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ORIENTALE AND SOUTH POLE-AITKEN BASINS ON THE MOON: PRELIMINARY GALILEO IMAGING RESULTS.

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On the near side of the Moon visible from Earth, the bright areas or "highlands" are composed of light-colored rock saturated with craters formed over eons by impacting meteors. Younger, less cratered, darker plains, or "mare," are composed of a thin layer of basaltic lava flows that erupted over 3 billion years ago and buried highlands-type rocks. The mare plains are concentrated into discrete, circular, topographically low regions called "basins," each of which typically also contains several concentric, ring-like belts of high mountains. Several dozen of these basins, from 300 to nearly 2000 kilometers in diameter, are filled to varying degrees with mare basalts [1,2]. The basins are thought to have formed more than 3.8 billion years ago, when the Earth, Moon, and other planets were bombarded by "leftover" asteroid-sized bodies being "swept up" gravitationally after accretion of the Solar System - hence the term "impact basins" generally applied to them [e.g., 3]. The impacting asteroids struck the Moon at velocities of around 20 km/s, excavating cavities hundreds of kilometers in diameter that penetrated deep into and perhaps even below the lunar crust. These fresh cavities promptly collapsed back in on themselves, perhaps through some combination of slumping of the cavity walls and rebound of the floors [4, 5, and others], creating the concentric belts of mountains or "basin rings."

The Imbrium basin, located in the northwestern part of the near side, has been recognized for nearly 100 years as one of the clearest examples of this type of feature [1,3,6,7,8,9,10]. An outer mountain ring, nearly 1200 km in diameter, marks a "step down" topographically from the surrounding highlands. The basaltic flows composing Mare Imbrium mostly fill the enclosed topographic depression. The interior of the mare plain also contains two well developed concentric belts of high mountains 700 and 900 km in diameter. These mountains are composed of light-colored rock like the highlands, and protrude from beneath the layers of basalt flows.

Like the Imbrium basin, most parts of other large near side basins were also buried by mare lavas that flooded in through fractures in the basin floors over the next several hundred million years. This obscured most of the original structure of the basins, including rocks excavated from tens-of-kilometers depths. Many questions about the formation and evolution of these basins, and about the nature of the lower crustal or upper mantle rocks possibly exposed within them, could be addressed if the obscuring cover of mare could be "seen through": What kinds of rocks form the inner regions of the impact basins? Are they monotonously similar from place to place, as suggested by the bland light color of highland rocks, or are there different types of rocks produced by a complex history of geologic activity? Are they like the rocks composing the highlands or are they different, providing a sample of the Moon's interior below its light-colored crust? What sequence of geologic events shaped the basins' floors and the rings of mountains in their interiors? These issues are pertinent not only to understanding lunar geology, but also to understanding the early evolution of the Earth. Our planet's geologic record of this early period has long been erased by erosion, volcanism, and plate tectonic processes, but the Earth like the Moon must also have experienced the fracturing and churning of its crust caused by basin formation. Understanding how these processes affected the Moon helps us to understand what role basin formation may have had in the Earth's earliest geologic evolution.

The Orientale basin, located at the western limb of the near side and in the adjacent portion of the far side, provides a "window" into the interior of a large impact basin. Orientale is the youngest and best-preserved of all the large lunar basins, and unlike the near side basins it contains only a patchy, discontinuous cover of mare lavas. Thus its interior structure and its deeply excavated rocks are visible at the lunar surface [3,8,10,11,12,13]. The Orientale basin was in the sunlit portion of the Moon during the flyby of *Galileo* through the Earth-Moon system on December 7-8, 1990 [14,15], and it was imaged with a resolution of 3 km by the spacecraft's Solid-State Imaging (SSI) camera. The SSI camera has seven color filters covering the wavelength range 0.4-1.0 microns, that is, in visible light and beyond red into the invisible, longer wavelength near-infrared range [16].

The multicolor nature of *Galileo*'s images can reveal aspects of the geology of the lunar surface that are not discernable from monochromatic, black-and-white images. Only a handful of minerals compose nearly all of the rocks on the visible surface of the Moon. The highlands are dominated by light-colored, aluminum-rich minerals called feldspars, and the dark color of the mare plains results from mixture of iron- and magnesium-rich ("mafic") minerals with a smaller fraction of feldspar and a titanium-rich mineral called ilmenite. Each of these minerals has a subtly different color within the wavelength range visible to the SSI camera, so that the color of a particular rock provides information on its mineral makeup.

Actual samples of lunar rock and soil have been returned to Earth only from six *Apollo* landing sites and three sites visited by automated Soviet *Luna* spacecraft. Detailed compositional information has therefore been determined directly only for a very restricted set of areas, all on the near side. By using *Galileo* images and laboratory measurements of returned lunar samples, compositional information provided by color was extrapolated away from the landing sites into regions seen poorly or not at all from Earth, including the lunar far side [17,18]. This was accomplished by a two-step procedure. First, to enhance the very subtle color differences on the lunar surface, images acquired through filters showing important color contrasts were ratioed to each other. Second, the image products were calibrated to the landing sites. Returned rocks and soils from the landing sites, whose color properties were measured in the laboratory, serve the same role as human flesh does when a color television is adjusted: by "tuning" color to accurately represent these known areas, an accurate color of unknown areas simultaneously results. These color determinations, when compared to color and compositional measurements of the returned samples, provide information on composition in areas from which samples have <u>not</u> been returned.

For example, the ratio of brightness in the 0.40 micron "violet" filter to brightness in the 0.75 micron filter is particularly useful geologically. Higher ratios indicate a "bluer" soil - in other words, a soil that reflects relatively more light at short wavelengths such as blue. In well-developed mare soils returned to Earth, a very "blue" soil color has been found to indicate a basalt composition rich in titanium. Maps of the near side constructed from ratioed telescopic photographs demonstrate a variety of mare units with different "bluenesses," and thus contents of titanium [19]. *Galileo* images yield analogous information on basalt compositions, except that they show not only the near side but also far side regions invisible from Earth [20]. Similarly, mafic minerals in returned lunar samples strongly absorb near-infrared light with a wavelength of about 1.0 micron, whereas feldspars do not. The ratio of brightness in the 1.0 micron SSI filter to brightness in the 0.75 micron filter is thus a measure of the content of mafic minerals in surface materials. This procedure of extrapolating compositional information into areas not sampled by landers has allowed us to determine some of the basic compositional properties of Orientale and other far side basins.

The landscape and physical geology of the Orientale basin are known from photographs acquired during American *Lunar Orbiter* and *Apollo* missions and by Soviet *Zond* spacecraft [3,8,10,11,12,13]. The basin's topographic depression is bounded by the 900-km diameter Montes Cordillera ring, which consists partly of an inward-facing scarp and partly of high mountains. Two inner concentric rings of high mountains, 480 and 620 km in diameter, are known collectively as Montes Rook. Outside of Montes Cordillera lies a broad region of ridges and grooves generally arranged radially to the basin. This surface, known geologically as the "Hevelius Formation," is interpreted as ejecta thrown from Orientale at the time of the basin-forming impact. The surface between Montes Cordillera and Montes Rook, the "Montes Rook Formation," is characterized by roughly equidimensional knobs 2 to 5 kilometers across set in smooth to gently rolling surface terrain. This origin of this material is not so well understood; some planetary scientists believe that it is also ejecta lofted by the basin-forming impact, but derived from deeper in the Moon than the Hevelius Formation. Light-colored plains inside the Montes Rook rings, the "Maunder Formation," have a cracked surface suggestive of cooling and fracturing of highland crustal material melted by the heat of the basin-forming impact. Three small regions of mare, Mare Orientale at the center of the basin and Lacus Veris and Lacus Autumnii nestled between the basin rings, account for the very limited amount of younger mare basalts erupted here. Very little is known about composition of the materials forming the basin: spectroscopic studies from Earth, where Orientale is barely visible, do indicate a feldspar-rich composition poor in mafic minerals [21].

Multicolor *Galileo* images of the Orientale basin have provided new indications of the composition of these geologic formations, so that questions about the origin and evolution of lunar basins can be more fully addressed [22]. Overall, like typical feldspar-rich highlands, the basin interior has a low abundance of mafic minerals indicating that basin formation did not excavate radically different rock types from depth. However one large crater within the Montes Rook Formation, called Lowell, does have an enhanced content of mafic minerals. The lunar mantle and lower crust are thought to be richer in mafic minerals than the upper crust forming the typical highlands, so Lowell may be a site where deep-seated rocks uplifted by basin formation have been exposed. The Maunder Formation and Montes Rook Formation appear as annuli with distinctive color properties, suggestive perhaps of small variations in feldspar-rich rock compositions. The Hevelius Formation exhibits subtle, patchy color variations, but there is no evidence of a concentric compositional zonation that might have resulted if the basin formed in a compositionally layered crust.

In the southeastern part of the Hevelius Formation, both the Hevelius Formation itself and small craters formed on top of it show evidence for a greater abundance of mafic minerals than in the basin interior or in typical highlands. The enhanced-mafic region covers an area of 200,000 to 400,000 square kilometers, comparable to the size of some of the smaller maria. The region also contains craters with dark haloes, seen from Earth and thought to have formed by excavation of a dark layer of mare material from a shallow depth [23,24]. This evidence all points to the existence of very old mare plains, buried by the Hevelius Formation when it formed as ejecta from the Orientale basin, whose ancient lavas have been excavated by small craters penetrating the thin ejecta layer. The presence of this mantled mare or "cryptomare" substantiates evidence from other studies which suggests that mare volcanism began before the end of the period of formation of large basins [25].

Galileo images of the lunar far side highlands also show the region of the South Pole-Aitken basin, one of the oldest known large basins on the Moon. With a diameter of 2000 kilometers, it is also the largest well-documented lunar basin [26]. Compared to typical highlands, the interior of the South Pole-Aitken basin is darker-colored in monochromatic images taken through single filters, though not as dark as the mafic-rich mare lavas. Multicolor images show that the content of mafic minerals within the basin is greater than in surrounding highlands, and the mafic content varies across the basin floor. Some mare plains occur here as scattered small patches [20,26], but are too small to account by themselves for the relatively large mafic component throughout the basin interior. Measurement of gamma-rays from the lunar surface, taken during the *Apollo* missions, also show that highland material within the South Pole-Aitken basin has a larger iron content than do typical highlands [27]. These observations present a contrast with the smaller

Orientale basin, where there is little evidence of magnesium- and iron-rich mafic rocks forming the basin's interior. Based on this combination of data from *Apollo* missions and *Galileo*, it appears that the South Pole-Aitken basin either contains a cryptomare or excavated mafic-rich rocks from the lower crust or upper mantle.

In summary, multicolor images of the Moon obtained by *Galileo* reveal variations in color properties of the lunar surface. Using returned lunar samples as a key, the color differences can be interpreted in terms of variations in the mineral makeup of the lunar rocks and soil. Thus the combined results of *Apollo* landings and multicolor images from *Galileo* allow extrapolation of surface composition to areas distant from the landing sites, including the far side invisible from Earth. Two very large impact basins visible in the multicolor images of the far side, the Orientale and South-Pole Aitken basins, have very different compositional properties as shown by these images. The Orientale basin, with a diameter of 1200 kilometers, appears to have excavated into rocks very similar to typical lunar highlands, rich in feldspars and poor in mafic minerals. Ejecta thrown out of the basin during its formation apparently thinly covered a substantial region of very old mare to the southeast, but the mare's dark mafic rocks have been excavated by later impact craters. In contrast, the interior of the 2000-km diameter South Pole-Aitken basin is much richer in mafic minerals than the surrounding highlands. Perhaps the South Pole-Aitken basin also contains regions of thinly covered ancient mare; alternatively, because it is larger that the Orientale basin, perhaps it excavated rocks richer in mafic minerals from the Moon's lower crust or upper mantle.

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