Topographic-Compositional Units on the Moon and the Early Evolution of the Lunar Crust

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The distribution of elevations on the moon determined by Clementine deviates strongly from a normal distribution, suggesting that several geologic processes have influenced the topography. The hypsograms for the near side and far side of the moon are distinctly different, and these differences correlate with differences in composition as determined by Apollo orbital geochemistry, Clementine global multispectral imaging, and ground-based spectroscopy. The hypsograms and compositional data indicate the presence of at least five compositional-altimetric units. The lack of fill of the South Pole–Aitken Basin by mare basalts suggests poor production efficiency of mare basalt in the mantle of this area of the moon.

The marked difference between the near and far side of the moon was evident from the first high-quality images obtained of the far side. The intensely cratered far side largely lacks the vast basaltic plains that cover a third of the nearside surface. Data collected by Apollo underscore this difference. The Apollo orbital geochemistry experiments showed that the farside crust overflown by those instruments is deficient relative to the near side in Th, Ti, and Fe and has lower Mg/Al ratios. The Apollo laser altimeter demonstrated that this nearside-farside dichotomy extends to lunar topography as well, showing that the near side stands an average of 3.2 km below the far side (*1*).

The Clementine mission provides data which strengthen the contrast between near and far sides. This mission collected near-global topographic data with a laser ranger (*2*). It also collected global multispectral imaging data in 12 wavelengths from 415 nm to 8 μm. The latter data set will make its greatest contribution after a lengthy calibration and data preparation process. However, we have produced a globally co-registered visible and near-infrared (NIR) data set with approximately 50-km resolution providing a global view of lunar albedo and color (*3*) between the latitudes of +75° and −75°. Figure 1 shows the 950-nm albedo, the 950/750-nm ratio, and lunar global topography, also between +75° and −75° latitude.

The hypsogram (the distribution of elevation as a function of area) of a planetary surface provides insight into very large-scale planetary processes. For example, the terrestrial hypsogram is bimodal and reflects a marked difference between the oceanic and continental lithospheres. The lunar hypsogram, although not distinctly bimodal, clearly shows more structure than the simple normal distribution of altitudes that might be expected from a saturated cratered surface (Fig. 2). Additionally, the nearside and farside hypsograms are distinctly different, not only in mean elevation, but in width as well. The nearside hypsogram shows a narrow distribution of elevations with a mean elevation of about 2 km below datum with a width at half height of about 2.5 km. The nearside curve appears to have at least two major modes. In contrast, the farside hypsogram is much broader, having a width at half height of almost 5 km and showing both the highest and lowest elevations on the planet. The farside hypsogram shows three major modes.

Our examination of the near- and farside hypsograms suggests that there are five major hypsographic units present on the moon, with mode peaks at −5.5, −3, −2, 0, and +4 km above datum. Although these units strongly overlap, placing unit boundaries between the mode peaks at −4, −2.5, −1, and +3 km shows that these hypsographic units exhibit contiguous spatial occurrences (Fig. 3). The unit at lowest elevations, between −7 and −4 km, is on the far side and corresponds primarily to the South Pole–Aitken impact basin. The unit between −4 and −2.5 km corresponds primarily to the nearside mare basalts. The hypsographic units are not always confined to one hemisphere. The unit between −2.5 and −1 km contains much but not all of the nearside highlands and extends onto the far side in the north and east. The unit between −1 and +3 km occurs chiefly on the far side, but like the −2-km mode, it is not confined to one hemisphere. Portions of this hypsographic unit extend around to the near side to the south, to the west near Orientale and Humorum, and in a broad arc from the mid-latitude east, around south of Nectaris up through and terminating in the eastern Central Highlands. The unit above +3 km is a compact area to the north of Korolev Basin.

We used Apollo orbital geochemistry, ground-based NIR spectroscopy, and Clementine global visible and NIR color data to characterize the compositional characteristics of these units. A correlation of topography and composition is evident from Apollo data (*4*). As our units are defined altimetrically, we were not surprised to find a similar relation coupling Clementine topography data with the Apollo orbital geochemistry data which covers a narrow range of equatorial latitudes. We also found correlations between topography and composition using ground-based and Clementine compositional data for portions of the moon not covered by the Apollo gamma ray and x-ray spectrometers.

Each unit defined above has distinct, but somewhat overlapping, geochemical characteristics based on examination of Apollo orbital geochemistry and Clementine multispectral data (Figs. 4 and 5). Excluding the mare and South Pole–Aitken Basin units; the −2-km unit, occurring principally on the near side, shows higher values for Fe, Th, and Ti and Mg/Al ratio, whereas the +4-km unit shows lower values for Fe, Th, and Ti. No Mg or Al data exist for the +4-km unit. The 0-km unit is intermediate in Fe, Th, and Ti and lower in Mg/Al ratio than the −2-km unit. With petrologic maps based on the Apollo geochemical data (*5*) and the results of ternary mixing models with ferroan anorthosite, Mg-suite–KREEP (potassium, rare-earth element, and phosphorus), and mare basalt as end-members (*6*), the +4-km unit is clearly dominated by anorthosite, whereas the other two units contain higher proportions of the more mafic components.

The Clementine multispectral data show that the −2-km unit has a somewhat lower albedo and a slightly lower value in the 950/750-nm ratio than the 0-km unit (Fig. 5). These multispectral parameters are commonly associated with mafic content, though this association must be treated with caution (*7*). The +4-km unit, indicated by mixing models to be highly anorthositic, is not anomalous in albedo or mafic ratio, being almost indistinguishable from the rest of the farside highlands. Higher albedos and lower values of the mafic-correlated ratio do occur, but in a broad area in the northern part of the central far side. These data may indicate that the correlation between Th and mafic content observed in the samples returned from the

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near side may not hold for the far side.

Finally, Earth-based spectroscopy has shown that exposures of the 0-km unit which extend onto the near side contain anorthosite in the rings of Orientale, Humorum, and Nectaris basins (8). Except for the discovery of anorthosite in Aristarchus crater (9) and the central peak of Alphonsus crater (10), nearside anorthosites identified to date are confined to the 0-km unit.

The primary characteristics to be addressed regarding the lunar nearside-farside dichotomy are the large differences in elevations, the compositional asymmetry, and the difference in the widths of the hypsographic curves. Additionally, the geochemical dichotomy between the near and far side may extend to the deep interior (11). On the lunar near side, all topographic lows have been filled by mare basalts, which may have flooded to a hydrostatic level (12). However, the lunar far side, although in general standing higher, exhibits a large topographic low in the South Pole–Aitken Basin, far below the level of the nearside mare. The South Pole–Aitken Basin does exhibit a small amount of mare material in its floor, but the basin is not filled to the near side mare level, though this ancient basin predates the mare (13). An analysis of the emplacement of mare basalts on the moon (14) showed that nearside crustal thicknesses required magma overpressures in excess of 20 MPa to allow extensive eruptions to occur, and clearly this overpressure was abundantly available on the near side. With the methods detailed in (14) and the 20-km crustal thickness calculated for the South Pole–Aitken Basin (2), a magma overpressure of only 6.4 MPa would allow eruptions to occur in this basin. Some process has inhibited eruption of mare basalts in this portion of the moon, and a deficiency of heat-producing elements relative to the near side is a likely candidate. Luna 10 and 12 gamma ray results for an area near the center of the South Pole–Aitken Basin show very low U and Th abundances (15).

Of the several models that attempt to account for the geochemical dichotomy, only impact and primordial differentiation processes can plausibly account for a hemispheric difference in mean elevation and surface composition. A single large impact or large multiple impacts could have thinned the nearside crust exposing a mafic lower crust (16) and depositing more anorthositic material on the far side (13). One would expect that the rim of this large basin would show the highest elevations rather than the antipodes, but one could also envision an impact of just the right size and velocity so that the emplacement of ejecta on the spherical moon would yield an antipodal thickening. This fortuitously sized impact could also explain the narrowness of the nearside hypsogram, as updoming of isotherms would have promoted extensive volcanism in the basin floor, leveling the long-wavelength topography and accounting for the −2-km hypsographic unit. It has been suggested, on the basis of remote sensing evidence, that the near side experienced a volcanic resurfacing event (17), which is supported by the presence of numerous types of ancient volcanic rocks of unknown volumetric importance in the sample collection (18). However, it is difficult to envision an impact that could have also imprinted a compositional hemispheric dichotomy on the lunar mantle as suggested

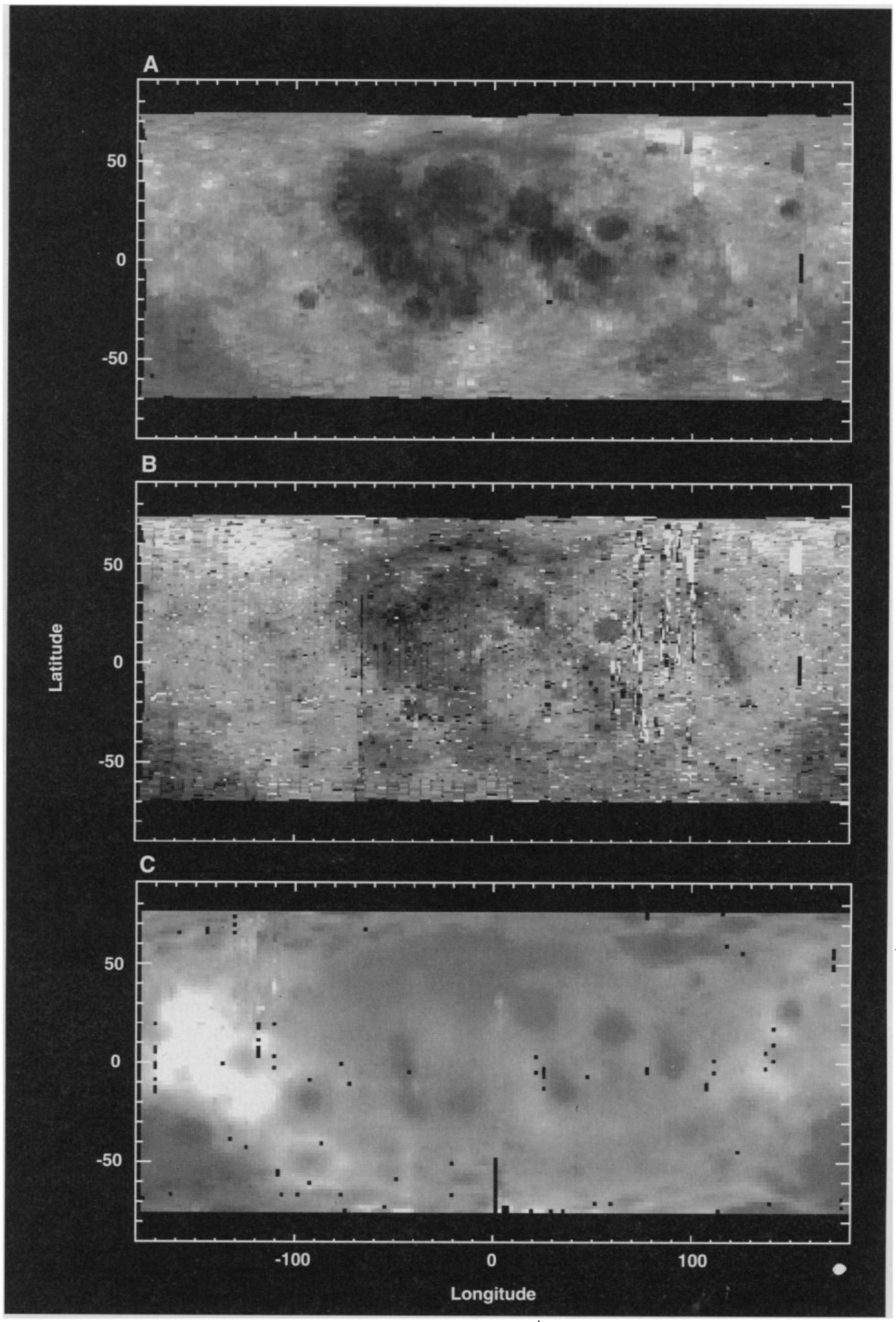


Fig. 1. (A) A 950-nm relative albedo image of the moon derived from Clementine multispectral imaging. The projection is simple cylindrical. **(B)** A 950/750-nm ratio image. The vertical striping in the central right portion of the image is due to images obtained at extreme photometric geometries for which adequate photometric correction has not yet been made. **(C)** Image of lunar topography obtained by the Clementine laser ranger. Highest elevations are white and lowest elevations are black. The data were constructed by (2) and gridded to 2° sampling. This image was then filtered with a Gaussian spatial passband to a resolution of 4°.

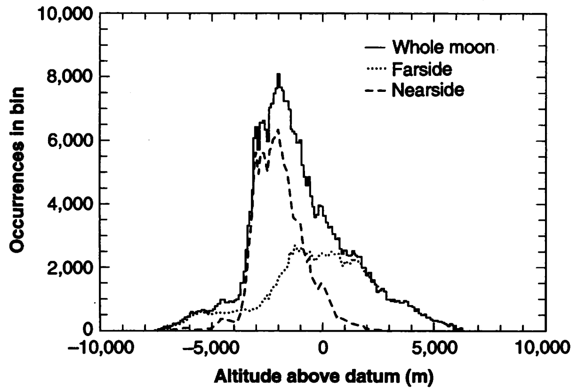


Fig. 2. The lunar hypsogram (solid line), with the nearside (dashed line) and farside (dotted line) hypsograms superimposed. The hypsograms were constructed from an equal-area projection of the data presented in Fig. 1C.

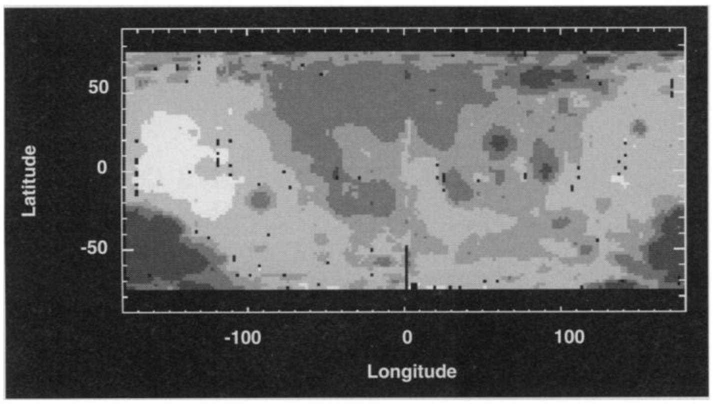
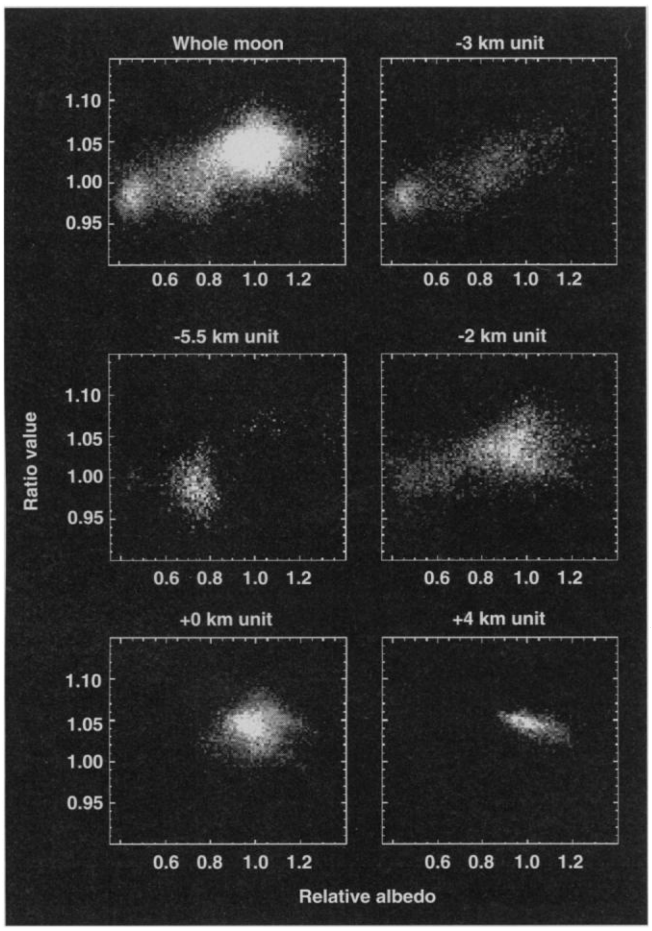


Fig. 3. Unit map based on the altimetric data presented in Fig. 1C. Units are defined by elevation contours at −4.0, −2.5, −1.25, and +3.0 km above datum.

by the absence of mare basalts in the South Pole–Aitken Basin and by other evidence (*10*).

As giant impact cannot easily account for the apparent deep-interior hemispheric compositional dichotomy, we propose an alternative hypothesis that the largest scale topographic features on the moon are the result of primordial crustal differentiation processes. These processes would have included large-scale lateral transport of lunar material to produce the hemispheric compositional asymmetry. We suggest that the anorthositic material making up the earliest lunar crust was not only concentrated near the surface by means of plagioclase flotation but accumulated on the far side over a large-scale convective downwelling and may have even formed a small "continent," now represented by the +4-km unit. A complementary convective upwelling under the nearside crust would serve to thin the crust through thermal erosion from below and to emplace surface lava flows due to net extensional stresses coupled with availability of magma near the surface (*19*). These processes provide explanations for (i) the narrowness of the nearside hypsogram as due to volcanic infilling of topographic lows over a convective downwelling, (ii) the presence of the +4-km hypsographic unit as



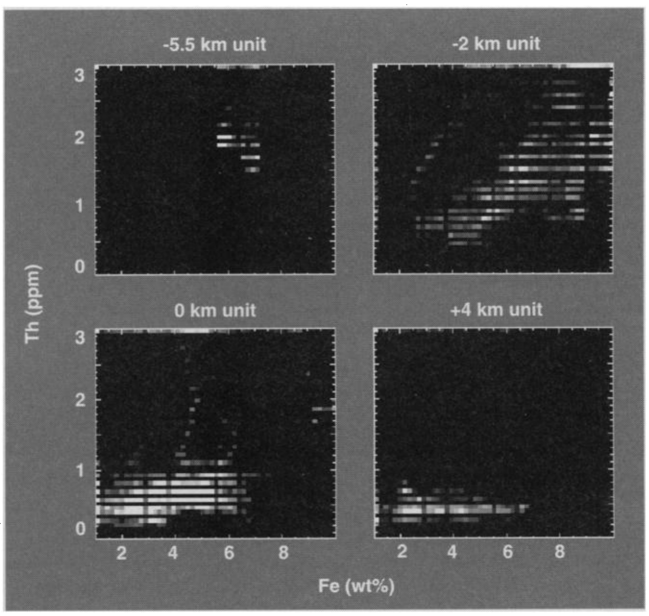


Fig. 4 (left). Scatter diagrams of Clementine albedo and color data. Each *x*-axis is the scaled albedo at 950 nm, and each *y*-axis is the value of the 950/750-nm ratio. Each of the hypsographic units are represented as well as the moon as a whole. **Fig. 5 (right).** Scatter diagrams of Th versus Fe derived from Apollo orbital geochemistry for the three highland units and the −5.5-km unit which largely represents South Pole–Aitken Basin.

a result of net compressive forces operating on the hot early crust over a convective downwelling, and (iii) the hemispheric surficial and interior dichotomy as due to lateral transport of material during differentiation. The model is in conflict with the simple geophysical argument that the high Rayleigh number of a 500-km-thick magma ocean will promote small-scale turbulent convection rather than global-scale convection, but the current degree of ignorance of nature, let alone behavior of the actual lunar magma ocean, may not make this a tightly binding constraint.

The distribution of elevations on the moon is distinctly irregular, and the near side and far side differ both in mean elevation and shape of the hypsographic curve. There is a correlation between topography and composition, and five hypsographic units have been defined with differing compositional characteristics. Two of these units, the South Pole–Aitken Basin and the nearside mare basalts, are clearly the result of impact and volcanism, respectively. The lack of extensive mare basalt fill in the South Pole–Aitken Basin, despite the thin crust in this region, suggests hemispheric compositional asymmetry in the deep lunar interior. Early giant impact can explain many of the observed characteristics, but not the deep-interior compositional asymmetry. Primordial differentiation processes can explain all of the observed compositional and hypsographic characteristics but suffer from the lack of an understood mechanism for causing global- rather than small-scale lateral convective transport.

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3. This data set was constructed by averaging all pixels in each charge-coupled device (CCD) camera image to a single pixel. Each "image-pixel" was then calibrated for camera gain and offset and integration time. The data were then projected into simple cylindrical coordinates. Each image was photometrically corrected with the Lommel-Seliger photometric function. Finally, an empirical phase function was derived from a portion of the far side highlands between the longitudes of the eastern South Pole–Aitken Basin and the western portion of the Orientale Basin.
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7. The albedo and the ratio of a band near 1 μm and a band on the continuum, usually around 560 or 750 nm, are typically used to infer the relative amounts of mafic material in mature lunar soils in multispectral images. However, these parameters are not unambiguously coupled to the mafic content of lunar soils. The albedo of a mature soil is due to the reflectance of the minerals making up the source rock, the reflectance of impact glasses produced by micrometeorite bombardment, and the amount of reduced iron in the soil in the form of submicroscopic blebs which are produced by the reduction of Fe^{2+} in minerals by solar wind–implanted hydrogen. Mafic minerals in source rocks vary widely in their reflectances, and each mineral is subject to the reduction process at different rates. Work by E. M. Fischer and C. M. Pieters (*J. Geophys. Res.*, in preparation) shows that there is no correlation between Al and visible albedo for highland areas overflown by Apollo x-ray spectrometers. The ratio of a band near 1 μm to a continuum band is not directly coupled to mafic content in that it decreases in value with increasing abundance of mafic minerals but increases in value with maturity, but the specific mineralogy of the source dictates the relative importance of these properties. Thus, these parameters must be used with care when specifying the composition.
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Clementine Observations of the Aristarchus Region of the Moon

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Multispectral and topographic data acquired by the Clementine spacecraft provide information on the composition and geologic history of the Aristarchus region of the moon. Altimetry profiles show the Aristarchus plateau dipping about 1° to the north-northwest and rising about 2 kilometers above the surrounding lavas of Oceanus Procellarum to the south. Dark, reddish pyroclastic glass covers the plateau to average depths of 10 to 30 meters, as determined from the estimated excavation depths of 100- to 1000-meter-diameter craters that have exposed materials below the pyroclastics. These craters and the walls of sinuous rilles also show that mare basalts underlie the pyroclastics across much of the plateau. Near-infrared images of Aristarchus crater reveal olivine-rich materials and two kilometer-sized outcrops of anorthosite in the central peaks. The anorthosite could be either a derivative of local magnesium-suite magmatism or a remnant of the ferroan anorthosite crust that formed over the primordial magma ocean.

The Clementine mission has provided global multispectral mapping of the entire moon in 11 bandpasses (415, 750, 900, 950, 1000, 1100, 1250, 1500, 2000, 2600, and 2780 nm) and altimetry profiles from about −75° to +75° latitude (*1*). In this report, we present preliminary interpretations of a small portion of these observations, from the Aristarchus region (latitude 18°N to 32°N, longitude 42°W to 57°W).

The geologic and compositional diversity of the Aristarchus region (*2–7*) and evidence for active emission of volatiles from Aristarchus crater (*8–9*) have led to proposals for surface exploration and resource exploitation (*10–12*). The 170 km by 200 km Aristarchus plateau, an elevated crustal block just west of the outer ring of the Imbrium Basin (Fig. 1), includes the densest concentration of sinuous rilles known on the moon. Most of these rilles begin at distinctive "cobra-head" craters (or irregular depressions), the probable source vents for a reddish dark mantling deposit (DMD) that blankets the entire elevated plateau; the DMD probably consists of volatile-rich pyroclastic glass (*4, 13, 14*). The plateau is embayed on all sides by mare basalts of Oceanus Procellarum. The well-preserved Copernican impact crater Aristarchus, 42 km in diameter, lies on the southeastern edge of the plateau. The Aristarchus plateau may have been the source region for a significant portion of the mare basalts of Oceanus Procellarum (*15*). The movement and temporary storage of a large volume of

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