On lunar asymmetries
2. Origin and distribution of mare basalts and mascons

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[1] A novel mechanism is proposed for the emplacement of mare basalts and the formation of mascons that does not involve melting or remelting of the source region. The source magmas are the remnants of the primordial lunar magma ocean and are rich in incompatible elements, including radioactive isotopes; potassium, rare earth elements, and phosphorus (KREEP); and volatiles. Exsolution of volatiles as the magmas cooled and crystallized (a process called second boiling) produced overpressures which drove the dense basalts upward to the surface, creating the mascons. This process occurred preferentially beneath nearside mare basins, where the crust is thinnest and lithostatic pressure is lowest. The delay between impact and magmatic extrusion reflects the time needed for the volatile-rich magma to cool to its second boiling point. Radioactive heating buffered the magmas against cooling and solidification, allowing for an extended period of magmatism. *INDEX TERMS:* 5455 Planetology: Solid Surface Planets: Origin and evolution; 6250 Planetology: Solar System Objects: Moon (1221); 8414 Volcanology: Eruption mechanisms; 8439 Volcanology: Physics and chemistry of magma bodies; *KEYWORDS:* Mascons, mare basalts, overpressure, second boiling

1. Introduction

[2] The Moon has a number of interesting asymmetries of uncertain origin. In a companion paper [*Loper and Werner*, 2002] we describe a novel mechanism, called tilted convection, possibly responsible for the creation of the observed thicker crust on the farside and the geochemical signature of the nearside crust [*Jolliff et al.*, 2000; *Wieczorek and Phillips*, 2000]. In this paper we focus attention on the unusual mass concentrations (mascons) in mare basins associated with impact craters on the nearside [*Muller and Sjogren*, 1986; *Arkani-Hamed*, 1998], addressing two related questions: why are mare basalts confined to the nearside, and how were they emplaced at the surface? The answer to the first question is intimately related to the process of tilted convection, while the answer to the second is based on the phenomenon of second boiling [*Bowen*, 1928].

[3] Until the early 1970s it was thought that mare lavas might be created during impact events [*Gornitz*, 1973]. There are two lines of reasoning against this hypothesis and in favor of a source region beneath the crust. First, impact heating would have mobilized crustal material and produced nonbasaltic volcanic deposits; the strong mantle signature [*Snyder et al.*, 1992] of mare basalts argues against impact providing either the material or the necessary heat. Second, the thermal anomaly associated with the impact event would have decayed within 500 Myr [*Arkani-Hamed*, 1973], which is too short a time to have permitted the delayed eruption of large amounts of very fluid basalt onto the lunar surface.

[4] Virtually every paper since 1973 dealing with the origin of mascons [e.g., *Solomon*, 1975; *Ringwood and Kesson*, 1976; *Jerde et al.*, 1994; *Hess and Parmentier*, 1995; *Elkins et al.*, 2000; *Hess*, 2000; *Zhong et al.*, 2000] assumes a source region that undergoes melting or remelting, typically deep within the mantle. In spite of its repetition in the literature, this is only an assumption. It has been justified on petrologic and geochemical grounds [e.g., *Schnetzler and Philpotts*, 1971; *Snyder et al.*, 1992], but such studies have not critically examined the alternative: that the source region never solidified in the first place. Remelting, subsequent to solidification, is an implausible process in lunar thermal history. It is generally agreed that the Moon was hot immediately following its formation and, on the whole, has been cooling ever since. The question is whether selective regions could have solidified and subsequently remelted. The only possible source of heat for remelting (other than impact energy, which is being ignored here) is the decay of radioactive isotopes which became concentrated during solidification and fractional crystallization of the primordial lunar magma ocean (LMO). Fractional crystallization concentrates radioactive isotopes and other incompatibles (including potassium, rare earth elements, and phosphorus (KREEP)) in the residual melt. Given that the strength of radioactive heating decreases with time (due to the finite half-life of the isotopes), it is difficult to produce a plausible scenario in which the residual melt would solidify at an early stage, when heating was strong, then remelt later, when heating was weaker. *Ringwood and Kesson* [1976, p. 1699] noted some time ago

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that "...no satisfactory explanation has yet been offered for the energy source responsible for remelting..." *Manga and Arkani-Hamed* [1991] present a conductive cooling model in which radioactive heating causes remelting at shallow depths, but this process is an artifact of their initial thermal profile, having the region which remelts being initially too cold.

[5] Given the temporal decrease in rate of radioactive heating, remelting can occur only if there is a significant reduction in the rate of heat loss. One possibility [*Arkani-Hamed*, 1973; *Manga and Arkani-Hamed*, 1991] is that the material ejected by an impact serves to insulate the region surrounding the basin, reducing heat loss. However, by the same token, excavation of crust would have increased heat loss within the basin itself, making it more difficult to maintain an active magma chamber beneath. Another possibility is to have the source material solidify by conductive cooling close to the surface, then be buried deep in the lunar mantle, where loss of radiogenic heat loss would be negligible [*Hess and Parmentier*, 1995; *Zhong et al.*, 2000; see also *Ringwood and Kesson*, 1976]. This requires the residual solid to be denser than the underlying mantle and to sink well into the mantle. Subsequently, radioactive heating would cause this material to buoy up and melt, producing the source material for the mare basalts. It is not clear that such an elaborate process (involving total solidification, sinking, heating, melting, and rising) could be completed in the relatively short time before the basalts first erupted and whether the buoyant material would in fact have a dominant spherical harmonic degree-1 behavior at depth. In what follows we present a simpler model of mare basalt emplacement involving only partial solidification, without any remelting. In this model the magma is the residual liquid of the LMO remaining at the top of the mantle in isolated pools, much as suggested some time ago by *Taylor* [1978].

[6] Lack of isostacy and the associated gravitational signal are the characteristic features of mascons [*Muller and Sjogren*, 1986; *Arkani-Hamed*, 1998]. The recent Clementine mission has again confirmed the existence of positive gravity anomalies over mascons and negative anomalies surrounding the basalt-filled mare basins [*Lemoine et al.*, 1997]. The positive anomalies are the result of the emplacement of high-density basalts on or near the surface, rather than structural relief on a lunar moho [*Wise and Yates*, 1970]. *Wieczorek et al.* [2001] have reexamined the densities of mare basaltic and picritic magmas relative to crustal material and found that some magmas may not have been intrinsically dense. However, the existence of the gravitational anomalies is definitive evidence that some magmas emplaced on the surface had an intrinsic density excess of significant magnitude. The principal goal of this paper is to describe a possible mechanism of nonhydrostatic emplacement of these dense magmas on the lunar surface.

[7] It is not clear how dense basalts could have risen through tens of kilometers of less dense crust. *Tait et al.* [1989, p. 107] note that "in general, magma will ascend...until it encounters crustal rocks which have a density less than that of the melt." This conclusion has been affirmed by *Walker* [1989] and *Ryan* [1994]. *Runcorn* [1974] argued that buoyant rise of magma coupled with contraction upon solidification could allow sufficient magma to rise into the impact cavity to produce the observed mascons. This mechanism is flawed by the assumption that the pooled, shallow magma contracted vertically as much as a deep magma column. A more plausible model was proposed by *Solomon* [1975] in which the source region for the magma was at sufficient depth within the mantle that the positive head difference produced in a vent by magma buoyant with respect to the mantle counterbalanced the negative head difference produced by magma dense with respect to the crust. Solomon's mechanism relies on remelting of mantle at depth, a process that appears to be questionable [*Ringwood and Kesson*, 1976]. It also relies on a melt pathway that is continuous in both depth and time. If the source region were shallow (i.e., immediately below the crust) or if magma propagated upward in discrete packets, that is, solitons [*Whitehead*, 1987; *Helfrich and Whitehead*, 1990], Solomon's mechanism would fail.

[8] The early Moon very likely was sufficiently hot to possess a magma ocean (LMO). As it cooled, dense silicates crystallized at the base of the ocean, producing a dense lower mantle, while buoyant silicates (ferroan-anorthositic feldspars) crystallized at the top, forming the crust. We [*Loper and Werner*, 2002] have proposed that tilted convection within the LMO drove some of the buoyant crust to the farside, producing the observed crustal and compositional asymmetry having a harmonic degree-1 distribution oriented toward Earth. The residual basaltic magma, which accumulated immediately below the anorthositic crust, was closer to the surface and at a lower pressure on the nearside than on the farside. A significant fraction of the KREEP elements, radioactive isotopes, and volatiles was likely concentrated in this residual magma by fractional crystallization. We shall argue that the thermal and compositional evolution of this residual magma led to the nearside formation of the mare basalts and associated mascons.

[9] In what follows we propose an alternate mechanism of basalt emplacement, involving second boiling, which does not rely on melting or remelting to produce the source magma and which does not rely on buoyant rise. Consequently, this mechanism can operate when the source magma is at a relatively shallow depth; in fact, it operates preferentially at shallow depths. Following a discussion of lunar features and evidence relevant to the emplacement of lunar basalts in section 2, we describe in section 3 the processes of tilted convection and second boiling and explain how the former is related to the geographical distribution of basalts and the latter can drive volcanic eruptions involving dense magmas. The resulting spatial distribution of basalts and the timing of eruptions are discussed in section 4. In section 5 the simple model is summarized, and some of the future work necessary to integrate it with current lunar science is outlined.

2. Relevant Features and Evidence

[10] In addition to the lack of isostacy, mare basalts exhibit a strongly asymmetric distribution, with nearly all occurring on the nearside [*Neumann et al.*, 1996]. The nearside also has a thinner crust; according to our model, this feature directly contributes to the nearside occurrence of

the basalts. An important constraint on any model is the timing of emplacement of mare basalts, ranging from 100 to 800 Myr following formation of the associated impact crater. Additional relevant evidence includes (1) the distinct geochemical compositions of mare basalts compared to anorthosites, (2) evidence of explosive volcanism, (3) evolution of progressively incompatible- and volatile-enriched basalt compositions, (4) the lack of large-scale relief of the basalts, and (5) the lack of mare basalts in several large basins (most notably the South Pole–Aitken basin) [*Heiken et al.*, 1974; *Jerde et al.*, 1994; *Staid et al.*, 1996, *Arkani-Hamed*, 1998].

[11] The nearside occurrence of basalt is in marked geochemical contrast to the farside occurrence of ferroan-anorthositic feldspar. Lunar-surface basalts typically occur within and/or near large impact basins on the nearside, whereas anorthosites are a predominant feature of the farside lunar highlands. Isotopic data, as well as crater counts, show that the mare basalts are significantly younger than pristine anorthosites [*Gornitz*, 1973]; the basalts must have been emplaced subsequent to the formation of the highlands. Recently, *Jolliff et al.* [2000] have demonstrated the existence of a distinct geochemical province, called the Procellarium KREEP Terrane (PKT), on the nearside. This may have been produced by the mechanism of tilted convection [*Loper and Werner*, 2002]; see section 3.1.

[12] There is ample evidence that mare basalts were emplaced by volcanic activity [*Arkani-Hamed*, 1998]. The dark mantling deposits on the lunar surface are of pyroclastic origin, glass droplets recovered from Apollo lunar samples very likely were formed by lava fountains of low-viscosity basaltic melts, and multispectral surface observations from Aristarchus indicate large deposits of volcanoclastic origin [*Heiken et al.*, 1974; *McEwan et al.*, 1994]. Many lunar samples have residual or evolved KREEP compositions and are enriched with incompatibles [*Warren*, 1985; *Jerde et al.*, 1994], indicative of an evolved or residual volcanic origin.

[13] In addition to the positive gravity anomalies which occur at the centers of mascons, negative gravity lobes surround many of them [*Arkani-Hamed*, 1998]. It is likely that these are a result of lithospheric flexure that developed subsequent to the emplacement of the mascons and are not directly related to the mechanism of emplacement. In what follows we shall focus on the mechanism of emplacement and not consider the origin of these lobes.

[14] The primitive geochemical composition of some mare basalts, particularly the picritic glasses, indicates a deep origin, hundreds of kilometers down in the lunar mantle [*Hess*, 2000]. These basalts likely are the residue of the initial solidification of the lunar magma ocean. A possible mechanism whereby they rose to the surface is discussed at the end of section 4.

3. Tilted Convection and Second Boiling

[15] In first portion of this section we describe the temporal evolution of the LMO during the process of crustal formation, assuming that tilted convection [*Loper and Werner*, 2002] was instrumental in this process. Following this we describe in section 3.2 the process of second boiling, which can provide the necessary overpressurization and temporary reduction of magma density needed to drive the dense magmas to the surface.

3.1. Tilted Convection

[16] Tilted convection (i.e., the tilting of individual plumes of rising and sinking fluid) spontaneously generates large-scale currents in fluid layers that are convecting vigorously [*Krishnamurti and Howard*, 1981]. The LMO likely was in such a convective state for much of its history. Subsequent to the establishment of lunar synchronous rotation, thermal radiative screening of Earth could have oriented these currents such that they transported buoyant crystals within the LMO to the farside, forming a thicker crust there. Initially, the LMO would have been global in extent, but as cooling and solidification proceeded, it would have become progressively more limited to nearside regions.

[17] If the transport via tilted-convection currents had been sufficiently vigorous, the LMO could have become confined to the nearside before the formation of the nearside crust. There is evidence in the lunar geochemical and geophysical record that this may have been the case. As the LMO progressively solidified, the remaining portion would have become more enriched in volatiles and incompatible elements, such as KREEP, and the crustal material which formed from it would have been similarly enriched. This may provide an explanation for the distinct geochemical signature of the PKT [*Jolliff et al.*, 2000]. Also, nearside confinement of the LMO may also provide an explanation of the lack of magmas in the South Pole–Aitken basin, provided the LMO beneath that region had substantially been filled with crystals transported by tilted-convection currents, prior to the basin-producing impact.

3.2. Second Boiling

[18] As noted above, a distinguishing feature of mare basalts is their positive gravitational anomaly, indicating a nonhydrostatic mechanism of emplacement. It is not sufficient to note that the mare basalts rose to a level close to the equipotential surface [*Runcorn*, 1974; *Solomon*, 1975] and postulate this as general property, independent of the density of the basalts themselves. The equipotential surface is a global feature of a planetary body, while the level to which magma rises is a result of a local balance of pressure and buoyancy, that is, the difference in density of magma and adjacent crust. An intrinsic magmatic density excess of 2%, say, could be compensated by thermal expansion, but with a coefficient of thermal expansion of magnitude 2×10^{-5}, this would require a temperature excess of more than 1000°. If positive buoyancy is not available to drive the magma upward, the only other possibility is pressure, specifically, superlithostatic pressure. Assuming a density excess of mare basalts over crustal material of 300–500 kg m^{-3}, a crustal thickness beneath impact basins of 30 km, and a local acceleration of gravity of 1.5 m s^{-2}, the required excess pressure would have been roughly 13–22 MPa (= 0.13–0.22 kbar). We propose that second boiling [*Bowen*, 1928], in a tectonic regime favorable for its occurrence, produced the necessary overpressure and triggered the basaltic eruptions.

[19] As a molten alloy (e.g., magma) containing volatiles (and other incompatibles) cools and crystals grow from the

melt, the remaining melt becomes progressively enriched in those constituents. If the lithostatic pressure is sufficiently low, the melt becomes oversaturated as cooling progresses and the volatiles exsolve, causing an overpressure within the chamber [*Morey*, 1922; *Blake*, 1984; *Tait et al.*, 1989; *Woods and Pyle*, 1997]. This process is called second boiling [*Bowen*, 1928; *Burnham*, 1979]. If the process occurs at constant volume, or at least in a confined region, the pressure increase can be relatively large. *Burnham* [1979, p. 477] noted that "enormous pressures (tens of kilobars) theoretically can be generated" by this mechanism, far more than the overpressure estimated above. *Tait et al.* [1989] have shown that significant overpressure can be achieved by crystallization of only a few percent of the liquid.

[20] Second boiling is sensitive to the lithostatic pressure. Consequently, whether second boiling occurs and what overpressures are produced within a magma chamber depend on the depth of the chamber. *Blake* [1984] estimated that this mechanism would operate in terrestrial magma chambers of silicic composition as deep as 7 km. Assuming that the same result applies for basaltic chambers, this implies that second boiling could occur to a depth of $\sim$40 km on the Moon, since lunar gravity is 1/6 that of Earth. *Hess* [2000] has suggested 30 km as a plausible depth of a KREEP-rich magma chamber, which is within the depth range where second-boiling may occur. Exsolution or boiling will occur preferentially at the top of the liquid region because the pressure is lowest there [*Woods and Cardoso*, 1997]. Once exsolution begins, the buoyant rise of volatiles within the magma chamber can magnify the overpressure achieved; *Woods and Cardoso* [1997] estimate that this mechanism alone could increase the pressure by as much as 10 MPa.

[21] The estimate of 13–22 MPa of required overpressure is an upper bound. It is likely that the amount of overpressure needed to initiate upward motion of the lunar magma through preexisting cracks was smaller than this, possibly much smaller. As the volatile laden magma rose, further exsolution triggered by the decrease of pressure would have decreased the effective density of the magma and accelerated the magma upward, producing a gas-driven eruption. As the magma pooled in depressed topographic regions on the surface, the volatiles would have escaped, leaving the dense basalt to produce the positive gravity anomaly.

[22] This mechanism requires that the volatile content of the magma within the chamber be sufficiently high to reach saturation. Both deductive reasoning and observational evidence support the contention that this indeed occurred. No matter what the initial volatile percentage of the LMO, as cooling and solidification proceeded, the remaining magma became more and more enriched in volatiles until saturation must have been reached. (Note, for example, that Figures 73, 75, and 77 of *Bowen* [1928] are valid for any initial volatile percentage.) The observational evidence in support of volatile exsolution includes several Apollo lunar soil samples containing glassy and partially crystallized spheres which have ages and compositions similar to the mare lavas and which contain olivine phenocrysts but which lack broken lithic or mineral fragments. The occurrence of such spherules is indicative of a gas-driven eruption rather than impact [*Heiken et al*, 1974]. An additional indicator of a gas-driven eruption is a cinder-cone complex near mare Imbrium [*Schaber*, 1973].

4. Location and Timing of Basalt Emplacement

[23] Second boiling occurs preferentially where the magma pressure is lowest. During the initial stages of solidification of the lunar magma ocean and formation of the crust, the magma would have underlain the crust everywhere and was very likely undersaturated in volatiles. Subsequently, the magma would have become isolated in separate chambers, located preferentially where the crust was thinnest. That is, more magma would have pooled beneath the nearside than the far. Also, second boiling would have occurred preferentially on the nearside, where the lithostatic pressure was lower. Where the crust is thick and lithostatic pressure is high, such as on the farside, second boiling may have been entirely suppressed. It is well established [e.g., see *Arkani-Hamed*, 1998, Figure 18] that the lunar crust is thinnest beneath the impact basins, due to rebound following impact and crustal excavation. It follows that these are the preferred sites for second boiling, volatile exsolution, and eruption. This provides an explanation of the close association of mascons with nearside impact basins.

[24] The question naturally arises: why was basalt emplacement delayed following impact? A simple and plausible answer is that the magma had not evolved to the stage of second boiling at the time of impact; its volatile content was not yet saturated. Also, the impact may have heated the magma and overlying crust, thereby delaying the onset of second boiling. Continued lunar cooling and magma solidification subsequent to the impact resulted, eventually, in the occurrence of oversaturation, exsolution, overpressurization, fracture widening, and gas-driven volcanic eruption. The cooling time, τ, of a chamber at depth L beneath a crust with thermal diffusivity κ is L^2/κ. If $\kappa \approx 4 \times 10^{-7}$ m^2 s^{-1}, then for a chamber 30–50 km below the surface, $\tau \approx 75$–200 Myr. This is a lower bound of the time for the magma to reach its second boiling point subsequent to impact; this simple calculation does not take into account the delay in cooling that would have been caused by the radioactive heat-producing elements in the magma.

[25] An impact basin invariably is strongly fractured. The fractures closest to the center of the basin are likely to be annealed by impact-generated heat, forming a competent central cap over the magma chamber. Cracks in an annular region outside the central area were most likely not annealed and remained incompetent due to the presence of a tensile tectonic regime (established by surficial contraction resulting from cooling). These fractures were likely the pathways for the erupting magma. The tectonic stress pattern in the crust due to mare loading would also cause eruptions preferentially at the basin rim [see *Solomon and Head*, 1979, Figure 14]. The magnitude of a given volcanic eruption will depend on many site-specific features, particularly the geometry of the magma chamber and the location of any continuous fractures from the chamber to the surface.

[26] The basalts found in a given mare consist of multiple flows that were extruded over several hundred million years following initiation of emplacement. These features can be

explained in the context of the present model as follows. Following a given eruption, the remaining magma, being undersaturated, would have remained dormant until cooling once again set the stage for a subsequent eruption. The rate of cooling and solidification of a source magma was delayed by internal heating due to radioactive isotopes. The tendency for the strength of radioactive heating to decay with time, due to the finite half-lives, would have been buffered by the progressive enrichment of the magma as fractional crystallization proceeded. Eruptions would have finally ceased at a given location when either cooling depressed the crustal-magma boundary sufficiently that the pressure exceeded the upper limit for second boiling or the last of the magma erupted or solidified.

[27] There is geochemical evidence [*Hess*, 2000] of a deep origin for the mare basalts having relatively primitive compositions. This has often been cited as evidence for deep remelting of the lunar mantle. However, a viable alternative is that these basalts are the unsolidified residue of the LMO. This residue was initially trapped within the mantle as intercrystalline liquid. This buoyant liquid gradually made its way to the surface via the process of compaction [*McKenzie*, 1984; *Bercovici et al.*, 2001]. The material could have retained its deep geochemical signature during the rise process if it traveled via discrete channels, which are known to occur in such situations [*Aharonov et al.*, 1995, 1997]. Upon reaching the crust-mantle interface, this liquid would have mixed into the remnants of the LMO that had pooled preferentially beneath the impact basins and would have participated in the eruptions driven by second boiling. The flux of primitive liquid would naturally have decreased with time, so that the erupting basalts became progressively more evolved as time progressed.

5. Summary and Discussion

[28] The goal of this paper is to propose a mechanism for the emplacement of mare basalts and the concomitant formation of lunar mascons. This mechanism does not involve solidification and remelting of the basalt source region. Rather, it is assumed that the source magmas are remnants of the primordial lunar magma ocean. These magmas are rich in incompatible elements, including radioactive isotopes, KREEP, and volatiles. The exsolution of volatiles as the magma cools and crystallizes (i.e., second boiling) provides the overpressure that drove the dense magma upward to the surface. This process occurred preferentially beneath the mare basins, where the crust is thin and lithostatic pressure is low. The delay between impact and magmatic extrusion reflects the time needed for the volatile-rich magma to cool to its second boiling point. The heat produced by the concentrated radioactive decay maintained the magmas in liquid state for a longer period of time than would be estimated from conductive cooling alone.

[29] The multiple flooding events observed in Mare Tranquillitatis show a geochemical evolution from the oldest basalts having low-Ti and few incompatibles to the youngest having very high-Ti composition [*Staid et al.*, 1996]. This suggests that following each eruption in the sequence, the residual magma experienced further solidification and chemical evolution, becoming more enriched in Ti and other incompatible elements. This process appears to have occurred three or four times within the chambers of the Tranquillitatis and Serenitatis basins. It is beyond the scope of this preliminary presentation to incorporate the vast amount of geochemical and petrologic data [e.g., *Snyder et al.*, 1992; *Jerde et al.*, 1994; *Staid et al.*, 1996] into a comprehensive model of magma evolution and eruption. This should be done both to determine the compatibility of the proposed mechanism with these data and to provide realistic constraints on the proposed processes.

[30] The South Pole–Aitken basin [*Lucey et al.*, 1994; *Arkani-Hamed*, 1998] places significant constraints on our model. While it appears a very likely candidate for mare basalt emplacement, the basin has only a small amount of mare material [*Lucey et al.*, 1994]. This indicates that at one time there was some volcanism but that it was not extensive. One possible explanation is that the LMO became confined to the equatorial nearside region prior to the formation of this basin.

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