FRONTIERS

Editor's Note M. J. O'Hara was a Principal Investigator in Experimental Petrology for all six Apollo missions which returned samples from the moon's surface between 1969 and 1974 and has published 22 previous contributions relating to lunar rocks since 1970. He began his career as a field petrologist, turned experimental petrologist, and then became a major element geochemist and eventually a theoretical trace element modeller. He has previously held professorial appointments at Edinburgh and Aberystwyth Universities in the UK, California Institute of Technology and Harvard in the USA, and Sultan Qaboos University in Oman. He is presently an Honorary Professor at Aberystwyth University after ten years as Distinguished Research Professor at the Cardiff University. He has been elected a Fellow of the Royal Society of London (1981), the Royal Society of Edinburgh (1969), and a Fellow of the Geochemical Societies of America and Europe (1997) and of the American Geophysical Union (2004). He has received the Murchison Medal of the Geological Society of London (1983) and the Bowen Award of the American Geophysical Union (1984).

Mike has always stood in the fore-front of scientific debate in his > 50 a scientific career. He worked on important topics such as the identification, nature and composition of primary magmas, the physics and chemistry of the melting process, the physical and chemical consequences of magma chamber processes, phase equilibria, the thermodynamics of melting, and trace element behaviour in response to magma generation and differentiation for both Earth rocks and materials from the Earth's moon. Part of this body of work (> 150 original scientific publications in class journals) is now acknowledged as fundamental truths in igneous petrology, and some is considered conjectural. All would agree that Mike has stimulated scientific debate on a wide range of issues, and that modern igneous petrology would not be the same without him. Many of our views on Earth problems have evolved and changed over the last 30 years since the advent of plate tectonics theory, but the two classic papers born at the same time by Mike O'Hara have stood well the time test: (i) The bearing of phase equilibria studies in synthetic and natural systems on the origin of basic and ultrabasic rocks, Earth Science Reviews, 1968, 4: 69—133; (ii) Are ocean floor basalts primary magmas? Nature, 1968, 220: 683—686.

This invited article "New moon from an old hand" by Professor O'Hara represents an objective and comprehensive overview on, and also gives his deep insights into, the lunar petrogenesis. This article provides excellent food for thought for the upcoming lunar orbiting/landing "exploration/exploitation" program of China. This article also emphasizes the critical importance of a basic petrologic understanding (also indirectly field observations) of a rock before attempting interpretations based on geochemical analyses.

(Yaoling Niu, Executive Editor, Department of Geosciences, University of Houston)

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New moon from an old hand

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Abstract The outcome of the Apollo lunar exploration program 1969—1974 was a model of lunar petrogenesis which ignored the probability of selective volatilisation of gases and alkalis from fire-fountaining lunar basalts. It overlooked the fact that the average compositions of the erupted basalts were those of plagioclase-saturated and low-pressure cotectic liquids on eruption, clearly indicating that they were not primary magmas. The basalts may have undergone evolution by gabbro fractionation within the lunar crust, perhaps in large lava lakes now solidified as the lunar maria. The existing model involving a global magma ocean and plagioclase flotation to form the lunar crust arises solely from the incorrect assumption that the basalts are primary magmas. The plagioclase flotation hypothesis requires the presence of a significant positive europium anomaly in the lunar highland crust, and was founded upon its alleged presence. However, that positive anomaly is neither established by the original data set nor by the much broader current data set. Critical observations, and experiments which will advance the debate are suggested, and alternative interpretations outlined.

Keywords: Apollo missions, lunar samples, volatilisation, plagioclase saturation, europium anomaly, alternative interpretations.

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This article provides a brief summary of the traditional interpretation of the first lunar samples recovered by American and Russian space programs 1969—1975, then surveys the arguments demanding a comprehensive revision of that interpretation and offers an alternative model. There are tens of thousands of pages of publications advancing or subscribing to the traditional interpretation and it is necessary for this author to present his reasons in some detail for doubting that interpretation. Nevertheless, this paper concludes by identifying 6 testable predictions, 5 critical targets for future space missions and 5 highly relevant earth-based studies which are needed to resolve the debate. In the interests of brevity, specific references to most sources are not included in this article. They are available from the handful of sources quoted.

1 Sources of information about the moon

Io, the innermost of the four large satellites of Jupiter, is very similar in size and mass to the moon. Today it is the most active volcanic body in the solar system. Remote sensing information for Io provides an example of the style of volcanic eruption which can be expected to have taken place on the moon.

There are many remote sensing data for the moon, from orbiting space craft and from telescopic studies. Sample collections are available from 6 successful Apollo missions and 3 unmanned Luna missions. About 30 meteorites derived from the moon are now known.

There is an extensive literature relating to the lunar samples and their interpretation, rather less about Io and the lunar meteorites. The "traditional" view of lunar petrogenesis which emerged from the American and Russian space programs between 1969 and 1974 is set out in S. R. Taylor's[1] book length review, extended and modified in two further substantial reviews by Heiken et al.[2] and Papike et al.[3].

The present author has the view differing from the traditional one of lunar petrogenesis since its inception in 1970 and has compiled the case for alternative interpretations in one review paper[4] and a paper concentrating on the Apollo 17 samples[5].

2 Background

The lunar surface is composed of igneous rocks and their impact-metamorphosed and impact-weathered derivatives. Discussion of their origins cannot be separated from a consideration of the evolution of ideas in igneous petrogenesis as a whole.

The Apollo lunar samples were received into a scientific community which had been brought up between 1950 and 1980 in the almost unchallenged belief that the several types of abundant terrestrial basalts were primary magmas[6]. This community was ready to accept that eruption of unmodified primary partial melts of the mantle was a commonplace event on the moon. Contamination, assimilation and hybridisation which had been extensively explored as mechanisms in igneous evolution prior to 1950 were becoming less fashionable. Three assertions which had underpinned the view that primary magmas abounded on Earth were (i) that the common terrestrial basalts were of great uniformity, (ii) that this uniformity could not survive variable amounts of partial crystallisation, and (iii) that observed trace element variations could not be produced by perfect fractional crystallisation. The first assertion has not stood the test of time and the arrival of more abundant data; the other two are invalidated by modelling of processes in more sophisticated magma chambers.

An alternative position admits that the major element compositions of basalts may be affected by low pressure fractionation, but holds that concentrations and ratios of the incompatible trace elements and the isotopes of Sr, Nd, and Pb will retain the characteristics imposed at their mantle source. This last proposition implicitly assumes both (iii) above and further (iv) assumes that there has been no crustal contamination, assimilation or refluxing of previously erupted basalt into the conduits and magma chambers. The space problem inseparable from the establishment of conduits through the crust and of high level magma chambers in volcanoes invalidates this last assumption.

Field relationships indicate that partial crystallisation of basalt magma within the crust is widespread. Experimental studies also demonstrates that most erupted basalts are residual from partial crystallisation at low pressures and, moreover, cannot be in equilibrium with a peridotite source region at upper mantle pressures[7]. Given the evidence for modification of major element composition at low pressures, it is essential to consider objectively what accompanying modification to trace element and isotopic ratios there may have been.

There was an over-enthusiastic adoption of the mare basalt hand specimens as primary magmas within months of the first sample recoveries (the history of this development is reviewed in a later section). The controversy over the interpretation of lunar petrogenesis arises directly out of that mis-identification. Any debate about lunar petrogenesis necessarily concentrates on the credentials of those hand specimen basalts as primary magmas

3 "Traditional" lunar petrogenesis

In the "traditional" view of the origin and evolution of the moon, the story begins with a giant impact on the proto-Earth about 4.55 Ga ago, scattering and volatilising a large amount of predominantly terrestrial crust and upper mantle material into orbit about the Earth. Some of this material re-condensed and accreted to form a volatile-depleted moon some 3500 km in diameter. That secondary accretion event is required to have taken place so rapidly that much of the heat imparted to the impact debris sheets was buried within the growing body by debris sheets from later impacts, to such an extent that a deep magma ocean of molten "average" moon composition was formed in the outer 400 km of the body.

Slow crystallisation of this huge magma body led to the production of a layered, progressively more differentiated sequence of mafic cumulates. Partway through this process, plagioclase became saturated in the residual liquid of the magma ocean. The plagioclase crystals floated to form a 30—150 km thick crust, taking with them much of the europium (Eu). Eu is a member of the rare earth elements (REE) which can readily reduce from Eu^{3+} to Eu^{2+} and in that state proxy for Sr^{2+} and become concentrated in the plagioclase structure. The mafic minerals, becoming increasingly iron-rich and titaniferous, continued to accumulate at the base of the shrinking magma ocean. This whole process of solidification was complete by about 4.3 Ga ago.

Part of the process of crust formation resulted at about 4.3 Ga in the development of a rock akin to granite (KREEP) which, as its name implies, is exceptionally rich in potassium (K), REE and phosphorus (P), and also has high concentrations of radioactive elements Rb, Sm, Th and U (and their radiogenic daughter isotopes). Large quantities of KREEP were exposed by the Imbrium impact and scattered long distances over the lunar highland surface.

From 4.3 Ga ago to 3.2 Ga or even earlier, incipient remelting at different depths of the layered cumulate mantle gave rise to a diverse variety of picritic primary magmas which erupted to form thick piles of flood basalts filling large craters on the lunar surface. Those maria formed more recently postdate the last period of major bombardment of the lunar surface at 4.1 Ga, and form the dark smooth areas visible on the lunar nearside today. These lavas are very poor in alkalis relative to terrestrial basalts, and contain very low to very high contents of titanium. Those lavas are represented by the hand specimens from the Apollo 11, 12, 15 and 17 missions.

In striking contrast to the situation in terrestrial basalt petrogenesis, the interpretation of lunar petrogenesis which was reached in 1969—1970 has changed little in the ensuing thirty years and displays a striking dichotomy. Almost every hand-specimen sample from the maria is supposed to be close to a little differentiated primary magma in composition. By contrast, every igneous rock contributing to the highlands is supposed to be completely differentiated to the point that no trace of its undifferentiated parent magma remains. A further dichotomy appears in the treatment of remote sensing data where lunar highland regoliths are assumed to be representative of the chemistry of 40—120 km of underlying crust, yet mare regoliths which uniformly indicate feldspathic average basaltic compositions are required to be unrepresentative of even the topmost flow units.

4 Assumptions implicit in the "traditional" model

The above "traditional" perspective of lunar petrogenesis is based on at least eight assumptions: (i) The lavas lost no material by selective volatilisation during eruption (otherwise the consolidated compositions would not be primary and nothing positive could be deduced about the volatile content of the moon as a whole). (ii) The mare magmas did not assimilate or in any way become contaminated by 4.3 Ga old KREEP-rich materials, which was presumably present in the crust through which the magmas ascended and small amounts of which were widespread in the regoliths over which the lavas flowed (otherwise primary status would be compromised and all inferences from trace element chemistry rendered questionable). (iii) The mare basins are filled by thick sequences of flood basalt flows, not by deep lava lakes (otherwise there is a probability of extensive differentiation by fractionation of gabbro from the basin-filling magma during its slow consolidation, and every reason to question the primary nature of the last dribbles of liquid erupted onto their surfaces). (iv) The hand specimens of picrite represent the average composition of the liquid which last erupted into the maria basins (otherwise their status as liquid compositions, let alone primary magmas, would again be untenable). (v) The picrite magma is a primary liquid which was produced by low mass fractions of partial melting at depths of 150 km and more, and erupted unmodified after lengthy transport (low mass fractions of melting are necessary to account for their high concentrations of incompatible trace elements). (vi) Plagioclase crystals floated through more than 100 km during the crystallisation of the postulated magma ocean. (vii) The spectacular deficiency of Eu relative to the other REE in the majority of lunar basalts is a characteristic of their source regions within the lunar mantle (otherwise it would imply that the lavas were residual liquids from substantial episodes of near surface gabbro fractionation, as is known to have occurred in terrestrial lava lakes). (viii) The Eu supposedly missing from the lunar mantle is to be found in the lunar highland crust. The other REE, being trivalent, were not taken up in the plagioclase floating to form that crust. Hence there is a complementary positive Eu anomaly relative to the other REE in the average lunar highland crust.

Each of these assumptions is insecure.

5 Doubts about the assumptions

(i) For the problem of volatilisation, the style of eruption seen at Io was unknown when the Apollo missions returned their samples. Lavas on Io are fire fountaining to heights of 10 km, more volatile components form plumes up to 250 km high and 700 km wide, and the cloud of sodium and sulphur escaping from the body's gravity field can be imaged with terrestrial telescopes. If Io had been visited before the moon one would question whether the community would have ignored the possibility of fire fountaining during the lunar eruptions, or so decisively rejected a role for selective volatilisation in the evolution of the lunar samples. Astonishingly, there is almost no mention of Io in the latest reviews of lunar petrogenesis, and a little mention of the moon in recent studies of volcanism on Io.

Selective volatilisation from small basaltic liquid droplets during fire-fountaining into hard vacuum leads to losses of sulphur and sodium in particular. It produces low oxygen fugacities in the remaining liquid, and a bias towards normative anorthite and hypersthene in the silicate composition. These are precisely the major chemical differences between lunar and terrestrial basalts. If eruption processes on the moon were similar to those on Io, it may be excessively optimistic to seek any primary or parental liquids among the returned samples.

Gases in the sulphur-carbon-oxygen system have driven the pyroclastic volcanism of Io, probably for the past 4.5 Ga. The contents of S and C even in consolidated lunar mare basalts are higher than in terrestrial basalts and would sustain volatile fugacities much higher than the lunar surface confining pressure at magmatic temperatures. Pyroclastic volcanism similar to that on Io was thus guaranteed on the moon, yet this fact receives only a one sentence comment by Papike et al.[3] without reference to Io or to the probable consequences for alkali contents of lunar basalts. There is a fuller consideration from Heiken et al.[2], again without reference to Io, and tending to play down the role of reduction by sulphur-loss and possible losses of alkalis during pyroclastic volcanism.

The argument by Taylor[8] that the pressure generating at a depth of 10^{-3} cm in the lavas would have suppressed volatilisation from lunar basalts may be rejected[9], because mare lavas from Apollo 11, 12, 15 and 17 vesiculated to greater depths than this. Some Apollo 15 specimens have more than 30% void space and contain vesicles as big as pigeon's eggs! That argument, and its companion of rapid cooling of a thin outer skin of the basalt, are irrelevant if we are dealing with small basalt droplets with long flight time in a 10 km high fire fountain. Volatilisation loss during fire-fountaining has been the issue since 1971, even more so since the exploration of Io since 1981. It is an issue which has not been properly addressed.

The large vacuum facility at the Lunar Receiving Laboratory in Houston was decommissioned in 1971 without publication of any experimental results to determine whether volatilisation from molten basalt would be an important factor. Thirty-three years later there is still an urgent need to conduct some definitive experiments on melting and extruding basalts in hard vacuum, to supplement the few already available. I suspect that these experiments should be carried out by remote control at the end of a long spoon extending from the International Space Station. If the traditional model is correct, these experiments can be safely conducted inside a depressurised cabin on any space vehicle.

(ii) Contamination of the basalts by KREEP has been an obvious possibility since 1971, and it is central to the debate about the primary nature of the mare magmas. Despite this, there has been no quantitative re-examination of the isotopic and trace element data to test whether this could be an important factor.

(iii) The proposition that the maria are thick piles of flood basalts is important to the traditional interpretation because it allows each individual flow, from first to last, to be a primary magma. For almost forty years since 1951 the standard texts for western igneous petrologists and geochemists advanced Ocean Island Basalts (OIB), Mid-Ocean Ridge Basalts (MORB) and Continental Flood Basalts (CFB) with each as primary magmas. However, petrographic, major element and experimental petrology data challenged this simplistic view. Erupted basalt compositions were modified towards low-pressure plagioclase-saturated cotectic character, the characteristic imprint of modification of the liquid compositions by partial crystallisation at low pressures. The debate quickened during the run-up to the recovery of the first lunar samples in 1969, with P. W. Gast becoming a major protagonist on behalf of the primary magmatists in 1968.

All available experimental petrology data find that partial melts of a dry peridotite mantle at high pressures can only be picritic, komatiitic or peridotitic, and not basaltic in composition——OIB, MORB and CFB are not in equilibrium with their supposed residual mantle peridotite at appropriate pressures[7]. Common basalt compositions, however, carry a trace element signal which cannot be reconciled with closed system perfect fractional crystallisation, but is consistent with equilibrium between crystals and liquid at low but variable mass fractions of melt. The debate ran throughout the period when the lunar sample returns. Public acclaim then effectively discounted the field, major element, petrological and experimental data for terrestrial basalts in favour of one particular interpretation of the trace element data[1,6].

The partial crystallisation processes which could give rise to the low pressure cotectic character of common basalts are not synonymous with closed system perfect fractional crystallisation and may be much more sophisticated (see Table 1 of ref. [7]). Low mass fractions of equilibrium or aggregated fractional partial melting are not the only processes which can account for the trace element geochemistry. Today the parental magmas of OIB are widely recognised as being picritic or komatiitic in character; most MORB are recognised as being significantly differentiated from their Moho-crossing parent liquids; and variable and complex patterns of contamination and differentiation have emerged among CFB.

The lunar lavas would have had low viscosity because of their low contents of alkalis. However, the formation of low angle lava fields of great extent is controlled mainly by eruption rate rather than by low viscosity (think of candle-wax). The exceptionally high rate of volcanic activity on Io leads only to the production of low angle cones, long lava flows and central calderas. Neither Venus nor Mars displays topographic features comparable to the lunar maria.

Equally probable, in view of the extremely flat and smooth surfaces of the lunar maria over distances exceeding 400 km, is that eruption rates were so rapid that lava ponded in the maria depressions, forming deep lava lakes, which then became the site of slow cooling and magmatic differentiation similar to that seen in some large terrestrial layered complexes such as the Bushveld. Overall eruption rates in the early and middle phases of the mare-filling activity, on which we have few constraints, will determine whether that filling was a long succession of individually cooled flow units, predominantly a succession of thick sills and intercalated lavas, a multiply refilled, growing and crystallising pool, or a single deep, slowly cooled lake of lava.

One may speculate on what forces powered such volcanism. The late eruptions at a single site on the surface may, however, span 250 Ma at Mare Tranquilitatis. Bugiolacchi et al.[10] infer three periods of irruption in Mare Nubium and Mare Cognitum, with each period spanning ~ 300 Ma and the whole spanning at least 1.2 billion years, two to three orders of magnitude greater than the time span associated with the major eruptive phase of terrestrial CFB volcanism. What might be expected as late eruptives on the surface of such lava lakes are not unmodified primary magmas, but rather the late residual liquids of advanced fractionation of gabbroic mineral assemblages within the lake or subcrustal magma chambers (consistent with an apparent trend in basalt compositions towards higher TiO_2 with time in both ancient and young maria).

(ⅳ) The proposition that the hand specimen compositions represent the average composition of the lavas last erupted onto the maria is irreconcilable with a large body of data (e.g. Figs. 1 and 2). The optical reflectance data also require an aluminous basalt to be a major component of the maria surface and Shkuratov et al.[16] find that Al_2O_3 is nowhere less than 11.3% (weight percent) anywhere in the maria, values which confirm the conclusion regarding probable plagioclase saturation of the average magmas erupted (Fig. 1). If the hand specimen compositions are adopted as the average target rock composition for regolith development, the amount of highland material required to be admixed in order to explain these high alumina contents is greater than observed petrographically. It is greater than is consistent with models of impact scattering of debris, and greater than is consistent with the very limited scattering of mare material onto adjacent highland surfaces. The data are consistent with eruption of fractionated, plagioclase-saturated liquids, which then differentiated locally into more mafic and more felsic portions during their consolidation. Such a scenario immediately clarifies what otherwise becomes the problem of their negative Eu anomalies.

The embarrassment to the traditional interpretation caused by the aluminous average compositions reported in 1971 for basaltic lithic fragments from the Apollo 11 and 12 regoliths is attested by the fact that similar data for Apollo 15 were reported only after having had their average composition "normalised" to that of the average hand specimen; the comparable data for the Apollo 17 regoliths have never been reported (with the exception of 3 clasts of very low titanium basalt which were considered representative enough to define the VLT magma type); and there is a long list of specific regolith samples for which the appropriate information is still awaited (see final section of this paper). There were no hand specimens of basalt, but only lithic clasts, from Apollo 14, Luna 16 and Luna 24, where their compositions are those of feldspathic basalts. A discrepancy has been obvious from the earliest years of the Apollo missions between the optical and other remotely sensed properties of the mare regolith and the properties of crushed hand specimens. No available studies have addressed this discrepancy by determining what is actually present in the regolith.

(ⅴ) There are possibly insuperable chemical engineering problems posed by the need to extract hot, highly corrosive silicate melts unmodified and uncontaminated, through 150—400 km of vulnerable silicate wall rock with which the magma would not be in equilibrium, and then through a density filter of 50 km of feldspathic crust, which is supposed to have floated on such magmas in the first place. These problems have defeated vast volumes of terrestrial MORB despite having to travel only about one tenth the distance, through a preheated pathway, and through a less effective density filter in the crust. Ocean Island Basalts and Continental Flood Basalts have likewise generally failed to emerge unscathed. Moreover, the rare primitive eruptives in such provinces do not typify the terminal stages of eruptive activity, as they are required to do in the traditional model of lunar petrogenesis.

(ⅵ) Plagioclase is approximately neutrally buoyant in plagioclase-saturated magmas, and the viscosity of such magmas increases sharply as plagioclase saturation is approached. Plagioclase crystals may not be able to sink or float through appreciable distances during the crystallisation of such liquids, the more so in a reduced gravity field. Sinking or floating may not be the important issue, however, because plagioclase manifestly solidifies predominantly at the floor of terrestrial magma bodies. The mechanism of plagioclase crystallisation may be different from nucleation in the main body of liquid followed by gravitational separation.

(ⅶ) The traditional model calls for the lunar mantle to consist of mafic cumulates formed from plagioclase-saturated magmas at pressures of up to 1 GPa. In the absence of such plagioclase saturation, there is no process to generate a global negative Eu anomaly in the lunar mantle.

However, even if all plagioclase crystals and all residual liquid were eliminated from those mafic cumulates, it is a requirement of phase equilibria that the initial liquids produced from those mafic cumulates by small mass fractions of renewed partial melting should be at or close to saturation with plagioclase at those pressures. Then, due to the rapid expansion of the plagioclase liquidus field with declining pressure between 1GPa and lunar surface conditions, such primary magmas would show plagioclase as a liquidus (phenocryst) phase before the appearance of pyroxene.

The phase equilibria of the hand specimen composi-

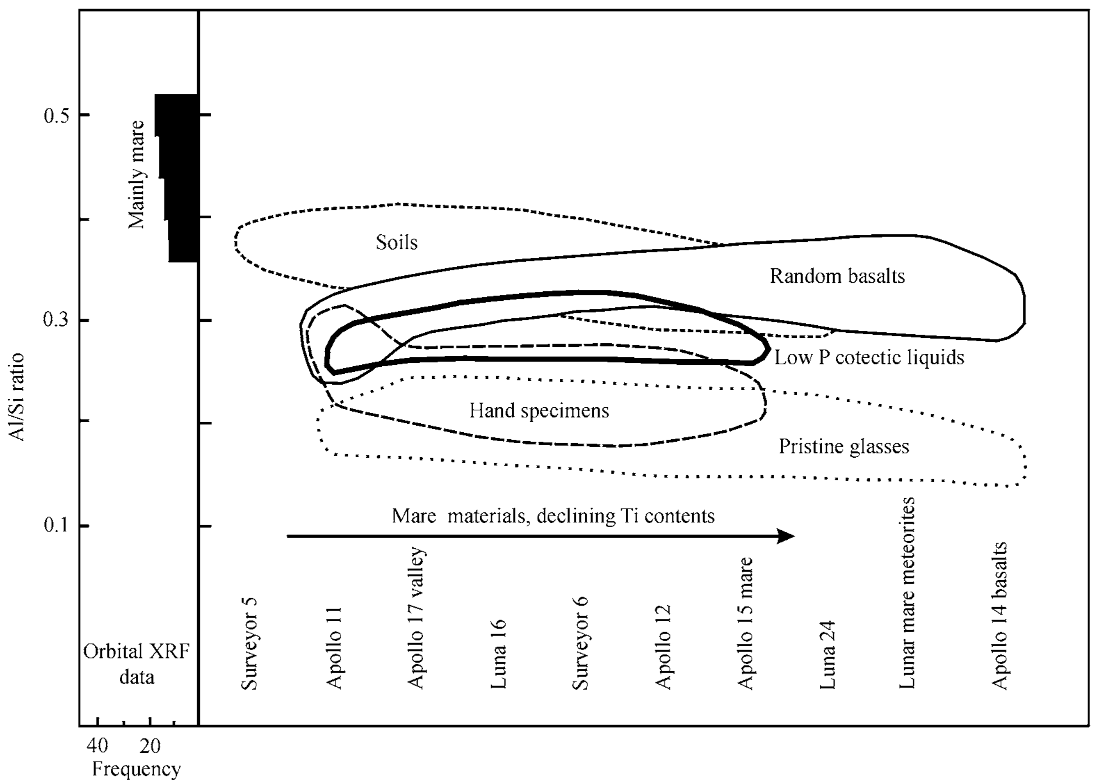

Fig. 1. (Redrawn from part of Fig. 2 in ref. [4]). Aluminium/silicon ratios in remotely sensed lunar mare surface materials suggest that average mare basalt compositions are significantly more feldspathic than the hand specimens. The vertical axis is the Al/Si ratio. Information is plotted by site or source. In the left hand box, histograms are plotted of the frequency of readings from the Apollo 15 and 16 orbital X-ray fluorescence experiments. Assuming 10 μm penetration in materials with a bulk density of 2 t per cubic metre, each individual reading represents the average composition of about 72000 t of material, i.e. a total of about 3.5 million tonnes of mare surface regolith. These reported values may be increased relative to the true target rock by the composition of the < 10 mm fraction in the soils which is known to be excessively feldspathic.

In the right hand part of the figure, fields of Al/Si ratios in analysed samples from a range of sites and occurrences are shown. Randomly sampled mare basalts (clasts in breccias, lunar mare meteorites, average compositions of lithic fragments in the regolith, small fragments recovered by automated sampling missions) are enclosed within a thin solid line. They have slightly lower Al/Si ratios than the bulk soils (enclosed by short dashed line) but have higher Al/Si ratios than the low pressure plagioclase-saturated cotectic liquids produced in experiments on mare basalts (enclosed in a heavy solid line). Both the randomly sampled basalts and the low pressure cotectic liquids have systematically higher Al/Si ratios than the majority of the hand specimens, with the possible exception of low-K basalt samples from Apollo 11 (all enclosed within the long dashed line). The hand specimens in turn have systematically higher Al/Si ratios than the pristine pyroclastic glasses identified at many sites (enclosed within the dotted line). The differences in average Al/Si ratio may seem small but they are very significant in terms of phase equilibria. With Al/Si < 0.25 plagioclase is never on the liquidus of the bulk compositions at any pressure; with Al/Si > 0.33 plagioclase is always on the liquidus at higher temperatures than pyroxene, and maybe before olivine as well.

Among the five known mare-derived lunar "basaltic" meteorites, A881757 has a large positive Eu anomaly and is texturally a gabbroic cumulate, probably from a low-Ti magma with small negative Eu anomaly. It has received much less attention in the 16 a since its discovery than has the next sample, discovered in 2002. LAP02205 is an inhomogeneous basalt (30%—40% plagioclase, 0—7% olivine, 4%—8% ilmenite in three thin sections) which exhibits subophitic texture suggestive of early plagioclase nucleation[11—15]. Based on the three reported bulk chemical analyses, Al_2O_3 is 8.95%—9.93% (weight percent) and Al/Si < 0.23, within the field of hand specimens in Fig. 1 and below the lowest limit of the cotectic liquids. However, the analyses were made on sub-sample beads representing no more than 0.02% of the whole meteorite and their alumina content is somewhat too low to support the reported mineralogy (30%—40% modal plagioclase with 33.3% (weight percent) Al_2O_3 + 52%—55% modal pyroxene with 1%—3% (weight percent) Al_2O_3).

The mare soils have as good a claim to represent average target rock in the top 5—10 m of the regolith as do the highland soils. They have Al/Si ratios which are slightly enhanced relative to the randomly sampled (aluminous) basalts, consistent with a small percentage of observable added fragments of highland-derived materials (values calculated assuming the average hand specimen composition for the basalt component are consistently higher than the observable amounts). Mare soil and randomly sampled basalt compositions are consistent with the average composition of the erupted mare magmas being close to those of plagioclase-saturated low pressure cotectic liquids and even slightly biased towards appearance of plagioclase before pyroxene. The hand specimens and pristine glasses cannot represent the average erupted basalt compositions.

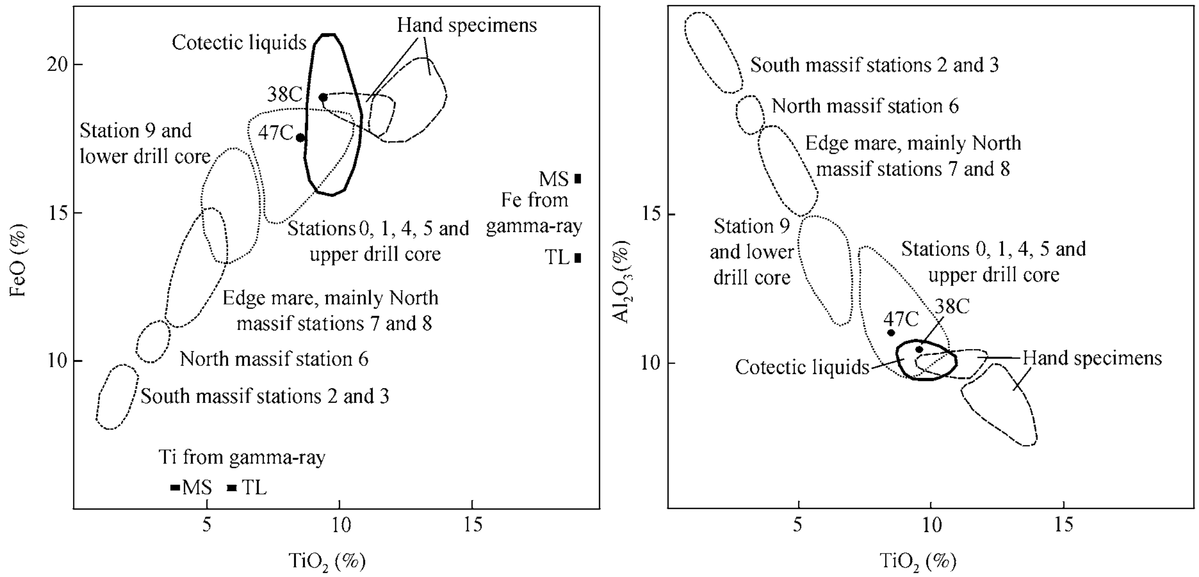

Fig. 2. (Redrawn from Fig. 3 in ref. [5]). Weight percent variation of FeO and Al_2O_3 as a function of variations in TiO_2 among analysed materials from the Apollo 17 site at Taurus Littrow, edge of Mare Serenitatis. Highland soils from five collection points are enclosed within short-dashed fields. Local feldspathic highland soils may be represented by the lowest TiO_2 field, but those from closer to the mare surface fall on a linear mixing line to the compositions of basaltic soils from station 9 and the lower drill core (thought to be the original surface material, now overlain by the ejected soil from Camelot crater composing the upper drill core). The compositions of all mare surface soils (fields with dotted boundaries) and the hand specimens (two fields with long dashed boundaries separating more aluminous, less titaniferous specimens from those held to be primary magmas) are shown. In both figures they define a possible linear correlation which is different from the mixing line between highland materials and the original mare surface soil. This line may express a post eruption differentiation within the basalt, yielding lower drill core soils as one extreme and hand specimens as the other. The field enclosing analysed experimental plagioclase saturated cotectic liquids obtained at atmospheric pressure is shown as a heavy solid line. 38C and 47C are the compositions of the average basalt lithic fragments in the most basalt-rich horizons of the drill core, calculated by removal of the other identified components whose compositions and abundances in each sample are known.

In the left hand figure the values of FeO and TiO_2 obtained from orbital gamma-ray measurements for the edge of Mare Serenitatis (MS) and Taurus Littrow itself (TL) are indicated. All data are consistent with the average basalt composition at the Apollo 17 site being somewhat more feldspathic than the plagioclase-saturated cotectic liquids and very different from the hand specimens.

tions are totally inconsistent with these requirements. Far from saturation with plagioclase on the liquidus at low pressure, they display obvious olivine and pyroxene precipitation before plagioclase appears. As pressure is increased they display further enhancement of the crystallisation of olivine and pyroxene before the appearance of plagioclase. Even if there is a negative Eu anomaly in the lunar mantle, the hand specimens cannot possibly represent primary partial melts of that source.

(ⅷ) There is no positive Eu anomaly in the average lunar highland composition, rather there may be a small negative anomaly. Fig. 3 is similar to Fig. 1, but displays the information for lunar highland materials from the Apollo missions. Al/Si ratios are consistent with there being either no anomaly or perhaps a small negative anomaly. The original data set which was interpreted to yield a substantial positive Eu anomaly in the lunar highland crust is displayed in Fig. 4. Correct interpretation of these data also indicates no anomaly or a small negative anomaly in the lunar highlands. Although subsequent information has lowered both the average Th content of the highland crust and the average value of the sum of REE at which a positive anomaly can be expected, the above conclusion remains unaffected.

The traditional model for lunar petrogenesis requires and predicts that there should be a substantial positive Eu anomaly in the average pre-3.9 Ga lunar highland crust, but it is not there. Belief in this positive Eu anomaly has sustained the lunar geochemical community for 33 a. Presence of a substantial positive Eu anomaly in the average pre-3.9 Ga lunar highland crust is the cornerstone of the plagioclase flotation hypothesis, the global magma ocean hypothesis, the cumulate mantle hypothesis and the mare primary magma hypothesis, none of which can survive without it.

Confidence in the existence of this anomaly is now so low that recent comprehensive reviews[2,3] on lunar petrology and geochemistry make no reference to it whatever. If there is no positive Eu anomaly in the lunar highlands, there can be no negative Eu anomaly in the lunar mantle unless the moon is globally depleted in Eu.

6 What the thermal and density consequences are if the hand specimens were primary magmas

The premise that primary magmas were erupted in abundance was widely accepted in the 1960s and 1970s. It

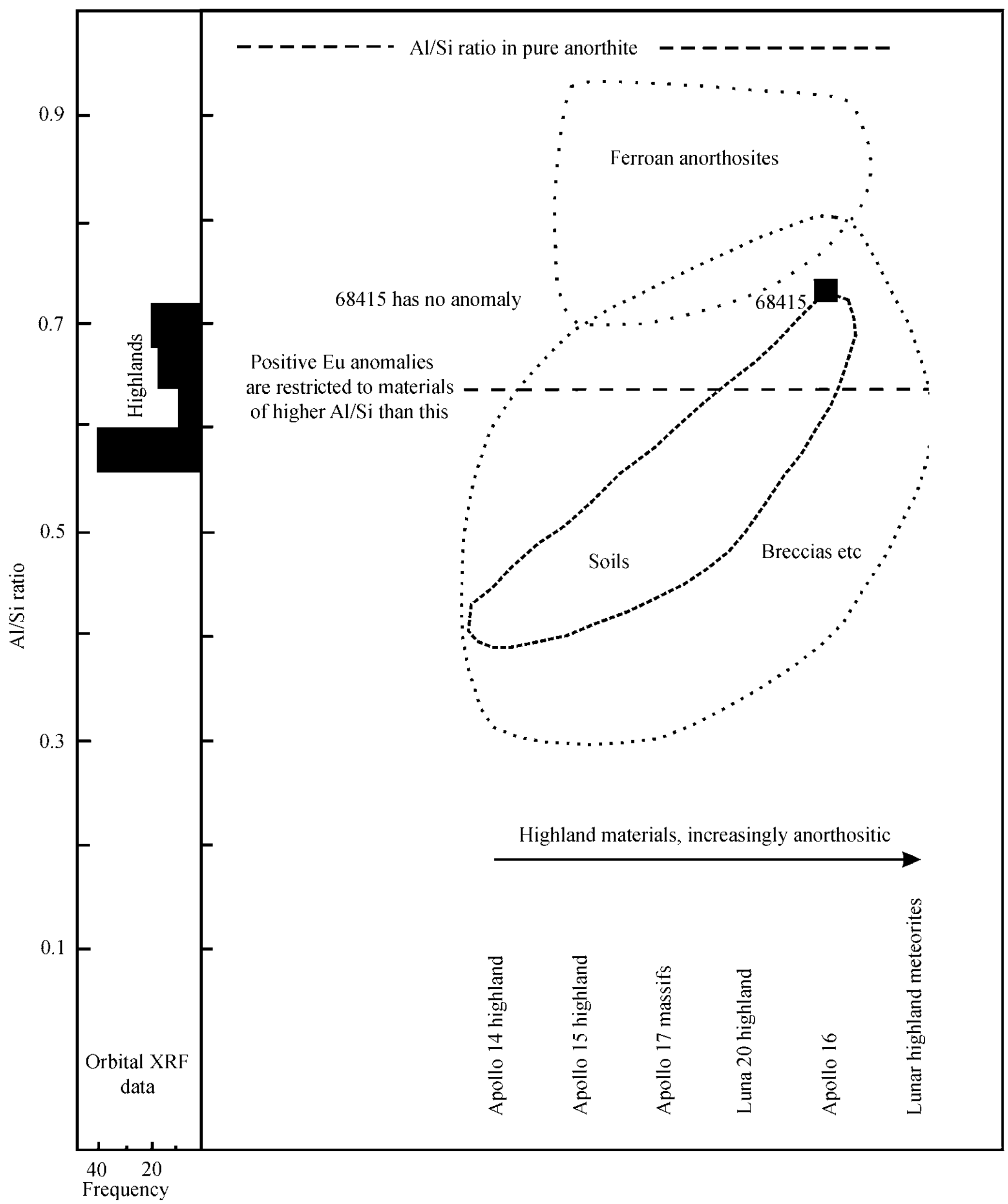

Fig. 3. (Redrawn from part of Fig. 2 in ref. [4]). Aluminium/silicon ratios in remotely sensed lunar highland surface materials also suggest that there is no significant europium anomaly in the average lunar highlands. The vertical axis in the main figure is the Al/Si ratio. Information is plotted by site or source. In the left hand box, histograms are plotted of the frequency of readings from the Apollo 15 and 16 orbital X-ray fluorescence experiments. Assuming 10 μm penetration in materials with a bulk density of 2 t per cubic metre, each individual reading represents the average composition of about 72000 t of material, i.e. a total of almost 6 million tonnes of highland surface. The same bias of Al/Si ratios to higher values because of the very feldspathic nature of the fine dust fraction, commented on in Fig. 1, may be present in these orbital data also.

In the right hand part of the figure the ranges of Al/Si ratios in some analysed samples from a range of sites and occurrences are shown. Compositions of ferroan anorthosites, most of which do have positive Eu anomalies, are enclosed in the sparsely dotted line. Those of the much more abundant breccias, brecciated norites, etc. are enclosed within the more densely dotted line. Most of these breccias are impact mixed materials whose compositions are in each case likely to average those of large masses of target crust. Sample 68415 is interpreted as a recrystallized impact melt of this type with many igneous petrographic features. The soils developed from the whole rock assemblage are enclosed within the most heavily dashed line and show a more restricted range of composition, entirely within the range defined by the probable components. Al/Si ratios are so high that almost all compositions will display plagioclase crystallisation at the liquidus, ahead of the appearance of other silicates. Positive Eu anomalies are restricted to samples with Al/Si greater than ~0.64. All data are consistent with an average lunar highland composition which will not display a substantial positive Eu anomaly.

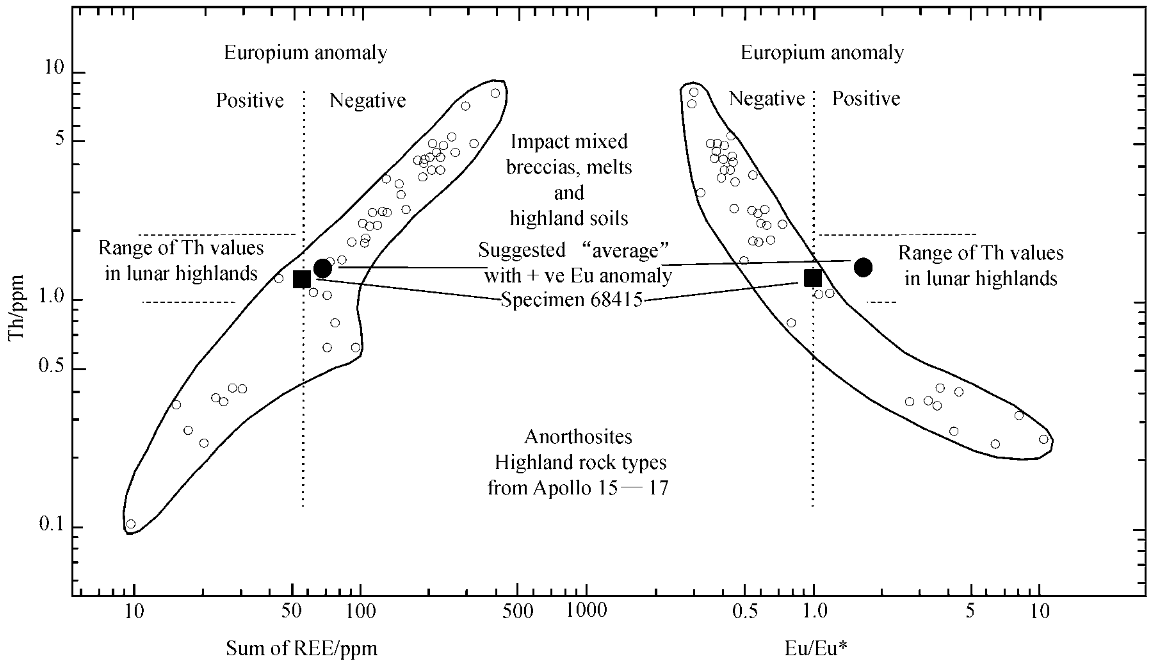

Fig. 4. (Redrawn from Fig. 3 in ref. [4]). Logarithmic plots of Th content in recovered lunar highland samples as a function of the sum of all REE in those samples (left hand figure) or of the magnitude and sign of the europium anomaly in those samples (right hand figure). Average Th contents in the lunar highlands were measured by gamma-ray spectrometry from orbit, yielding the range of values indicated in both parts of the figure. The data support an average total REE content ~65 ppm as originally deduced[1] and predict a negligible, or small negative Eu anomaly in that average composition. Sample 68415 falls very close to the indicated average. The data do not support the significant positive Eu anomaly of ~1.6 in the average highland composition (right hand figure, with the alleged point falling outside the envelope of all data) which underpins all of traditional lunar petrogenesis.

was particularly seductive because it immediately invested a sample with fundamental importance. It is a stepping stone to mantle source mineralogy, pressure of formation and the mantle dynamics leading to its partial melting. Breath-taking vistas in planetology and cosmology unfold before the possessor of such a talisman. But primary magmas have uncomfortable attributes. Investigation of their phase equilibria at high pressures constrains the permissible mineral assemblage and mineral chemistry (but not the mineral proportions) of the mantle residue from which they may have separated at any postulated depth. It also constrains the pressure (depth) and temperature at which the magma formed.

If the residual mantle is required to be at least bimineralic (olivine, pyroxene), and the mass fractions of melting are postulated to be low, the phase equilibria for each sample define a unique depth and temperature within the lunar mantle at a specific time. The assemblage of these depth-temperature points for all the primary magmas might define an approximate postulated palaeo-selenotherm, both at consolidation of the cumulate mantle and during subsequent remelting.

The possible selenotherm at 4.3 Ga and again at 3.5±0.3 Ga so defined by the putative mare primary magmas is grossly super-adiabatic. The putative cumulate mantle would, moreover, have increased in density upwards due to the increasing Fe/Mg ratio of the silicates and the eventual appearance of ilmenite as a cumulus phase. Both factors would have driven convective overturn in the outer 400 km of the lunar mantle. This mantle overturn has been advanced as a cause of the renewed partial melting of the cumulate pile, more magnesian, low titanium cumulates partially melting because of their adiabatic decompression; less magnesian, high titanium cumulates melting as they sink into hotter regions.

This hypothesis of lunar mantle overturn should be added to the above list of assumptions implicit in the "traditional" model. Without it, there is no obvious reason why a mantle which has been solidified by slow cooling should undergo renewed partial melting unless all mare melting can be ascribed to the effects of impact by large projectiles[17]. In the traditional model the basalts are required to be small mass fraction partial melts. The volume of basalt erupted since 3.9 Ga (and there may have been much more in earlier mare structures since it has been buried or fragmented by the bombardment about 4.1 Ga) requires a large volume of the outermost lunar mantle to have been involved in such overturn and remelting.

But the evidence of extensive surface tectonic deformation which should result from this overturn is manifestly absent from the lunar crust.

7 How the misunderstanding came about

The Lunar Sample Preliminary Examination Team

(LSPET) characterised all the returned materials from the Apollo missions between 1969 and 1974 before their distribution to the approximately 150 internationally distributed Principal Investigators. That team developed and promulgated concepts, ideas and interpretations based on their own background and skills. Included in that team were two trace element geochemists.

P. W. Gast played a major role in the inception, design and implementation of the lunar sample science program, acting as Chairman of the Lunar Science Application and Planning Team from 1969, Chief of the NASA Planetary and Earth Sciences Division at the Manned Spacecraft Centre, Houston from 1970 and as an active Principal Investigator throughout. He was a committed believer in the prevalence of primary magmas and was additionally a strong proponent of the view that trace element geochemistry was at least as a powerful tool as experimental petrology in unravelling magma genesis. So it is, but in this instance the approach became a casualty of ignoring the major element and phase equilibria considerations altogether, and much of what might be termed the field constraints as well.

LSPET also included S. R. Taylor who came from a research school committed the ultimate primary magma hypotheses embodied in the pyrolite model of terrestrial upper mantle composition.

The LSPET report in 1969 on the Apollo 11 lunar samples from Mare Tranquilitatis asserted that soils and hand specimens had ‘similar but unique compositions’ and concluded that the unique composition had been a silicate liquid, thereby laying the foundations for subsequent events. By the first lunar science conference in early 1970 the hand specimens were predetermined by LSPET and many other workers to be primary magma compositions, despite the discrepancy which had already emerged between the hand specimen compositions and that of the average target rock which had formed the regolith at the Apollo 11 site.

Samples from Apollo 12 received similar treatment in 1970, although LSPET this time commented on the discrepancy in composition between the hand specimens and the average target rock forming the soils.

The Apollo 11 and 12 basalt compositions, however, were found (1971) to possess deep negative europium anomalies, indicating an event of extensive plagioclase separation somewhere in their evolution, *yet plagioclase is never saturated at or anywhere near the liquidus of the hand specimen compositions at any pressure*. The compositions of the average target rocks which had formed the regoliths, on the other hand, implied an erupted magma composition which could be plagioclase saturated at the low pressure liquidus, an observation which implied that the basalts were derivative liquid compositions from gabbro fractionation at low pressure, and not primary magmas.

This should have prompted a reevaluation of the original primary magma assertion. Instead, the discovery of the negative Eu anomalies led to the development of five inter-dependent hypotheses, which were essential to maintaining the original assumption that the hand specimens were primary magmas, and its corollary that the negative Eu anomalies must, therefore, be a feature of their mantle source region. These hypotheses were: (i) An alleged positive Eu anomaly was to be found in the plagioclase-rich average lunar highland composition, necessary to provide an alternative repository for the missing Eu; (ii) There had been an impact-generated global magma ocean, required to provide a physical environment in which plagioclase might be separated from the lunar mantle; (iii) The plagioclase would have floated from that magma ocean to form the lunar crust, required to separate the plagioclase into the crust from the residual mafic mantle; (iv) The consolidation of the rest of the magma ocean formed a layered differentiated cumulate pile with an in-built negative Eu anomaly, required to account for the negative Eu anomalies and relatively low Mg/Fe ratios of the alleged primary magmas; (v) The cumulate mantle subsequently underwent overturn, necessary to explain the postulated later remelting of the mafic cumulates to yield the hand specimen basalts. This is also required because the cumulate pile created in (iv) would have been gravitationally unstable and deposited with a super-adiabatic thermal gradient.

This edifice of hypotheses failed to appreciate the force of the italicised statement above, which is irreconcilable with the proposed model. The basalt hand specimens cannot be low mass fraction melting primary magmas derived from a plagioclase-saturated lunar mantle mineral assemblage. This inconsistency was first recognised as early as 1981, based on phase equilibria studies by a multitude of independent and sometimes fiercely competitive workers in many different laboratories.

Nor can this structure of hypotheses survive the absence of a positive Eu anomaly in the average lunar highlands or the discrepancy between the hand specimen compositions and the average erupted basalt composition at each site.

Since the papers by O’Hara[4,5,7,9] there has been only one response from Taylor[8] which sought to uphold the absence of selective volatilisation, the existence of a positive Eu anomaly in the average lunar highlands and the traditional interpretation of the hand specimens as primary magmas. To those arguments there has been a reply[9]. There has to date been no debate about the discrepancy between hand specimen and average basalt compositions.

8 Alternative model for the formation of the lunar crust

It is the author’s opinion that as one of the multiple working hypotheses to be prudent to consider, we should envisage that the moon was not the volatile-depleted body envisaged by the traditional interpretation. The moon may have been a body with a 'normal' budget of volatiles, as was probably the case for Io. The lunar basalts still contain almost twice the sulphur content of terrestrial MORB (in spite of their losses during eruption) and a few basalt specimens are known to retain relatively high alkali contents. If there was originally a more abundant budget of volatiles, the moon may have evolved initially by "wet" melting of the mantle (4.5—4.4 Ga) leading to the early formation of a devolatilised calc-alkaline crust.

What is more certain is that later (4.3—3.2 Ga) the moon evolved by "dry" partial melting of the primitive lunar mantle, driven by initial heat and perhaps by declining tidal deformation. Parental magmas reaching the crust were predominantly very low-titanium feldspathic basalts with negligible Eu anomalies. Eruption was coupled with extensive volatile losses and reduction while the magma falling back on the surface ponded in impact-generated basins to form the maria.

Those dry, alkali-depleted and reduced basaltic magmas then underwent extensive partial crystallisation of norites and gabbros in near-surface magma chambers and the consolidating lava lakes. This produced the extensively fractionated residual basalt compositions which escaped onto the surfaces of the maria and formed the target rock for regolith formation. Three striking features of those low pressure partial crystallisation events were (ⅰ) an increase of TiO_2 in the residual liquids up to the ca. 9.5% (weight percent) level at which Ti-rich oxide phases begin to crystallise from these alkali-poor liquids, (ⅱ) concomitant generation of a progressively larger negative Eu anomaly in the residual liquid due to prolonged plagioclase fractionation (and of a complementary positive Eu anomaly in the underlying cumulate gabbros), (ⅲ) decrease of the $Mg^{\#}$ to a point where the residual liquids cannot be in equilibrium with a magnesian olivine-pyroxene bearing mantle. The impact fragmented debris of such cumulate sequences formed prior to the great bombardment at 4.1 Ga may form a substantial proportion of the clasts in lunar highland breccias. The surviving maria are products of the waning phase of this activity.

9 Loose ends in the alternative model

This alternative model has to find an adequate explanation for the origin of the mafic hand specimen compositions, and explain why they differ systematically from the average magma composition erupted.

These hand specimens may not represent liquid compositions in spite of their apparent quench-textured character. In most terrestrial magmas quench crystals only form at cooling rates that preclude significant crystal settling, except possibly in the case of komatiites. In the alkali-poor, low viscosity lunar basalts quench crystal formation may have taken place at cooling rates which nevertheless permitted significant gravitational accumulation of those crystals. This is the author's opinion. A viable alternative process which has been suggested would interpret the hand specimens as materials which had quenched onto the walls of lava tubes from the passing magma and so became enriched in those mafic components which could most readily form quench crystals.

The alternative model also has to provide some explanation for the exceptionally mafic pyroclastic glass bead compositions. When interpreted as primary magmas of their present composition in the traditional model, these pyroclastic beads play a major role in defining the super-adiabatic gradient and extreme depth of melting commented upon above. To derive either the average erupted basalt compositions or those of the hand specimens (as liquids) from such parental liquids is not simple and would require extensive but unsampled complementary ultramafic cumulates to be present.

These pyroclastic beads undoubtedly do represent a range of liquid compositions that have also clearly been exposed to hard vacuum at high surface temperature. It might be unwise to expend too much effort seeking the origin of their present compositions until we know more about the effects of selective volatilisation from silicate liquids in such circumstances. In the present state of knowledge the pyroclastic bead compositions do not fit comfortably into either the traditional or the alternative model, an observation indicating neither model is complete.

There is, incidentally, no requirement for a giant impactor event on the Earth in order to generate the moon in this scenario, reopening the question of how the moon comes to be where it is.

10 Basalt petrogenesis elsewhere in the Solar System

On the Earth the evidence for extensive evolution of basaltic magmas between source region and vent has multiplied in the past 35 a. Central volcanic complexes and calderas on the Earth are associated with high level magma chambers, partial crystallisation of magmas and eruption of residual liquids biased towards low-pressure cotectic compositions. High level magma chambers cannot, however, be the site of whatever low-pressure modification has affected continental flood basalt compositions and subcrustal magma chambers are preferred.

Evidence relating to basalt genesis from Venus, Mars, Io, Vesta and the parent bodies of the basaltic achondrite and mesosiderite meteorites has also increased greatly in amount during the same period. The crust of Venus is riddled with central volcanic complexes which suggest an abundance of high level magma chambers in which partial crystallisation of parental magmas might occur. The surface of Mars has the largest central volcanic complexes and some of the largest calderas known in the solar system, again potential sites of advanced low pressure partial crystallisation and there is evidence of solidified gabbroic magma chambers ~ 300×600 km in lateral extent and several km thick[18]. The majority of lavas erupted on the surfaces of Mars and Venus are likely to be extensively modified by partial crystallisation and assimilation within the crusts and central volcanic superstructures on those planets; most SNC group meteorites derived from Mars are cumulates.

There is an abundance of central volcanic features and calderas on Io. The lavas erupting on Io are anticipated to be evolved basalts on the basis of the existence of numerous large calderas which imply extensive high-level magma chambers. There is also a probability of refluxing of the partial melt compositions at low pressure over a period of 4.5 billion years.

The parent planet of the basaltic achondrite meteorites had a crust covered with low pressure cotectic plagioclase-saturated basic extrusives. These 4.5 Ga old lavas have the sodium, volatile and siderophile element depletion and the high sulphur abundance of lunar mare basalts. They display a range of negligible to moderately negative Eu anomalies. Their geochemistry can now be interpreted as products of crust-forming, periodically recharged, periodically tapped magma chambers. Complementary slowly-cooled orthopyroxeneite and gabbro cumulates are known among the achondrite meteorites and some (Moore County, Serra de Magé) have the requisite substantial positive Eu anomalies.

Ancient igneous rocks from the Mesosiderite Parent Bodies have similar relationships, with one of the gabbro clasts containing the most extreme positive Eu anomaly known.

Some very effective mechanism of volatile and sodium loss has to be found to arrive at these meteorite compositions from chondritic or carbonaceous chondritic starting materials.

11 Predictions and further actions

The essence of a satisfactory hypothesis is that it should make predictions that can be tested and either proved or disproved.

The alternative interpretation of mare basalt petrogenesis suggested here predicts that (i) the average compositions of the small lithic fragments in the Apollo 17 regolith will be found to be close to those of low-pressure plagioclase-saturated cotectic basalts, like those reported from the Apollo 11 and 12 sites; (ii) diligent search among vitrophyric lithic fragments from the regolith at the Apollo 12, 15 and 17 mare sites will find evidence of small plagioclase phenocrysts in an appropriate composition groundmass, similar to those reported from the Apollo 11 site; (iii) a few such plagioclase phenocrysts are present in small amounts in the vitrophyric groundmasses of some of the mafic hand specimens but they might be very difficult to find and even more difficult to prove conclusively absent; (iv) a significant part of the gabbroic debris in highland breccias from Apollo 14, 15, 16 and 17 can be linked to the evolution of earlier mare basalt magmas. An objective study of the compositions and relative abundances of these plutonic and basaltic clasts would constrain the character and extent of possible intra-crustal fractionation of the mare basalts; (v) remote sensing of the layers exposed in the walls of Hadley Rille will demonstrate compositions akin to the surface regoliths, not that of the mafic hand specimens and the same will be true of the average regoliths on the steep sides of the rille, which should be more mafic than the surface regoliths if the “traditional” version were true; (vi) high resolution multi-spectral imaging of the composition of materials exposed in the walls and debris aprons of mare-penetrating impact craters (e.g. Archimedes, Aristilus, Autolycus, Bullialdus, Goclenius, Helicon, Leverrier, Lambert, Pytheas, Timocharis) will demonstrate that they penetrate feldspathic gabbros and basalts, not picritic primary magmas.

All the above can be tested with available samples or readily accessible measurements. Other relevant studies which would advance the debate, but might require developments in technique or might become targets for future missions, include (vii) high resolution remote sensing of, or better a visit to the huge blocks on the floor of Hadley Rille and (viii) the materials exposed in the slumped walls of Copernicus, or (ix) obtaining a few 100 m long drill cores almost anywhere in the maria; (x) that the vents erupting the glass bead deposits may also have carried up xenoliths of the underlying stratigraphy; (xi) further detailed studies of the compositions and temperatures of the magmas erupting on Io and of the composition of the gas cloud released.

The list of other desirable earth-based studies includes (xii) reexamination of the seismological and gravity data for the mass concentrations associated with the lunar maria, to determine to what extent they require a layered stack of basalts in the maria, and to what extent they support or exclude the presence of laterally extensive bodies of massive plutonic gabbros within the maria[18]; (xiii) extended mathematical studies of all possible tidal contributions to lunar volcanism; (xiv) studies of the eruption of appropriate basalt compositions into hard vacuum; (xv) critical re-examination of the published data base for the Rb-Sr system in particular for evidence of variable contamination of lavas by an ancient KREEP component; (xvi) determination and publication of the average com position of basaltic lithic fragments in lunar regolith samples from Mare Tranquilitatis (10002, 10084 and drill core 10004/5); Oceanus Procellarum (12001, 12023, 12030, 12032, 12033, 12037, 12042, 12044 and drill cores 12025/28); Mare Imbrium, Palus Putredenis (15012, 15013, 15021, 15030, 15040, 15070, 15080, 15221, 15251, 15271, 15470, 15500, 15530, 15600, 15601 and drill cores 15001, 15010/11); and Mare Serenitatis, Taurus-Littrow (70011, 70160, 70180, 71040, 71060, 71500, 72160, 72501, 75060, 75080, 76501, 79220, 79240 and drill cores 73001/3, 74001, 79001/2 and 70001/9).

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