acquired with double exposures (long and short), it is anticipated that estimated values for this readout error can be tested and improved with in-flight data. The second source of error is a more poorly defined additive signal due to scattered light. The presence of scattered light has been noted in UVVIS frames acquired for the limb of the moon (wavelength-dependent 12 to 15% at 25 pixels from the limb), but no algorithm has yet been derived for its removal. Although absolute radiance values have not been evaluated, errors would certainly be larger than the 4% estimated for relative color.
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Ancient Multiring Basins on the Moon Revealed by Clementine Laser Altimetry

Paul D. Spudis, Robert A. Reisse, Jeffrey J. Gillis

Analysis of laser altimetry data from Clementine has confirmed and extended our knowledge of nearly obliterated multiring basins on the moon. These basins were formed during the early bombardment phase of lunar history, have been filled to varying degrees by mare lavas and regional ejecta blankets, and have been degraded by the superposition of large impact craters. The Mendel-Rydberg Basin, a degraded three-ring feature over 600 kilometers in diameter on the lunar western limb, is about 6 kilometers deep from rim to floor, only slightly less deep than the nearby younger and much better preserved Orientale Basin (8 kilometers deep). The South Pole–Aitken Basin, the oldest discernible impact feature on the moon, is revealed as a basin 2500 kilometers in diameter with an average depth of more than 13 kilometers, rim crest to floor. This feature is the largest, deepest impact crater yet discovered in the solar system. Several additional depressions seen in the data may represent previously unmapped ancient impact basins.

Multiring basins make up the basic structural, geological, and topographic framework of the lunar crust (*1*, *2*). Over 40 basins have been recognized and mapped on the moon [see, for example, (*1*)], in varying states of preservation. Although there is little controversy regarding the presence and configuration of very fresh basins, such as the magnificent Orientale basin on the western limb of the moon (*1*), the mapping and ring detection of very degraded, nearly obliterated multiring features is controversial (*3*). Controversy attends both the question of a given degraded basin's existence (*3*) and, if existence is granted, its size and the configuration of its rings (*2*–*5*). Until now, such ancient features have been delineated largely through photogeologic mapping (*1*, *2*). Altimetric data from Clementine provide a means to test both the presence and configuration of ancient basins on the moon.

The laser altimetry experiment of the Clementine mission is described elsewhere (*6*, *7*). The data consist of points of elevation along the spacecraft orbital track (roughly, lines of longitude); each orbital ground track is separated by 2.5° at the equator, the amount of moon rotation per spacecraft revolution. The laser return detector accepted as many as four returns for each transmitted pulse, resulting in considerable noise and false returns. The distribution of real returns along an orbital track is variable, depending on terrain and solar phase angle. Real data make up as little as 15% of the total returns from the laser pulsing in very rough terrain near 0° solar phase angle but may be nearly 100% of the returns for smooth maria overflown late in the mission, when solar phase angles were larger. However, the distribution of real returns along ground tracks is more or less continuous at crosstrack scales (~100 km), permitting the topographic point data to be gridded, binned, and contoured into a global topographic map (*6*, *7*). This map has a surface resolution of about 200 km, adequate for the study of the global figure, regional topography, and the configuration of the largest lunar landforms, multiring basins.

The Mendel-Rydberg Basin [discovered by Hartmann and Kuiper (*5*); named by Wilhelms *et al.* (*9*)] is typical of ancient, degraded basins (*1*, *5*, *8*, *9*). The basin, located on the western limb of the moon just south of the fresh, well-preserved Orientale Basin, is buried by ejecta from that structure (Figs. 1 and 2) and displays three rings measuring 630 (rim), 460, and 200 km in diameter (*1*). The laser profile of Mendel-Rydberg (Fig. 1) clearly shows the basin depression, averaging about 5 to 6 km in depth; inflections in the relief profile are coincident with the rings mapped by photogeology (*1*). Mendel-Rydberg appears to be at least partly filled by mare lavas (dark region in basin center; Fig. 1), most of which are buried by Orientale ejecta (Figs. 1 and 2); such ancient maria are widespread on the western limb of the moon (*10*–*12*). Analysis of gravity information in this region (*7*) indicates that a nearly flat free-air anomaly and a large positive Bouger anomaly are coincident with the mapped position of the basin, suggesting that dense rocks, probably the mantle, are uplifted close to the surface in this region of the moon. Thus, the basin's presence is indicated not only by photogeologic and topographic information but by compositional and geophysical data as well.

Another highly degraded feature is the Coulomb-Sarton Basin [discovered by Hartmann and Wood (*8*); named by Lucchitta (*13*)], located on the northwestern portion of the lunar far side (Fig. 3) (*1*, *8*). This basin is difficult to see on Lunar Orbiter images; it was thought to display three rings measuring 530, 400, and 180 km in diameter (Fig. 3) (*1*). Clementine altimetry reveals a basin about 500 km in diameter, averaging 6 km in depth, rim to floor (Fig. 3). Although the main basin rim is clearly evident, inner rings are weakly expressed; a single inner ring is visible at a diameter of about 200 km (Fig. 3). According to Wilhelms (*1*), the diameter of the rim of Coulomb-Sarton is uncertain, and he thought that the 400-km ring could be the basin topographic rim. The best evidence from Clementine altimetry suggests that the basin consists of two

P. D. Spudis and J. J. Gillis, Lunar and Planetary Institute, 3600 Bay Area Boulevard, Houston, TX 77058, USA.
R. A. Reisse, Science Inquiries, 312 Patleigh Road, Catonsville, MD 21228, USA.

relatively well-defined rings 490 and 200 km in diameter (Fig. 3).

We have systematically examined the global altimetry for evidence for other basins and confirm the existence of several degraded features. The Mutus-Vlacq Basin [discovered and named by Wilhelms (9)], an ancient basin southwest of Mare Nectaris (centered at 52°S, 21°E) and classified as "probable" by Wilhelms (*1*), was detected by the altimetry; it is about 700 km in diameter and averages about 3 km in depth. Infilling by highland plains deposits (9) and possibly by ancient mare lavas may have significantly reduced the relative relief of the basin. Multiple profiles through the basin suggest that it is at least a two-ring basin, displaying an interior ring about 500 km in diameter. Because the Mutus-Vlacq Basin is over 700 km in size, it is likely to be a true, multiring basin (*2*); additional rings either were obliterated by subsequent impacts or the rings are so subtle that they are indiscernible in the relatively coarse altimetry data. Other basins confirmed by Clementine altimetry data include the Freundlich-Sharonov [600 km in diameter; 18.5°N, 175°E; (*1*)], Tsiolkovsky-Stark [700 km in diameter; 15°S, 128°E; (*1*)], and Schiller-Zucchius [325 km in diameter; 56°S, 44.5°W; (*1*, *5*, *8*)] basins.

In addition to the confirmation of mapped multiring basins [for example, (*1*, *2*)], we have found evidence for previously undescribed basins. Two depressions northeast of Mare Moscoviense may be remnants of ancient degraded basins. One of these features is about 330 km in diameter, centered at 30°N, 165°E, and the other is about 450 km in diameter, centered at 50°N, 165°E, nearly coincident with the crater D'Alembert (about 255 km in diameter) but much larger. The depression surrounding D'Alembert suggests that the named feature may not be a crater but rather the inner ring of an ancient basin, as is also the case for certain other crater-like depressions on the moon, such as Grimaldi. Confirmation of these features as true basins awaits further analysis of the altimetry data.

The existence of a very large, ancient basin on the far side of the moon was suspected from analysis of Earth-based photographs. A cluster of massifs near the south pole, termed the Leibnitz Mountains, suggested to Hartmann and Kuiper (*5*) that a large basin probably existed on the far side, just beyond the southern limb of the moon. Subsequently, a large depression was detected by photographic altimetry from images taken by the Russian lunar probe Zond (*14*), and Stuart-Alexander (*15*) mapped the outline of a very large basin (about 2000 km in diameter) centered near 50°S, 180°; this feature was named the South Pole–Aitken Basin (*1*, *15*), or informally, "Big Backside Basin" (*16*). Subsequent geologic mapping of isolated massifs, mountain ranges, and large scarps in the highlands suggested that this basin is actually somewhat larger, about 2500 km in diameter, and centered at 56°S, 180° (*1*, *9*). The Apollo 15 laser altimeter ground track crossed somewhat inside the northern edge of the basin; the altimeter profile suggested that the basin floor is about 5 to 6 km below the mean elevation of the surrounding highlands (*17*).

Clementine altimetry has revealed the topography of the South Pole–Aitken Basin (Figs. 4 and 5) in nearly all of its awesome proportions. (Topography of the south pole from stereogrammetry is not yet processed, so we cannot see the extension of the basin into the polar latitudes, beyond 70°S.) The basin displays a nested structure (Fig. 4), with a central depression about 2000 km in diameter and a rim crest about 2500 km in

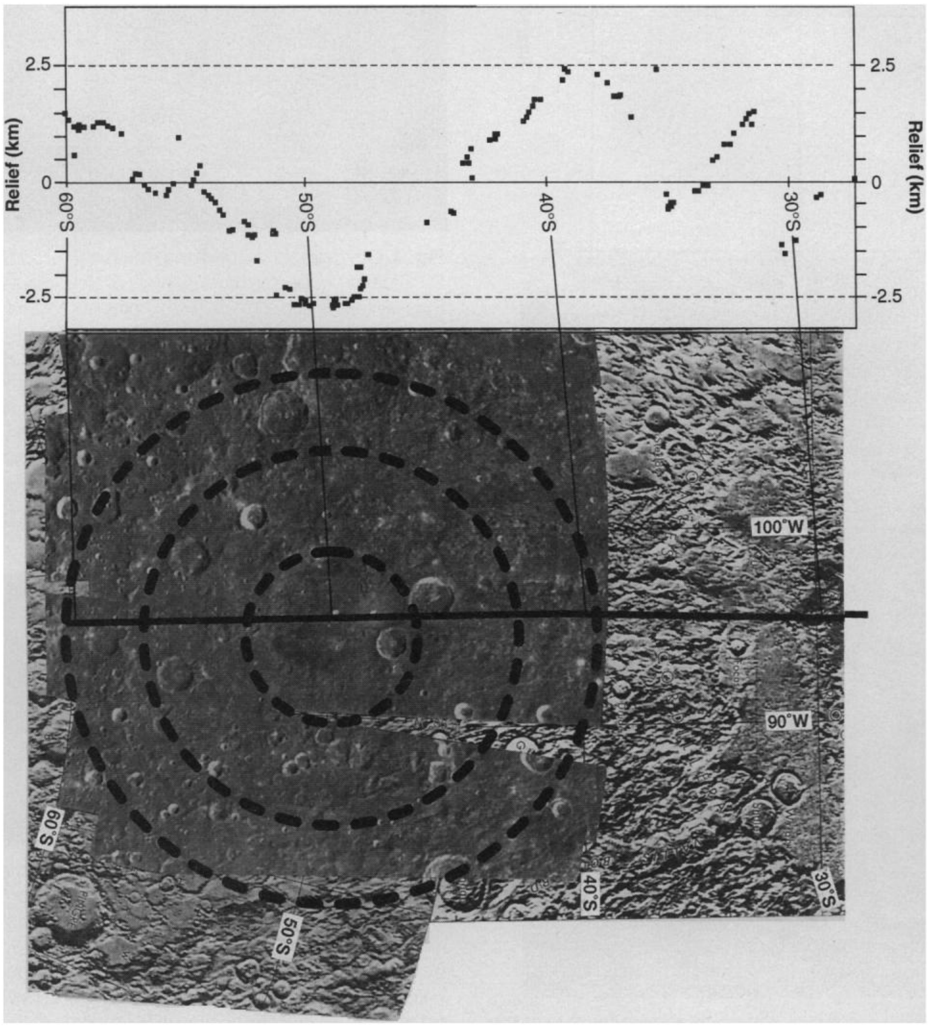

Fig. 1. Mosaic of Clementine images of the Mendel-Rydberg Basin on the west limb of the moon. Topographic profile (top) from orbit 71 (longitude 95.6°W) shows the basin as a large, regional depression averaging 5 to 6 km in depth. All three rings, mapped by Wilhelms (*1*), are confirmed in the altimetry data. Clementine mosaic overlain on a U.S. Geological Survey shaded relief map of the moon.

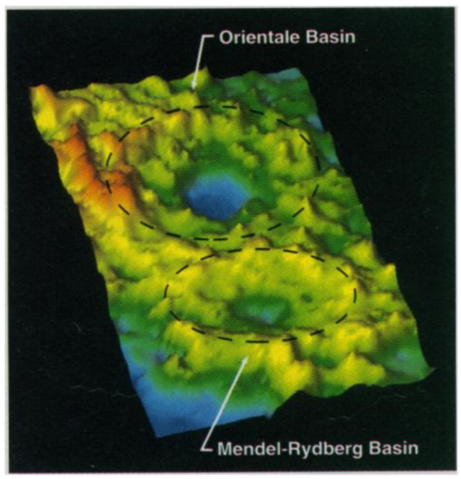

Fig. 2. Perspective shaded relief image of Clementine altimetry data for the Orientale and Mendel-Rydberg basins; topographic rim ring of each basin is indicated by dashed line. Colors indicate elevation; orange corresponds to elevations of 5 to 6 km above and blue corresponds to elevations of 3 to 4 km below the mean lunar datum (*7*).

diameter. The average depth of the South Pole–Aitken Basin is about 12 km from rim crest to basin floor (Fig. 4); previous data from Apollo ranging covered only the extreme northern part of the basin. The floor of the basin is irregular, mainly because many younger impact craters and basins are superposed on South Pole–Aitken (for example, the Apollo Basin at 35°S, 153°W). The inner depression may represent an irregular inner ring (Fig. 4); this feature could correspond to an inner ring 1800 km in diameter, described by Wilhelms (*1*, *9*), who advocated the larger figure of 2500 km for the diameter of the basin. Additional structural features may be developed outside this 2500-km-diameter basin rim (*1*, *2*).

As previously recognized (*12*, *18*, *19*) and discussed at length (*20*), the South Pole–Aitken Basin coincides with a major mafic compositional anomaly in the lunar highlands. A variety of evidence, from lunar basins (*2*) and terrestrial craters (*21*), and theory (*22*) suggest that the transient cavity for such a basin-forming impact must have been at least 1000 km in diameter. Such a cavity would have excavated the entire lunar crust at the impact site and quarried material from depths as great as 120 km within the moon. Thus, even though the ejecta from such an impact would be largely of crustal provenance (*1*, *2*), significant quantities of the lunar mantle may be incorporated in the rocks that make up the floor of the South Pole–Aitken Basin. Mantle materials may account, at least in part, for the large mafic anomaly seen within the South Pole–Aitken Basin (*12*, *18*, *20*), although our analysis of that data is continuing (*20*). Subsequent multiple impacts, resurfacing by mare lavas, and fine-scale impact gardening have produced complex geology on the basin floor. Therefore, although rocks from the lunar mantle may

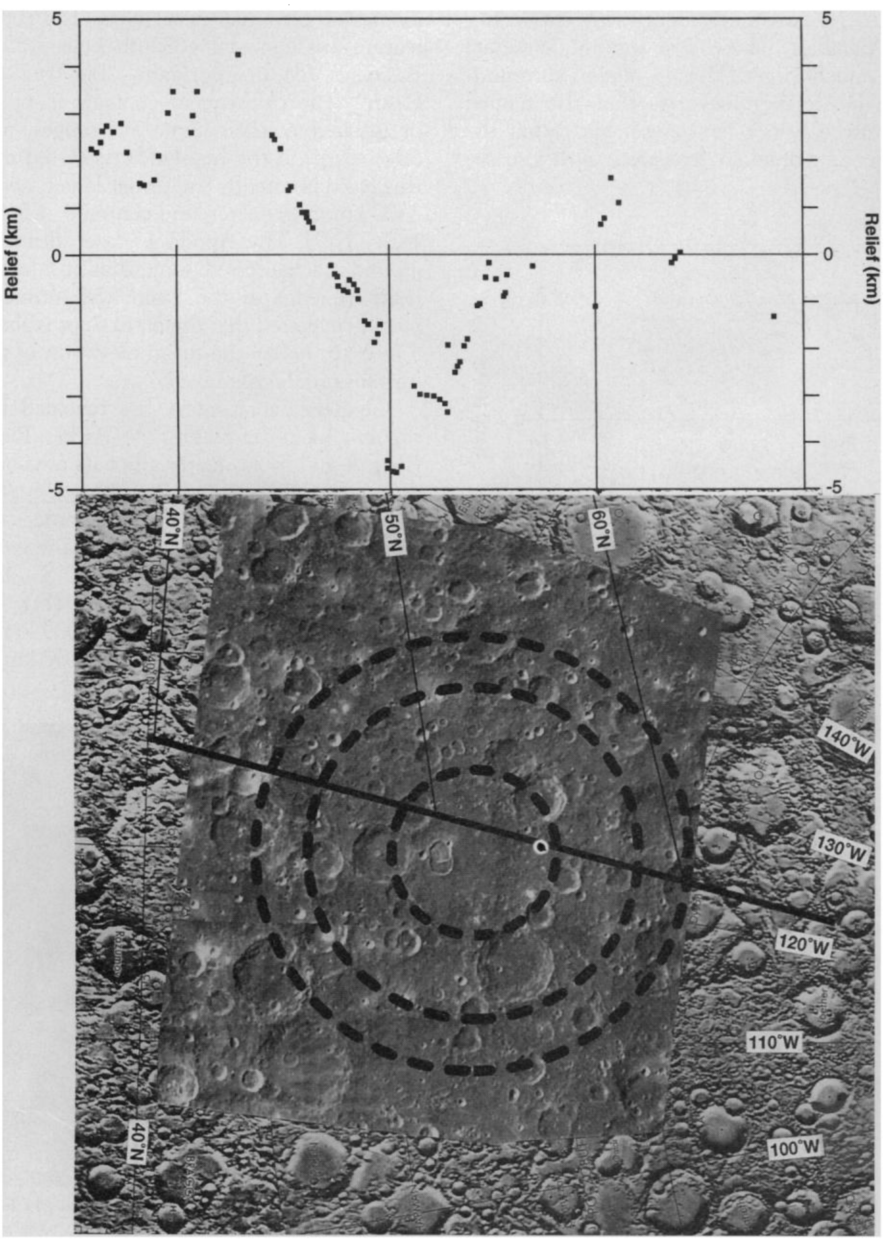

Fig. 3. Mosaic of Clementine images of the Coulomb-Sarton Basin on the northwestern far side of the moon. Topographic profile (top) from orbit 214 (longitude 124.3°W) shows a large basin averaging 6 km in depth; the floor of postbasin crater Weber (50 km in diameter) lies an additional 1.5 km below the basin floor. Coulomb-Sarton is one of the oldest, most nearly obliterated lunar basins. The Clementine mosaic is overlain on a U.S. Geological Survey shaded relief map of the moon.

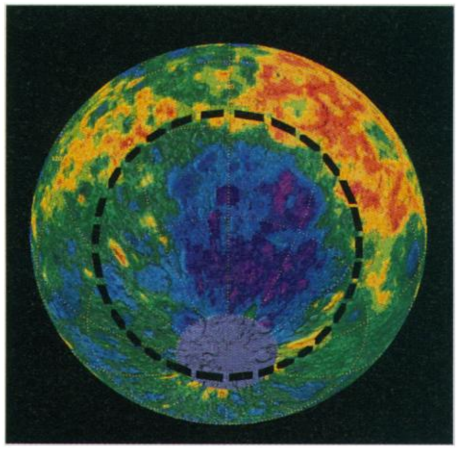

Fig. 4. Orthographic view of the moon centered at 50°S, 180° (approximate center of the South Pole–Aitken Basin) (*1, 15*) with Clementine altimetry (*7*) color coded by elevation (red = +7 km; purple = −8 km). The basin structure consists of a topographic rim about 2500 km in diameter (dashed line), an inner shelf ranging from 400 to 600 km in width (mostly green), and an irregular depressed floor (blues and purple); average basin depth (rim to floor) is about 12 km. The gray zone near pole has no altimetry coverage.

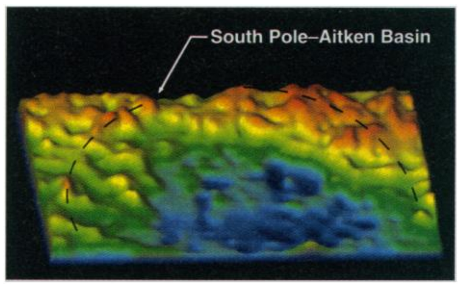

Fig. 5. Perspective shaded relief image of the South Pole–Aitken Basin constructed from Clementine altimetry data; basin topographic rim ring shown by dashed line. Elevations are coded by color; orange colors are the highest at about 7 km above the mean lunar radius, and the lowest areas are purple at about 8 km below the mean. This impact feature is over 2500 km in diameter and averages 12 km in depth, making it the largest, deepest impact basin known in the solar system.

be exposed within this basin, they are likely mixed with other material (*19*).

The detection of a population of ancient, multiring basins with the altimetry data from Clementine has several implications for both the geological evolution of the moon and for our understanding of the other terrestrial planets. A variety of basin sizes, morphologies, and relative preservation states are evident in the altimetry data. This topographic information has confirmed and extended the detailed photogeologic mapping of the basins, which represent the fundamental topographical and structural features of the lunar crust. The confirmation that a large population of ancient basins exists in the lunar highlands strengthens arguments that the highlands are saturated with craters of very large diameter (*23*). A corollary of this observation is that at least the upper few kilometers to tens of kilometers of the lunar crust has been brecciated and mixed on scales of tens to hundreds of kilometers, confirming earlier suppositions (*1*, *23*).

The amount of relief displayed by some of these features is astounding. Basins such as Mendel-Rydberg and South Pole–Aitken date back to the earliest stages of lunar history (some time between 4.3 to 3.9 billion years ago), yet they preserve relief indicating that very little relaxation of topography has occurred. Such preservation of relief suggests that attempts to date lunar basins by measuring the rim topography and the relative amounts of relaxation by viscous flow (*24*) probably are not valid. Near-isostatic compensation, as seen in basins such as Mendel-Rydberg (*7*), must have occurred nearly contemporaneously with the impact, probably in the form of the dynamic rebound and uplift of relatively dense mantle rocks during the modification stage of basin formation (*7*, *25*).

The altimetry data from Clementine both confirm previously mapped basins and have led to the recognition of additional degraded structures. Thus, global topography is a valuable tool in the mapping of planetary surfaces. The confirmation of a large number of very degraded, ancient basins on the moon suggests that comparable photogeologic mapping of ancient basins on other terrestrial planets [summarized in (*2*)] probably has accurately depicted the configuration of these early crusts [compared to (*3*)]. Future missions to Mars and Mercury that carry instruments for the regional mapping of large-scale topography can help us decipher the early impact record of the crusts of these other terrestrial planets.

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The South Pole Region of the Moon as Seen by Clementine

E. M. Shoemaker,* M. S. Robinson, E. M. Eliason

The Clementine mission has provided the first comprehensive set of high-resolution images of the south pole region of the moon. Within 5° of latitude of the pole, an area of an estimated 30,000 square kilometers remained in shadow during a full lunar rotation and is a promising target for future exploration for ice deposits. The Schrödinger Basin (320 kilometers in diameter), centered at 75°S, is one of the two youngest, least modified, great multiring impact basins on the moon. A large maar-type volcano localized along a graben within the Schrödinger Basin probably erupted between 1 and 2 billion years ago.

A primary scientific objective of the Clementine mission was to map the spectral reflectance of the lunar surface at 11 wavelengths (*1*). Images taken above 70° latitude also reveal the lunar surface illuminated by the sun at angles that are ideal for discriminating subtle morphological features and thus for deciphering the stratigraphy and structure of the lunar surface. In this report, we present observations and interpretations of the geology of the south polar region, which was the least known part of the moon before the Clementine mission.

The highest resolution images of the south polar region were taken during the first 5 weeks of the mission. Nearly complete coverage between 70° and 90°S was obtained with the ultraviolet-visible (UV-VIS) camera during this period (Fig. 1). A broad swath of the terrain between 90° and 120°W longitude had never been satisfactorily observed and thus was essentially "luna incognita" on most existing lunar maps (*2*). Of particular interest is the area within 5° of the pole.

As the moon rotated during the first month of the Clementine mission, it became clear why a substantial area around the south pole is blank on global maps. A large fraction of this area, totaling an estimated 30,000 km^2, remains in shadow in the present phase of precession of the lunar pole (Fig. 1). Much of this shadowed area is part of an irregular topographic depression partly bounded on the sub-Earth side by high terrain known informally as the Leibnitz Mountains and, at westerly and easterly longitudes, by the high rims of several ancient large craters. It is possible that the depression coincides with a

E. M. Shoemaker, U.S. Geological Survey and Lowell Observatory, Flagstaff, AZ 86001, USA.
M. S. Robinson and E. M. Eliason, U.S. Geological Survey, Flagstaff, AZ 86001, USA.

*To whom correspondence should be addressed.