On lunar asymmetries
1. Tilted convection and crustal asymmetry

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[1] It is proposed that lunar crustal asymmetries are the result of convective processes acting early in the Moon's history, during the magma-ocean phase and after synchronous rotation was established. Buoyant anorthositic crystals were transported to the farside by a large-scale circulation, called tilted convection, known to occur spontaneously in chaotic convective systems. The circulation was oriented toward the farside of the Moon by a small temperature contrast produced by radiative thermal shielding due to the proximity of Earth. Crustal thickening near the equator resulted from the modification of tilted convection by the Coriolis force. The anorthosite that was transported to the farside and equator may be a major cause of the observed crustal asymmetries and of the associated offset of the center of figure from the center of mass and bimodal hyposgram. The selective transport may have resulted in a nearside excess of incompatible elements, leading to the formation of the Procellarium KREEP terrane. *INDEX TERMS:* 1221 Geodesy and Gravity: Lunar geodesy and gravity (6250); 5410 Planetology: Solid Surface Planets: Composition; 5430 Planetology: Solid Surface Planets: Interiors (8147); 5455 Planetology: Solid Surface Planets: Origin and evolution; 6250 Planetology: Solar System Objects: Moon (1221); *KEYWORDS:* Moon, crust, asymmetry, tilted convection

1. Introduction

[2] The Moon has a number of interesting asymmetries of uncertain origin. In this paper we propose an explanation of its crustal asymmetries, including the displacement of the center of mass and center of figure (CM/CF) and nearside enrichment in incompatible elements. The physical asymmetries include (1) a skewed distribution of topographic elevations, in which the farside is on average 3.2 km above the nearside, resulting in a bimodal hypsogram; (2) a mean crustal thickness 8–12 km greater on the farside; (3) equatorial crust on average 9.5 km thicker than at the poles, revealing a flattened geoid; and (4) a CM/CF offset of approximately 1.68–1.93 km [*Lucey et al.*, 1994; *Zuber et al.*, 1994; *Neumann et al.*, 1996]. In a companion paper [*Werner and Loper*, 2002] we consider the origin and distribution of mare basalts and the associated lunar mascons.

[3] The CM/CF offset has in the past been attributed to gravitational and geometrical variations [*Kaula*, 1974], including core displacements [*Stevenson*, 1980] and multilayered crustal thickening [*Wieczorek and Phillips*, 1998]. However, gravity and topography data from the Clementine Mission make it clear that "the asymmetrical distribution of crust accounts for almost all of the offset of the center-of-figure of the Moon from its center-of-mass" [*Neumann et al.*, 1996, p. 16,848].

[4] There appear to be two alternatives concerning the evolution of thick crust on the farside: it is either due to an intrinsic lunar asymmetry, perhaps due to lateral variations in mantle structure [*Bills and Ferrari*, 1977] or composition [*Wasson and Warren*, 1980], or due to dynamic, that is, convective processes [*Lingenfelter and Schubert*, 1973; *Runcorn*, 1975; *Hess and Parmentier*, 1995]. We propose a mechanism which fits in the latter alternative. The bimodal lunar hypsogram is more similar to that of Earth than other terrestrial planets. (Mars has a hemispheric asymmetry, but not a bimodal hypsogram.) Earth's crustal asymmetry is known to be the result of plate tectonic motions, driven by mantle convection, and the associated formation of continental crust. Although there is no evidence for tectonism on the Moon, the role of convective motions in transporting crust early in lunar evolution deserves reconsideration.

[5] *Runcorn* [1975] proposed that early lunar convection, associated with its warming and core formation, was simple and large scale, that is, dominated by first- and second-order spherical harmonics. A somewhat similar convective model has been proposed more recently to explain the asymmetric distribution of mare basalts [*Hess and Parmentier*, 1995; *Zhong et al.*, 2000] but might conceivably be capable of producing the crustal asymmetry as well. In Runcorn's model the first-degree pattern is responsible for the accumulation of the crust on the farside, forming the highlands. This model relies on a cold undifferentiated early Moon, so that first-degree harmonics dominated the convective pattern, and does not explain how the convective pattern came to be oriented with respect to Earth. If the Moon formed hot [*Cameron*, 1986], Runcorn's mechanism would be implausible. The model proposed more recently [*Hess and Parmentier*, 1995; *Zhong et al.*, 2000] is rather more elaborate than Runcorn's. It involves solidification of a layer of dense,

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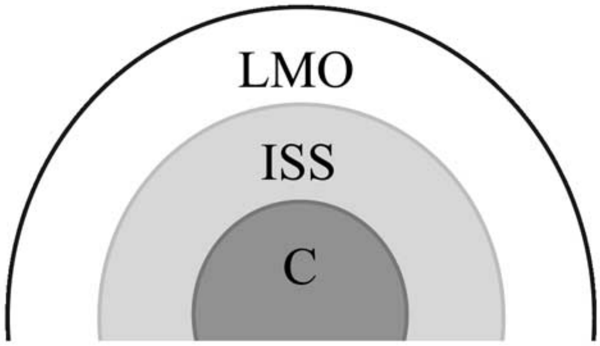

Figure 1. A cross section of the initial lunar structure. C denotes the metallic core, ISS denotes an initial layer of dense solid silicates, and LMO denotes the molten lunar magma ocean.

ilmenite-rich cumulates near the top of the mantle. This layer sinks to the base of the mantle, where it heats due to radioactive decay. It subsequently becomes convectively unstable, with a dominant spherical harmonic degree 1 motion, and rises back up through the mantle. In this paper we propose an alternative convective model which is more direct than this, in that it does not involve convection through the mantle or remelting of cumulates.

[6] *Lingenfelter and Schubert* [1973] proposed a model in which convection, possibly occurring in a near-surface layer, was dominated by high spherical harmonics. They postulated "the effect of all convection cells is some net transport on a global scale into a particular hemisphere" (p. 178) but did not provide explanations how this preferential transport occurred and why it was oriented with respect to Earth. In what follows we shall elaborate upon the Lingenfelter-Schubert model, proposing an explanation how vigorous convection can result in preferential surficial transport and why this was oriented with respect to Earth. The principal aims of this paper are to describe the processes involved and to set out the arguments for and against the proposed mechanism. Many of the processes involved in the proposed model are not well quantified at present. It is hoped that this paper will catalyze studies rectifying this deficiency, leading to a better assessment of the plausibility of the model proposed here and to a better understanding of early evolution of the Moon.

[7] This paper is organized as follows. The initial thermal state of the Moon and its early evolution, prior to crustal formation, are outlined in section 2, while the initial lunar structural evolution is discussed in section 3. Tilted thermal convection, including the mechanism of formation of a large-scale current system and how it became oriented with respect to Earth, is described in section 4. The asymmetric growth of the farside crust is described in section 5. The resulting crustal asymmetries are summarized in section 6.

2. Lunar Initial State and Early Evolution

[8] Lunar mare basalts, together with a large body of geochemical and petrological evidence, provide strong evidence that the Moon was hot immediately following its formation and has been cooling ever since [*Heiken et al.*, 1974; *Warren*, 1985; *Jerde et al.*, 1994]. This conclusion is reinforced by the fact that most sources of heat are associated with the Moon's early history: impact energy, tidal deformation, and radioactive heating due to short-lived isotopes. If the Moon had been created by the collision of a large planetesimal with the proto-Earth, the associated thermal energy would have been more than sufficient to vaporize lunar material [*Cameron*, 1986]. Additional heating of the Moon could have been produced by strong tidal deformation when it was near the Roche limit, the critical disruption distance. These heat sources make it very likely that the Moon was partially or completely molten immediately following its formation [*Boss and Peale*, 1986].

[9] The Moon is believed to have formed slightly outside the Roche limit. Any object close to that limit would experience strong tidal dampening and quickly evolve to a state of synchronous rotation with Earth [*Stacey*, 1992]. Once synchronous rotation had been achieved, perturbations caused by massive impacts would have persisted for only short periods of time [*Melosh*, 1975]. Thicker farside crust and thinner polar crust, once established, will result in the Moon having its axis of maximum rotational inertia normal to the orbital plane and axis of minimum rotational inertia directed toward Earth. Thus the development of a thickened farside crust would tend to stabilize the Moon's synchronous rotation. It is reasonable to assume, as we shall, that the Moon was in synchronous rotation as it cooled.

[10] The initial compositional structure of the Moon, following its hot formation, is assumed to consist of three regions, including a small central metallic core, an intermediate layer of solid, dense silicates, and a topmost layer of liquid silicates; see Figure 1. The top layer is often referred to as the lunar magma ocean (LMO). The existence of a layer of solid silicates below the LMO, as opposed to above it, is dictated by the disparity of the adiabatic and liquidus gradients of silicates with pressure, so that a cooling body of convecting liquid first reaches the liuidus at its base [*Wasson and Warren*, 1980]. In this simple model any partially molten region at the base of the LMO is taken to be negligibly thin. The relative thicknesses of these layers are of little importance in our model, provided the LMO was sufficiently deep that vigorous convective motions ensued during cooling and crustal formation.

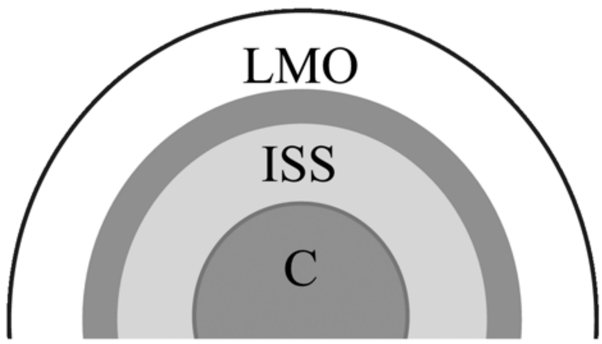

Figure 2. The first phase of lunar structural evolution: solidification of a cumulate layer of olivine and/or pyroxene at the base of the LMO, depicted by the dark layer.

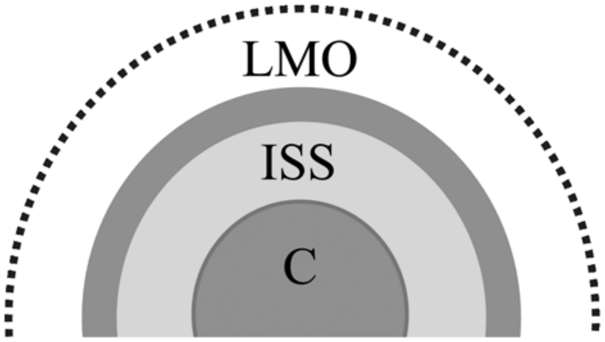

Figure 3. The second phase of lunar structural evolution: solidification of isolated buoyant anorthositic crystals, depicted by the dotted line.

[11] The Moon may have had a "chilled" crust due to the strong surface cooling, but this would have been a transient mobile part of the convection within the LMO. True crustal formation began only after the LMO evolved to the point that buoyant anorthositic feldspar accumulated at the top. This evolution is described in the following section, where we consider initial crustal formation.

3. Initial Structural Evolution

[12] In the initial phase of lunar structural evolution a layer of dense silicates (olivine and/or pyroxene) accumulated at the base of the LMO, as shown in Figure 2 [*Langmuir*, 1989; *Tonks and Melosh*, 1990; *Snyder et al.*, 1992; *Solomatov and Stevenson*, 1993a]. This layer likely grew by direct solidification, as opposed to crystal settling. The only process capable of producing suspended crystals is homogeneous nucleation. This requires a significant level of supercooling, estimated to be 20 K by *Solomatov and Stevenson* [1993b]. Given the relative slopes of the liquidus and adiabat, supercooling in the LMO increases with depth, reaching a maximum at the contact between liquid and underlying cumulates. It is well known in metallurgy that such supercooling does not occur in metallic systems. Rapid growth of crystals on the boundary of the melt maintains supercooling at very small levels. The same situation is almost certain to prevail in silicate systems. Well before significant supercooling might have been established, crystals existing at the base of the LMO would have grown upward, obviating the need to nucleate crystals in the interior of the LMO. That is, it is likely that the base of the LMO lies above the depth marked "nucleation" in Figure 2 of *Solomatov and Stevenson* [1993a]. In this scenario, LMO is entirely liquid at this stage of lunar evolution.

[13] As the dense silicates solidified at the base of the LMO, a buoyant residue was created which drove vigorous convective motions in the LMO. Convection within the LMO was driven simultaneously by cold liquid created at the surface by radiative cooling; there was no solid crust at this stage.

[14] As cooling and crystallization of dense silicates proceeded, the composition of the LMO evolved to the point where buoyant anorthositic feldspar began to crystallize. This marked the beginning of lunar crustal formation. Initially, the crystals would have been small and isolated, as depicted schematically in Figure 3. Since, at this stage of evolution, there was no solid surficial layer to which these crystals could weld, they were held in suspension close to the top of the LMO by turbulent convective motions and moved about by large-scale currents. We propose that such currents existed and were oriented so as to move the buoyant crystals from the nearside to the farside, leading to the preferential formation and growth of crust on the farside. The form and orientation of these currents are described in the following section.

4. Tilted Convection

[15] The LMO was in a state of vigorous convection, driven by compositionally buoyant material released at the base due to solidification of dense solid and by the formation of dense material at the top due both to radiative cooling and to the solidification of buoyant anorthosite. The possible forms of convective motions have been identified principally by laboratory experiments. These forms are characterized by the Rayleigh number, *Ra*, which is a ratio measuring the destabilizing influence of the buoyancy force on a fluid parcel relative to the stabilizing actions of viscosity and heat conduction: $Ra = (\Delta\rho)gL^3/\mu\kappa$, where $\Delta\rho$ is the density contrast, g is the local acceleration of gravity, L is the layer thickness, μ is the kinematic viscosity, and κ is the thermal diffusivity.

[16] With increasing *Ra*, a horizontal layer of fluid experiences (1) a static state, where no fluid motion takes place ($0 < Ra < \sim 1.7 \times 10^3$); (2) steady convection having a cellular structure, referred to as Rayleigh-Benard convection ($\sim 1.7 \times 10^3 < Ra < \sim 10^4$); (3) unsteady convection cells ($\sim 10^4 < Ra < \sim 5 \times 10^5$); (4) a chaotic state, where unsteady convection occurs with no cellular structure ($\sim 5 \times 10^5 < Ra < \sim 2 \times 10^6$); and (5) tilted convection ($\sim 2 \times 10^6 < Ra$) [*Krishnamurti and Howard*, 1981]. In this last state, chaotic convection spontaneously develops a large-scale structure, characterized by tilted trajectories of fluid parcels, with parcels rising and sinking at an angle from the

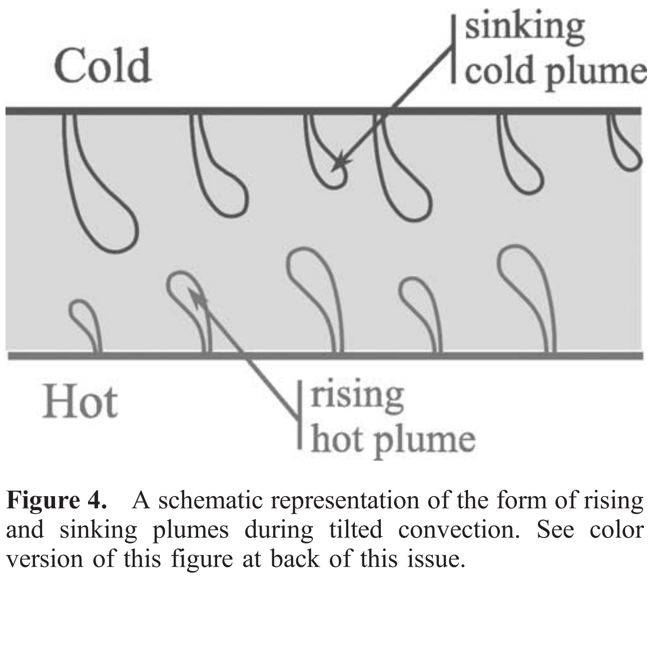

Figure 4. A schematic representation of the form of rising and sinking plumes during tilted convection. See color version of this figure at back of this issue.

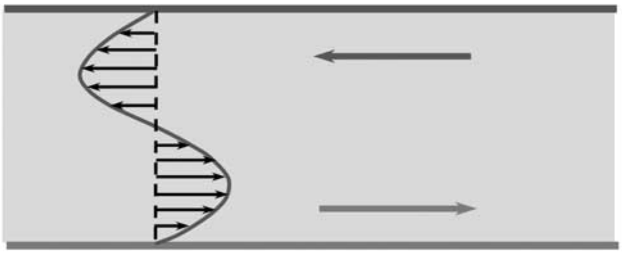

Figure 5. A schematic representation of the large-scale flow associated with tilted convection. See color version of this figure at back of this issue.

vertical, as depicted schematically in Figure 4. Note that no cellular structure is present in tilted convection. The tilted trajectories of fluid parcels transport horizontal momentum in the vertical direction, creating and sustaining large-scale horizontal flow in one direction at the top of the liquid layer and in the opposite direction at the bottom, as depicted in Figure 5 [*Krishnamurti and Howard*, 1981]. Tilted convection, being a global property of the convecting layer, is very likely to be insensitive to local perturbations in the form of foundering dense quenched crust, suspended crystals, meteorite impacts, and the like. The directional momentum produced by tilted convection appears to be capable of transporting anorthosite crystals large distances and hence creating an asymmetric crustal distribution. We shall return to this point in the following section, after the strength of convection in the LMO and the orientation of tilt are considered.

[17] The magnitude of the Rayleigh number in the LMO depends on a number of factors, some of which are well known and others which are less so. The least known is the thickness of the LMO. Using the definition of the Rayleigh number and the experimental results presented above, the LMO will experience tilted convection, provided it is thicker than $L_{crit} = (Ra_{crit}\ \mu\kappa/\Delta\rho g)^{1/3}$ with $Ra_{crit} = 2 \times 10^6$. The viscosity of the LMO can be estimated by assuming it is roughly the same as that of the basaltic glasses found at several Apollo landing sites. The dynamic viscosity of those glasses has been estimated [*Delano*, 1990; see also *Basaltic Volcanism Study Project*, 1981, Figure 5.2.1] to be to be (within a factor of 2 of) six poise (0.6 kg m^{-1} s^{-1}) at their liquidus temperature. (The effective viscosity can be somewhat larger if the fraction of crystals is large, but this can occur only in a very thin surficial layer). Let us take $g = 1.5$ m s^{-2}, $\kappa = 10^{-6}$ m^2 s^{-1} and take a modest value for the density contrast of 3 kg m^{-3} (i.e., a 0.1% contrast). With these values, $L_{crit} = 3$ m. Note that this thickness is relatively insensitive to changes in the parameter estimates; depending on each to the 1/3 power. It follows that convection in the LMO almost certainly was sufficiently vigorous that tilted convection occurred.

[18] To produce a thicker farside crust, the tilted trajectories of the convective parcels must be oriented toward the farside. It has been shown experimentally [*Krishnamurti and Howard*, 1981] that the orientation of tilt can be controlled by a small thermal variation in the convective system. Specifically, tilt is oriented such that the horizontal current near the upper surface is directed away from the hotter region. *Wasson and Warren* [1980] noted that the radiative heat loss at the lunar surface is uneven due to the proximity of Earth, which partially shields the nearside from radiative cooling. This effect was capable of producing a nearside temperature increase of ~2.5% (21 K) at a distance of 2 Roche limits and ~1.3% (11 K) at 3 Roche limits. We propose that this small variation in temperature between the nearside and farside caused the tilted convection to be aligned from the nearside toward the farside.

[19] Initially, the LMO may have been partitioned into a number of domains in which the tilts and currents were oriented randomly. However, the domain or domains having the proper orientation with respect to the Earth would have been more vigorous and would have grown, by means of domain-boundary migration, at the expense of those domains with unfavored tilts. The end result would have been one global-scale domain aligned with respect to the nearside/farside axis, as depicted in Figure 6. Once established, this orientation would have persisted, and we argue in the following section that this large-scale motion was capable of producing the observed crustal asymmetry. Note that the accumulation of protocrust on the farside is a result of the dynamics of tilted convection and not a consequence of the nearside-farside temperature gradient.

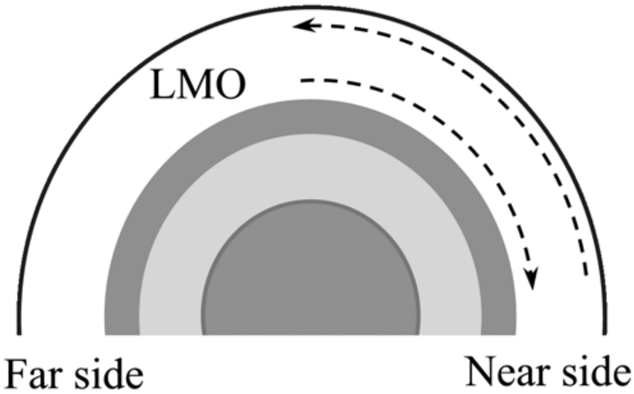

Figure 6. The orientation of the large-scale convective currents, associated with tilted convection, relative to Earth.

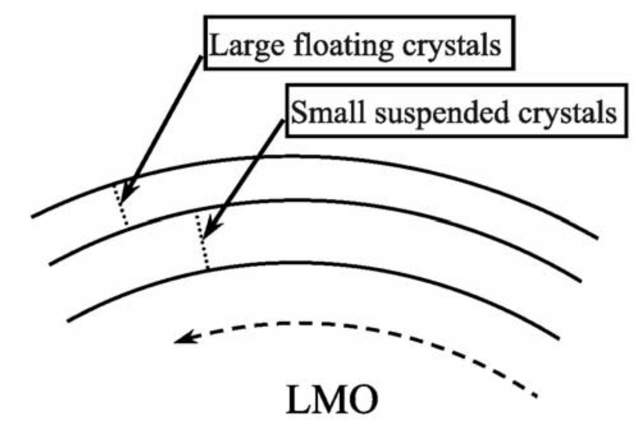

Figure 7. A schematic depiction of the floating and suspended crystals at the top of the LMO. Both types are swept toward the farside by the large-scale current.

[20] A second source of convective asymmetry in the LMO arises from the action of the Coriolis force. This controls convective dynamics if the Ekman number is small, that is, if $\mu \ll \rho\Omega L$, where ρ is the density, Ω is the rotation rate, and L is the thickness of the LMO. The rotation rate of the Moon, in synchronous rotation at a distance of two Roche limits from Earth, say, would have been 2.4×10^{-4} s^{-1}. With a density of 3×10^3 kg m^{-2}, it follows that the Coriolis force would have been dynamically important if the thickness of the LMO exceeded 1 m, which it very likely did. The effect of the Coriolis force in tilted convection is not yet known. However, it does provide a mechanism whereby the convective pattern in the LMO was sensitive to the lunar latitude. Given that, it is plausible that tilted convection produced the crustal thickening observed on the lunar equator in addition to that on the farside.

5. Growth of the Farside Crust

[21] The large-scale currents of tilted convection would have easily swept the initial anorthositic crystals to the farside. There the crystals would have pooled and welded (via Ostwald ripening [*Hills and Roberts*, 1990; *Glicksman et al.*, 1992]), forming the beginning of the farside crust. Consider now the subsequent growth of that crust as unconsolidated crystals were swept from nearside to far by tilted convection. There are two questions to be addressed. First, was the lateral transport of crystals sufficient to produce the observed asymmetry? Second, were the crystals sufficiently small to remain in suspension and produce a thick farside crust?

[22] The observed excess thickness of farside crust is roughly 10 km, while the timescale for cooling of an LMO of 400 km thickness, say, is roughly 1000 years $\approx 3 \times 10^{10}$ s [*Tonks and Melosh*, 1990]. If the proposed mechanism produced the excess thickness in this time interval, the rate of thickening would have been roughly 10 m yr^{-1} $\approx 3 \times 10^{-7}$ m s^{-1}. The speed of convective motion in a terrestrial magma ocean of 1000 km depth has been estimated by *Tonks and Melosh* [1990] to be 1.5 m s^{-1}. Since this speed varies weakly (typically as the 1/3 power) with parameters such as layer depth, we will take 1 m s^{-1} as a typical convective speed in the LMO. For the purpose of quantification, we will assume that the speed of horizontal motion associated with tilted convection is a moderate fraction (e.g., 10%) of the convective speed, that is, roughly 0.1 m s^{-1}, although it might well exceed that speed. At this speed the necessary flux would have been accomplished if the depth-integrated amount of suspended crystals were roughly 6 m. If the suspended-crystal layer were thicker than 1 km, as seems very plausible, the fraction of solid crystals within it would be <1%. The proposed process can readily transport the requisite material flux with a modest volume fraction of suspended crystals, provided they remained suspended.

[23] Consider now the question of crystal suspension. If the crystals were large, they would have pooled close to the surface of the LMO, and as they were swept to the farside, they would have been added to the margin of the crust, rapidly forming a global crust of nearly uniform thickness. Alternatively, if they were sufficiently small, the crystals would have been in suspension in a relatively deep layer near the top of the LMO, much as frazil ice is suspended in a rapidly flowing river or in polar polynas [*Omstedt*, 1985a, 1985b]. *Tonks and Melosh* [1990] reasoned on dynamic grounds that crystals smaller than 0.5–1.0 cm diameter can remain in suspension by turbulent mixing. *Solomatov and Stevenson* [1993a] came to a similar conclusion using energy arguments, noting "The radius of about 1 cm must be considered as an absolute upper bound above which fractional differentiation is guaranteed" (p. 5375). Would a significant fraction of the crystals remain small enough to stay in suspension? Crystal sizes for a terrestrial magma ocean have been estimated by *Solomatov and Stevenson* [1993b] to be close to the critical range: 1 cm or a bit smaller. This conclusion is dependent on a number of factors, including the cooling rate and the composition of the melt and crystal. Consequently, the answer to the question is not clear without a relatively detailed calculation, which is beyond the scope of the present paper.

[24] Crystals smaller than about 1 cm would remain suspended in the convecting magma, while those larger would sediment to the surface. As noted above, the fraction of such crystals is uncertain. Also uncertain is their rheological behavior and fate. If they were relatively large, few and far between, they would have pooled at the surface,

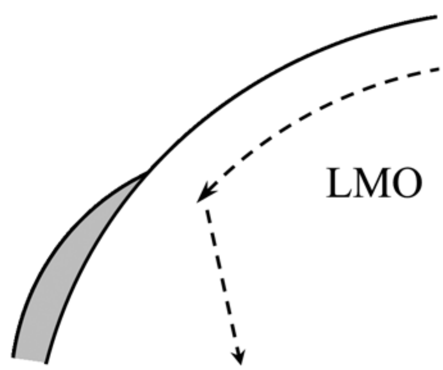

Figure 8. The conjectured trajectories of suspended crystals as they encounter the edge of the rigid, farside crust, depicted by the darkened crescent.

remained isolated, and been carried by the large-scale current to the farside crust. There they would have adhered to its perimeter, increasing its area. Alternatively, there might have been enough large floating crystals to form a layer. These crystals might have remained unconsolidated, behaving similar to slush or grease ice, which occurs in the polar oceans. This unconsolidated layer of slush would not have significantly inhibited convective heat loss, so that the vigor of the underlying convection would be roughly the same as in the absence of that layer. Alternatively, the floating crystals might have been welded into floes by Ostwald ripening. It is likely that these floes would have been dynamically weak, behaving physically in a manner similar to the initial chilled crust, except that they would have remained afloat. Both the frazil (i.e., suspended) and slush (i.e., floating) crystals would have been swept toward the farside by the large-scale currents at the top of the LMO associated with tilted convection, as illustrated in Figure 7. However, the dynamic situation changes dramatically where the surface layer is welded together and the mode of heat loss through that layer changes from convective to conductive.

[25] Beneath the rigid crust the vigor of convection would have been significantly reduced, as would the ability to hold frazil crystals in suspension. However, the change of cooling style would likely be accompanied by a change of large-scale convective motion, with the change favoring continued transport of frazil crystals, as illustrated in Figure 8. A good kinematic analogy of this change of motion is seen at the circum-Pacific continental margins. As oceanic crust moving toward a continent encounters the margin, it detaches from the surface and plunges downward at an angle placing it beneath the continent at depth. In the terrestrial case the cold lithospheric slabs are dense and continue to descend. In the lunar case the crystals were buoyant. Small-scale convective motions in the descending magma would diminish with distance, allowing the buoyant crystals to rise and underplate the farside crust. This scenario is somewhat speculative and is difficult to quantify, but it does provide a possible, and perhaps even plausible, mechanism whereby the crust on the farside could have been made thicker than that on the nearside.

[26] The physical processes involved in crystal transport by tilted convection are complex and not well quantified. The goal of the rather speculative discussion in this section has been to demonstrate that the proposed mechanism appears dynamically plausible. A considerably more detailed analysis is required to make a more definitive statement.

6. Resulting Asymmetries

[27] In the proposed model, anorthositic protocrust that formed near the surface during early lunar cooling was transported toward the farside and equator by tilted convection, resulting in a large-scale crustal asymmetry. The asymmetric distribution of farside and nearside crustal thickness accounts for nearly all of the center of mass/center of figure offset, while the thickening of equatorial crust likely accounts for the flattened geoid [*Neumann et al.*, 1996]. The crustal asymmetry and associated CM/CF offset was retained as the LMO solidified and the Moon cooled to its present state.

[28] The preferential transport to the farside of anorthosite would have led to a concentration of incompatible elements on the nearside. The effect of this may be seen in the geochemical province called the Procellarium KREEP terrane [*Jolliff et al*, 2000]. This possibility is discussed further in the companion paper [*Werner and Loper*, 2002].

[29] The model presented in this paper has been substantiated by a few order-of-magnitude estimates, but several key mechanisms need a much more detailed assessment before the model can be taken seriously. The key issues appear to be the flux of solid particles carried by tilted convection, the fraction of particles held in suspension by turbulent motions, and the manner in which the particles are deposited on the farside. It is hoped that this paper will serve to stimulate studies of these issues.

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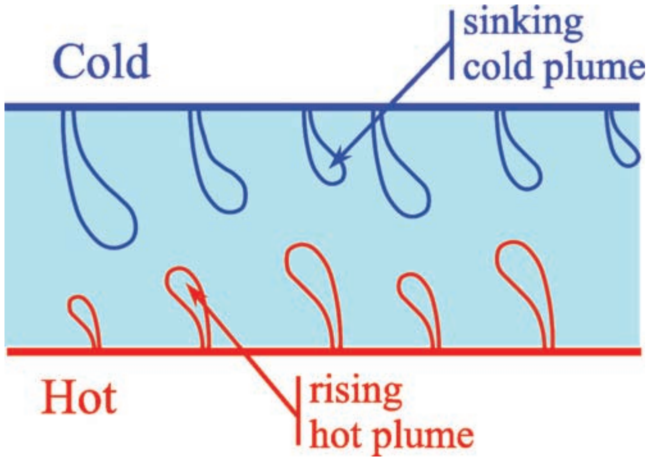

Figure 4. A schematic representation of the form of rising and sinking plumes during tilted convection.

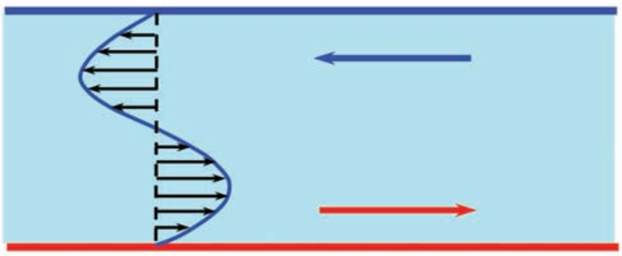

Figure 5. A schematic representation of the large-scale flow associated with tilted convection.