LUNAR BOUGUER GRAVITY ANOMALIES: IMBRIAN AGE CRATERS. J. Dvorak, Div. of Geological and Planetary Sciences, California Institute of Technology, Pasadena, California, 91125; R.J. Phillips, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, 91103.

Impact cratering is a well recognized process operating on the surface of the Moon. Interpretation of lunar crustal history by the examination of impact crater degradation has a distinct advantage over the examination of other landforms in that each impact event occurred essentially instantaneously and that similar crater structures were initially formed within any given crater diameter range. Subsequent modification of this original form is the result of the action of a variety of processes, so that the continual bombardment of the Moon by large impacts provides a record of crustal processes operative throughout lunar history. Our contribution to the study of lunar impact craters is to constrain the structure and evolution of these features by an analysis of the gravity anomalies associated with them.

These gravity anomalies are derived by differentiating with respect to time the Doppler residual of a transponded radio signal received by the Earth-based tracking system (Sjogren et al., 1976). The contribution of the surface topography to each local gravity anomaly has been included in our analysis by utilizing the data simulation technique described by Phillips et al., (1978). The remaining non-topographic contribution is termed the Bouguer gravity anomaly and is due to lateral density variations within the lunar crust.

We have previously reported on the Bouguer anomalies associated with four post-Imbrian craters (Dvorak and Phillips, 1977). These are craters which formed after the last major stage of mare flooding and which exhibit no evidence of long term post-impact modification or adjustment. A negative Bouguer anomaly (i.e., a low density region or mass deficiency) was shown to be associated with each of these post-Imbrian craters. This negative anomaly was attributed to the occurrence of brecciated and crushed material created by these impacts and presently underlying these features. Model calculations showed that the magnitude of the mass deficiency varied with the cube of the crater diameter.

Our current work has included an analysis of older lunar craters which have undergone significant modification of their original structures. The remainder of this discussion will center on the interpretation of the Bouguer gravity anomalies associated with Imbrian age craters.

The Imbrian system for the Moon is defined as that time interval between the formation of the last few multiringed basins and the last episode of global mare flooding. Lunar craters which formed within this time interval are identified by their stratigraphic relations with these two major lunar geologic events. When clear stratigraphic relations are not evident, morphologic indicators of the degradation of the crater rim structure are used to define the relative age (Pohn and Offield, 1970). These approaches may suffer from regional biases due to a crater's proximity to the most recent lunar multiringed basins or to the complex emplacement sequence of lunar mare lava.

Nonetheless, we have utilized these age criteria to identify several lunar craters of Imbrian age for which low altitude gravity data is available.

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Snellius	83 km diameter	Neper	142 km diameter
Piccolomini	89	Petavius	176
Hecateaus	120	Humboldt	200

These Imbrian craters are very similar in gross morphology to the post-Imbrian craters analyzed earlier in that they both have relatively flat floors and scalloped or terraced interior walls. The larger craters of each age group also have central peak complexes. The depth/diameter ratio for these Imbrian craters is almost identical to the post-Imbrian craters. The major distinctions in morphology between these age groups are a more subdued appearance of the Imbrian craters and a larger number of superposed craters. The larger Imbrian craters also have interior rilles and a broad central updoming of their floors. Varying amounts of volcanic units are found interior to many of these Imbrian craters.

For each of the craters listed above the Bouguer gravity anomaly is zero, that is, there is no detectable net mass deficiency or excess associated with any of these features* (i.e., $|\Delta g| \lesssim 3\text{-}5$ mgals). This is very different from the result for the post-Imbrian craters which, as mentioned earlier, have negative Bouguer anomalies attributed to material brecciated by the impact.

If a similar low density region is presently associated with the Imbrian craters, then the zero Bouguer anomalies would indicate that there is also present a high density component of similar magnitude so that there is no net mass anomaly. Further, since we have a range of crater diameters in both age groups, the mass excess component of the Imbrian age craters must have a dependency on crater diameter similar to the cubic relation of the low density component for post-Imbrian craters. We are currently of the opinion that no geologic process would operate over this range of crater diameters to produce high density components resulting in a zero mass anomaly. Therefore, our tenative conclusion is that the original porosity of this low density brecciated region has been either removed or suppressed by later geologic events. The nature of such possible events is the subject of research currently in progress.

Also of interest in this discussion is the relation between changes in crater morphology and the occurrence of zero Bouguer gravity anomalies, in particular, the origin of the interior rilles and the broad floor updoming. Radial and concentric rille patterns are present in Petavius and Humboldt. Also interior to these two craters are dark units, presumably volcanic, which lie discontinuously along the crater floor-wall contact and a broad central updoming of the floors of both of these craters. Neper is slightly different in that its floor is completely covered with mare material and it has no discernible interior rilles. However, accurate topographic data for Neper, derived from the Apollo 17 ALSE radar (Elachi et al., 1976), shows a maximum

*These results are preliminary estimates for Piccolomini and Hecateaus. Final determinations of the Bouguer anomalies for these two craters will be reported on at the meeting in Houston.

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uplift of ~325 meters.

Interpretation of these interior crater structures has centered on the concept of isostatic support by the lunar mantle. That is, the lunar mantle has deformed upwards in response to the lower vertical stresses beneath the crater bowl. According to this model the lunar mantle continued to upwell, fracturing and doming the lunar crust, until the differential stresses at some level (depth of compensation) within the lunar mantle fell below the yield stress. This process results in the movement of higher density mantle material displacing lower density crustal material. This net upward flow of higher density material to an isostatic state should produce an observable positive Bouguer gravity anomaly of at least ~15-30 mgals. This is clearly not seen, so that, the origin of the rille structures and central updoming must be the result of a different process.

We propose that these features are due to the intrusion of igneous material into fractures created by the impact. Schultz (1976) has previously proposed this mechanism for the origin of floor-fractured lunar craters. Estimates for the expected gravity anomaly can be made from the amount of observed uplift. Treating the lunar crust as an elastic half-space and approximating the intrusive body as either a sphere or a thin disk leads to estimates for the Bouguer anomaly of ~0.5 to 3 mgal, that is, essentially zero; consistent with the observed Bouguer anomaly.

Summary

Bouguer gravity anomalies have been computed for six Imbrian age craters. In all cases a zero anomaly was determined; quite distinct from our earlier findings of a negative anomaly for post-Imbrian craters. We tentatively conclude, on the basis of the examination of many craters of varying diameters, that the low density regions giving rise to the post-Imbrian anomalies have either been removed or suppressed by a process not yet identified acting on these Imbrian craters. Further, these zero anomalies do not support the isostatic hypothesis for the formation of the rilles and the broad central uplifts within the largest of these Imbrian craters. We propose that these interior structures are the result of igneous intrusion into fractures originally formed by the impact.

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