PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Two-Stage Generation of Lunar Mare Basalts

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Two-stage generation of lunar mare basalts

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The Taylor–Jakeš model of two-stage melting for the generation of the mare basalts is reconsidered and expanded. Melting of the outer 1000 km of the Moon early in its history was soon followed by the deposition of a thick series of mafic adcumulates to form a Lower Mantle. Mafic orthocumulates then sank to form the Upper Mantle (60–300 km) while semi-contemporaneous crystallization of feldspar, as a mesh which did not sink and trapped minor mafics, formed the crust. The Rb–Sr model ages of about 4.6 Ga and the Eu anomalies reflect this event. The crystal fractionation gave rise to appreciable enrichment in l.i.l. elements in the pore material of the crustal and Upper Mantle orthocumulates, including a concentration of uranium that is related to the levels at which radioactive heating and second-stage melting occurred, to produce mare basalts from 3.8 to 3.1 Ga. Pore-material melting preserved the 4.6 Ga model ages. The high-Ti and low-Ti basalts are related to shallower and deeper source levels, respectively, in the mafic orthocumulate pile. Convective cells would become numerous as the thickness of the magma shell decreased, to produce complex and variable fractionating systems. Asymmetrical near-surface features such as crustal thicknesses, 'KREEP'-rock distribution, and mare-basalt eruption sites, would be expected from lateral variations in the effectiveness of cumulate fractionation at around 4.6 Ga.

1. INTRODUCTION

The Moon is composed predominantly of a crust rich in calcic plagioclase feldspar, averaging about 60 km in thickness, and a mantle of ultramafic rock extending to about 1000 km. Below that depth of solid lithosphere, a partly molten zone, that is at present unknown in terms of it being divisible into an asthenosphere and a core, extends for the remaining 738 km of the Moon's radius (Dainty, Goins & Toksöz 1975).

The feldspathic crust includes anorthosites, norites and troctolites ('ANT' suite) but seems to be chiefly of an average 'gabbroic anorthosite' composition (pyroxene + plagioclase). In contrast, the basalts that flooded the mare basins long after the extensive meteoritic bombardment and cratering of the feldspathic crust are relatively low in alumina and from geochemical evidence they are clearly not derived by partial melting of the crustal rock suite. Their source is widely accepted as being the underlying ultramafic mantle material.

The question then arises as to the genetic relationship between the feldspathic crust and the ultramafic mantle. Earlier suggestions that the crust was a primitive, late condensate produced by sequential accretion are nowadays discounted not only because the feldspathic rocks are refractory but because of close geochemical links between the ANT-suite and the mantle-derived basalts. The preferred alternative is that the Moon melted either totally or in an outer zone soon after accretion, and that gravity-controlled crystal sorting produced a lower-density mineral crust overlying a complementary layer of denser mafic minerals. Present-day controversy centres on whether the mare basalts are generated by partial melting of those mafic cumulates, or of a deeper zone of mantle material that did not participate in the early stage of melting and crystal sorting. The former, 'two-stage melting' hypothesis is explored, developed and favoured in this paper.

2. CHEMICAL CONSTRAINTS ON MARE BASALT GENESIS

At the First Lunar Science Conference (1970) in Houston, two highly significant but apparently irreconcilable features of mare basalt chemistry were made evident. First, the basalts were found to be strongly depleted in europium relative to the other rare-earth elements (e.g. Haskin *et al.* 1970) and secondly, plagioclase was not on the liquidus of the basalts subjected to dry melting experiments (Ringwood & Essene 1970). Evidence for the lack of water and for a low oxygen fugacity in the Moon's crystallization environment required acceptance of the chemical constraints, including the concept that europium was concentrated as Eu^{2+} in the plagioclase minerals. The europium anomaly could be explained, therefore, by early plagioclase floating to form a primitive crust (Wood *et al.* 1970), such that the basalts or their source rocks were depleted in Eu. But if this occurred, then plagioclase was a liquidus phase of the primitive melt and should persist as such in the basalt crystallization sequence. The writer pointed out, during that discussion, that this anomaly could be resolved if mafic minerals were concentrated as cumulates complementary to the plagioclase cumulates, and if the basalts were generated as partial melts of those mafic cumulates. Thus the Eu-anomaly would be imposed during the first melting and crystal sorting stage, and plagioclase would be eliminated from the liquidus of the mare basalts because a mechanically concentrated mafic component would be involved in the second stage of melting. That hypothesis was not developed until fairly recently when Taylor & Jakeš (1974) developed a refined model for two-stage melting of cumulates, based on the same concept.

The Taylor–Jakeš model takes several other factors into account. Since the Apollo 11 discoveries, substantial data on r.e.e. abundances indicate that most of the feldspathic crustal rocks show positive Eu anomalies, in contrast to the negative Eu anomalies of the mare basalts. Also the mare basalts fall into two groups: the high-titanium basalts (Apollo 11, Apollo 17) which crystallized 3.8 to 3.6 Ga ago, and the low-titanium basalts (Apollo 12, Apollo 15, Luna 16) which crystallized 3.4 to 3.1 Ga ago. The low-Ti basalts have the lower negative Eu anomaly and r.e.e. abundances, approximating more closely to those of primitive chondritic patterns than is the case for any other lunar rocks. Taylor & Jakeš proposed, therefore, that the mare basalts were generated by partial melting at two different levels in the mafic cumulate pile, and that the low-Ti basalts came from the deeper, least fractionated layer that was the latest to melt. It was implied that either ilmenite-rich or olivine–pyroxene-rich cumulates melted to produce the basalts. The fact that terrestrial cumulates often contain pore material less refractory than the cumulus phases (Wager, Brown & Wadsworth 1960), which would melt first during partial melting, now needs to be considered in this type of model.

A further constraint on mare basalt genesis is imposed by their contrasting model and crystallization ages. The model ages of about 4.6 Ga imply that Rb–Sr fractionation last occurred then, for all except the high-K, Apollo 11 basalts (3.85 Ga model ages). Albee & Gancarz (1974) have proposed that the second-stage melting of the mafic cumulates, at 3.8–3.1 Ga, produced mare basalt liquids that were not equilibrated with the residual solid phases, probably because of the absence of water and hence a reduced ionic diffusion capacity. Melting of only the pore material would contribute to this solution of the age problem, except that at least the outer fringes of the mafic cumulus minerals would need to melt in order to suppress plagioclase from the liquidus (although only slight suppression, if any, is necessary; see O'Hara *et al.* 1974).

3. A REVISED TWO-STAGE MELTING MODEL

Several workers have proposed that shortly after accretion, the outer 200–300 km of the Moon was totally melted and fractionated. Taylor & Jakeš (1974) proposed 1000 km of melting, the inner 'core' being of primitive, undifferentiated material. The larger-scale melting is favoured here because it provides a mechanism for the exceptionally high concentration of large ion lithopile (l.i.l.) elements in the outer part of the Moon, without postulating anomalously high initial lunar abundances.

TABLE 1. ESTIMATES OF URANIUM DISTRIBUTION (PARTS/10^9)

Total Moon (estimates from analogy with meteorites or from thermal models)

Allende inclusions	100	(Anderson 1974)
carbonaceous chondrites	60	(Taylor & Jakeš 1974)
chondrites and Lunar Heat-flow	59	(Ganapathy & Anders 1974)
howardites	23	(Toksöz *et al.* 1972)
thermal model	11	(Hays 1972)

Lunar samples (see text for sources)

anorthositic crustal average	130
mare basalts (low-K) average	240
highland feldspathic basalts/gabbros	1200
KREEP-rich materials	3500
granitic materials	9000
γ-ray, all data av. crust	450
γ-ray, Fra Mauro (KREEP region)	2500
γ-ray, Fs-highlands minimum	100

Lunar model distribution

undifferentiated asthenosphere (10% vol.)	50	
Lower Mantle adcumulates (50%)	0	
Upper Mantle + Crust (40% residue)	110	
av. mafic orthocumulates (30%)	12	($\times \frac{3}{4} = 9$)
av. crust (10%)	400	($\times \frac{1}{4} = 100$)
10% crustal partial melts	4000	(KREEP)
Lower mafic orthocumulates (l.m.o.)	4	($\times \frac{1}{2} = 2$)
upper mafic orthocumulates (u.m.o.)	20	($\times \frac{1}{2} = 10$)
5% pore material in l.m.o.	80	(unmelted mesostasis)
10% pore material in u.m.o.	200	(melted mesostasis = mare basalts)

The element uranium is taken as an example (table 1). A total Moon content of about 60 parts/10^9 is favoured by most investigators, from heatflow data (Ganapathy & Anders 1974) but slightly lower contents can be contained within a fractionation model and a 50 parts/10^9 value is used to illustrate this. Very high values are recorded from the analysed crustal samples (Hays 1972; Lovering & Wark 1975) and the orbiting γ-ray experiment (Trombka *et al.* 1974). If the volumes of the lunar shells are calculated, and an undifferentiated asthenosphere discounted in the calculation of U-distribution for the remaining 90% volume, the values shown near the end of table 1 emerge. Hays (1972) has calculated that 50 parts/10^9 of U would raise temperatures to 1600 °C after 4.6 Ga, which could account for the present, partly molten asthenosphere/core. By postulating initial melting of the outer 1000 km, table 1 shows how U could be greatly increased to a 110 parts/10^9 average in the crystalline outer 300 km (40% volume) of Upper Mantle + Crust by postulating an inner 700 km (50% volume) of U-free, Lower Mantle adcumulates. The latter are cumulates deposited so slowly that chemical-element diffusion between interstitial and overlying melt results in growth of the cumulus crystals at near-constant composition, and hence the 'chemical expulsion' of pore liquid (Wager *et al.* 1960). Since the average crust contains about 400 parts/10^9 (γ-ray data) in 10 % of the lunar volume, 12 parts/10^9 of uranium can be allocated to the Upper Mantle mafic cumulates (30 % volume). The KREEP rocks may result from crustal partial melting, as shown in table 1, but the high overall U-content of the crust is probably due to initial admixture of feldspathic crust with a U-rich, KREEP-rich residual liquid from the major fractionation episode.

The mafic cumulates of the Upper Mantle would be deposited in a layered sequence above, and in a gradational relationship with, the adcumulates of the Lower Mantle. Olivine, Ca-poor pyroxene and spinel are the likely early cumulus phases (Kushiro & Hodges 1974). Upward in the sequence, plagioclase and Fe–Ti oxides would precipitate and, ultimately, apatite, K-feldspar, a silica phase, etc., by analogy with terrestrial basic layered intrusions (Wager & Brown 1968). Cumulus-phase crystallization and deposition would cause the successive contemporary liquids to change composition upward in the layered sequence. It is suggested that as the volume of the residual liquid decreased and the number of separating crystal phases increased, there was an increase in rate of crystal deposition. This would produce orthocumulates (Wager *et al.* 1960) in which the contemporary intercumulus liquids were trapped to crystallize as low-temperature pore material. Such pore material would vary in composition through the Upper Mantle mafic cumulate pile. Arbitrary values for U, to reflect this, are shown at the end of table 1. If the lower orthocumulates contain 4 parts/10^9, then 5 % pore material (in which the U would be located) would contain 80 parts/10^9. The higher orthocumulates, shown as half the pile for averaging-out purposes, would contain 20 parts/10^9. Assuming the amount of pore material increases upward, from zero in the adcumulates to 10 % at this level, the pore material would contain 200 parts/10^9 U. Hence total melting of the 'mesostasis' or pore material would produce the levels of U found in the average mare basalts (table 1).

On the basis of heat production related to U-content alone, this model could provide for generation of mare basalts in the upper orthocumulates at a depth of about 150–200 km, the whole mafic cumulate pile extending from 60 to 300 km depth. Below the basalt generation level, U contents would be too low (0–4 parts/10^9) to produce basalts by partial melting, except that an undifferentiated core could have heated up, by now, to melting temperatures.

The model is shown in figure 1, where the volume of pore material in the orthocumulates is exaggerated to illustrate the contrast with the adcumulates. The changing composition of the pore material, upward, is critical in explaining the generation of the two types of mare basalt. The high-Ti basalts are not only richer in r.e.e. and higher in Sm/Eu ratio (i.e. greater negative Eu anomaly) than the low-Ti basalts, but other trace element contents also reflect generation from a pore material more advanced in the layered fractionation sequence (table 2). Hence the high-Ti basalts are generated from the higher orthocumulate levels, and since the U-content would be higher there, this could account for the earlier melt generation (3.8–3.6 Ga). Experimental studies by Kesson (1975, figs 2 and 4) show Ol–Px–Ilm–Liq equilibrium at about 170 km for the high-Ti basalts, and Ol–Px–Liq equilibrium at about 220 km for the low-Ti basalts.

A problem in this type of model is that for the high-Ti basalts, their very high titanium contents would probably not be reached until very late fractionation stages, when Na and Fe/Mg should be much higher, and Cr much lower than shown by the analyses (Ringwood & Green 1975). In regard to Na, the question of variable alkalis loss during vesiculation at the lunar surface is still in question. For Fe, Ti and Cr, these are the three elements additional to Eu that contrast strongly with terrestrial analogues in terms of valency state. Although this observation may not stand up to quantification, it seems unsafe to reject the other elemental data shown on table 2 in favour of those three elements. So far as Ti enrichment with fractionation is concerned, direct terrestrial analogies are not possible. The late-stage liquids of the Skaergaard intrusion, for example, contained only about 2 % TiO_2 after 95 % had solidified (Wager & Brown 1968, table 10). Even the 'low-Ti' lunar basalts contain 2–3 % TiO_2 at FeO levels similar to those of the late-stage Skaergaard liquids. Clearly the lunar Ti contents were at very high overall levels, which could accelerate rapidly as the volume of liquid decreased. According

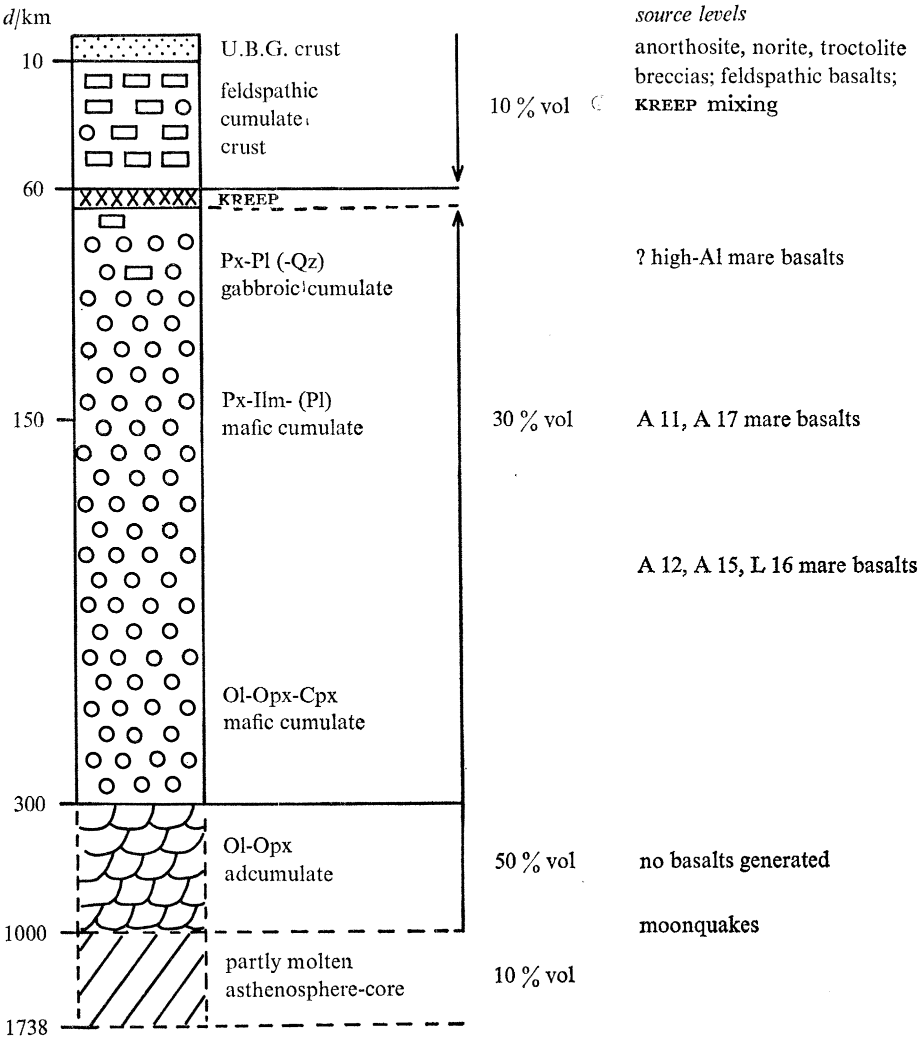

FIGURE 1. A proposed model for the generation of mare basalts by second-stage melting of mafic orthocumulates. Only the upper 300 km is drawn to scale. The zone of cumulates from 60 to 300 km is depicted as orthocumulates (i.e. with pore material between the listed cumulus crystals). U.B.G., Upper Border Group (early chilled and downward-crystallized zone). Px, pyroxene; Pl, plagioclase; Qz, quartz or other silica phase; Ol, olivine; Ilm, ilmenite; Opx, orthopyroxene; Cpx, clinopyroxene; A, Apollo; L, Luna; 'KREEP', rock rich in potassium (K), rare-earth elements (r.e.e.) and phosphorus (P).

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to the model presented here, high-Ti basalts were generated by partial melting of mafic cumulates in which the *pore material* had become strongly enriched in Ti by crystal fractionation. It does not require melting of ilmenite *cumulates* which would be deposited at a higher layered level.

Table 2. Average composition of Apollo groups of lunar basalts

mass %	Apollo 11	Apollo 12	Apollo 15
SiO_2	40.10	47.10	46.10
TiO_2	12.20	3.17	2.17
Al_2O_3	8.60	12.80	8.63
FeO	18.90	17.40	21.67
MgO	7.74	6.80	10.46
CaO	10.70	11.40	9.85
Na_2O	0.46	0.64	0.31
K_2O	0.30	0.07	0.06
P_2O_5	<0.2	0.17	0.09
MnO	0.25	0.24	0.28
Cr_2O_3	0.37	0.31	0.48
FeO/FeO + MgO	0.71	0.72	0.67
parts/10^6			
Rb	5.1	1.4	<1
Li	17	5.9	5.9
Ba	440	63	58
Nb	24	13	<10
Sc	97	40	38
Y	162	39	29
Yb	20	5.2	4.3
Zr	594	110	72
Co	31	64	61
Ni	6.6	70	76
V	73	160	187

Analyses from Christian *et al.* (1972).

The trend of this fractionation pattern would be to produce a zone of residual material, sandwiched between the feldspathic crust and the uppermost mafic cumulates, saturated with phases additional to the mafics such as plagioclase, K-feldspar and apatite, and rich in l.i.l. elements such as the rare-earths. This is shown as a KREEP horizon on figure 1. There is widespread support for KREEP liquids being generated by partial melting of feldspathic crustal rocks, presumably through impact-generated heating (e.g. Hays & Walker 1974). As pointed out earlier in this paper, however, the very high l.i.l. content of KREEP material suggests generation of a strongly fractionated KREEP layer (strong negative Eu anomaly) which may have mixed with the feldspathic crustal rocks (positive Eu anomaly) during impacts preceding those responsible for partial melting. Also, the γ-ray data indicate a concentration of KREEP material in localized parts of the lunar surface (Trombka *et al.* 1974).

The cumulate model may account for asymmetry of the latter type. Adcumulate formation requires transfer of crystallization heat, which is best effected by magma convection currents. During formation of the upper 300 km of orthocumulates, the convective cells would be more numerous in order to accommodate depth-diameter constraints. Such a complex of cells would probably give rise to variable patterns of crystal fractionation and to variation in the effectiveness of extreme residual liquid generation. While this is only a tentative suggestion, the main point to be made is that variations in crustal thickness, KREEP-material distribution, and sites and types of mare basalt generation should be expected from this model. A simpler model of basalt generation from a fairly homogeneous mantle, quite apart from failing to explain some chemical and isotopic-age anomalies discussed in this paper, would require, in a tectonically inactive Moon, similar products along all radial sections of the outer Moon.

4. Summary of evolution stages

(i) Rapid accretion, with total melting of the outer 1000 km of the Moon.

(ii) A thin crustal skin (1 km) solidifies. Major fractionation (*ca.* 4.6 Ga) begins. Olivine and Ca-poor pyroxene sink. Pore liquid is expelled by adcumulus growth at 300–1000 km depth, so no radiogenic heat source exists there for later partial melting.

(iii) Plagioclase crystallizes and remains just below the surface skin while most mafics sink (Ol, Opx, Cpx, Sp). The feldspathic crust (60 km) traps some mafics to produce feldspathic Mg-norites and gabbroic anorthosites. Plagioclase takes Eu^{2+}. Pore liquid contains U, r.e.e., and other l.i.l. elements.

(iv) Sunken mafic cumulates (Eu^{2+} depleted) fractionate upward (60–300 km) as orthocumulates. Pore liquid increases upward in relative volume and in content of Ti, U, r.e.e., K, P, etc. Ti–Al-rich cumulates develop near the top. Late anorthosites rich in Fe and r.e.e., and with negative Eu, develop at the base of the crust. Kreep-rich liquids develop as final fractions, very rich in U and other l.i.l. elements, and with maximum negative Eu anomaly.

(v) Non-equilibrium mixing and melting of the feldspathic crust by impacts (4.6–3.9 Ga). Early mixing with Mg-rich primitive skin from above and with KREEP-rich layer from below. Plutonic fragments (dunites, troctolites) excavated from the lower crust.

(vi) Radioactive heating of upper mafic orthocumulates. Melted pore material rich in Ti, S, U, r.e.e., etc., from a high level but below a cumulus Ti-phase horizon. No melt equilibration with residual cumulus phases (i.e. 4.6 Ga model ages). Apollo 17 and low-K Apollo 11 basalts generated (3.8–3.6 Ga). High-K Apollo 11 basalts generated with some Rb–Sr equilibration with upper cumulus plagioclase (i.e. 3.85 Ga model ages).

(vii) Later radioactive heating of lower mafic orthocumulates, poorer in heat-source elements than the upper orthocumulates. No Rb–Sr equilibration (4.6 Ga model ages). Apollo 12, Apollo 15 and Luna 16, Ti-poor basalts generated (3.4–3.1 Ga). Pore material was low in r.e.e. and a minimal negative Eu anomaly is present. Pore melt includes Fe–Ni metal concentration; magma passage through the upper oxide zone produces Fe^{2+}/Mg as high as in the Ti-rich basalts and hence (by metallic iron depletion), higher Ni:Fe ratios in the metal phase.

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