MAGMA GENESIS IN A BATTERED MOON: EFFECTS OF BASIN-FORMING IMPACTS

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Abstract. Magma genesis in the Moon could have been significantly altered by large impacts if they melted solidified residual liquids and late cumulates from the 'magma ocean'. Calculations of the heat required to melt these materials, under different assumed conditions, are compared to estimates of the total kinetic energy of the Imbrium impact. For a significant amount of these materials to have been melted, they must have been near their solidus temperatures, the impacts must have been very large, and the lunar lithosphere must have been locally heated at depths of 70 to 140 km. Unless the Imbrium impact released at least the maximum estimated kinetic energy, only larger impacts, e.g., the proposed 'Gargantuan' impact, could have augmented the intrinsic lunar heat budget enough to locally alter the abundance, timing of eruption, and chemical compositions of lunar magmas. The mechanical and thermal energy generated by such an impact could have been critical in creating (1) the higher concentrations of radioactive elements in the Imbrium/Procellarum area by migration of residual liquids driven by differential lithospheric thickness; and (2) hybrid mare basalts (representing varying proportions of late cumulates and/or residual liquids incorporated into primitive magmas rising from the partially molten lunar interior). Complete compositional spectra of lunar basalts are to be expected, from primitive mare basalts to pure KREEP and to Ti-rich varieties. Comparison of the Gargantuan/Imbrium area with ancient basins in the eastern nearside area suggests that the interplay between the Moon's internal heat engine and the timing of large impacts was a crucial factor in determining the time of lunar volcanism and the chemical composition of the lavas.

1. Introduction

Major features of the Moon (center of figure – center of mass (CF–CM) offset, concentration of maria on the nearside, high levels of surface radioactivity in the Imbrium area) are clear indications that physical asymmetries are an important part of lunar history. Because of their size, large late impacts such as Imbrium and Gargantuan must have had a significant local effect on magma genesis and the Gargantuan Impact has been proposed to have had such an effect (Cadogan, 1974). In this paper we will present and interpret information in a manner that describes the effect that large, late impacts and the center of figure – center of mass offset had on magma genesis.

The generation of magmas requires heat. The basic heat budget of the Moon has been fairly well constrained by several generations of thermal model calculations, which have been increasingly constrained by observational data (e.g., Hubbard and Minear, 1976;

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Solomon and Longhi, 1977). For an impact to have any significant effect on the course of magma genesis and the chemical composition of the magmas it must significantly alter the heat budget. Furthermore, the energy imparted by the impact to the Moon must heat and perhaps melt part of the Moon at some depth (we do not consider molten ejecta in this assessment because it is only a surficial effect). We calculate the amount of heat required to significantly alter the compositional options of magma genesis at depth in Imbrium and Gargantuan sized areas and compare those amounts of heat with estimates (Croft, 1977) of the kinetic energy of the Imbrium impact. The role of even larger impacts, e.g., Gargantuan, is evaluated. A mechanism is postulated for selectively melting parts of the lunar lithosphere at depths well below the bottom of the transient cavity.

In the latter part of the paper we use the concepts presented about magma genesis and compare them to the observational data supplied by orbital gamma-ray and X-ray measurements, photogeologic results, and analyses of lunar samples.

2. Heat Required to Melt Solidified Residual Liquids and Late Cumulates

Croft (1977) reports various estimates of the kinetic energy of the Imbrium impact (1 x 10E32 to 10E34 ergs, i.e., 10E24 to 10E26 cal). Earlier, larger impacts (e.g. Gargantuan) must have imparted even more energy. We assume that an area of the lunar crust below the transient cavity is heated to some depth by this energy and examine the consequences for different total volumes and average crustal temperatures at the time of impact. The basic data used in these calculations are given in Table I.

TABLE I

heat of fusion* = 400 cal g^{-1}
heat of capacity* = 0.239 cal g^{-1}
density* = 3.34 gm cm^{-3}
solidus of residual liquid = 1000 °C

* Data are from Hubbard and Minear (1975).

In these calculations the heat from the impact is used to heat the lunar crust and to melt those materials with the lowest solidus temperatures. These calculations are approximate, but this does not affect the conclusions because a wide range of conditions are assumed and because the estimates of the energy of the Imbrium impact vary over a factor of 100. The temperature of the lunar crust at the time of the Imbrium impact is estimated from diagrams in Hubbard and Minear (1976) to be 1200 °C at 250 km depth. If the results of Solomon and Longhi (1977) are used, the temperature will be higher at shallower depths e.g., 1000 °C at 140 km. Near surface temperatures are assumed and the thermal gradient is assumed to be linear between the surface and 250 km. The median temperature of the assumed lunar volume is then taken as the base temperature of the entire volume. The heat from the impact is then used to heat the crustal material from that base temperature to 1000 °C. At 1000 °C, 1.0% of the assumed volume of crust is melted; this volume represents the solidified residual liquid and/or late cumulates that are postulated to be melted at depth by the impact. A solidus of 1000 °C is approximately correct for residual liquid and perhaps 80 °C too low for ilmenite and clinopyroxene rich cumulates (Hess *et al.*, 1978). The results are given in Table 2 for the cases assumed.

We used three approaches to estimating the depth at which the low melting point material (solidified residual liquids and late cumulates) was located. First, we assumed that the zone of low melting point material was at the base of the low density crust, and used the crustal thickness reported by Bills and Ferrari (1976) for the area surrounding Imbrium (60 to 70 km). Second, we assume that the global seismic discontinuity at 60 km depth plausibly marks the shallowest depth at which solidified residual liquid is a significant component of the lithosphere. Third, we used the results of Solomon and Longhi (1977) to obtain a maximum depth (140 km) at which solidified residual liquids and late cumulates may have been located.

Cases 1, 2, and 3 in Table II illustrate the effects of increasing the volume of crustal material that is uniformly heated to a temperature of 1000 °C before 1.0% of that volume is melted. Case 1 approximately corresponds to Orientale, Cases 2 and 4 to Imbrium, and Cases 3 and 6 to Gargantuan. The base temperature of 100 °C is low but serves to show that large amounts of energy must be expended in heating cold crustal material to 1000 °C. A base temperature of 550 °C (Case 4) is perhaps more realistic and results in a twofold reduction in the amount of heat needed. In Cases 5 and 6 we increase the base temperature to 900 °C and the depth to 140 km, which causes the amount of energy required to significantly decrease. Cases 5 and 6 were calculated because the results of Solomon and Longhi (1977) show that the zone of residual liquid could have remained molten until the Imbrium impact. The 900 °C base temperature may be too high for the entire 140 km of lithosphere, but is consistent with the high temperatures found by Solomon and Longhi (1977) for the zone of residual liquids at about 140 km depth. In effect, Cases 5 and 6 calculate the energy needed to increase the temperature of the stated volume of crust by 100 °C, bringing the zone of residual liquid at 140 km depth to its assumed melting temperature of 1000 °C.

In the last three columns we compare the total thermal energy required to result in 1% of the crust being melted with estimates of the kinetic energy of the Imbrium impact (Croft, 1977). The lesser the percentage of the estimated Imbrium impact energy required, the more probable is impact melting at depth.

The major conclusions from Table II are:

(1) Only the upper estimates of impact energy for Imbrium are consistent with the possibility of impact melting at depth below the transient cavity. Perhaps even larger impacts, e.g., Gargantuan, are required before impacts have a significant effect on the genesis of lunar magmas.

(2) Very large impacts are required to melt solidified residual liquids and late cumulates if the base temperature is low.

(3) If the materials to be melted are near their melting temperatures, large impacts are more likely to have been significant sources of additional heat.

TABLE II

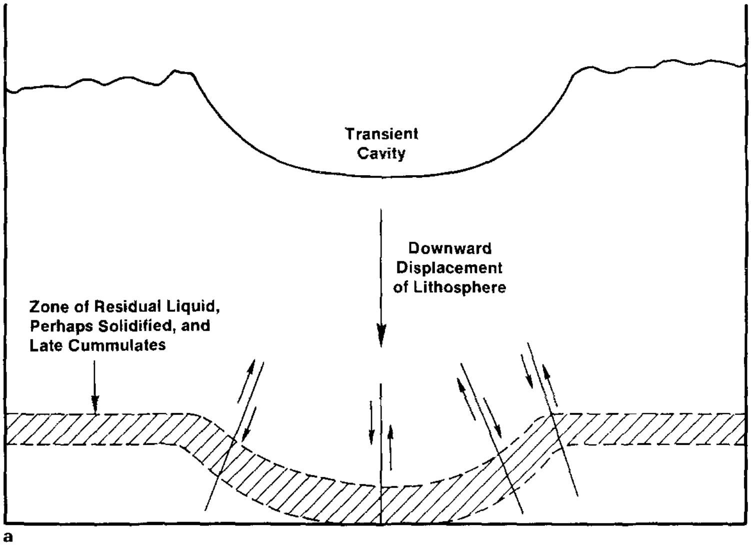
Energy required to heat the lunar crust and to melt residual liquids and late cumulates

	Radius (km)	Depth (km)	Base Temp. (°C)	Energy for heating to 1000 °C (× 10E25 cal)	Energy to melt 1.0% (× 10E25 cal)	Energy total (× 10E25 cal)	Percent of kinetic energy of Imbrian impact		
							$E = 2.4 \times$ 10E24 cal	$E = 2.4 \times$ 10E25 cal	$E = 2.4 \times$ 10E26 cal
Case 1.	250	70	100	1.14	0.018	1.16	483%	48.3%	4.83%
Case 2.	500	70	100	4.56	0.07	4.63	1930%	193%	19.3%
Case 3.	1000	70	100	18.2	0.29	18.5	7710%	771%	77.1%
Case 4.	500	70	550	2.28	0.072	2.35	980%	98%	9.8%
Case 5.	500	140	900	1.01	0.072	1.08	450%	45%	4.5%
Case 6.	1000	140	900	4.03	0.29	4.32	1800%	180%	18.0%

Any impact melting at depths of 70 to 140 km depth in the Moon must occur by mechanisms not generally considered in the extensive literature on impact and explosion craters because the impact melting generally considered is that which occurs in or adjacent to the transient cavity (Croft, 1977). Dence *et al.* (1977) discuss localized melting at depth below the transient cavity of a terrestrial impact crater. This melting occurred along fractures, which became zones of high friction during the downward displacement and subsequent rebound of the central area below the impact. In a Moon with a hot, perhaps partially molten zone (e.g., as in Solomon and Longhi, 1977) mechanical stresses occurring during rebound of the central zone may be preferentially dissipated in this hot zone because it would be a weak area. Such focused conversion of mechanical energy into heat would conveniently place the heat where it could have a significant effect on petrogenesis. The mechanism hypothesized to produce localized heating far below a transient cavity is illustrated in Figure 1a and 1b. Such impact melting at terrestrial impact craters is probably limited to occurrences such as those described in Dence *et al.* (1977) because the terrestrial crustal rocks were at temperatures well below their solidi. For the same reason, the latest of the large lunar impacts, such as Orientale, may have caused little or no melting at depth.

The depth to which large impacts excavated could have had a major effect on lunar petrogenesis if it approached the depth at which the residual liquids and late cumulates were located. Head *et al.* (1975) present data and arguments showing that the maximum depth of excavation for the Imbrium impact is less than about 30 km, rather than the much greater depths calculated by Moore *et al.* (1974), 130 km, or Dence *et al.* (1974), greater than 200 km. For excavation depths less than 30 km, the zone containing residual liquid and late cumulates would have remained unexcavated. The petrogenesis described in this paper would probably not have been feasible in a Moon where large, late impacts had excavated into and extensively disrupted the zones of residual liquids and late cumulates. Although a larger impact like Gargantuan would have excavated deeper than Imbrium, it did not penetrate below the crust; there is no evidence from orbital X-ray Mg/Al variations along the lunar surface that either the Gargantuan or Imbrium impact ejected mafic mantle material from beneath the crust (Andre and Adler, 1980). Depth/diameter ratios for the Gargantuan basin are estimated to be less than 1/37, which suggests lateral stripping rather than the hemispheric scooping of simple craters (Wilhelms, 1983).

It also seems feasible that these larger impacts contributed directly to the development of highly fractionated residual liquids and late cumulates by augmenting the heat budget of the zones containing these materials to the extent that they were given a second chance to produce extremely fractionated materials. The Gargantuan impact would have affected magma generation over a much larger area than later, smaller impacts. Should the later, smaller impacts have been insignificant contributors to the lunar heat budget and the Gargantuan impact an important augmenter, then the production of basaltic magmas in the lunar nearside would have been largely unrelated to the impacts that produced the basins which are now flooded by mare basalts.



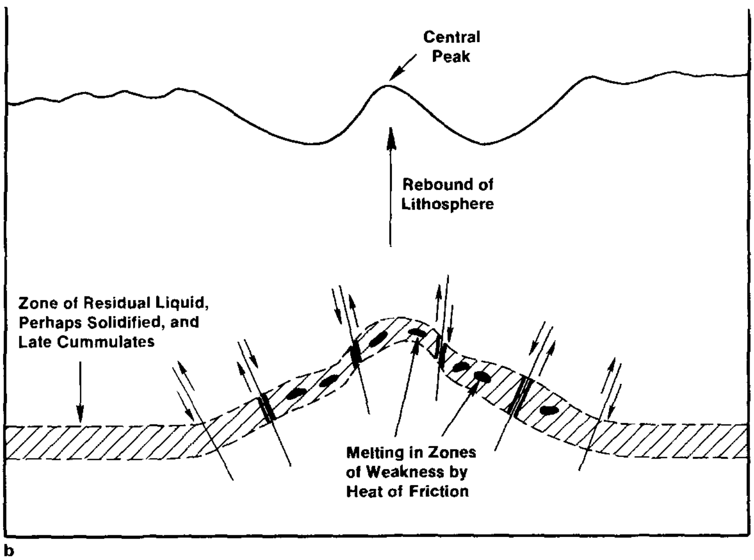


Fig. 1a, b. During a large impact the lithosphere below the impact will first be displaced downward and then, during the rebound, displaced upward. These figures illustrate how this displacement and the postulated accompanying localized conversion of mechanical energy to heat via friction in zones of weakness leads to localized melting. These zones of weakness are presumed to be caused by the presence of residual liquid, or, if the residual liquid is solidified, the presumed cause is low strength resulting from high temperatures.

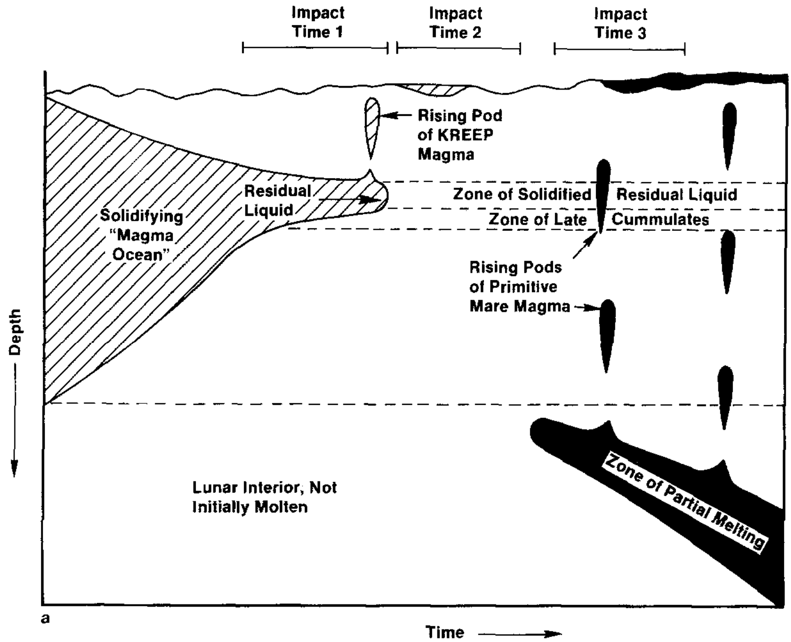
3. Effects of Impact Heating on Lunar Petrogenesis

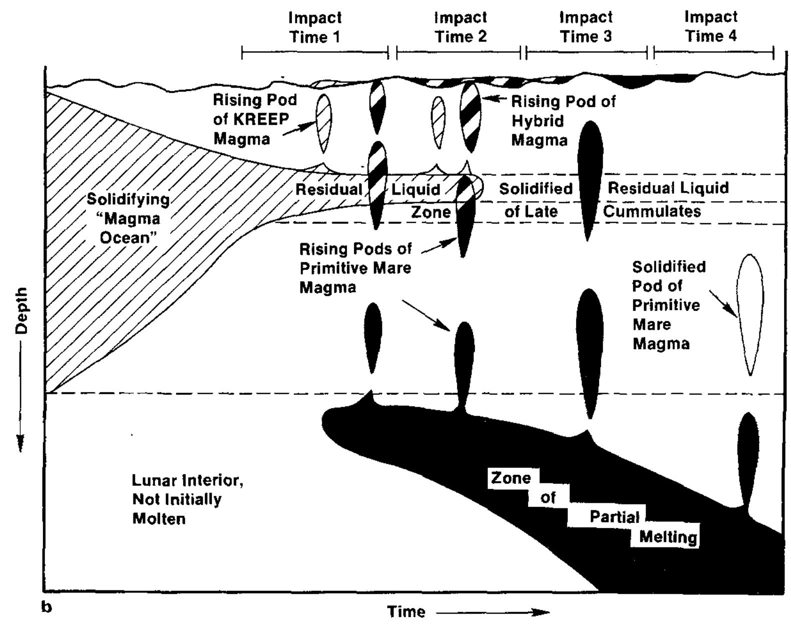
The observational record and thermal model calculations (Solomon and Longhi, 1977; Hubbard and Minear, 1976) show that the Moon may have possessed enough heat to support abundant magma genesis and volcanism without the additional heat from an impact such as Imbrium. In assessing the effect of deep impact heating on magma genesis we will assume that the major effect of such heating was the remelting of solidified residual liquids and/or late cumulates. We will compare the possible consequences of this melting against the overall thermal history of the Moon, as described by thermal model calculations (Solomon and Longhi, 1977; Hubbard and Minear, 1976).

Figures 2a and b are a synthesis of the thermal model calculations of Solomon and Longhi (1977), Hubbard and Minear, (1976) and Minear and Fletcher (1978), with petrogenetic concepts published by Shirley and Wasson (1981) and Hubbard and Minear (1975). The salient thermal features of both figures are: (1) the rapid crystallization of the 'magma ocean', (2) the development of a zone of residual liquid that remains molten long after solidification of the 'magma ocean', (3) the partial melting of primitive lunar material, and (4) descent of the zone of partial melting to greater depths. The difference between the two figures is that for Figure 2a the residual liquid solidifies before the zone of partial melting achieves significance, whereas in Figure 2b residual liquid is still present when the zone of partial melting can produce mare basalt magma. This difference may have been very important to lunar petrogenesis.

In both Figures 2a and b we show KREEP basalt magmas rising to, or near to, the lunar surface by the mechanism of Shirley and Wasson (1981). Also shown is the rise of primitive mare basalt magmas from the zone of partial melting of the primitive lunar material as postulated by Hubbard and Minear (1975). The pods of primitive mare basalts are assumed to rise according to the mechanism proposed by Muller and Muller (1980). Later in lunar history, when such pods must traverse too great a distance of lithosphere, where the temperature is too low, it is assumed that they lose too much heat, solidify and fail to reach the lunar surface. At this time eruption of lava stops.

For the case depicted in Figure 2b, primitive mare basalt magmas rise to the region where residual liquids remain, mix with these liquids and continue to the surface as hybrid magmas. The chemical compositions of the hybrid magmas depend on the mixing ratio of primitive mare basalt magma to residual liquid and on the degree of differentiation of the residual liquid. The residual liquid may merely contain increased concentrations of incompatible elements with minimal fractionation of diagnostic element ratios. That is, until the onset of clinopyroxene crystallization there will be little change in the rare-earth abundance ratios (Hubbard and Gast, 1971; Gromet *et al.*, 1981). Assimilation of such residual liquids will simply increase the concentrations of Fe, Ti, U, Th, K, REE, Zr, etc. in the hybrid magma relative to the primitive magma. Residual liquids that have crystallized clinopyroxenes but not ilmenite will have rare earth abundance patterns that are enriched in the light rare-earths; they will also be high in Ti and Fe. These hybrid magmas will then have rare-earth abundance patterns less steeply sloping than those of


Impact
Time 1
Impact
Time 2
Impact
Time 3
Rising Pod
of KREEP
Magma
Residual
Liquid
Solidifying
"Magma
Ocean"
Zone of Solidified
Residual Liquid
Zone of Late
Cummulates
Rising Pods
of Primitive
Mare Magma
Depth
Lunar Interior, Not
Initially Molten
Zone of Partial Melting
a
Time


Impact
Time 1
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Time 4
Rising Pod
of KREEP
Magma
Rising Pod of
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Magma
Solidifying
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Ocean"
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Liquid
Zone
Solidified
of Late
Residual Liquid
Cummulates
Rising Pods of
Primitive Mare
Magma
Solidified
Pod of
Primitive
Mare
Magma
Depth
Lunar Interior,
Not Initially
Molten
Zone
of
Partial
Melting
b
Time

KREEP, fractionated Sc/Ti ratios and no change in La/Ti or Zr/Ti ratios. Once ilmenite crystallizes the rare earth abundance patterns of all residual liquids are assumed to be nearly identical (Shirley and Wasson, 1981) and Ti and Fe concentrations are greatly reduced. These hybrid magmas will have the rare-earth abundance pattern, and perhaps concentrations, of KREEP rocks and will have fractionated Zr/Ti, La/Ti, and Sc/Ti ratios. These 'KREEP' basalts will differ from those addressed by Shirley and Wasson (1981) by having major element compositions similar to those of mare basalts, rather than major element compositions controlled by liquid-solid phase equilibria in the lunar crust. For the reasons given in Ringwood and Kesson (1976), the primitive mare basalt magmas will not assimilate the late cumulates and, because of this, mare basalts with high Ti and the rare-earth abundance patterns of clinopyroxene will not be produced in this Moon.

At the top of Figures 2a and b we denote different periods of time during which large impacts are assumed to occur. In both Figures 2a and b an impact occurring at Time 1 will simply add heat to a Moon that is already capable of sustaining volcanism. An impact at Time 2, Figure 2a, can reinstate residual liquid, having the effect of prolonging the time when KREEP volcanism is possible. An impact at Time 3, Figure 2a can reinstate residual liquid, which when mixed with ascending primitive mare basalt magma will result in hybrid mare basalts. For the Moon depicted in Figure 2b a large impact may not increase the diversity in magma types simply because the Moon can already produce abundant hybrid magmas. But, if the impact energy is adequate to melt late cumulates of clinopyroxene and/or ilmenite, then an important increase in diversity of magma compositions is possible because these liquids are now available for mixing with the primitive magma. An impact that melts late cumulates when pods of primitive mare basalt magma are rising can result in the production of hybrid, high-Ti mare basalts when the primitive magma mixes with remelted late cumulates.

Impacts occurring at Time 4 are assumed to have no effect on petrogenesis because the solidified residual liquids have cooled to temperatures where they cannot be extensively remelted by the impact energy and because primitive mare basalt liquids solidify before they reach the solidified residual liquids.

Because the energy of Imbrium sized impacts may be too little to have a significant effect on the genesis of lunar magmas, they are probably not the impacts to be associated with Figures 2a and b. Rather, the very large impacts (e.g., Gargantuan) should be considered. Such very large impacts seem appropriate to effect important changes in the genesis of lunar magmas. They are the most obvious means of converting a Moon, whose heat budget is consistent with Figure 2a, into one whose heat budget leads to the diverse magma compositions indicated in Figure 2b. The smaller the heat remaining from lunar

Fig. 2a, b. These figures illustrate the interplay between the solidifying magma ocean, the zone of residual liquids, partial melting of the deeper lunar interior and large impacts. Figure a illustrates a cooler Moon where the residual liquid solidifies before partial melting of the deeper lunar interior results in migration of magmas to the surface. Figure b illustrates a Moon where residual liquid remains well into the time when magmas are rising from depth. The mixing of primitive magma and residual liquid to produce hybrid magmas is discussed in the text, as are the effects of large impacts at different times.

formation and decay of K, U, and Th, the more important are very large impacts in the genesis of lunar magmas. It would have required very large impacts to generate the heat at depth to melt late cumulates, leading to the production of A-11 and A-17 mare basalts.

In summary, large late impacts have little effect on the course of differentiation or variety of lunar magma compositions unless they generate enough heat to melt late cumulates, that may later mix with ascending primitive mare basalt liquids to produce additional varieties of hybrid magmas. Otherwise, such impacts merely increase the time available for magma genesis and volcanism by augmenting the heat budget of the Moon.

3.1. THE TIMING OF THE IMPACTS

Several factors work to maintain material in a molten state at depth long after an impact occurred. Once the residual liquid has become sufficiently concentrated in K, U, and Th, it will remain molten or at temperatures near the solidus for long periods of time (Solomon and Longhi, 1977; Shirley and Wasson, 1981). Because the late cumulates are located close to the zone of residual liquid, they will remain at similarly high temperatures. Any heat emplaced at the depths where solidified residual liquids and late cumulates are, will melt these materials first because they have lower solidi than other crustal materials. Impact brecciation will reduce the thermal conductivity of near surface material, resulting in slower loss of impact and radiogenic heat from depth (Arkani-Hamed, 1974). The magmas produced by impact-assisted volcanism may simply be KREEP, for impact Time 2 in Figure 2a. For impacts occurring during partial melting at depth, the possible resulting hybrid magmas will appear on the lunar surface at times and locations that are determined more by partial melting at depth than by a specific large, basin-forming event. The essential role of the impact is to set the stage for production of hybrid magmas by melting solidified residual liquids and/or late cumulates, thus making magma mixing possible at times when it is otherwise impossible.

A very large impact occurring at Time 3 in Figure 2a could convert this 'cool' Moon to a 'warmer' Moon locally (as in 2b), resulting in more abundant and prolonged volcanism in and around the area of the large impact. This may have been the major effect of the Gargantuan impact on the genesis of lunar magmas.

The timing of a very large impact relative to the differentiation of residual liquids and production of late cumulates may have been an important factor in determining the chemical composition of mare basalt magmas. Specifically, the production of A-11 and A-17 mare basalts requires very efficient separation of residual liqud from late cumulates of clinopyroxene and ilmenite (Hubbard and Minear, 1975; Ringwood and Kesson, 1976). The existence of the A-11 and A-17 mare basalts requires that igneous differentiation of the 'magma ocean' had been very extensive before the clinopyroxene and ilmenite cumulates were melted by a very large impact. This differentiation may have proceeded using the heat from lunar formation alone, or augmented by previous very large impacts.

4. Remote Sensing Evidence of the Role of Impacts in Magma Genesis

Photogeologic and orbital geochemical data are used to describe the chemical diversity in lunar lavas and the temporal and spatial distributions of these lavas. This requires discussion of: (1) the evidence for ancient lunar basins, (2) the chemical compositions of early volcanic units that provide a fragmentary record of early magma evolution and, (3) comparison of the Gargantuan impact area with other volcanic areas. Throughout this section, the distribution of volcanism and the chemical composition of the lavas is related to the thermal models shown in Figures 2a and b and to various large impacts.

Ancient basins are obscure features on the Moon because their topographic outlines are subdued, textural features are degraded, and the volcanic fill does not have the appearance of mare basalt units. However, four basins have been described that ante date those reported by Stewart-Alexander and Howard (1970): Al-Khwarizmi-King (El-Baz, 1973); Gargantuan (Cadogan, 1974); Aitken (Wood and Gifford, 1980); and Balmer (Maxwell and Andre, 1981). The largest of these basins, Gargantuan, has 3 rings of 850, 1200, and 1600 km radius and equates most closely to the volumes of Cases 3 and 6 in Table II. The total kinetic energy of the Gargantuan impact would have been far greater than that of the Imbrium impact and the base temperature of the lithosphere when these earlier basins formed would probably have been higher than that of Case 3, creating more favorable conditions for the melting of residual liquids and late cumulates, and increasing the chances for chemical diversity in the magmas produced.

4.1. THE GARGANTUAN BASIN

The Gargantuan basin rim entirely encompasses the Imbrium basin, once thought to be the largest basin on the Moon. In fact, the outer ring of Gargantuan mapped by Whitaker (1981) includes Oceanus Procellarum, Maria Imbrium and Serenitatis, and most of Maria Humorum, Nubium and Tranquillitatis – i.e., approximately one quarter of the lunar surface. Its size and location help to account for the lower elevations and thinner crust of the central and western near side and the higher levels of natural radioactivity in the Imbrium and the Procellarum area (Cadogan, 1974). Eruption of KREEP basalts is interpreted by Cadogan (1975) to be a result of the Gargantuan impact rather than the Imbrium impact. In support of this, he cites results indicating that KREEP is located outside the Imbrium Basin but within the Gargantuan impact area. He proposed that the low density of KREEP basalts and an insufficiently rigid crust (partly caused by higher lithospheric temperatures) to support them prevented the development of a mascon. This less rigid crust would help explain why there is unusually low relief for the rings defining the Gargantuan and other ancient basins: this low relief is not likely to be due to degradation by impacts (Schultz, 1979). It is more likely the result of a thinner lithosphere at the time of formation (Whitaker, 1981), which allowed isostatic adjustment. Thus, the largest basin-sized impacts early in lunar history have a greater potential than later impacts to alter the abundance, the timing of eruptions, and the chemical compositions of lunar magmas because of their size and because the Moon was hotter.

4.2. CHEMICAL DIVERSITY OF VOLCANIC UNITS AND IMPLICATIONS ABOUT LUNAR THERMAL HISTORY

Orbital X-ray (see Appendix I) and gamma-ray data (see Appendix II) from a number of investigators have been used to compare the thermal history of the eastern nearside maria to the central and western maria where the hypothesized Gargantuan impact would have had maximum influence. The comparison will be better understood in light of the following regional chemical trends inferred from orbital geochemical data:

(1) The nearside terra surface of the Moon (90W to 90E) has Al, Fe, Mg, Ti, and Th concentrations skewed toward less anorthositic compositions than the far side (see comparative histograms for the near and far sides in Andre and Strain, 1983).

(2) Subsurface material excavated from the Smythii basin, the Nectaris basin, and other large craters on the near side suggests that the surrounding more mafic, less aluminous terra is surficial and that highly anorthositic material like that typical of the far side exists at depth (Andre 1981; Andre and Strain, 1983).

(3) If the apparent resurfacing of the nearside terra is primarily due to ejecta from a basin-sized impact, it must have been considerably larger than Nectaris and Smythii (Andre, 1981) to eject more mafic material from a lower stratum of the crust.

(4) Superposed on the nearside and farside surfaces just described are both maria and local anomalies of highly mafic material. The latter are interpreted as very early volcanic units on the basis of albedo, morphology, surface texture, relative elevation, dark haloed craters, and Al, Mg, Fe, Th, and Ti concentrations from orbital data (see discussion of Figure 3).

The location, chemical composition, and ages of these early volcanic units, compared to later ones that fill most of the nearside basins, are valuable clues to the chronology of magma production and distribution.

To best illustrate the range of chemical compositions on the Moon from the orbital perspective, the following points have been plotted on an Al_2O_3 versus MgO diagram (Figure 3): selected sample and orbital points from the anorthositic and mare basalt units, early volcanic units (points 1–5: see Caption and Appendix III for descriptions), and an early buried Mg-rich mare basalt exposed at the crater Picard (Andre *et al.*, 1979). Other useful reference points have been included, such as typical nearside terra and farside terra points and a calculated value for urKREEP (Warren and Wasson, 1979).

The field labelled Common Apollo Mare Basalts (see Hubbard, 1979) shows the decrease in Al_2O_3 with increasing MgO expected for crystallization and settling of ferromagnesian minerals. The orbital data for most maria suggest a rather different trend; that is, a simultaneous increase of Al_2O_3 and MgO. This trend is nearly orthogonal to mixing with anorthositic terra material, supporting the contention of Hubbard (1979) that the higher Al_2O_3 values of average maria, relative to common Apollo mare basalts, indicate that aluminous mare basalts are the predominant component of the eastern maria.

Orbital gamma-ray Fe data of Davis (1980) versus the Th data of Metzger *et al.* (1977) are plotted in Figure 4. The data cluster into 3 groups according to Th concentrations: (1) Th concentrations less than about 1.0 ppm, labelled Typical Anorthositic Terra; (2) Th concentrations from about 1.5 ppm to about 3 ppm, labelled Typical Baslatic Areas, which exclude western nearside maria; and (3) Th concentrations greater than

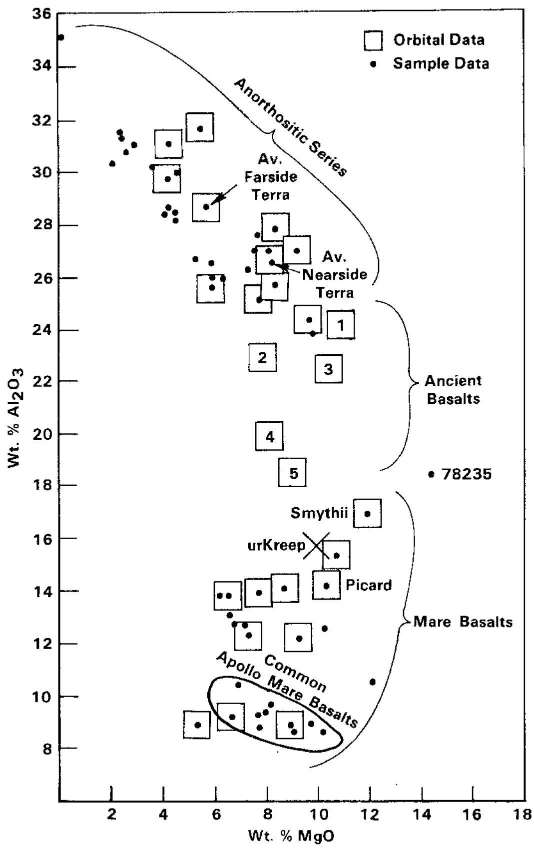

Fig. 3. This figure shows Al_2O_3 and MgO data from lunar samples and orbital measurements. Data from lunar samples are shown by dots and data from orbital measurements are shown by squares. The X represents a calculated composition (Warren and Wasson, 1979). Data points for the ancient basaltic units are numbered. They are: (1) the southern unit of the Smythii Basin; (2) Light-colored plains of Nectarian age within the Al-Khwarizmi-King Basin in the eastern farside; (3) Light-colored plains of Imbrium/Nectarian age within the Balmer Basin on the eastern limb of the lunar nearside; (4) Low albedo unit north of Necturis; and (5) between maria Fecunditatis and Serenitatis. These areas are described in Appendix III. The data for Picard are from Andre *et al.* (1979).

about 4.5 ppm, labelled Imbrium/Gargantuan Area, that include Maria Imbrium, Cognitum and areas around Aristarchus, Archimedes, Fra Mauro and Lalande.

The Al_2O_3 versus MgO data for ancient basalt areas and major maria can be combined with Th data to evaluate the various thermal histories illustrated in Figures 2a and b. To do so, one must consider that two processes may skew the values measured for isolated early volcanic units from the true Th, MgO and Al_2O_3 values of the magmas: (1) horizontal and vertical mixing of the basalt layers with the surrounding and underlying terra and (2) incomplete spatial resolution of the volcanic units from surrounding terra units by the orbital X-ray and gamma-ray detectors. The ancient basalt units in Figure 3 that plot along a mixing line between anorthositic terra and maria illustrate this point. Thus,

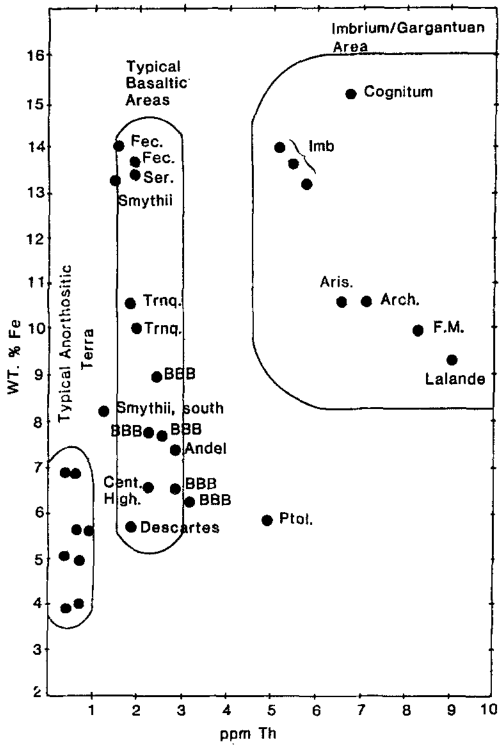

Fig. 4. This figure shows Fe and Th data obtained by the orbital gamma ray experiment. Fe values are from Davis (1980) and have been normalized to correct for inter-mission differences (see Appendix II). The Th data from from Metzger *et al.* (1977).

we may assume that one or both of the processes mentioned above have skewed the basalt values toward the anorthositic series. Consequently, thorium concentrations are also skewed toward anorthositic terra values, which are typically less than 1 ppm. Note that among the maria plotted in Figure 4, only those on the western nearside have thorium concentrations in excess of 5 ppm. Mare Crisium lavas are known to contain less than 0.5 ppm Th from Luna 24 sample data (Blanchard *et al.*, 1978). From these data and data for the other eastern maria, we infer that the lithosphere under these areas contained little or no thorium-rich residual liquid for mare basalt magmas to assimilate by mixing; that is, such residual liquid had largely or totally solidified before partial melting at depth produced significant amounts of primitive mare basalt magma in this eastern region of the nearside. Even before mare basalts flooded these basins, there is no indication that residual liquids rich in thorium were available because the basalts that filled the sourthern part of the Smythii basin (Point #1) in the Imbrium to Nectarian period have only about 1.2 ppm Th (Haines *et al.*, 1978). Even allowing for 60% anorthositic terra component versus 40% basaltic material, the concentration of Th in the Smythii lavas could not be greater than 2.0 ppm.

There is evidence, however, that in mid to early Nectarian times (preceding the volcanism in the sourthern part of the Smythii basin), Th-rich residual liquids were involved in magma genesis in several places on the eastern nearside. Two light-colored plains units emplaced within that time frame have unusually high thorium values, relative to the surrounding terra, and lie within the ring systems of the following ancient basins: (1) Balmer – Point #3 on Figure 3: Th = 4.0 ppm; (2) the partially outlined basin around Mare Marginis (Wilhelms and El-Baz, 1977) on Figure 3: Th = 3.4 ppm. In addition, MgO and Al_2O_3 values for plains material in the ancient Balmer basin indicate a mixture of 1/3 mare basalt and 2/3 anorthositic terra material; thus the deconvoluted Th of 4.0 ppm (Haines *et al.*, 1978) is increased to 11.0 ppm in the basalt. Given the uncertainties in the deconvolution analysis and the mixing calculation, the 11 ppm Th value is not significantly different from the Th concentrations of KREEP basalts (Warren and Wasson, 1979). From this we conclude that the basalts in the Balmer basin are either KREEP basalts or assimilated large amounts of Th rich residual liquids. For each of these areas, we infer that abundant residual liquid remained molten until this time or was remelted by the impacts. The volume of these earlier lavas appears to be much less than that of the later lavas. From the thermal models in Figures 2a and b we suggest that these lesser volumes of lava indicate that the Moon was not yet producing abundant magma by partially melting the deep lunar interior. Perhaps some of these basaltic compositions are the product of an earlier style of magma genesis, that resulted when the formation of smaller, ancient impact basins promoted extrusion of diverse residual liquids by impacting into a thin lithosphere. Perhaps Figure 2a describes the thermal regime in this part of the Moon.

The Apollo 11 and 17 mare basalts (except the A-11 high K) suggest that Th rich residual liquids had extensively disappeared from below this region by about 3.7 b.y. ago. The Apollo-11 high K mare basalts show that this separation of ilmenite and clinopyroxene rich cumulates from residual liquids was not always complete or that the ascending primitive mare basalt magma mixed with both remelted late cumulates and residual liquid.

From the above observations we suggest that Th rich residual liquid was abundantly available for magma genesis in Nectarian times but that it had become scarce under the eastern maria by late Nectarian/Imbrium time. In contrast, under the Gargantuan/ Imbrium impact zone Th rich residual liquid apparently remained molten for about another billion years (Soderblom *et al.*, 1977).

4.3. Effects of a Timely Large Impact

The data labeled Imbrium/Gargantuan Area in Figure 4 have long attracted attempts to explain their presence (Metzger *et al.*, 1973; Schonfield and Meyer, 1973; Soderblom *et al.*, 1977, Hubbard, 1979; Hawke and Head, 1978; and various others). Hubbard and Woloszyn (1977) noted that the Th rich areas are also Fe rich areas and that both Th rich and Fe rich (predominantly mare) areas are heavily restricted to the regions of low surface elevation; this finding applies to both the data classified in Figure 4 as Typical Basaltic and Imbrium/Gargantuan Area. It has been shown from analysis of the heat flow data (Langseth *et al.*, 1976) that the high concentrations of K, U, and Th are surficial, i.e., less than a few kilometers thick. Soderblom *et al.* (1977) noted that the general area of high Th is also the area where the youngest mare basalts are most common and postulated that mare volcanism was prolonged here because higher concentrations of K, U, and Th at depth had prolonged volcanism. Shirley and Wasson (1981) imply that K, U, and Th rich residual liquids were concentrated below this area and later emplaced on the surface as KREEP. Considering these results in the context of magma genesis described here, we expect in and around the Imbrium/Gargantuan area a wide range of mare basaltic compositions from primitive mare basalt to hybrid mare basalts that contain large amounts of residual liquid rich in K, U, and Th. Mare basalts rich in Ti and with trace element abundance patterns similar to those of A-11 high K mare basalts are also to be expected.

There are three possible reasons why basalts rich in K, U, and Th are abundant in and around Imbrium. They are: (1) this region always possessed a high concentration of K, U, and Th because of a compositional heterogeneity dating from lunar accretion, (2) during differentiation of the 'magma ocean', K, U, and Th were concentrated in the source regions for volcanism in this area, and (3) the Imbrium or Gargantuan impacts altered lunar petrogenesis so as to produce lavas having high concentrations of K, U, and Th. The first two explanations for this cannot be seriously addressed with present data. From the considerations earlier in the paper, it seems unlikely that the Imbrium impact provided enough additional heat to so significantly alter the course of petrogenesis but, the Gargantuan impact probably did. How the Gargantuan impact could have influenced this region is examined below.

Shirley and Wasson (1981, their Figure 4) present a mechanism that may have resulted in a concentration of residual liquid in the Imbrium area. This mechanism is adapted to the present problem in Figures 5a and b. In Figure 5a we sketch the difference in crustal thickness between near and far sides of the Moon, which results in the CF–CM offset (Kaula *et al.*, 1974), and a zone of residual liquid, and the mechanism of Shirley and Wasson (1981), showing how the zone of residual liquid could be concentrated under the thinner crust of the lunar near side. For this mechanism to be feasible, the CF–CM offset must have occurred before the residual liquid solidified or, solidified residual liquid may have been remelted by the large impacts that may have caused the CF–CM offset. The amount of residual liquid under the Imbrium basin may have been additionally increased by the further reduction in lithostatic pressure that resulted following excavation of the Imbrium basin. In order to allow effective lateral transport over the required distances, the movement probably occurred before the residual liquid was reduced to an especially small (less than about ten percent) fraction of the zone in which it was concentrated. Such a volume of residual liquid would be a percent or so of the initial volume of the 'magma ocean' under this area and would transport a large fraction (1/2 or more?) of the K, U, and Th of the local 'magma ocean'. This residual liquid would not yet be evolved enough to crystallize clinopyroxene and/or ilmenite (Hess *et al.*, 1978; Shirley and Wasson, 1981). The orbital gamma-ray data for maria (Hubbard, 1979; Soderblom *et al.*, 1977) require that this process leave very little K, U, Th rich residual liquid near the late cumulates below the areas now occupied by the eastern maria. Furthermore, the

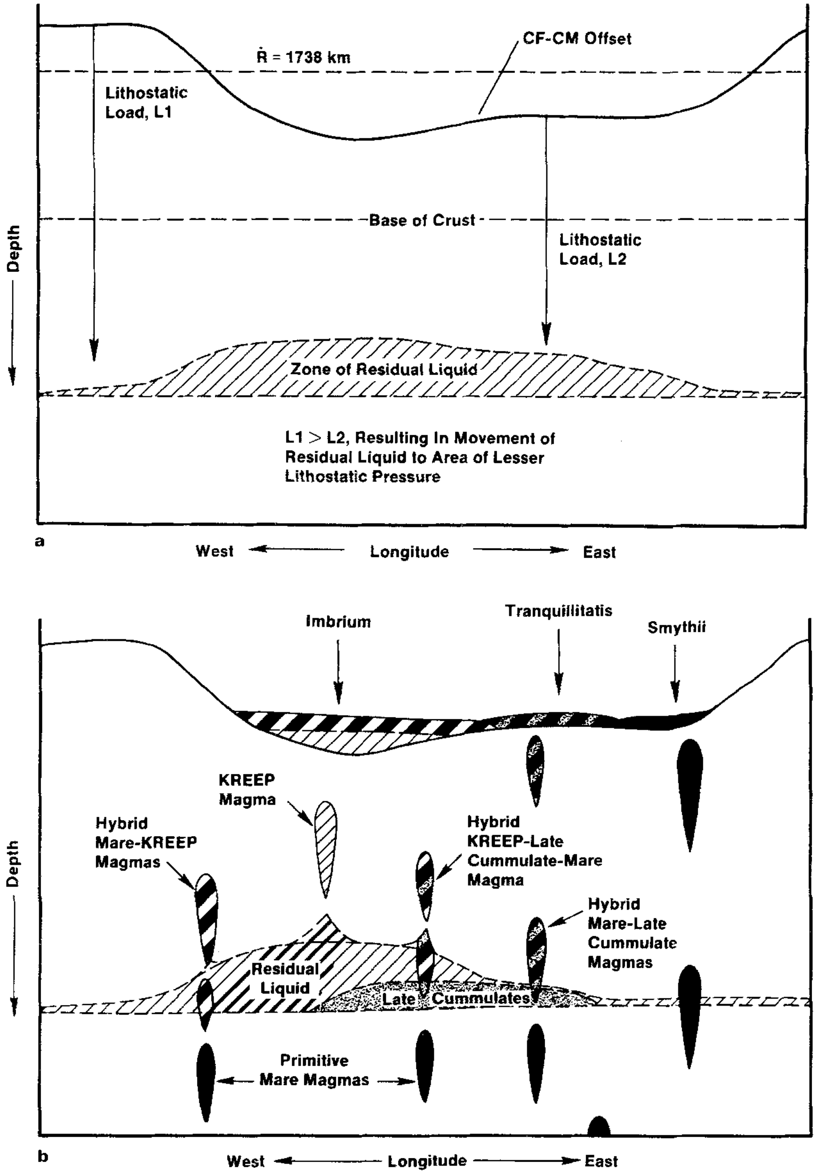

Fig. 5a, b. In Figure a we elaborate on a mechanism proposed by Shirley and Wasson (1981) to produce lateral migration of magma. In this case we presume that a very large impact, e.g., Gargantuan (Cadogan, 1974) caused the CF–CM offset and the resulting difference in lithostatic load. This difference in lithostatic load then results in migration of residual liquid to areas of low lithostatic load. We presume that the Imbrium impact additionally decreases the lithostatic load locally, resulting in further concentration of residual liquid under the Imbrium Basin. In Figure 5b we further elaborate this situation to illustrate how continuing crystallization of the residual liquid during its lateral migration could result in lateral separation of late cumulates and their parental liquids. In b we also illustrate the interplay of primitive magmas rising from depth with residual liquid and late cumulates. The late cumulates must be melted by a large impact before mixing, as discussed in the text.

A-11 and A-17 mare basalts require efficient separation of this residual liquid from the late cumulates (Hubbard and Minear, 1975; Ringwood and Kesson, 1976).

Because the high Ti mare basalts of Tranquillitatis (Apollo 11) and the Apollo 17 region must be accounted for, we propose that, by the time the residual liquid had moved westward, under these areas, it had evolved to the point where extensive ilmenite crystallization occurred. At this time the K, U, Th rich residual liquid could have migrated further west or migrated upward as suggested by Shirley and Wasson (1981). Western Tranquillitatis perhaps overlies a transition zone where the K, U, Th rich residual liquid was poorly separated from the ilmenite cumulates, and later became part of the Apollo-11 high-K mare basalts.

In the area of the Gargantuan Basin and the future site of the Imbrium impact, we propose that the low density residual liquid began to migrate upward according to the mechanism of Shirley and Wasson (1981) to produce 'KREEP' volcanism. We propose that primitive mare basalt magmas were migrating upward under this area and mixed with the residual liquid to produce lavas of various hybrid chemical compositions. The higher contents of K, U, and Th under the Imbrium area resulted in prolonged volcanism in this area because they reduced the loss of heat from depth, which in turn leads to more extensive and/or prolonged partial melting at depth.

If the thermal regime of the Moon was similar to that sketched in Figure 2a, as suggested earlier, then the role of the Gargantuan impact is most succinctly described as having locally converted the thermal regime to one similar to that of Figure 2b. Alternatively stated, the Gargantuan impact equipped the Moon, already capable of very limited volcanism, to produce much more extensive and chemically varied volcanism in the area most directly affected by the impact.

5. Conclusions

The concepts, observations and hypotheses discussed above are summarized in the conclusions given below.

(1) Large late impacts, at least as large as Imbrium, may have added enough heat to the lunar heat budget to assist magma genesis and volcanism. It is more probable that even larger, earlier impacts (e.g., Gargantuan) were the ones that had important effects on the generation of lunar magmas. The heat added by impacts could have significantly increased the range of chemical compositions of mare basalts only if the heat added was enough to cause melting of late cumulates. The high Ti mare basalts sampled by Apollos 11 and 17 are the best indication that adequate heat was added.

(2) Mare basalts have hybrid chemical compositions produced by mixing of two magmas: (1) a primitive mare magma produced by partially melting the deep lunar interior and (2) a variety of highly evolved residual liquids and remelted cumulates.

(3) Lavas having chemical compositions intermediate between those of primitive mare basalts and KREEP basalts are considered a common feature of lunar volcanism in the Imbrium area and were produced by mixing of primitive mare basalt magmas with K, U,

Th rich residual liquids. The high Ti mare basalts of Apollos 11 and 17 indicate that late cumulates were remelted and the resulting magma mixed with primitive mare basalt magma. The mare basalts in Smythii are perhaps the best examples of the primitive mare basalt magma.

(4) The CF–CM offset provided lithostatic pressure differentials resulting in Th rich residual liquids being concentrated under Imbrium and environs. The consequence of this is that the lavas of this area have high Th concentrations and volcanic activity was prolonged.

(5) Large, late impacts that occur after the lunar thermal engine has ceased to produce abundant magma are not themselves able to produce significant volcanism, e.g., the Orientale impact.

(6) In comparison to the abundant, more recent volcanism associated with the Gargantuan/Imbrium area, ancient basins in the eastern nearside limb area (e.g., the Balmer Basin) contain much lesser amounts of basaltic material and that material typically has Th concentrations indicating the presence of Th rich residual liquid at depth when that volcanism occurred. The sparse abundance of basaltic material perhaps indicates that the thermal engine of the Moon was not yet capable of producing abundant magma by partially melting the deep lunar interior.

(7) Comparison of volcanism in the Gargantuan/Imbrium area with volcanism in ancient basins in the eastern nearside area suggests that the interplay between the Moon's internal heat engine and the timing of large impacts was a crucial factor in determining the type of lunar volcanism and the chemical composition of the lavas.

(8) The high concentrations of lavas and the younger volcanism of the western maria are suggested to be consequences of the proposed Gargantuan impact.

Appendix I: Orbital X-Ray Data

In order to confidently use the orbital X-ray data to extend information about concentrations of Mg and Al in surface soils to areas that were not sampled, it is important to understand how accurate the orbital chemical data are. We have compared the results of different data reduction and calibration procedures used by a number of investigators (Adler, Hubbard, Bielefeld, and Andre). All agree that 2 sigma precisions for calculated Al_2O_3 values are about ± 1.0 weight percent and those for MgO are ± 1.5 weight percent. Figure A-1 shows how closely the final calculated values compare for areas containing more than 10 data points. This figure compares concentrations calculated by Hubbard (1979) with those calculated by Adler *et al.* (1972). Andre and Bielefeld (Bielefeld *et al.*, 1977) recalculated the conversion from intensity ratio to concentration ratio used by Adler *et al.* (1972) and found only slightly different conversion factors. The data reduction used by Hubbard (1979) is totally independent of previous work.

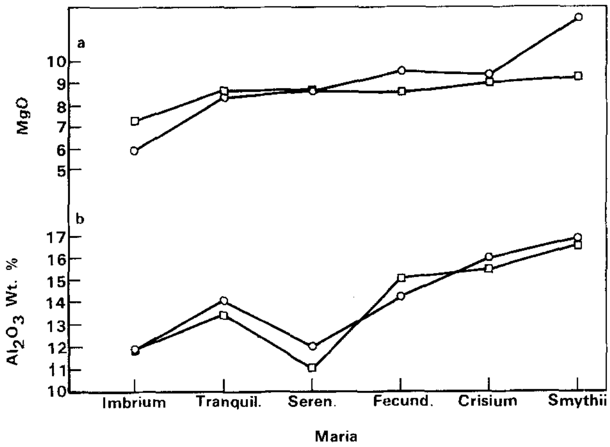

Fig. A-1. Data from Adler *et al.* (1972) are shown by squares for various maria and compared to data from Apollo-15 independently reduced by Hubbard (1979).

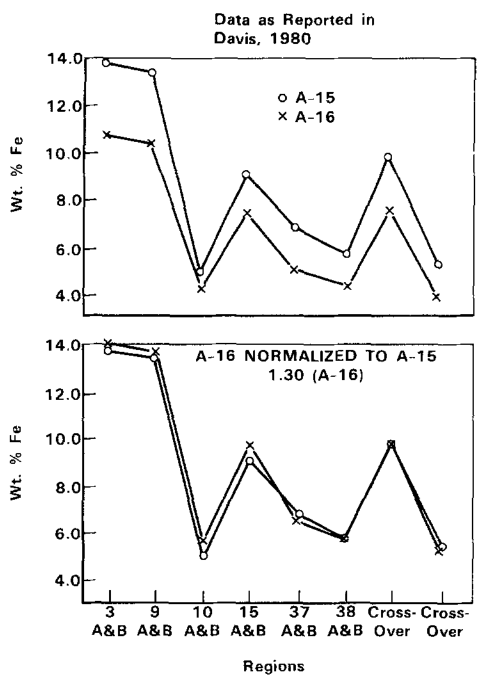

Fig. A-2. Fe values from Davis (1980) for the Apollo-15 mission (circles) and the Apollo-16 mission (crosses) are shown in the upper part of this graph. Note the systematic difference between data from the two missions. We normalized the Apollo-16 data to the Apollo-15 data and compare the result in the lower part of this graph.

Appendix II: Orbital Gamma Ray Data

The orbital gamma-ray data of Davis (1980) were used for the Fe values shown in Figure 4. The regions are those defined by Metzger *et al.* (1977). We used only regions for which the data have 1 sigma error of ± 1.5 weight percent Fe or less. We have normalized the Apollo-16 Fe values to those from Apollo-15. The justification for this step is shown in Figure A-2, where the offset between mission values for common areas is shown. Figure A-2 also demonstrates the results of increasing the Fe values for Apollo-16 by a factor of 1.3. We elect to normalize the Apollo-16 data to Apollo-15 data because all but one of the ground truth calibration points used by Davis (1980) are for Apollo-15 data. The result is that the Apollo-16 Fe values used in this paper are about 1.3 weight percent higher than those used previously where Apollo-15 data were normalized to those for Apollo-16, i.e., just the reverse.

Appendix III: Descriptions of Early Basaltic Units

In Figure 3 several data from orbital X-ray measurements are accompanied by numbers. The areas to which these data pertain are described here.

Point #1: The southern part of the Smythii basin does not have the albedo or morphologic characterisitcs of mare basalt, yet it is believed to be an early volcanic unit because of higher thorium and titanium concentrations (Haines *et al.*, 1978; Davis, 1980), and higher magnesium and lower aluminum concentrations (Figure 3) than the terra to the east or west.

Point #2: Unusually high Mg/Al ratios for a terra surface on the far side (compare to typical farside terra point) and higher Ti and Fe concentrations (Davis, 1980). Dark haloed craters suggest the presence of old mare-like volcanic deposits beneath a veneer of highland debris (Schultz and Spudis, 1979), located in Al-Khwarizmi-King.

Point #3: Light plains material fills a portion of the ancient Balmer Basin (Maxwell and Andre, 1981) on the eastern limb. The plains units, relative to the surrounding terra, have higher Fe, Th, Mg, and lower concentrations of Al as well as a gravity anomaly, greater than + 40 milligals, that indicates emplacement of a dense material in this terra region (Haines *et al.*, 1978).

Point #4: The area surrounding a system of graben North of Mare Nectaris has (1) Mg/Al concentrations that exceed the nearside terra mode, (2) a mantled appearance and patches of smooth dark material, (3) low elevations, and (4) unusually low albedos. Furthermore, the presence of graben indicates tectonic activity whereby magmas could have migrated to the surface (Andre and Strain, 1983).

Point #5: The pre-Imbrian units surrounding the crater Taruntius between Maria Fecunditatis and Tranquillitatis have unusually high Mg/Al concentrations compared to the subsurface material exposed at Taruntius crater. Albedoes and topographic features suggest volcanic deposits (Andre and Strain, 1983).

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