GEOPHYSICAL RESEARCH LETTERS, VOL. 28, NO. 21, PAGES 4023-4026, NOVEMBER 1, 2001

The composition and origin of the lunar crust: Constraints from central peaks and crustal thickness modeling

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Abstract. Spectral-reflectance data of lunar central peaks have revealed that the Moon's crust varies both laterally and vertically in composition. We correlate the depths of origin of materials that make up central peaks with a geophysically derived dual-layered crustal thickness model and find that the peak compositions are consistent with this stratified model. Specifically, peaks composed exclusively of rocks containing more than 85% plagioclase (by volume) come from this model's upper crust, whereas peaks that contain some norite or gabbro-norite come from the model's lower crust. Extrapolating these data we find that the Moon's upper crust is composed of 88±4% plagioclase, corresponding to 29 to 32 wt.% Al_2O_3. The most-mafic lower portion of the crust is composed of 65±8% plagioclase, having an Al_2O_3 content that lies between 18 and 25 wt.%. We show that the lower portion of the crust is consistent with having formed by cumulate flotation in a lunar magma ocean.

1. Introduction

One of the surprises of the Apollo program was the revelation that the Moon's highland crust is highly anorthositic in composition [e.g., *Wood et al.,* 1970]. It is now widely accepted that this is a result of the crystallization and subsequent flotation of plagioclase in a near-global magma ocean [e.g., *Warren,* 1985]. Continuing sample, remote-sensing and geophysical analyses have led many to further suggest that the crust becomes increasingly mafic with depth. If this is indeed true, then did the lower portion of the crust similarly form as a byproduct of a lunar magma ocean, or by some other process? We address this question by placing constraints on the vertical compositional gradients present within the lunar crust.

Many pieces of evidence have been used to support the hypothesis that the crust is either vertically zoned or stratified in composition. (1) An intracrustal seismic discontinuity ~20-km beneath the surface of the Apollo 12 and 14 sites [e.g., *Toksöz et al.,* 1974] suggests some form of compositional stratification within the crust at this locale. (2) The ejecta of large impact basins is often more mafic than the surrounding highlands [e.g., *Reid et al.,* 1977; *Ryder and Wood,* 1977; *Bussey and Spudis,* 2000]. (3) The central peaks of some complex craters have highly noritic compositions [e.g., *Tompkins and Pieters,* 1999]. (4) The noritic composition of the South Pole-Aitken basin has been suggested to be representative of deep crustal material [e.g., *Lucey et al.,* 1995; *Pieters et al.,* 1997; *Wieczorek and Phillips,* 1998]. And (5) the relationship between the Moon's gravity and topography is consistent with some form of density stratification within the crust [*Wieczorek and Phillips*, 1997]. While many of these observations are only strictly valid for specific regions of the crust, collectively they are suggestive of a more global phenomenon.

In this paper we first test the specific hypothesis that the lunar crust is stratified, possessing distinct upper anorthositic and lower noritic layers. We correlate the central peak compositions of *Tompkins and Pieters* [1999] with a dual-layered crustal thickness model proposed by *Wieczorek and Phillips* [1998] and find that these two studies are mutually consistent. Second, the central peak compositions are extrapolated to infer the composition of the upper and lower crustal layers. Finally, we show that the composition of the lower crust is consistent with having a magma-ocean cumulate-flotation origin.

2. Central Peak Compositions and Crustal Thickness

Using Clementine multispectral reflectance data, *Tompkins and Pieters* [1999] examined the central peaks of just over one hundred complex craters. By parameterizing the measured Clementine spectra with spectra of mixtures of lunar minerals, the composition of geologic units within these peaks were classified into 11 distinct rock types (see Table 1; While weak mafic absorption features are present in the GNTA1 and GNTA2 compositions, they cannot be uniquely attributed to either high- or low-calcium pyroxene). Since these craters are approximately randomly distributed across the lunar surface, and since central peaks are derived from varying depths within the crust, this dataset offers the possibility of investigating systematically lateral and vertical variations in crustal composition. For example, *Tompkins and Pieters* [1999] noted that the central peaks of craters that formed within large impact basins were in general more mafic than those that formed within the highland crust. They considered this to be consistent with the hypothesis that large impact basins excavate through the upper crust, bringing deep seated and more mafic lower-crustal materials to the surface. In this paper we further quantify this observation by using a geophysically-derived crustal thickness model.

Assuming that the lunar crust is stratified into distinct upper anorthositic and lower noritic layers, *Wieczorek and Phillips* [1998] constructed a dual-layered crustal thickness model of the Moon using the Clementine gravity and topography fields [*Lemoine et al.*, 1997; *Smith et al.*, 1997]. (Here we use an updated model that utilizes the Lunar Prospector gravity field of *Konopliv et al.* [1998]). Since modeling planetary gravity fields is inherently nonunique, this model made the assumption that most of the crustal thickness variations

Paper number 2001GL012918.
0094-8276/01/2001GL012918$05.00

occurred within the upper crust. This would be a reasonable expectation if impact cratering is the dominant process that redistributes crustal materials on the Moon. The thickness of the upper and lower crustal layers in this model were constrained by the depths of the intracrustal and crust-mantle seismic discontinuities observed beneath the Apollo 12 and 14 sites [e.g., *Toksöz et al.,* 1974]. Though a recent re-analysis of the Apollo seismic data suggests that the crust is thinner than originally suspected [*Khan et al.*, 2000], this will not affect the thickness of this model's upper crust.

We next compare the expected depth of origin of materials that make up central peaks with the thickness of this model's upper crust. The rationale is that if the depth of origin of a central peak is greater than the local thickness of the upper crust, then the peak should be composed of lower crustal materials. This improves upon the classification method used by *Tompkins and Pieters* [1999] which relied solely on whether a crater formed within an impact basin or the highland crust. We take the upper crustal thickness for each crater as the average thickness one crater diameter away from its center. Following *Tompkins and Pieters* [1999], we use the model results of *Cintala and Grieve* [1998] to determine a central peak's depth of origin beneath the pre-impact surface. This model assumes that the materials that make up a central peak originate from the maximum depth of melting that occurs in the impact process, which is approximately twice that of the crater's maximum depth of excavation.

In Figure 1 we plot the locations of the craters used in this study. Those craters whose central peaks are predicted to be derived from the model's upper crust are numerous (there are a total of 90) and are roughly randomly distributed across the lunar surface. The central peaks of these craters are predicted to have an origin ∼5 to 30 km beneath the surface. Only 18 craters are predicted to sample the lower crust, in contrast to 44 from the *Tompkins and Pieters* [1999] study, and these craters should sample materials from up to ∼20 km beneath the intracrustal interface.

Our main results for this section are plotted in Figure 2. In each graph, the depth of origin of a complex crater's central peak is plotted versus the local thickness of the upper crust. Points that plot above the one-to-one line should have peaks that are derived from the model's lower crust, whereas peaks that plot below this line should originate from within the model's upper crust. In Figure 2A, only those peaks

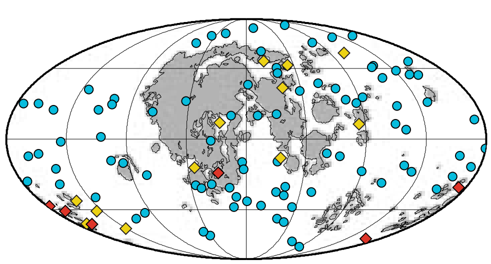

Figure 1. Location map of the craters used in this study. Those craters whose peaks are derived from the upper and lower crust are plotted as circles and diamonds, respectively. "Most-mafic lower crust" symbols represent central peaks that contain some norite or gabbro-norite. Gray shading represents the lunar maria, center meridian is 0° longitude, and the map is in a Mollweide projection.

Table 1. Mineralogy of the upper and lower crust

Rock Type and Assumed vol.% Plagioclase	Modal Abundance (vol.%) Upper Crust	Lower Crust	Most-Mafic Lower Crust
anorthosite (95±5)	40	14.4	0
GNTA1 (87.5±2.5)	34.4	18.5	4.2
GNTA2 (82.5±2.5)	15.7	26.6	17.2
anorthositic gabbro (70±10)	2.2	4.2	4.2
anorthositic gabbro-norite (70±10)	3.0	4.4	7.5
anorthositic norite (70±10)	2.7	16.4	29.7
anorthositic troctolite (70±10)	1.2	3.2	0
gabbro (50±10)	0.6	1.4	4.2
gabbro-norite (50±10)	0	5.7	17.2
norite (50±10)	0	5.3	15.8
troctolite (50±10)	0.4	0	0

that are composed exclusively of materials that contain more than 85% plagioclase by volume are plotted. All of these peaks are, within error, consistent with having an origin in the model's upper crust. Peaks that contain some norite or gabbro-norite are plotted in Figure 2B, and all of these are consistent with having an origin in the lower crust. We note that five of these mafic peaks are located within the South Pole-Aitken basin, and that the remaining peak is from the crater Bullialdus which lies close to the Nubium basin. The one occurrence of troctolite plotted in Figure 2B is consistent with having either an upper or lower crustal origin. These results suggest that our updated version of the *Wieczorek and Phillips* [1998] dual-layered crustal thickness model is a good predictor of where to find highly anorthositic and mafic rock types.

The peaks that are plotted in Figure 2 constitute just more than half of those in the *Tompkins and Pieters* [1999] database. Those that were not plotted contained lithologies intermediate in composition (60 to 85% plagioclase) and showed no clear correlation with being derived exclusively from either the model's upper or lower crust.

3. The Composition of the Moon's Upper and Lower Crust

In this section we use the dual-layered crustal thickness model and central peak compositions to constrain the composition of the upper and lower crustal layers. We implicitly assume that the central peaks used in this study are randomly distributed both across the lunar surface and with depth. Furthermore, if a peak contains multiple lithologies, we make the assumption that each rock type occurs in equal proportions for this region of the crust. While these are probably valid assumptions when averaged over the numerous peaks that sample the upper crust, they are probably less valid for the small number of peaks that sample the lower crust.

There are several ways to address the bulk composition of the crust, and we first consider the average proportion of rock types that are present in the upper and lower crustal layers. Our results are summarized in Table 1. It is seen

Table 2. Bulk properties of the lunar crust

Parameter	Upper Crust	Lower Crust	Most-Mafic Lower Crust
Plagioclase, vol.%	88±4	78±6	65±8
Al_2O_3, wt.%	29–32	24–29	18–25
Density, kg m^{-3}	2855±35	2938±49	3038±69

that 40% of the upper crust is composed of pure anorthosite (a rock that contains more than 90% plagioclase by volume), and furthermore, that 90% of the upper crust is composed of rocks that contain more than 80% plagioclase. The majority of the remaining material is composed of intermediate lithologies such as anorthositic norite, anorthositic gabbro-norite, anorthositic gabbro, and anorthositic troctolite.

Since we predict that only 18 central peaks are derived from the lower crust, our derived composition for the lower crust should not be considered to be as robust as our upper crustal results. Furthermore, because of uncertainties associated with our adopted crustal thickness model, as well as the modeled depth of origin of central peak materials, it is possible that a few upper crustal central peaks may have been misclassified as having a lower crustal origin (for instance, two highly anorthositic central peaks in Figure 2A lie just above the one-to-one line). Given the small sample of lower crustal central peaks, a few misclassifications would heavily bias a determination of the average lower-crustal bulk composition.

Recognizing the above sampling problem, we analyze a subset of the lower-crustal central peaks that might be representative of a mafic lower-crustal end-member composition. This "most-mafic lower crust" is based on the 6 central peaks that contain some norite or gabbro-norite. Our results show that this end-member composition lacks pure anorthosite and is considerably more mafic than the upper crust, being composed of 33% norite and gabbro-norite and 30% anorthositic norite. When compared to the upper crust, the most-mafic lower crust is seen to contain a greater relative abundance of norite with respect to gabbro. For example, in the upper crust, anorthositic norite, anorthositic gabbro-norite, and anorthositic gabbro all occur in roughly equal proportions. In the most-mafic lower crust, though, anorthositic norite is ∼7 times more abundant than anorthositic gabbro and norite is ∼4 times more abundant than gabbro. Similar results hold for the average lower crustal composition as well (see Table 1).

We next analyze the average composition of the upper and most-mafic lower crust in terms of their bulk plagioclase and Al_2O_3 content. These values play an important role in constraining aspects of lunar magma-ocean models, such as its initial depth and how efficiently plagioclase is removed from the crystallizing magma via flotation processes [e.g., *Warren,* 1985, 1990]. Using the data in Table 1, we find that the upper crust is composed of 88±4% plagioclase by volume, and that the most-mafic lower crust is composed of 65±8% plagioclase. We compute the Al_2O_3 content of these compositions by using the assumption that the mafic phases consist of equal proportions of olivine and orthopyroxene having molar Mg-numbers of 0.63 and 0.66, respectively, and that the plagioclase has an An_{96} composition [e.g., *Warren,* 1990]. Under these assumptions, the upper and most-mafic lower crust are found to have an Al_2O_3 abundance of 30.5±1.5 and 21.5±3.5 wt.%, respectively. The unfractured density of the upper and most-mafic lower crust are computed to be 2855±35 and 3038±69 kg m^{-3}, respectively (see Table 2). We note that the density of the lower crust used in the crustal thickness model of *Wieczorek and Phillips* [1998], 3100 kg m^{-3}, is consistent with our computed density of the most-mafic lower crust.

Our computed bulk composition of the upper crust is considerably more feldspathic than previous estimates. *Tompkins and Pieters* [1999] found the upper crust to be composed of ∼82% plagioclase, in comparison to our value of ∼88%. Because of the manner in which their value was computed, though, it should be considered only as a minimum estimate. Using Clementine derived iron abundances, *Lucey et al.* [1998] estimated the soils of the lunar highlands to have an Al_2O_3 abundance that lies between 27 and 29 wt.%. While our lowest estimate is consistent with *Lucey et al.*'s upper limit, our average value of 30.5 wt.% is more felsic than their average. Using the five most feldspathic lunar meteorites, *Korotev* [2000] obtained an Al_2O_3 abundance of 28 wt.% for the uppermost portion of the lunar crust, which again is slightly less feldspathic than our determination. We suspect that these two studies may have underestimated the abundance of plagioclase in the upper crust by being based on near surface samples. Our estimate, in contrast, is based on central peaks that are derived from up to 30 km beneath the surface. We note that our estimated abundance of plagioclase for the upper crust lies within the range of 91.6±9.1% that is representative of the Apollo pristine ferroan-suite rocks [*Warren*, 1990].

4. Origin of the Moon's Lower Crust

The evidence of this study combined with that presented in the introduction strengthens the case that the lunar crust is either globally stratified or becomes increasingly mafic

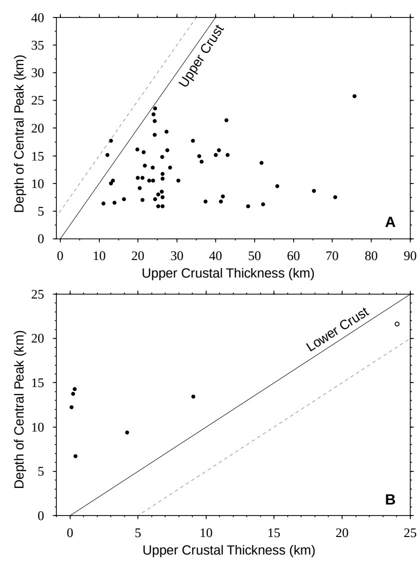

Figure 2. Plots of the depth of origin of central peak materials versus the thickness of the upper crust. Plot A is for those peaks that are composed exclusively of materials that contain greater than 85% plagioclase. Filled circles in plot B are for those peaks that contain some norite or gabbro-norite, and the unfilled circle is a single occurrence of troctolite. The dotted lines represent a possible 5-km uncertainty in the crustal thickness and central peak depth of origin determinations.

with depth. Assuming this to be the case, what is the origin of this vertical gradient in composition? One hypothesis put forth by *Head and Wilson* [1992] is that mare basaltic intrusions in the crust could have substantially modified the composition of a primary magma-ocean flotation crust. However, given the observation that the lower portion of the crust is primarily noritic in composition, as opposed to gabbroic, basaltic intrusions have probably not played a dominant role in affecting the bulk crustal composition.

It has also been proposed that the lower portion of the crust may be composed of Mg-suite plutonic rocks [e.g., *Reid et al.,* 1977; *Ryder and Wood,* 1977]. Gamma-ray data obtained from the Lunar Prospector mission, however, is making this scenario increasingly unattractive. Using this data, *Jolliff et al.* [2000], *Korotev* [2000], and *Wieczorek and Phillips* [2000] have argued that most of these plutonic rocks may instead have originated exclusively from within the regions of Mare Imbrium and Oceanus Procellarum.

We suggest that both the upper and lower portions of the crust could have formed by the process of magma-ocean cumulate flotation. In an investigation of the conditions under which a plagioclase-rich flotation crust could form, *Warren* [1990] noted the important role that the magma ocean's density played. Specifically, the density of the magma ocean was shown to determine the maximum quantity of mafic silicates that could be incorporated into the crust while still remaining positively buoyant. It is well known that as a magma ocean crystallizes that it becomes increasingly iron rich, and as *Warren* [1990] has quantified, increasingly dense as well. Thus, the proportion of mafic silicates that the flotation crust could support should increase as magma-ocean crystallization proceeds.

Using the model of *Warren* [1990], we find that near the terminal stage of magma-ocean crystallization (i.e., just before ilmenite begins to crystallize) that an assemblage of plagioclase and mafic silicates would float if this assemblage was made of more than $\sim$69% plagioclase by volume. Since we have determined the most-mafic portion of the lower crust to be composed of 65$\pm$8% plagioclase, we conclude that the lower portion of the crust could have formed by cumulate flotation in a magma ocean.

This scenario of crustal genesis seems to predict a crust that should be compositionally zoned, as opposed to stratified like the geophysical model that was tested in this paper. While a zoned crust may turn out to be a more realistic representation of crustal structure than a stratified one, the model of *Wieczorek and Phillips* [1998] does, nonetheless, appear to approximate fairly well the relative proportions of highly anorthositic and more mafic lithologies present within the crust.

Acknowledgments. We thank Randy Korotev and an anonymous reviewer for comments that improved this paper. This research was supported by the Lunar Data Analysis and Planetary Geology and Geophysics Programs under NASA grants NAG5-8707 and NAG5-4555, respectively.

References

Bussey, D. B. J., and P. D. Spudis, Compositional studies of the Orientale, Humorum, Nectaris, and Crisium lunar basins, *J. Geophys. Res., 105,* 4235-4243, 2000.

Cintala, M. J., and R. A. F. Grieve, Scaling impact melting and crater dimensions: Implications for the lunar cratering record, *Meteorit. Planet. Sci., 33,* 889-912, 1998.

Head, J. W., and L. Wilson, Lunar mare volcanism: Stratigraphy, eruption conditions, and the evolution of secondary crusts, *Geochim. Cosmochim. Acta, 56,* 2155-2175, 1992.

Jolliff, B. L., J. J. Gillis, L. Haskin, R. L. Korotev, and M. A. Wieczorek, Major lunar crustal terranes: Surface expressions and crust-mantle origins, *J. Geophys. Res., 105,* 4197-4216, 2000.

Khan, A., K. Mosegaard, and K. L. Rasmussen, A new seismic velocity model for the Moon from a monte carlo inversion of the Apollo lunar seismic data, *Geophys. Res. Lett., 27,* 1591-1594, 2000.

Konopliv, A. S., A. B. Binder, L. L. Hood, A. B. Kucinskas, W. L. Sjogren, and J. C. Williams, Improved gravity field of the Moon from Lunar Prospector, *Science, 281,* 1476-1480, 1998.

Korotev, R. L., The great lunar hot spot and the composition and origin of the Apollo mafic ("LKFM") impact-melt breccias, *J. Geophys. Res., 105,* 4317-4345, 2000.

Lemoine, F. G., D. E. Smith, M. T. Zuber, G. A. Neumann, and D. D. Rowlands, A 70th degree lunar gravity model (GLGM-2) from Clementine and other tracking data, *J. Geophys. Res., 102,* 16,339-16,359, 1997.

Lucey, P. G., D. T. Blewett, and B. R. Hawke, Mapping the FeO and TiO_2 content of the lunar surface with multispectral imagery, *J. Geophys. Res., 103,* 3679-3699, 1998.

Lucey, P. G., G. J. Taylor, and E. Malaret, Abundance and distribution of iron on the Moon, *Science, 268,* 1150-1153, 1995.

Pieters, C. M., S. Tompkins, J. W. Head, and P. C. Hess, Mineralogy of the mafic anomaly in the South Pole-Aitken Basin: Implications for excavation of the lunar mantle, *Geophys. Res. Lett., 24,* 1903-1906, 1997.

Reid, A. M., A. R. Duncan, and S. H. Richardson, In search of LKFM, *Proc. Lunar Sci. Conf., 8th,* 2321-2338, 1977.

Ryder, G., and J. A. Wood, Serenitatis and Imbrium impact melts: Implications for large-scale layering in the lunar crust, *Proc. Lunar Sci. Conf., 8th,* 655-668, 1977.

Smith, D. E., M. T. Zuber, G. A. Neumann, and F. G. Lemoine, Topography of the Moon from Clementine lidar, *J. Geophys. Res., 102,* 1591-1611, 1997.

Toksöz, M. N., A. M. Dainty, S. C. Solomon, and K. R. Anderson, Structure of the Moon, *Rev. Geophys., 12,* 539-567, 1974.

Tompkins, S., and C. M. Pieters, Mineralogy of the lunar crust: Results from Clementine, *Meteorit. Planet. Sci., 34,* 25-41, 1999.

Warren, P. H., The magma ocean concept and lunar evolution, *Annu. Rev. Earth Planet. Sci., 13,* 201-240, 1985.

Warren, P. H., Lunar anorthosites and the magma-ocean plagioclase-flotation hypothesis: importance of FeO enrichment in the parent magma, *Am. Mineral., 75,* 46-58, 1990.

Wieczorek, M. A., and R. J. Phillips, The structure and compensation of the lunar highland crust, *J. Geophys. Res., 102,* 10,933-10,943, 1997.

Wieczorek, M. A., and R. J. Phillips, Potential anomalies on a sphere: Applications to the thickness of the lunar crust, *J. Geophys. Res., 103,* 1715-1724, 1998.

Wieczorek, M. A., and R. J. Phillips, The Procellarum KREEP terrane: Implications for mare volcanism and lunar evolution, *J. Geophys. Res., 105,* 20,417-20,430, 2000.

Wood, J. A., J. S. Dickey, U. B. Marvin, and B. N. Powell, Lunar anorthosites and a geophysical model of the Moon, *Proceedings of the Apollo 11 Science Conference,* pp. 965-988, Pergamon Press, New York, 1970.

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(Received January 28, 2001; revised May 22, 2001; accepted June 25, 2001.)