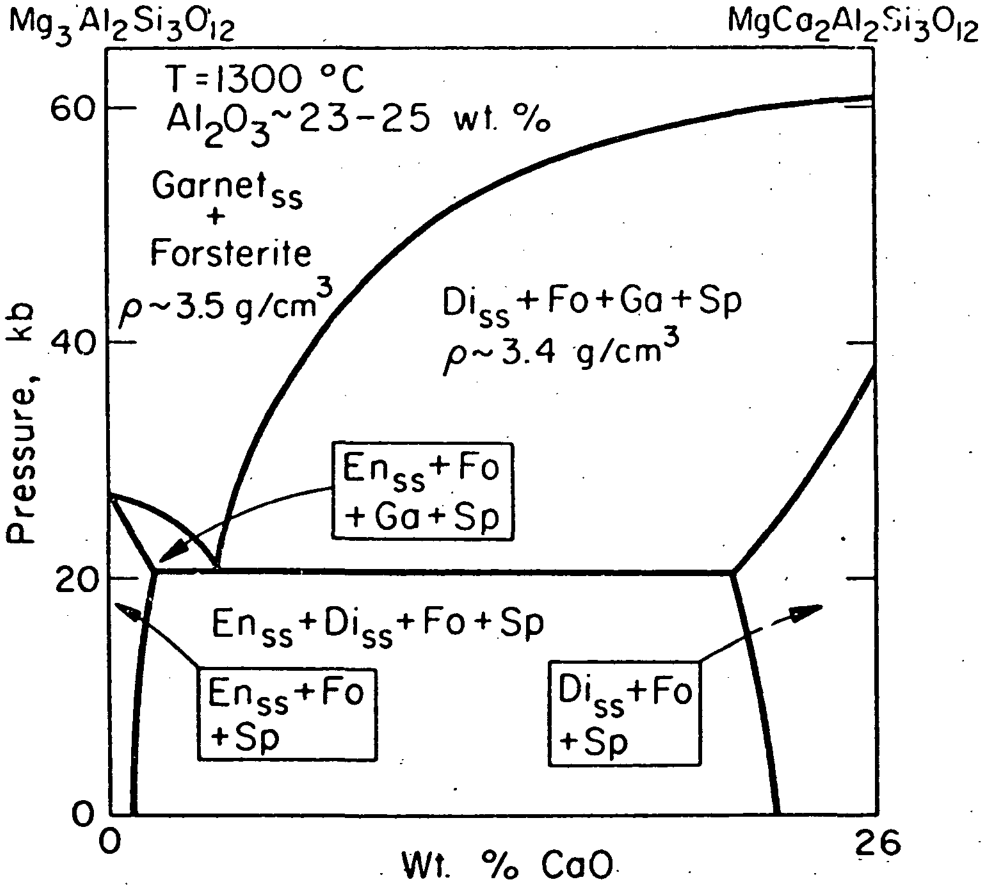
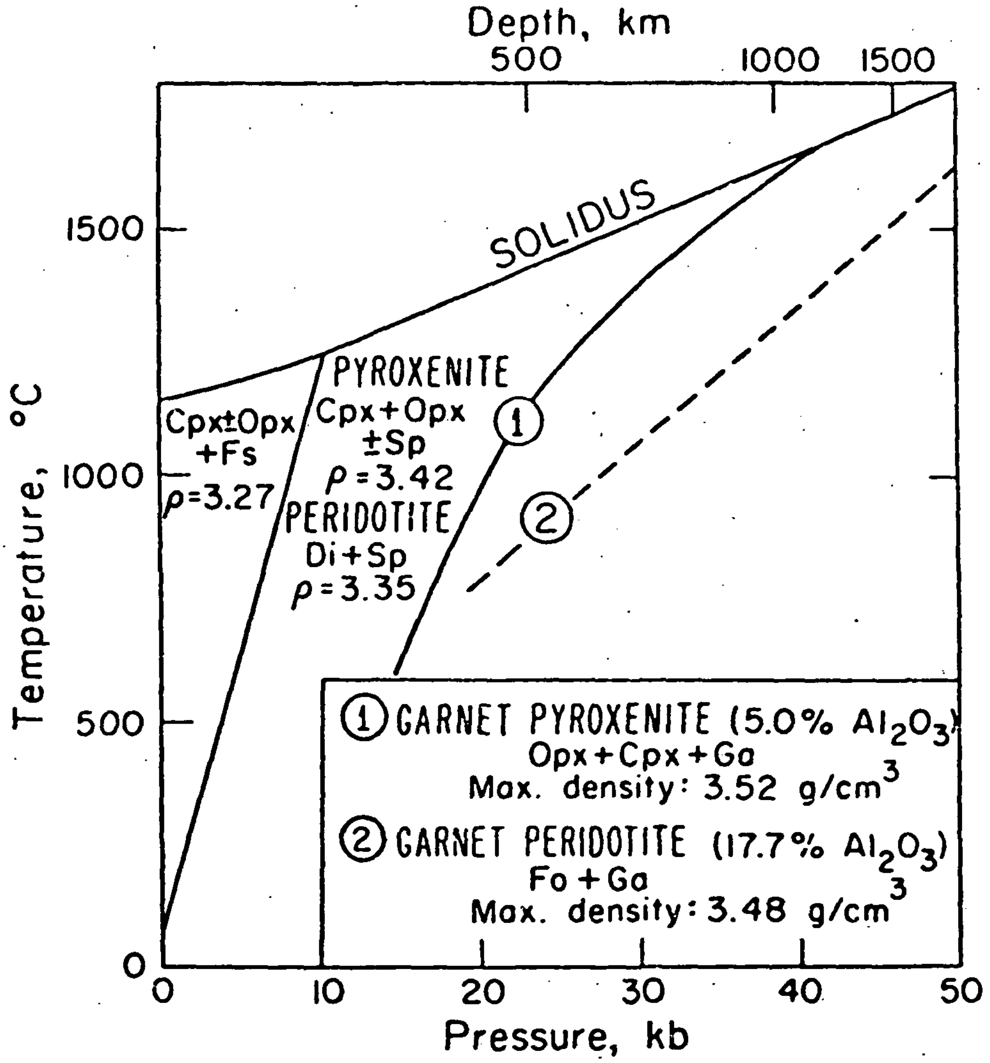
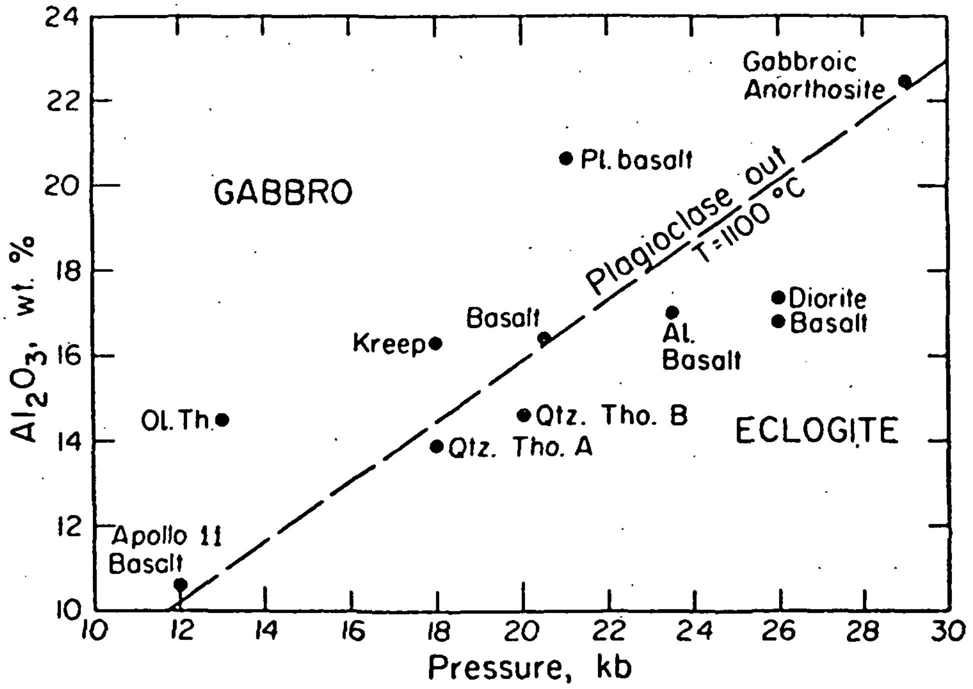

Depth, km
100
200
300
400
500
600
800
1600
1400
1200
1000
800
600
Temperature, °C
0
10
20
30
40
Pressure, kb
Lunar temperature
$CaAl_2SiO_6$ pyroxene
$\rho = 3.43$
Anorthite + Gehlenite + Corundum
Grossular + Corundum
Plag + Px
Plag + Px + Ga
Plag + Px + Ga + Qtz
Px + Ga + Qtz ± Ky
PLAGIOCLASE STABLE
$\rho \sim 3.3 - 3.4$ g/cm^3
PLAGIOCLASE UNSTABLE
$\rho \sim 3.4 - 3.5$ g/cm^3
Cpx + Plag + Al + Opx
Cpx + Plag + Ga + Ol + Opx
Cpx + Plag + Ga + Qtz
Cpx + Ga + Qtz
Basalt
Gabbroic Anorthosite

Fig. 6

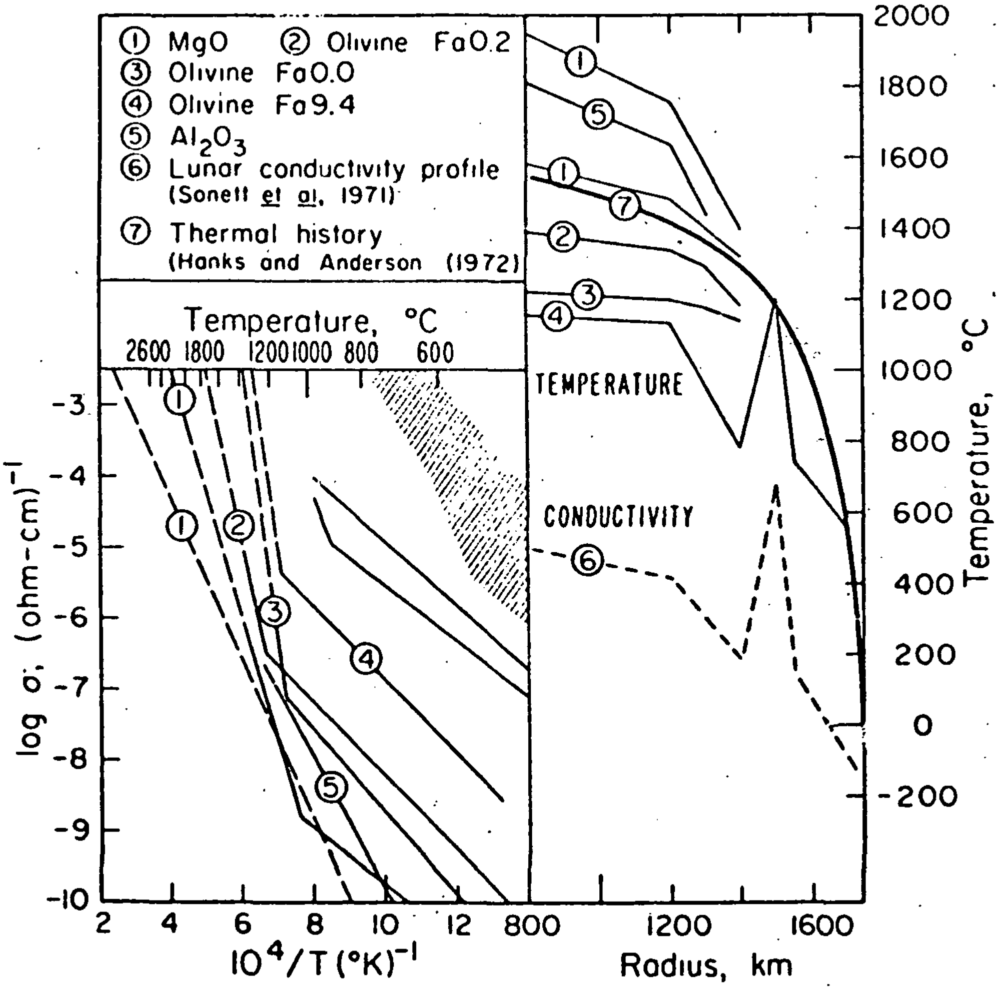


Mg3Al2Si3O12
MgCa2Al2Si3O12
T=1300 °C
Al2O3~23-25 wt. %
Garnetss + Forsterite
ρ~3.5 g/cm3
Diss+Fo+Ga+Sp
ρ~3.4 g/cm3
Enss+Fo +Ga+Sp
Enss+Diss+Fo+Sp
Enss+Fo +Sp
Diss+Fo +Sp
Pressure, kb
60
40
20
0
0
26
Wt. % CaO

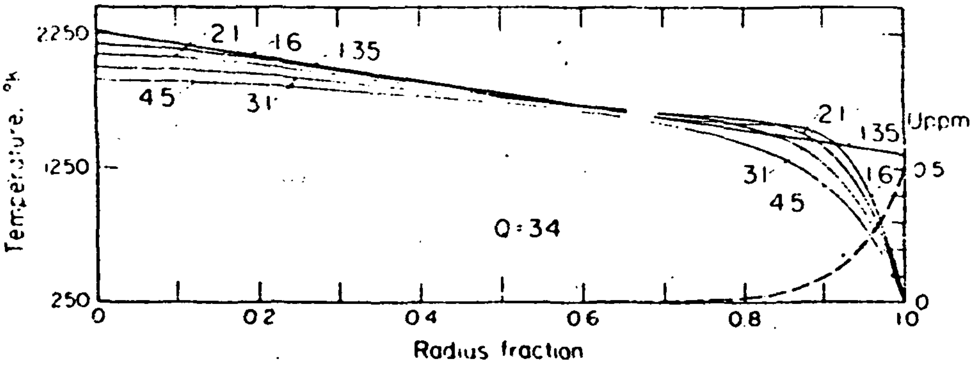

Depth, km
500
1000
1500
SOLIDUS
Temperature, °C
1500
1000
500
0
Cpx±Opx
+Fs
ρ=3.27
PYROXENITE
Cpx+Opx
±Sp
ρ=3.42
PERIDOTITE
Di+Sp
ρ=3.35
①
②
① GARNET PYROXENITE (5.0% Al$_2$O$_3$)
Opx+Cpx+Ga
Max. density: 3.52 g/cm^3
② GARNET PERIDOTITE (17.7% Al$_2$O$_3$)
Fo+Ga
Max. density: 3.48 g/cm^3
0
10
20
30
40
50
Pressure, kb

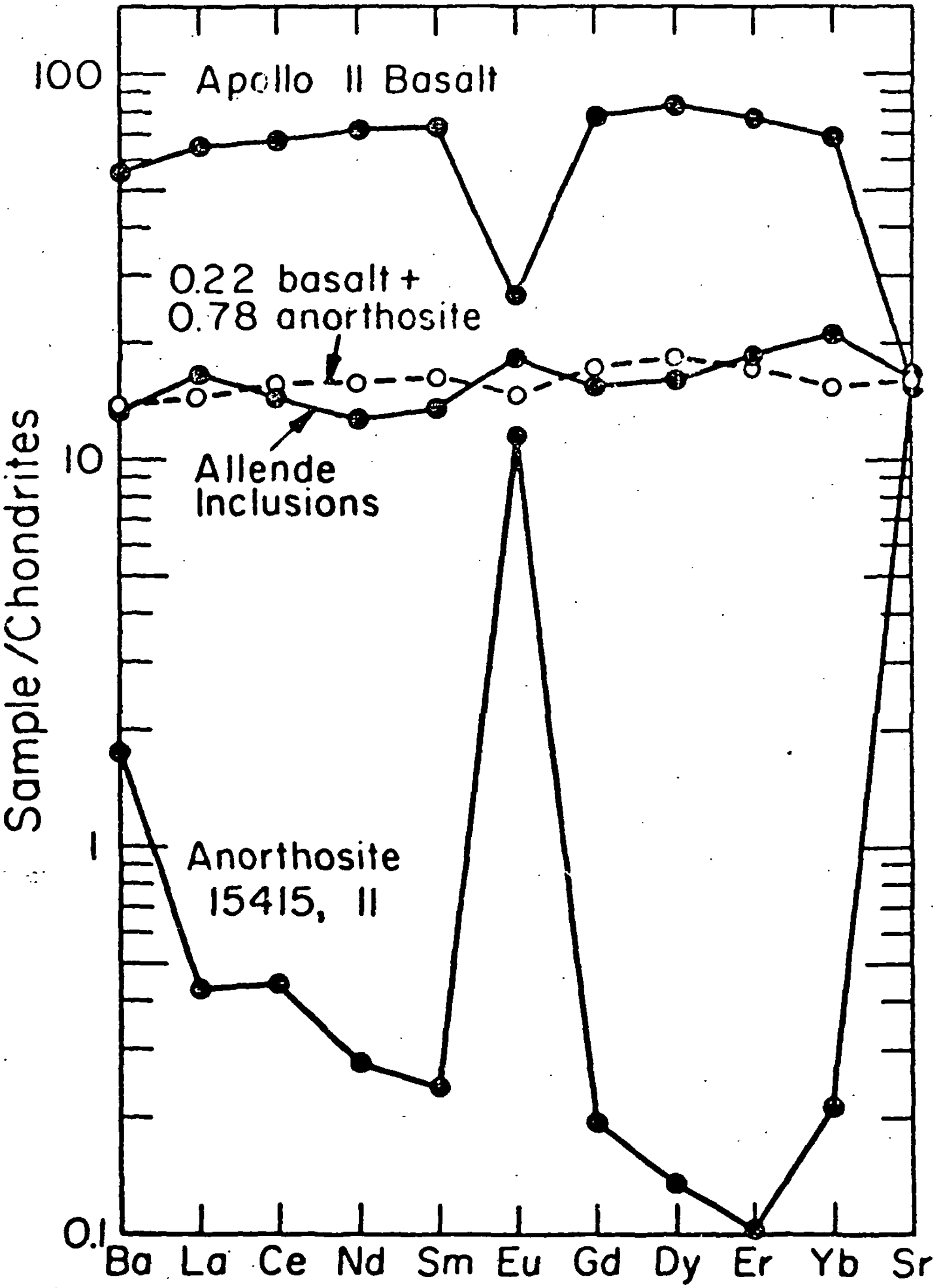


Al_2O_3, wt. %
24
22
20
18
16
14
12
10
10
12
14
16
18
20
22
24
26
28
30
Pressure, kb
GABBRO
ECLOGITE
Plagioclase out
T=1100 °C
Gabbroic Anorthosite
Pl. basalt
Diorite
Basalt
Al. Basalt
Basalt
Kreep
Qtz. Tho. B
Qtz. Tho. A
Ol. Th.
Apollo 11 Basalt



① MgO
② Olivine Fa0.2
③ Olivine Fa0.0
④ Olivine Fa9.4
⑤ Al_2O_3
⑥ Lunar conductivity profile (Sonett et al, 1971)
⑦ Thermal history (Hanks and Anderson (1972)
Temperature, °C
2600 1800 1200 1000 800 600
TEMPERATURE
CONDUCTIVITY
log σ, (ohm-cm)$^{-1}$
-3
-4
-5
-6
-7
-8
-9
-10
2 4 6 8 10 12
$10^4/T$ (°K)$^{-1}$
800 1200 1600
Radius, km
2000 1800 1600 1400 1200 1000 800 600 400 200 0 -200
Temperature, °C


2250
1250
250
Temperature, °K
21
16
135
45
31
21
135
Uppm
31
45
167
0.5
0
Q=34
0
0.2
0.4
0.6
0.8
1.0
Radius fraction


Apollo 11 Basalt
0.22 basalt +
0.78 anorthosite
Allende
Inclusions
Anorthosite
15415, 11
Sample/Chondrites
100
10
1
0.1
Ba
La
Ce
Nd
Sm
Eu
Gd
Dy
Er
Yb
Sr

END

DATE

FILMED

AUG 30 1973