CLARKE MEMORIAL LECTURE


ORIGIN OF THE MOON

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## 1.  INTRODUCTION

This lecture was delivered at a time when the only information

available to me on lunar rocks consisted of preliminary chemical

data obtained by the Lunar Sample Preliminary Examination Team (LSPET,

1969) and some preliminary investigations on the mineralogy and

petrology of Apollo 11 samples which were being studied in Canberra.

Preparation of this paper was inadvertently delayed, and a vast

amount of detailed data on the lunar rocks has since been published,

principally in Science 167, No. 3918, 1970 and in the Proceedings of

the Apollo 11 Lunar Science Conference Vols. 1, 2 and 3.  In this

paper, I shall cover much the same ground as was covered in the

Clarke Lecture, but will incorporate more recent chemical and

petrological information where appropriate.  Fortunately, most of

the more general boundary conditions on which I based my discussion

of the origin of the moon have been amply confirmed by the new data.

This is a tribute to the excellence of the work carried out by

the Lunar Sample Preliminary Examination Team.

## 2. NATURE OF APOLLO 11 CRYSTALLINE ROCKS

### (a) General Properties and Distribution

Perhaps the single most important discovery of the Apollo 11 mission which landed in Mare Tranquilitatus was that the crystalline samples returned were clearly identifiable as mafic igneous rocks closely related to basalts and dolerites. The principal minerals were pyroxene, plagioclase and ilmenite, with smaller amounts of olivine, other ore minerals, cristobalite, glass and other minor minerals. The textures were typically igneous and similar to those of terrestrial basalts and dolerites (Figure 1). Major element chemical compositions of nearly all rocks were very similar. Detailed trace element and isotopic studies (Compston et. al., 1970 a,b) revealed, however, that they could be divided into two groups with slightly different average compositions, probably representing two separate flows. (Table 1) These results gave strong support to the earlier hypothesis (e.g. Baldwin, 1963) based upon a variety of observational evidence that the maria consisted of great floods of basaltic rocks. Alternative hypotheses, e.g., that the maria were dried-up lake sediments or deep seas of dust could be discarded for all practical purposes.

The question is often asked whether we are entitled to make broad generalizations from a single grab-sample from one spot on the moon. What kind of conclusions might we reach if we attempted to infer the history of the earth from samples obtained at a single random location? The moon is kinder to the scientist in this respect than the earth.

Figure 1    Photograph of thin section of a typical

Apollo 11 crystalline rock.

It does not possess a hydrosphere or atmosphere; the major geological cycle which operates on the earth does not appear to have operated on the moon. The evolution of the lunar surface appears to have been much more simple than that of the earth, and the principal features were generated more than 3 billion years ago, and have not been greatly disturbed since. The principal agent altering the lunar surface has been meteorite impact, and this has had the effect of extensively redistributing and stirring near-surface material, so that any single sample of "soil" contains small rock fragments which have been derived from a very large area of the lunar surface. It is most significant that about 95% of the recognisable rock fragments in the soil are composed of the same mineral assemblage as was found in the larger crystalline rocks of local origin, and most of the smaller glass fragments and spheres were also shown after analysis to be derived ultimately from mafic igneous rocks. We have also the evidence (Turkevich et. al., 1969) of the Surveyor 5 analysis from a location some tens of kilometers away on the same mare and the Surveyor 6 analysis from a different and distant mare (Sinus Medii—Franzgrote et. al., 1970). Both of these chemical analyses yielded compositions approximately similar to Apollo 11 rocks and indicated the widespread occurrence of rocks of this general nature. Finally, the preliminary analyses of Apollo 12 rocks from Oceanus Procellarum are generally similar to those of Apollo 11 rocks. (LSPET, 1970) Although there are some important

Table 1

Average compositions of Group 1 and Group 2 Apollo 11
crystalline rocks after Compston et. al., (1970b) compared with
analyses of terrestrial oceanic tholeiite (Engel et. al., 1965)
and typical basaltic achondrite (Duke and Silver, 1967).  Group
1 and 2 compositions represent averages of 6 analyses.

| | Apollo 11 Crystalline Rocks | | Basaltic | Oceanic |
| | Group 1 | Group 2 | Achondrite | Tholeiite |
| --- | --- | --- | --- | --- |
| $SiO_2$ | 40.28 | 40.47 | 49.54 | 49.34 |
| $TiO_2$ | 11.88 | 10.32 | 0.68 | 1.49 |
| $Al_2O_3$ | 8.95 | 10.41 | 12.69 | 17.04 |
| $Fe_2O_3$ | —— | —— | —— | 1.99 |
| $FeO$ | 19.91 | 18.72 | 18.57 | 6.82 |
| $MnO$ | 0.24 | 0.27 | 0.53 | 0.17 |
| $MgO$ | 7.60 | 6.66 | 6.86 | 7.19 |
| $CaO$ | 10.53 | 11.48 | 10.36 | 11.72 |
| $Na_2O$ | 0.64 | 0.49 | 0.42 | 2.73 |
| $K_2O$ | 0.31 | 0.09 | 0.05 | 0.16 |
| $P_2O_5$ | 0.18 | 0.11 | —— | —— |
| $S$ | 0.23 | 0.16 | —— | —— |

second order differences, the Apollo 12 rocks are clearly recognizable as first cousins to Apollo 11 rocks. All of this evidence strongly supports the overall characterization of the lunar maria as consisting of mafic igneous rocks. High resolution Orbiter photography suggests that the maria may be composed of large numbers of overlapping thin flows of basaltic-type rocks analogous to plateau-basalts.

Having recognized lunar basalts as chemically and petrologically closely related to terrestrial basalts, it is natural to consider the hypothesis that their origins are analogous. Terrestrial basalts are known to form by partial melting process at substantial depths in the earth's mantle and the chemistry and phase relationships involved in this process are now reasonably well understood (Green and Ringwood, 1967). It is tempting to hypothesize that lunar basalts have formed by analogous partial melting process in the lunar interior. This hypothesis has been forcefully advocated by Baldwin (1963) on the basis of his investigations of the physiographic relationships between lunar maria and impact craters. There is, however, an alternative hypothesis that the lunar maria have formed by impact melting when large planetesimals collided with the moon during its final stages of formation (Urey, 1952; Öpik, 1967).

These two hypotheses have very different consequences with respect to information which the lavas are capable of providing

about the lunar interior.  If lunar basalts are of internal origin,
we can study their chemistry and phase relationships in order to
place strong constraints upon the nature of the source regions from
which they were derived, using experimental methods similar to those
employed by Green and Ringwood (1967).  This approach has been
employed by Ringwood and Essene (1970b).  On the other hand, if
lunar lavas are of impact origin, we obtain information only about
near-surface material.  After studying the preliminary data provided
by the LSPET team, my colleagues and I formed the opinion that the
Apollo 11 lavas were very probably of internal origin and pro-
ceeded on this assumption.  Nevertheless, several scientists strongly
advocated the impact melting hypothesis at the Houston Apollo 11
meeting, and a controversy developed.  The accumulation of subse-
quent detailed evidence has made it practically certain that the
Apollo 11 rocks and probably all of maria are indeed of internal
origin.  We will review some of this evidence later.

### (b)  Major Element Composition

Relative abundances of most major components ($SiO_2$, $Al_2O_3$, $CaO$,
$FeO$, $MgO$) fall within the same range as are displayed by terrestrial
basalts and basaltic achondrites.  (Table 1)  There are, however,
some significant differences, notably the abundance of $TiO_2$ in lunar

basalt is much higher than in terrestrial basalts and achondrites. $Cr_2O_3$ is also much higher in lunar basalt (av 0.3% $Cr_2O_3$) than in terrestrial basalt (av 0.01% $Cr_2O_3$), but is similar to the achondritic abundance (av 0.3% $Cr_2O_3$). On the other hand, $Na_2O$ is much lower in Apollo 11 basalt compared to terrestrial basalt and is generally similar to the achondrites. It appears that the very high abundance of $TiO_2$ in the <u>rocks</u> from the Apollo 11 site may be somewhat atypical. The $TiO_2$ abundance in the lunar <u>soil</u> was substantially lower, as were the $TiO_2$ abundances in Apollo 12 rocks and at the Sinus Medii (Surveyor 6) site. Sodium and chromium abundances on the other hand, appear to be uniform in samples from all sites measured.

A notable feature is the comparative constancy of $\dfrac{FeO}{FeO + MgO}$ ratios in nearly all lunar rocks and the high and uniform abundances of $Cr_2O_3$. Microprobe analyses (Essen et. al., 1970) showed that the $\dfrac{FeO}{FeO + Mgo}$ ratios of the earliest ferrogmagnesian crystals to form from all the lunar samples were approximately constant and equal to 0.25.

(c) <u>Incompatible Non-volatile Trace Elements</u> e.g., U, Th, Zr, Ba, Light Rare Earths, Ta,

Incompatible elements are those possessing ionic radii and charges which inhibit their ready substitution in the principal

rock-forming minerals. As a result, these elements tend to become strongly concentrated in the liquid phase during crystal-liquid differentiation processes. Results by the LSPET, amply confirmed by many other workers, demonstrated that this class of elements is concentrated in Apollo 11 basalts by factors of 30 to 100 over chondritic (primordial) abundances. This implies that extraordinarily efficient crystal-liquid fractionation mechanisms were involved during the formation of Apollo 11 rocks. Most absolute abundances of these elements fall in the concentration ranges observed for varieties of terrestrial alkali basalts. However, the relative abundances differ in important respects from those of terrestrial basalts. This is seen in Figure 2 from Gast and Hubbard (1970), which shows the abundances of Ba and some rare earths in Apollo 11, Apollo 12 and basaltic achondrites normalized to chondritic abundances. The generally sub-parallel patterns which would have been reinforced if other incompatible elements (e.g., U, Th) had been included, strongly imply derivation from source material possessing the chondritic abundances of this group of elements. Notice the spectacular depletions of europium—a feature which has caused a great deal of discussion. This is primarily due to the highly reduced state of lunar basalts (see below) which causes europium to occur dominantly in the divalent state, $Eu^{2+}$, possessing different crystal chemical

Figure 2.  Rare earth and barium abundances from Apollo 11 and

12 lunar samples and from some basaltic achondrites.  The H1-Rb

group and sample 10020 represent Apollo 11 rocks.  Most of the

Apollo 11 rocks fall between these samples as does the Apollo

11 soil 10084.  In contrast the Apollo 12 rocks 12051, 12053

and 12002 occupy a generally intermediate position between the

Apollo 11 rocks and the basaltic achondrites (meteorites).

Apollo 12 soils 12070 and 12044 have much higher rare earth

abundances than the corresponding rocks and fall within the

Apollo 11 range (After Gast and Hubbard, 1970).
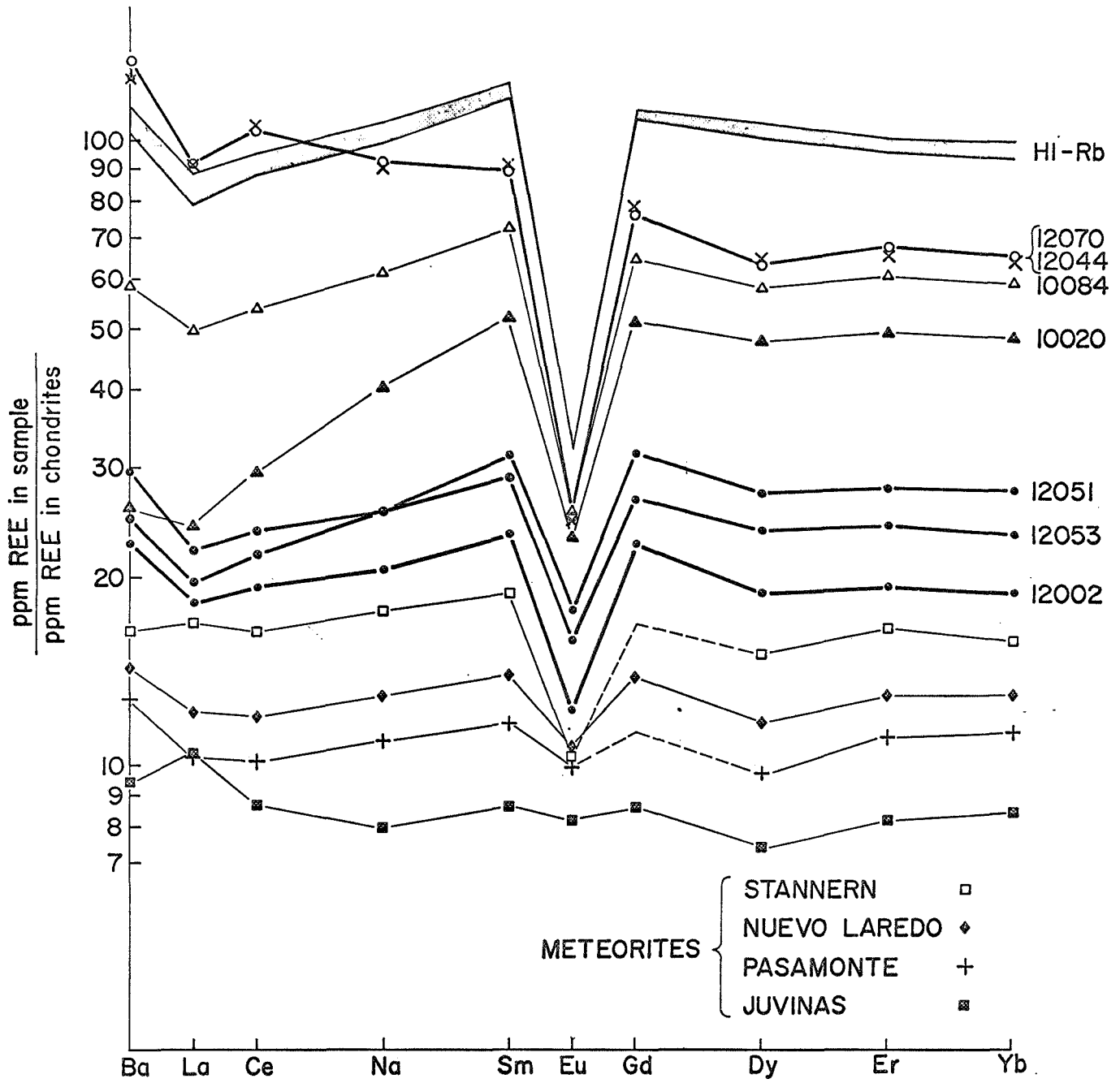
properties to the neighboring trivalent rare earths $Sm^{3+}$ and $Gd^{3+}$.
In more oxidized terrestrial systems, most europium occurs as $Eu^{3+}$
and europium anomalies of this magnitude are not observed in mafic
rocks.

An important feature of Figure 2 is the intermediate position
of the Apollo 12 patterns between the abundance patterns of Apollo
11 rocks and basaltic achondrites. There appears to be a complete
continuum between these two extremes. These relationships, together
with the very close mineralogical and petrological resemblances
between lunar basalts and basaltic achondrites which were commented
upon by numerous workers at the Apollo 11 Conference in Houston
strongly suggest that the basaltic achondrites might also be derived
from the moon.

### (d)   Volatile Metals:  Na, K, Rb, Cs, Zn, Cd, Hg, Bi, Tl, In, Ga, Pb, Sb, As

Preliminary analyses by the LSPET indicated that, when appro-
priately normalized, the elements Rb, K, Na, Zn, Pb, and Ga were
systematically depleted in lunar basalts compared to terrestrial
basalts by factors of 3 to 9. This group of elements is characterized
by relatively high volatility under high-temperature, reducing condi-
tions. In the Clarke Lecture, I placed great emphasis upon the

significance of depletion of this class of elements, and assumed it to be characteristic of the source regions from which the lunar basalts were derived.

Subsequent accurate analyses by Keays et. al., (1970), Baedecker and Wasson (1970), Morrison et. al., (1970) and Smales et. al., have confirmed this fundamental depletion pattern, and extended it to many more volatile elements. It is now clear that Na, K, Rb, Cs, Zn, Cd, Hg, Bi, Tl, In, Ge, Pb, Sb and As are depleted relative to terrestrial basalts by factors which vary from 3 to 100. In turn, terrestrial basalts are depleted in this group of elements compared to primordial abundances by factors of 3 to 10 (Ringwood 1966a).

At the Houston meeting, a controversy developed about the origin of these depletions in lunar material. One group insisted that the depletions were characteristic of the source regions of lunar basalt and accordingly provide a clue of fundamental importance to the chemical processes by which the moon formed. (e. g. Ringwood and Essene, 1970a; Ringwood, 1970). The other group claimed that the volatile elements had simply distilled from the lunar lava flows after extrusion, and hence their relative depletions were not characteristic of the source regions. (e.g. O'Hara et. al., 1970 a,b).

This controversy is now settled for all practical purposes. Isotopic Rb-Sr studies (Compston et. al., 1970b; Albee et. al., 1970;

Ganapathy et. al., 1970; Gast et. al., 1970; Hurley and Pinson, 1970)

and Pb-U studies (Compston et. al., 1970; Tatsumoto, 1970; Gopalan

et. al., 1970) showed that strong depletion of Rb and Pb (relative

to Sr and U) in lunar basalts as compared to terrestrial basalts

occurred about 4.6 billion years ago during the formation of the moon

and long before the lunar basalts were erupted. This feature must,

therefore, be a characteristic of the source regions. Additional

arguments by Ringwood and Essene (1970b) and Goles et. al., (1970)

showed that the depletions of Na, and K almost certainly did not

occur by volatilization from the lunar lavas during and after extrusion.

If it is accepted that the depletions of Rb, Pb, Na and K are of pri-

mary origin, it is reasonable to assume that the corresponding deple-

tions ~~after~~ of other volatile metals are similarly primary.

(e)  Siderophile Elements:  Ni, Cu, Ga, Ag, Au, Ir

LSPET preliminary results indicated that the siderophile elements

Ni (strongly) and Cu (significantly) were depleted in lunar basalt

compared to terrestrial basalts. Subsequent accurate analyses by

Keays et. al., (1970) have confirmed and extended this pattern. Ni,

Cu, Ga, Ag, Au and Ir were found to be depleted compared to terrestrial

basalts by factors of 3 to 10. This is attributed to equilibration

of lunar basalts with metallic iron as a consequence of their lower

oxidation states than terrestrial basalts (see below) followed by partial removal of the metal phase.

## (f) Oxidation State

Numerous workers drew attention at the Houston Conference to the fact that Apollo 11 basalts commenced to crystallize at an oxygen fugacity of $10^{-13.5}$ atm. (1200°C) as compared to the corresponding oxygen fugacity for terrestrial basalts of about $10^{-8}$ to $10^{-9}$ atm. As a result, the $Fe^{3+}$ ion is not detectable in ore minerals and pyroxenes from lunar rocks (Agrell et. al., 1970; Hafner and Virgo, 1970) whereas it is always a significant component of corresponding terrestrial minerals. The low oxidation state is also responsible for the widespread occurrence of free metal in Apollo 11 basalts as well as species such as $Ti^{3+}$ and $Cr^{2+}$ inferred to occur in solid solution in some ore minerals and olivine respectively. A further consequence of the low oxidation state of lunar basalts is the absence of any evidence of the presence of hydrated minerals and carbonates in the crystalline lunar rocks. The species $CO_2$ and $H_2O$ are dominantly reduced to CO and $H_2$ at the oxygen fugacity prevailing.

## (g) Melting Relationships at One Atmosphere

Several workers have carried out melting experiments upon Apollo 11 basalts or upon synthetic analogues. In general, the results are closely concordant although there are a few discrepancies

arising out of inadequate control of oxidation states during experiments. Ringwood and Essene (1970 a, b) showed that the liquidus phases at $1050^{\circ}$ C were armalcolite (a new mineral: $(Fe_{0.5}Mg_{0.5})\ Ti_2O_5$, with the pseudobrookite structure) and olivine ($Fo_{74}$). With falling temperature, armalcolite reacted with liquid to produce ilmenite ($1120^{\circ}$ C) whilst olivine reacted to form pyroxene ($1120^{\circ}$ C). At this temperature the degree of crystallization increased rapidly with abundant cotectic crystallization of pyroxene, plagioclase and ilmenite. These phases continued to crystallize until the solidus was reached at about $1090^{\circ}$ C.

The experimental phase relationships closely matched those observed in natural Apollo 11 basalts. Several workers found armalcolite as an early phase and inferred a reaction relation with ilmenite. Likewise, olivine in Apollo 11 samples was interpreted to be in reaction relationship with pyroxene. The crystallization sequence of Apollo 11 rocks inferred from petrological criteria was identical with that of the synthetic specimen.

The relatively late crystallization of plagioclase is an important feature. In our experiments plagioclase did not appear until about 30% of the liquid had crystallized as olivine, pyroxene and ore minerals. This feature was observed by all other experimenters. In some experiments on another Apollo 11 basalt slightly different in

composition, more than 50 percent of the rock crystallized before plagioclase appeared (Weill et. al., 1970). Clearly the magma was far from being saturated with plagioclase on extrusion.

In most experimental work, the crystallization interval between solidus and liquidus was found to be quite small, between $60^\circ$ C and $120^\circ$ C. Furthermore, the temperature interval between entry of the major phases——olivine, pyroxene, ore and plagioclase——was mostly also found to be quite small and on the order of 30 to $40^\circ$ C.

O'Hara et. al., (1970 a,b) have made much of this feature claiming that it demonstrates that Apollo 11 basalts were "almost cotectic indicating that lunar basalts are not primary magma, but the residual liquids of advanced near-surface crystal fractionation". This conclusion is clearly wrong. The closeness of Apollo 11 basalts to a cotectic of major minerals is to be measured not by temperature intervals but by the amount of crystallization necessary to bring the liquid from its observed composition to the cotectic composition. We have seen that Apollo 11 basalt must crystallize 30 to 50% of ores and ferromagnesian minerals before the plagioclase——ilmenite——pyroxene cotectic is reached. Clearly, they were far from the low-pressure cotectic when erupted and could not have undergone extensive near-surface fractionation. Additional arguments relating to this point are given later.

## (h)  Ages

Only two research groups were successful (by January 1970) in the difficult task of determining accurately the ages of Apollo 11 rocks by Rb-Sr methods.  Albee et. al., (1970) obtained an age of 3.65 ± 0.10 billion years, whereas Compston et. al., (1970a) obtained 3.78 ± 0.10 billion years.  These methods were based on internal mineral isochrons and date the time of crystallization.  Turner (1970) obtained a group of ages close to 3.7 by using the argon 40/argon 39 dating method.  Ages obtained by the lead-uranium method were also consistent with these values (Tatsumoto, 1970).  More recently, Papanastassiou and Wasserburg (1970) have obtained a Rb/Sr age (internal mineral isochron) for Apollo 12 rocks of 3.3 billion years.

## (i)  High Pressure Behavior

A detailed investigation of high pressure phase relationships in typical Apollo 11 basalt and in possible source materials was undertaken by Ringwood and Essene (1970 a,b).  Their results are shown in Figure 3.  Less extensive but generally concordant results on a lunar rock were reported by O'Hara et. al., (1970 a,b).  An interesting feature is the relatively low pressure at which Apollo 11 basalt (density 3.3 gms/cc) transforms to a very dense eclogite 3.7 gms/cc).  It was possible to show conclusively that the moon could not be composed entirely of Apollo 11 rock, or indeed, of

any basaltic rock, because these would lead to too high a mean density and would contradict the moon's moment of inertia (Ringwood and Essene 1970 a,b). Thus, the Apollo 11 basalts must represent differentiates from a more primitive source material with lower Fe/Mg ratio. Further studies on possible source materials by Ringwood and Essene showed that to satisfy the moon's moment of inertia coefficient ($I/MR^2 = 0.402 \pm .002$) which is very close to that of a sphere of uniform density, the moon could not contain more than 6% $Al_2O_3$ and very probably, not more than 6% CaO. It was concluded that the moon's interior was dominantly composed ferromagnesian silicates low in Al and Ca.

## 3. PETROGENESIS OF APOLLO 11 BASALT

The high and variable abundances of the incompatible elements (Figure 2, Section 2c) in Apollo 11 basalts imply the operation of efficient crystal-liquid fractionation processes. Opinion at the Houston meeting was divided between two views:
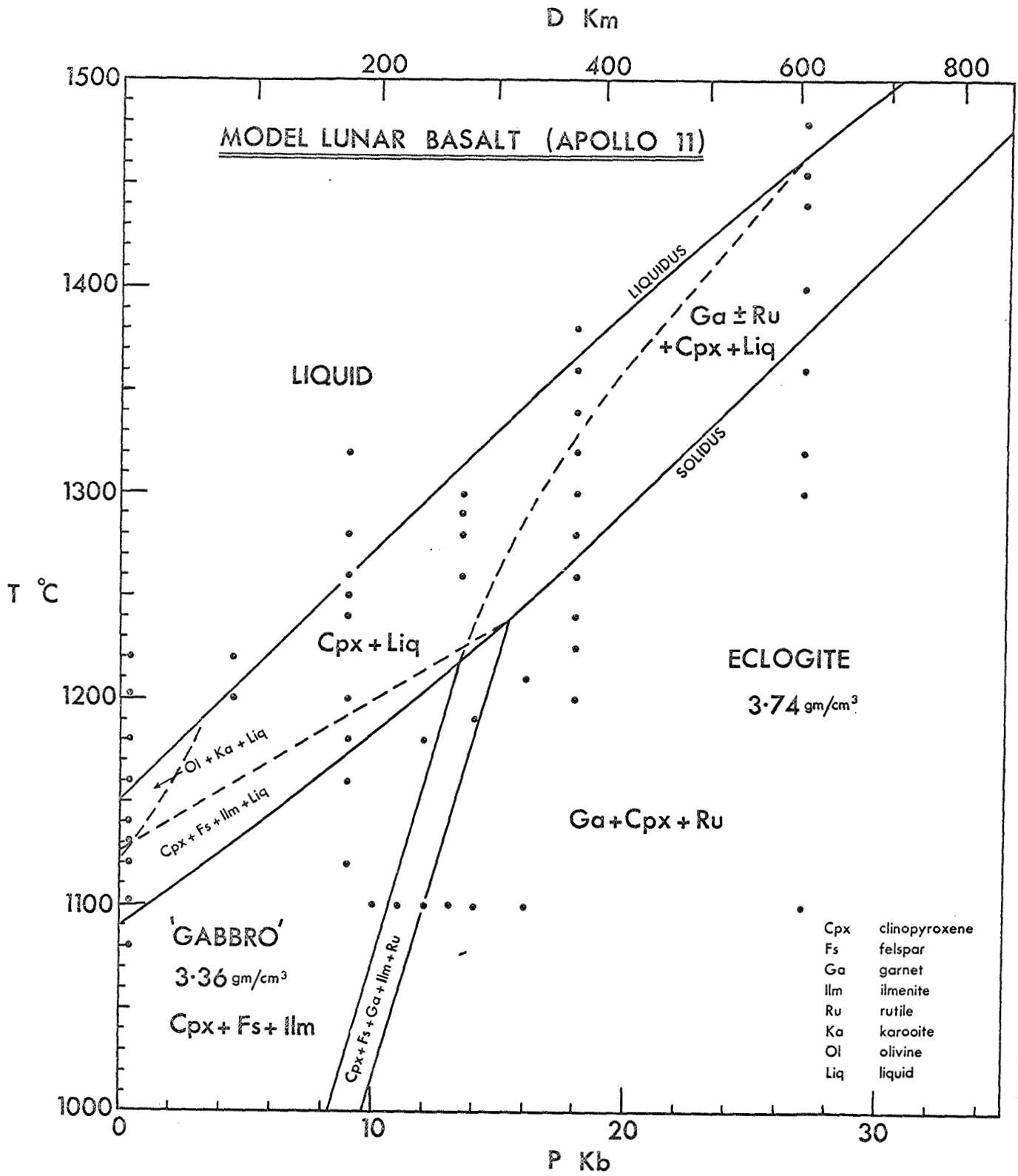
(i) Apollo 11 basalts were produced by a small degree of partial melting in the lunar interior which permitted strong concentration of incompatible elements into the first liquid to form. The liquid was then separated from the source region and ascended to the surface (e.g. Ringwood and Essene 1970 a,b).

- 15 -

(ii). The strong concentrations of incompatible elements were

produced by advanced high-level crystallization differentia-

tion in large lava lakes.  The Apollo 11 lavas are thus regarded

as the residual liquids resulting from this extensive, near-

surface fractionation process.  (e.g. O'Hara et. al., 1970 a,b).

Grounds for further controversy no longer exist since the second

alternative has been shown not to be feasible.  (Ringwood and Essene

1970b).  Initially the argument was based upon the claim that Apollo

11 basalts were near or at the cotectic of three major phases.  We

have seen that this is not correct and that to the contrary, Apollo

11 basalts are far removed from the pyroxene—plagioclase—ilmenite

cotectic.  Extensive high-level fractionation would indeed drive the

lavas toward the cotectic.  Conversely, the fact that they are far

removed from cotectic composition means that extensive low pressure

fractionation has not operated.

This conclusion is amply verified by several other lines of

evidence.  Consider Figure 2, which demonstrates the occurrence of

a ten-fold variation in the abundances of incompatible elements among

Apollo 11 and 12 rocks.  If these are to be explained by fractional

crystallization, more than 90 percent of the original magma must

have crystallized to produce the rocks with the highest incompatible

Figure 3.  Stability fields of mineral assemblages and melting

equilibria in average Apollo 11 basalt composition at high

pressures and temperatures.  Each dot represents a separate

experiment.  (Armalcolite is now the approved mineral same

corresponding to the term "Karooite" used in the figure).

MODEL LUNAR BASALT (APOLLO 11)

D Km

T °C

P Kb

LIQUID

LIQUIDUS

Ga ± Ru
+ Cpx + Liq

SOLIDUS

Cpx + Liq

ECLOGITE

3·74 gm/cm³

Ol + Ka + Liq

Cpx + Fs + Ilm + Liq

Ga + Cpx + Ru

'GABBRO'

3·36 gm/cm³

Cpx + Fs + Ilm

Cpx + Fs + Ga + Ilm + Ru

| Cpx | clinopyroxene |
| Fs | felspar |
| Ga | garnet |
| Ilm | ilmenite |
| Ru | rutile |
| Ka | karooite |
| Ol | olivine |
| Liq | liquid |

element abundances. However, this would imply corresponding major changes in the $\frac{FeO}{FeO + MgO}$ ratios of the rocks which serve as an index of the degree of fractional crystallization. In fact, the variations of $\frac{FeO}{FeO + MgO}$ ratios between different rocks are small. The high concentrations and relatively uniform distribution of $Cr_2O_3$ (av. 0.3%) among Apollo 11 and 12 rocks is another indication that they have not undergone extensive absolute or relative fractionation by crystallization differentiation. Chromium is strongly concentrated in the earliest ore minerals and pyroxenes to separate. Extensive fractional crystallization leads rapidly to almost complete removal of chromium from the magma (Ringwood and Essene, 1970b).

The abundance patterns of Figure 2 combined with the major element compositions of the rocks are characteristic of partial melting processes where the major elements in the liquid are buffered by equilibrium with residual unmelted phases in the source regions, whilst incompatible elements are strongly concentrated into the liquid phase according to the degree of partial melting. Haskin et. al., (1970) and Gast and Hubbard (1970) showed that to account for the enrichment of rare earths shown in Figure 2 by fractional crystallization at high levels, up to 95% of the original liquid would need to have crystallized as plagioclase. This is clearly impossible, since

plagioclase is not on the liquidus of Apollo 11 rocks. Several other arguments showing that Apollo 11 lavas were formed by a small degree of partial melting of source material in the lunar interior and not by extensive high-level crystallization differentiation are given by Ringwood and Essene (1970b).

If we accept that Apollo 11 basalts were generated by a process involving a small degree of partial melting of source material, at what depth in the lunar interior did the partial melting occur and what was the nature of the source material? There are two approaches to this problem. Ringwood and Essene determined the compositions of the liquidus and near-liquidus phases of Apollo 11 basalts as a function of pressure (Figure 3). Since the equilibrium between crystals and magma is independent of the proportions of crystals and liquids present, it follows that Apollo 11 basalt could have formed by a small degree of partial melting of mineral assemblages composed dominantly of the observed liquidus phases.

From Figure 3, we see three distinct pressure regimes according to the nature of the liquidus phase: A low pressure regime, in which the liquidus phases are olivine and armalcolite, an intermediate pressure regime in which the liquidus phase is a highly sub-calcic clinopyroxene (7% CaO, 4% $Al_2O_3$, $Fs_{21}En_{64}Wo_{15}$) and a high pressure

regime in which clinopyroxene and garnet are near-liquidus phases.
Ringwood and Essene (1970b) showed that the mineral assemblages of
the low pressure and high pressure regimes were too dense to be
representative of the lunar interior. On the other hand, the pyrox-
enite composition of the intermediate pressure regime (depths of 200
to 500 km) went much closer towards providing an explanation of the
moon's mean density and moment of inertia. Further detailed studies
showed that Apollo 11 basalt was almost saturated with orthopyroxene
at near-liquidus temperatures between 10 and 15 kb. It was possible,
therefore, that substantial amounts of orthopyroxene might be
present in the source region in addition to the sub-calcic clinopyroxene.
These studies permitted the synthesis of a model lunar pyroxenite
(Table 2) capable of yielding the average Apollo 11 basalt composi-
tion by a small degree of partial melting at depths of 200 to 500 km.
Experimental studies (Figure 4) of the P, T stability fields of
mineral assemblages displayed by this pyroxenite showed that it was
capable of providing a satisfactory explanation observed mean density
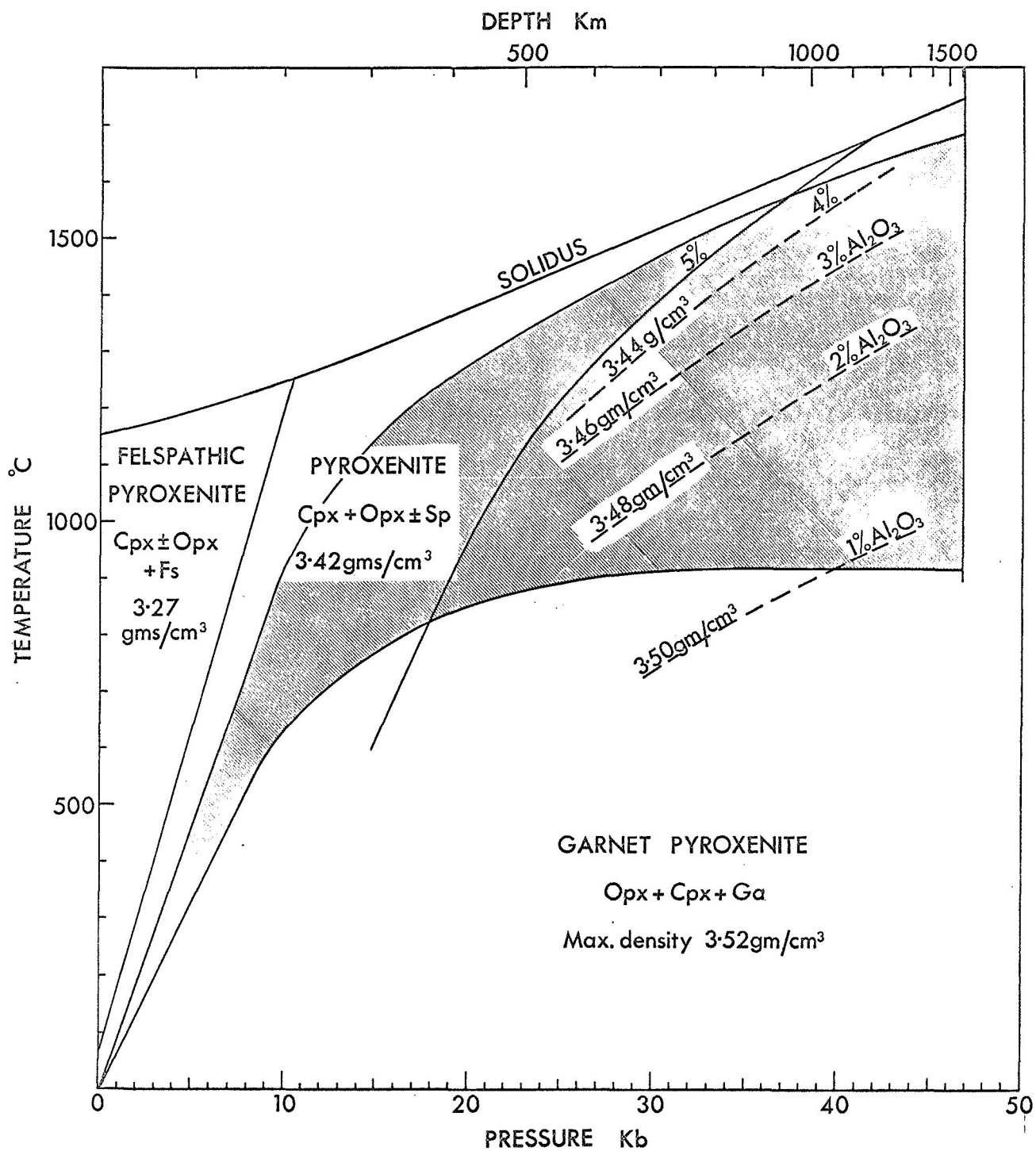and moment of inertia of the moon.

The experimental studies thus led to a very simple model for
the origin of the lunar basalts. Although the experiments permit
some variability in the composition of the source region, and it is

Table 2

Composition of model lunar pyroxenite which is capable of yielding Apollo 11 basalts by a small degree of partial melting. If the moon were composed of material of this composition, the observed lunar density and moment of inertia would be satisfied. This composition is not unique, and it is possible that olivine was also a constituent of the source region. (After Ringwood and Essene, 1970b).

| | |
|---|---|
| $SiO_2$ | 52.0 |
| $TiO_2$ | 1.0 |
| $Al_2O_3$ | 5.0 |
| $Cr_2O_3$ | 0.4 |
| $FeO$ | 13.5 |
| $MgO$ | 22.5 |
| $CaO$ | 4.0 |
| $Na_2O$ | 0.1 |

Figure 4.  Stability fields and densities of mineral assemblages
displayed by model lunar pyroxenite (Table 2) in relation to
the probable range of lunar internal temperature distributions.
(shaded region).    After Ringwood and Essene (1970b).

DEPTH Km

500 1000 1500

SOLIDUS

5% 4%

3% Al₂O₃

3·44 g/cm³

3·46 gm/cm³

2% Al₂O₃

3·48 gm/cm³

1% Al₂O₃

3·50 gm/cm³

1500

1000

TEMPERATURE °C

FELSPATHIC
PYROXENITE

Cpx ± Opx
+ Fs

3·27
gms/cm³

PYROXENITE

Cpx + Opx ± Sp

3·42 gms/cm³

500

GARNET PYROXENITE

Opx + Cpx + Ga

Max. density 3·52 gm/cm³

0 10 20 30 40 50

PRESSURE Kb

possible that olivine may be present as a separate phase in addition to the pyroxenes, there can be little doubt that the Ca and Al contents of pyroxenes and the olivine/pyroxene ratio in the lunar basalt source region are substantially lower than in the earth's mantle. Within the framework of our present understanding of high pressure phase equilibria, it does not appear possible to generate Apollo 11 and terrestrial basalts from source materials possessing similar major element abundances.

Further arguments indicating that if the Apollo 11 basalts formed by a partial melting process, the source region must lie deep in the lunar interior, are derived from considerations of the moon's thermal history and strength. The Apollo 11 and 12 basalts crystallized 1.0 to 1.3 billion years after the moon had formed. Regardless of any reasonable assumptions which can be made about initial temperature distribution and distribution of radioactivity, the outer 200 km of the moon would have cooled by thermal conduction over this period to a mean temperature of about $500^{\circ}$ C (maximum temperature at 200 km is about $1000^{\circ}$ C). Because of its larger area to volume ratio, cooling on the moon is effective to greater depths than on the earth and the lunar lithosphere is accordingly much thicker and stronger than the earth's. It is most difficult to understand how any partial melting process could, therefore, occur in the cool outer 200 km of the moon. The source would need to be deeper, in

a region which had not been affected by cooling and in which increase of temperature by accumulation of radioactive heat was still possible. Another argument is connected with the preservation of mascons-circular regions characterized by high positive gravity anomalies which occur in some maria. Urey (1968) and others have emphasized that these require that the lunar lithosphere beneath the maria and mascons has possessed substantial strength ever since the maria and mascons were formed, and that therefore, the lithosphere must have been quite cool at the time the mascons formed. It would be difficult to form the maria by partial melting within the lithosphere and at the same time, have this region sufficiently cool to possess the considerable long-term strength necessary to support the mascons.

To avoid these latter difficulties, Urey appealed to a near-surface origin of the maria with the melting caused by meteorite impact. However, we have previously demonstrated that the maria are strongly fractionated relative to the average composition of the moon. Urey's hypothesis implies that the fractionation must have occurred by crystallization differentiation near the surface of the moon. We have previously shown that the observed fractionation could not have been caused by crystallization differentiation. and thus Urey's hypothesis must, therefore, be rejected. Additional arguments against an impact origin for the maria were given by Ringwood and Essene (1970b).

*discussed*

All the evidence ~~used~~ so far points to an origin of the maria

by a small degree of partial melting at a depth greater than 200 km.

I should mention one important observation which is believed by some

workers not to be consistent with this hypothesis. This is the

spectacular europium anomaly shown in Figure 2 which is caused by

europium being present in the divalent state under lunar redox condi-

tions, so that it has crystal chemical properties rather similar to

$Sr^{2+}$. Those workers who studied rare earth distributions in lunar

basalts concluded that plagioclase should be present in the source

region's of lunar basalt and that the deficiency was cuased by $Eu^{2+}$

remaining behind in plagioclase relatively to the other trivalent

rare earths, during partial melting. A source region of plagioclase

and high-Mg pyroxenes was, therefore, favored.

This hypothesis leads to several difficulties. The most serious

is that Apollo 11 basalts were not saturated with plagioclase when

they were erupted. If plagioclase had been a component of the

residual mineral assemblage remaining behind after partial melting,

all magmas reaching the surface should have been saturated with

plagioclase which should, therefore, have been on the liquidus. As

we saw previously, this is not the case. The difficulty is of a

fundamental nature and a solution is not in sight. Further difficulties

arise from the high pressure observations that the postulated

plagioclase bearing mineral assemblage is unstable at a high pressure

and would not persist below about 200 km. I have previously detailed

the arguments against an origin of lunar basalts by partial melting

in the outer 200 km of the moon.

An explanation of the europium anomaly in terms of the model

of partial melting of a pyroxenite source region is by no means

ruled out. The relevant partition coefficients for this system are

not yet determined at the redox state existing on the moon. I think

that there is a good chance that this model will be able to explain

the anomaly. Experiments are now under way to measure appropriate

partition coefficients, and will provide a key test by the model

advocated here.

## 4  SOME BOUNDARY CONDITIONS FOR THEORIES OF LUNAR ORIGIN

Some of the more important properties of lunar basalts ahve

been summarized in the preceeding section. Reasons for believing

that they have been formed by a small degree of partial melting

deep within the lunar interior have been stated.  If we accept

this hypothesis, what are the important points of resemblance

between lunar basalts and terrestrial basalts and between their

respective source regions?  What are the important differences?

What bearing do these relationships have on theories of lunar

origin?

### (a)  Overall Similarities between Earth and Moon

(i)   The moon and the earth's mantle are both dominantly

composed of ferromagnesian silicates with subordinate CaO

and $Al_2O_3$.

(ii)  The relative abundances of most of the non-volatile,

incompatible class of trace elements in the source regions

of lunar and terrestrial basalts appear to have been similar

and closely related to chondritic or primordial abundances.

(iii)  The absolute abundances of most of the non-volatile

oxyphile elements in lunar basalts fall within the range

of concentrations of these elements displayed by terrestrial

basalts.

(iv)  Elements which are comparatively volatile under high

temperature reducing conditions e.g., K, Rb, Pb, Tl, Bi, In,

are relatively depleted in the earth (by factors of 5-10)
compared to the probable abundances of these elements in
the primordial solar nebula (Gast, 1960, Ringwood 1966a,b).
Likewise, this group of volatile elements is also relatively
depleted in the moon.

The above similarities, particularly (iv) might be taken
to indicate that some of the fundamental chemical fractionation
processes which occurred when the earth and moon formed from the
solar nebula were similar, and tentatively, might point in the
direction of a genetic relationship between earth and moon.

(v)  This suggestion is supported by the history of tidal
evolution of the earth-moon system, which implies that the
moon was once only 2.8 earth radii distant from earth.
(Gerstenkorn, 1955).  This is almost identical with Roche's
limit and it does not appear likely that the similarity
between these distances is a mere coincidence as is implied
by the capture hypothesis,  (Öpik, 1961).  Additional reasons
for rejecting the capture hypothesis are given in the next
section.  If capture is rejected, the tidal history indicates
that the moon was probably born very close to the earth and,
therefore, a close genetic relationship might be inferred.
(c.f. Section 7).

## (b)  Chemical Differences between Earth and Moon

Superimposed on the general resemblances which exist between moon and earth (above) there are some very important specific differences:

(i)  The moon is strongly depleted in iron relative to the earth.  If a core is present, it cannot amount to more than a few percent of the mass.

(ii) Apollo 11 basalts are strongly depleted in many siderophile elements relative to terrestrial basalts (e.g. Ganapathy et. al., 1970).

(iii)  The moon is much more strongly depleted in volatile metals (e.g. Na, K. Rb, Cs, Pb, In, Tl, Zn, Hg, etc.), than the earth compared to primordial abundances. (Section 2d).

(iv)  The $\dfrac{FeO}{FeO + MgO}$ molecular ratio in the source regions of Apollo 11 basalt is probably between 0.20 and 0.26 compared to a probable value for this ratio of 0.12 in the source regions of terrestrial basalts (Green and Ringwood 1967, Ringwood 1970b).

(v)    The mineralogy of the lunar mantle is probably

pyroxene-dominated as compared to a preponderance

of olivine in the terrestrial mantle.  The ratios

of $Al_2O_3$ and CaO to total pyroxenes are smaller in

the lunar mantle than in the terrestrial mantle.

Thus, important differences exist in the relative

abundances of the major components, $SiO_2$, MgO, FeO,

$Al_2O_3$ and CaO, between the lunar interior and the

earth's mantle.  (Ringwood and Essene 1970b,

Ringwood 1970b).

(vi)   Studies of the chemistry of rare earths in lunar

and terrestrial basalts (Haskin et. al., 1970; Gast

and Hubbard, 1970) indicate that calcium-rich

clinopyroxene is a less abundant phase in the lunar

mantle than in the terrestrial mantle.

(vii)  Terrestrial basalts and their source regions are

much more oxidized (oxygen fugacity of $10^{-8} - 10^{-9}$

atm. at $1200^{\circ}$ C) than lunar basalts and their source

regions ($fO_2 = 10^{-13.5}$ atm. at $1200^{\circ}$ C).  (Section 2f).

(viii) As a consequence of the low oxygen fugacity in the

moon, $H_2O$ and $CO_2$ are unstable relative to $H_2$ and CO

at magmatic temperatures. Water and carbon dioxide
are, therefore, very rare in lunar rocks compared to
terrestrial rocks.

## 5. BEARING OF APOLLO 11 DATA ON THEORIES OF LUNAR ORIGIN

We will consider first, the traditional hypotheses of lunar
origin—Fission, Binary Planet and Capture. The conclusions relating
to the similarities and differences between earth and moon which
were discussed in the previous section, have a vital bearing on
these hypotheses. In all hypotheses, the first order problem is to
explain the large difference in density of earth and moon, which
implies a major fractionation of iron between the bodies.

### (a) The Fission Hypothesis

Darwin (1880, 1962) developed a theory according to which the
moon and earth were originally combined in a single body which
rotated with a period of four hours, so that the solar sides were
raised every two hours. He estimated that the fundamental mode of
the earth's free oscillations was one hour, and suggested that a
resonance effect was established between the solar tides and free
oscillations, leading to the development of an enormous tidal bulge.

This ultimately became unstable, and the tidal bulge was thrown off

from the earth to form the moon.  Darwin's theory provided an elegant

explanation for the moon's density which is similar to the uncom-

pressed density of the earth's outer mantle.  However, a series of

fatal objections to Darwin's original hypothesis was raised by

Jeffreys (1930) and others, and it was generally discarded.  See also,

MacDonald (1964).

Ringwood (1960) suggested a new variant of Darwin's hypothesis

arising from a discussion of the formation of the earth by accretion,

as in Section 6.  It was argued that after accretion, the extent of

reduction and consequently the amount of metal phase increased from

the centre of the earth towards its margins.  This configuration is

highly unstable, and there is the possibility that segregation of

metal into the core might have been catastrophic.  If, towards the

end of the primary accretion process, the rate of rotation of the

earth was close (within about 20%) to the instability limit, the

rapid segregation of the core might have decreased the earth's

moment of inertia, and accordingly increased its angular velocity

sufficiently to cause instability and fission.  According to Ringwood's

suggestion, the excess angular momentum of the earth-moon system was

carried away by the large, primitive atmosphere which was also

disrupted and escaped during the cataclysm. A similar hypothesis

was subsequently suggested and developed in greater detail by Wise

(1963). The modified fission hypothesis has since been considered

favourably by O'Keefe (1966), Cameron (1966) and others. Although

it is recognized by all concerned that this hypothesis requires a

highly favourable and ad hoc combination of initial conditions if

it is to be appliȼable, and is therefore of low intrinsic probability,

itṣ ability to explain the density of the moon, and the difficulties

faced by alternative hypothesis of lunar origin have combined to

keep the fission hypothesis alive.

What, then, is the bearing of the new data from Apollo 11 on the

status of this hypothesis? According to earlier versions either <u>solid</u>

or <u>liquid</u> material was thrown out of the earth's upper mantle after

the core had formed, and the moon was formed from this condensed

upper mantle material. It would, therefore, be anticipated that the

compositions of lunar basalts and terrestrial basalts formed by the

partial melting of similar source material in the earth's upper

mantle and in the moon would also be generally similar. The many

important compositional differences between lunar and terrestrial

basalts and between their respective source regions, as summarized

in section 4 effectively contradict this consequence. Particularly

difficult to explain are the differences in abundances of volatile elements, siderophile trace elements, major elements (Si, Mg, Fe, Al, Ca) and oxidation states. These difficulties are sufficient in my opinion to dispose of the earlier versions of the fission hypothesis which require that the moon formed from <u>solid</u> or <u>liquid</u> material thrown off by the earth's outer mantle.

Recently, modifications of the fission theory have been suggested by Wise (1969) and O'Keefe (1969). Both point out that after fission, a strong tidal interaction would ensue between earth and the newly formed moon ~~(considered initially to be solid or liquid)~~. This would cause the transformation of rotational energy into thermal energy, resulting in the volatilization of the outer regions of the earth and moon and the formation of a massive primitive atmosphere, mainly of volatilized silicates, amounting to 4% (Wise) or 10-20% (O'Keefe) of the mass of the earth. Both authors are concerned primarily with explaining the discrepancy between the angular momentum needed for fission and the total angular momentum of the present earth-moon system. They suggest, following Ringwood (1960), that the excess angular momentum of the earth-moon system was carried out of the system by escape of this primitive atmosphere.

Wise suggests that "Roasting of a newly formed moon adjacent to a tidally heated incandescent earth may account for a lunar magmatic

source depleted in volatile alkali elements and enriched in refractory elements as suggested by first analyses of Apollo 11 specimens". O'Keefe also had something similar in mind as indicated in his abstract.

In my opinion, the simple high-temperature roasting of a condensed moon would be insufficient to account for the strong selective depletions of volatile metals in the moon, which would require a much more intensive high-temperature processing than indicated. Furthermore, the roasting process does not readily account for the inferred differences in major elements and mineralogy between the moon and the earth's mantle.

Nevertheless, the model suggested by Wise and O'Keefe provides an environment in which the chemical fractionations might well be explained. Both authors advocate a primitive atmosphere of volatilized silicates from 3 to 20 times more massive than the present moon. If most of the material now in the moon had condensed from that atmosphere, and had fractionated during the process, the observed composition of the moon might be explained. A modification of this kind leads to a hypothesis having many features in common with the precipitation hypothesis of Ringwood (1966a, 1970a) which maintains that the material now in the moon was precipitated from a massive,

hot, primitive terrestrial atmosphere to form a swarm of fractionated moonlets and that the moon formed by the coagulation of this swarm. Perhaps one could go a step further than O'Keefe and Wise to suggest that rotational instability during core formation threw off the earth's massive hot, primitive atmosphere, (Ringwood, 1960), but did not affect the solid or liquid upper mantle. The moon then precipitated _in_ _toto_ from this primitive atmosphere.

Lead isotope data on Apollo 11 rocks (Gopalan et. al., 1970; Tatsumoto, 1970) show that if the material now in the moon was derived from the earth by fission or by a related process, the time of derivation must have been close to 4.6 billion years ago when the earth was formed. O'Keefe's (1969) suggestion of delayed fission some 3.5 billion years ago requires modification.

(b)  Binary Planet Hypothesis

The mass of the moon is about $\frac{1}{80}$ of that of the earth and, moreover, the moon carries most of the angular momentum of the earth-moon system. These distributions are unlike those of all other planets and satellites in the solar system in which satellites account for a much smaller proportion of the total mass and angular momentum. The distribution of mass and angular momentum between earth and moon

is not unlike those of binary star systems, and it has frequently been suggested (e.g. Latimer, 1950; Kuiper 1954, 1963; Orowan 1969) that the origin of the earth-moon system is analogous to that of a binary star system.

According to this theory, moon and earth formed in close proximity but separately and independently by direct accretion from similar parental material. Instead of becoming a separate planet, the moon orbited the earth. This immediately raises the problem of explaining the moon's low density. Earlier attempts (eg. Ramsay, 1949) to provide an explanation in terms of a silicate-metal high pressure phase transformation at the core-mantle boundary in the earth have been reduced to a state of neglible probability by recent high pressure experimental data (e.g. Birch, 1960). It has been postulated that earth and moon accreted from a mixture of preexisting silicate and metallic iron particles in the solar nebula, and that in some way, the earth received a greater proportion of metal particles. Physical processes which have been invoked to cause this metal/silicate fractionation have been vague and implausible, depending heavily upon ad hoc assumptions. The latest is the suggestion by Ganapathy et. al., (1970) that a magnetic interaction between iron particles in the nebula may have caused preferential accumulation of iron in the earth.

This was based upon a physical mechanism proposed by Harris and Tozer (1967) which was, however, shown to be untenable by Banerjee (1967). Further difficulties for the binary planet hypotheses arise from geochemical considerations (Ringwood 1966 a,b) which show that it is most unlikely that the earth accreted from a preexisting mixture of metal and silicate particles in the solar nebula.

Results from the study of Apollo 11 basalts have a decisive bearing upon this hypothesis. Let us assume, despite the difficulties mentioned above, that the earth and moon accreted from a well-mixed reservoir of metal particles and silicate particles in the solar nebula, and that an unknown physical process caused metallic iron to accrete preferentially upon the earth, ultimately to segregate into the core. In this case, the earth's mantle and the moon would have formed from the same reservoir of silicate particles in the nebula. We would expect on this hypothesis that the compositions of the earth's mantle and moon should be very similar and that lunar and terrestrial basalts formed by partial melting of these similar source regions should also be generally similar. This consequence is directly contradicted by the several major chemical differences which have been inferred to exist between lunar and terrestrial basalts and between their respective source regions. (Section 4).

It does not appear possible to explain these on the basis of the binary planet hypothesis.

### (c)  Capture

The capture hypothesis has become popular during recent years. This maintains that the moon was formed as an independent body in some other region of the solar system and subsequently passed close to the earth in an orbit which permitted it to be captured.  There are many versions, the most widely discussed being those of Gernsten-korn and Urey.  For capture to occur, an extremely favourable and critical conjunction of orbits of earth and moon must be assumed. Regardless of details, all capture hypotheses invoke the occurrence of an event of extremely low intrinsic probability.  Furthermore, the capture hypotheses offer no explanation of the deficiency of the moon in iron relative not only to the earth, but also to the other terrestrial planets.

For capture to occur under the least unfavourable conditions, moon and earth should move in very similar orbits, implying that moon and earth were born in the same region of the solar system and presumably, from the same parental material.  Even if it is assumed that the moon was captured from a highly eccentric orbit, in which case the probabilities of capture are much lower, it is hard to avoid

the conclusion that the moon was born among the terrestrial planets,

in all of which the abundance of iron is much higher than in the moon.

Indeed, Ringwood (1966b) and Ringwood and Clark (1970) have shown that

the abundance of iron relative to silicon and magnesium is probably

the same in Mars, Venus and earth, and similar to that in chondritic

meteorites and in the sun. The relative deficiency of iron in the

moon is thus a problem of the first order, not to be lightly resolved

by postulating an origin for the moon in some other region of the

inner solar system.

Clearly, if the capture hypothesis is to be taken seriously, it

must possess some singularly attractive advantages in other directions,

in order to offset these profound disadvantages.

## (1) Gerstenkorn capture hypothesis

As a result of tidal friction between earth and moon, the earth

is transferring angular momentum to the moon which accordingly is

speeding up and moving further away, ~~from the earth~~. At the same time,

the earth's rotation is slowing down, and the length of the day is

increasing. The rate of increase in length of the day is known from

astronomical observations and establishes the present magnitude of

tidal friction between moon and earth. Assuming that this was

constant, Gerstenkorn (1955) calculated the position of the lunar

orbit backwards in time and showed that about two billion years ago

the moon was only 2.8 earth radii distant from the earth, which is

almost identical with Roche's limit. As the moon closely approached

the earth, the inclination of the lunar orbit increased sharply and,

providing that it was not destroyed at Roche's limit, its orbit

passed over the poles of the earth and became retrograde, rapidly

moving away from the earth. Reversing the time sense, Gerstenkorn

accordingly argued that the moon had been originally captured by the

earth on a retrograde orbit, and its subsequent history followed (in

reverse) the course of the previous discussion.

Subsequent more elaborate calculations (e.g. MacDonald, 1964)

have generally confirmed Gerstenkorn's results, but have shortened

the time of closest approach to a period between 1.8 and 1.2 billion

years ago. MacDonald and others pointed out that the moon and earth

would be strongly heated and extensively melted at the time of

closest approach and that surface features on the moon would be

completely obliterated. It follows that the present topography of

the moon must be younger than the time of closest approach. All

conclusions of this type rest upon the assumption that the mechanism

of tidal dissipation within the earth has not changed greatly with

time. Although they would concede some modest variations, it is

probable that most pre-Apollo 11 advocates of the capture hypothesis

would have maintained that the time scale for closest approach of moon to earth was unlikely to be in error by more than a factor of two and that the moon's features must, therefore, be much younger than the age of the earth.

The Apollo 11 results have destroyed the entire basis of this class of hypotheses, including the MacDonald "many moon" hypothesis. The ancient ages of Apollo 11 rocks (3.7 billion years) and the fact that the highlands are much older than the maria, show that the inferred timescales of evolution of the lunar orbit and close approach of moon to earth are seriously wrong, apparently because the present rate of tidal dissapation is atypical.

Alfven and Arrhenius (1969) have recently advocated a hypothesis based on postulated spin-orbit resonances according to which the moon was captured on a retrograde orbit and evolved into direct orbit without coming closer to the earth than eight earth radii. In principle this would avoid the catastrophic effects of close approach as in Gerstenkorn's theory. However, their mechanism requires a number of highly speculative assumptions. Recalling that the original capture event is one of very low intrinsic probability, these additional necessary assumptions which are unsupported by direct evidence necessarily render this version of the capture hypothesis even more tenuous and speculative.

Singer (1968) has proposed an extension of tidal theory based upon the assumption of a frequency dependent dissipation function. His objective was to remove one of the difficulties of the Gerstenkorn theory—namely that the earth would be extensively melted during the time of closest approach. However, his model has the moon periodically penetrating inside Roche's limit, so that it would be strongly deformed, heated and perhaps destroyed during the interval of close approach. Singer (1969) recognises that these consequences are tolerable only if the time of closest approach was at about 4.5 billion years ago. Accordingly, he abandons the Gerstenkorn-MacDonald time scale for tidal evolution by assuming that the present rate of tidal dissipation in the earth is atypical and much higher than on the average, occurred in the distant past.

As discussed earlier, the Apollo 11 rock ages imply that this latter assumption is almost certainly correct. Nevertheless, the primary reason for preferring the capture hypothesis in the first place was to live with the short time scale of tidal evolution found by Gerstenkorn. Once this is abandoned, the principal justification (small though it be) for the capture hypothesis disappears.

We have seen that the capture hypotheses so far discussed do not explain the low iron content of the moon compared to the other terrestrial planets, nor do they provide an explanation of the other

characteristic chemical properties of the moon which were discussed
in Section 4. Moreover, capture is a process of very low intrinsic
probability. Finally, the short tidal evolution timescale which
provided the primary rationale for the capture hypothesis is almost
certainly incorrect. Until these very serious drawbacks are overcome,
the above capture hypotheses hardly warrant further serious consid-
eration.

### (ii)  Urey capture hypothesis

Urey (1962, 1963, 1965) has attempted to explain the low iron
content of the moon compared to the earth on the basis of capture
of the moon by the earth during formation of the solar system about
4.7 billion years ago. Urey attempts to avoid the intrinsic improba-
bility of a unique lunar capture by postulating that a generation of
lunar sized "primary objects" were present in the solar system before
the planets were formed and that a period of intense collisions
occurred causing disintegration of nearly all the primary objects
into a mixture of generally small metal and silicate particles, which
were subsequently subjected to some kind of physical fractionation
in the solar nebula. The terrestrial planets are supposed to have
formed by accretion from this fractionated debris. Urey suggested
that a few (out of thousands) lunar sized objects survived these
catastrophes and that the moon is one of these.

Urey's original evidence for the existence of an early genera-
tion of lunar sized objects was based upon conclusions (then shared
by many, including the author) that some kinds of meteorites had
formed at high pressures in the centres of lunar-sized objects.
Subsequently, these conclusions were shown to be incorrect by Anders
and coworkers and they have been almost universally abandoned.

A major aspect of Urey's hypothesis was his proposal, based
upon then-existing measurements of the iron abundance in the sun,
that the moon was a "primary object" possessing the solar abundance
of iron (and other metals). The much higher abundance of iron in
the other terrestrial planets was assumed to have occurred as a
result of physical metal-silicate fractionations during the collisions
and fragmentations of the primary lunar objects. Recently, new and
improved determinations of the abundance of iron in the sun (e.g.
Garz et. al., 1969) have shown that the solar iron abundance is in
the same range (relative to silicates) as occurs in chondritic meteor-
ites, the earth, Mars and Venus. This removes the basis of Urey's
hypothesis. Furthermore, the strong depletion of volatile metals in
the moon relative to the primordial and terrestrial abundances of
these metals (Section 4) is hardly consistent with the assigned
properties of the "primary objects".

## 6. TOWARDS A NEW HYPOTHESIS OF LUNAR ORIGIN

One of the most important results arising from the study of

Apollo 11 rocks has been that the "standard" theories of lunar

origin — fission, binary planet and capture — are no longer

tenable in the forms in which they were earlier stated. They

must either be developed into new forms which are consistent

with the Apollo 11 data, or else they must be totally abandoned.

A start towards developing such a new form of the fission hypothesis

has been made by Wise (1969) and O'Keefe (1969).

Alternatively, we must explore in a different direction for

a new type of hypothesis. An acceptable working hypothesis must be

capable of explaining the major chemical similarities between earth

and moon and the tidal evidence, both of which suggest the existence

of some kind of genetic relationship between earth and moon (Section

4). At the same time, it must explain the fractionation of iron

and the other important chemical differences between earth and moon

which were outlined in Section 4. The "precipitation" hypothesis

developed by Ringwood (1966b, 1970) may provide a possible framework

for interpreting these relationships. This maintains that during

the later stages of accretion of the earth a massive primitive

atmosphere developed which was hot enough to selectively evaporate

a substantial proportion of the silicates which were accreting.

Subsequently the atmosphere was driven away by particle radiation

from the sun as it passed through the T-Tauri phase. The relatively non-volatile silicate components were precipitated close to the earth to form a swarm of planetesimals or moonlets as the atmosphere was dissipated, and the moon formed by accretion of these chemically fractionated planetesimals.

The details have been stated by Ringwood (1970) and a summary only is given here. It was proposed that the earth accreted directly in the solar nebula from planetesimals of primordial composition resembling the Type 1 carbonaceous chondrites. These contain completely oxidized iron together with large amounts of water, nitrogen, sulphur and carbonaceous compounds, and have retained the primordial abundances of most elements except for extremely volatile substances. It was assumed furthermore that accretion of the earth occurred over a period on the order of $10^6$ years or less, and that accretion was completed just before the sun entered its T-Tauri phase characterized by rapid mass-loss and the generation of a solar wind some $10^6$ to $10^7$ times more intense than the present solar wind.

Formation of the earth under these boundary conditions is strongly influenced by the gravitational potential energy dissipated during accretion which in turn controls the chemical equilibria in the accreting material. The accretion energy per gram is plotted against radius of the growing earth in Fig. 5. It increases

Fig. 5.   Relationship between energy of accretion and radius of

the growing earth.   The principal stages of accretion are

also shown in relation to the energy of accretion and

approximate surface temperatures.   (After Ringwood, 1970).
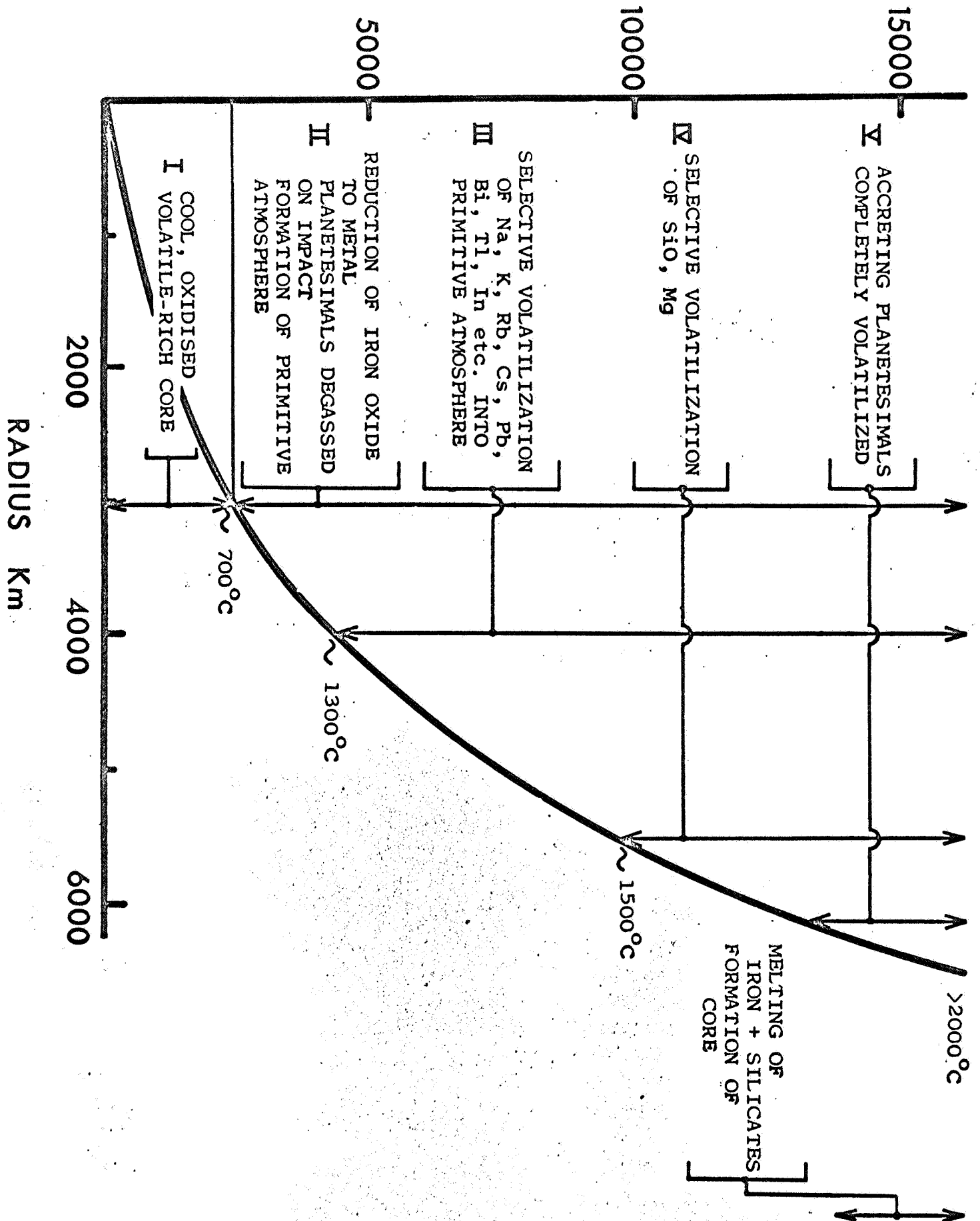
approximately as the square of the radius, reaching 15,000 cals/gm during the final stages.

During the early stages of accretion, the energy evolved is small and accretion is relatively slow. The temperature is accordingly low and is buffered by the latent heat of evaporation of volatiles, e.g. $H_2O$, in the planetesimals. During this stage (Fig. 5, I) a cool, oxidized volatile-rich nucleus of primordial material, perhaps about 10% of the mass of the earth, is formed.

As the mass of the nucleus increases, the energy of infall of planetesimals becomes sufficient to cause strong heating on impact, leading to reduction of oxidized iron by carbon and formation of a metal phase. This is accompanied by degassing, and the formation of a primitive atmosphere, mainly of CO and $H_2$ (Stage II, Fig. 5). With further growth (Stage III) both the temperature and intensity of reduction increase and metals which are comparatively volatile under high temperature <sub>reducing</sub> conditions (eg, Na, K, Rb, Pb, Zn, Hg, In, Tl) are volatilized into the primitive atmosphere. During Stage IV, the surface temperatures exceed 1500°C and the relevant equilibria (Ringwood 1966a) show that silicate minerals are selectively reduced and evaporated into the primitive atmosphere, whilst metallic iron continues to accrete upon the earth. Finally, during Stage V, after segregation of the earth's core, which causes a further evolution of 400-600 cals/gm of gravitational energy for the whole earth, silicates from the outer mantle are directly evaporated into the

primitive atmosphere. The mass of the primitive atmosphere is about one quarter of that of the earth and it is composed mainly of CO and $H_2$ with about 10 percent of volatilized silicates.

It is assumed that this primitive atmosphere was dissipated immediately after accretion or during the later stages of accretion by a combination of factors (1) intense solar radiation as the sun passed through a T-Tauri phase, (ii) mixing of the rapidly spinning high-molecular-weight terrestrial atmosphere with the low-molecular-weight solar nebula in which it is immersed, (iii) magnetohydrodynamic coupling resulting in the transfer of angular momentum from the condensed earth to the primitive atmosphere, and, more speculatively, (iv) rotational instability of the atmosphere caused by formation of the core (modified fission hypothesis — (Ringwood, 1960; O'Keefe, 1969; Wise, 1969). The relative importances of these processes are not known, but it seems likely that the intense solar wind from the T-Tauri phase of the sun played a major role.

As the result of a combination of these processes, the massive primitive atmosphere was dissipated. On cooling, the silicate components were precipitated to form an assemblage of earth-orbiting planetesimals resembling Öpik's sediment ring. A further fractionation according to volatility occurred during the precipitation stage, since the less volatile components were precipitated first at relatively high temperatures and close to the earth, whereas the more volatile

components were precipitated at lower temperatures and further from the earth. The silicates precipitating at relatively high temperatures would probably have grown into relatively large planetesimals ($10^2$-$10^7$ cm diam.) which would tend to be left behind by the escaping terrestrial atmosphere. However the more volatile components precipitating at relatively low temperatures were more likely to have formed fine, micron-sized particles or smoke, which would be carried away with the escaping atmosphere by viscous drag, and hence lost from the earth-moon system. The moon then accreted from the sediment-ring of earth-orbiting planetesimals.

Ringwood (1970) showed in greater detail that this "precipitation" hypothesis accounted for the fractionation of iron and silicates between earth and moon in the context of a close genetic relationship between earth and moon. Chemical fractionations within the cooling primitive atmosphere also provide a basis for interpreting the strong depletions of volatile metals in the moon, the fractionation of some major oxyphile elements between moon and earth, the relative depletion of siderophile elements in the moon and the different oxidation state of the moon as compared to that of the earth's mantle.

CONCLUSION

The precipitation hypothesis complements the "sediment-ring" hypothesis of Öpik (1961, 1967) according to which the moon formed

by the coagulation of a swarm or sediment ring of earth-orbiting planetesimals or moonlets. Öpik's hypothesis was proposed on the basis of his studies of lunar cratering and tidal evolution, and was not concerned with explaining the origin and composition of the planetesimals which is the principal contribution of the present hypothesis.

The precipitation and fission hypothesis are related since according to the former, the material now in the moon is regarded as having been derived ultimately from the earth — not from the solid mantle, but from the massive primitive terrestrial atmosphere. The latest versions of the fission hypothesis by O'Keefe (1969) and Wise (1969) maintain that fission was accompanied by the development of high temperatures and the formation of a massive primitive terrestrial atmosphere of volatilized silicates. This atmosphere was believed to be from 3 to 20 times more massive than the moon. These hypotheses, although developed from different premises to those of the precipitation hypothesis, clearly lead towards an environment of lunar origin which has important elements in common with that of the precipitation hypothesis. Cameron (1970) starting from yet another direction, finally derived a model according to which the earth develops a massive hot atmosphere containing volatilized silicates and the moon is ultimately formed from the atmosphere.

Although the hypotheses of Öpik, O'Keefe, Wise, Cameron and the author differ both in minor and major respects, and have been arrived at via different paths, it is tempting to see the beginning of a consensus. I am convinced that in one way or another the material now in the moon was ultimately derived from a massive hot primitive atmosphere which once surrounded the earth and that the chemical differences between earth and moon can be interpreted on this basis.

## 7. ACKNOWLEDGEMENTS

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