GRAVITY MODELS OF LARGE IMPACT STRUCTURES ON ANCIENT MARS: IMPLICATIONS FOR IMPACT PROCESSES AND CRATER MODIFICATION

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Introduction: Measurements by the Mars Orbital Laser Altimeter (MOLA) on the Mars Global Surveyor spacecraft reveal the presence of hundreds of quasi-circular depressions (QCDs) distributed across the surface of Mars. Detectable in the elevation data as clear depressions, QCDs are roughly circular topographic features with limited relief that consequently have little or no expression in the visible wavelength imagery. Their topographic morphology suggests an impact origin with large amounts of subsequent deposition on the crater floor, accounting for the subdued topography [1-3]. A variety of materials may contribute to the floor deposits. In order of increasing density, these include impact ejecta deposits from nearby large impact basins, sedimentary material, and volcanic deposits. Alternatively, the subdued topography has been interpreted as evidence for viscous crustal relaxation early in martian history [4].

Because the various fill materials differ in density, gravity observations can potentially help distinguish among the competing hypotheses. We have therefore examined the gravity signatures both of large visible craters and of QCDs. We show that most of the structures we have examined (18 of 21, 86%) require the presence of material that is denser than the surrounding crust. This is consistent with the presence of lava flows as crater fill but inconsistent with the primary crater fill being low to intermediate density material, such as impact ejecta or sedimentary deposits. In many cases, the gravity anomaly is sufficiently large that even uncompensated floor fill can not explain the anomaly. In these cases, super-isostatic uplift of the mantle is probably required. The existence of such uplift places important constraints on both the impact process and on the subsequent preservation of crater relief. In particular, it is difficult to reconcile the preservation of several kilometers of super-isostatic mantle uplift with a viscous relaxation model for the surface topography. In a few cases (3 of 21 cases observed here, 14%), the gravity anomaly implies that material inside the crater is less dense than the surrounding crust and may be predominantly related to deposits of impact ejecta.

Method: The currently available gravity model is reliable up to harmonic degree 72, corresponding to a resolution of 300 km [5]. We therefore limit ourselves to structures with diameters larger than about 300 km. Because the crater diameter is effectively about half of the gravity anomaly wavelength, such structures are well observed in the gravity model. We use a cosine-tapered, high pass filter to remove wavelengths longer than 1000 km from the gravity field. We remove the effects of both the surface topography and its compensating root assuming a mean crustal thickness of 50 km [6] and an elastic lithosphere thickness of 10 km, a value that is typical of for early, Noachian age surfaces [7]. A range of crustal densities has been inferred for Noachian geologic units from spectral admittance modeling of Mars [7]. Our results are only weakly sensitive to the assumed crustal density in the range 2600 – 2900 kg m^{-3}. We examined a total of 40 impact structures from our database of impact crater and QCD topography [8-10]. Of these, we retained a total of 21 structures with diameters between 289 and 475 km (7 visible craters, 14 QCDs) in the analysis, for which there was a clear correlation between the impact structure and the gravity anomaly.

Results: Figure 1 shows the residual gravity anomaly for each impact structure, plotted as a function of the depth anomaly for the structure. The depth anomaly is defined as the difference in depth between the observed structure and the expected depth for a pristine crater of that diameter [8-10]. If the shallowness of the QCDs is due to post-impact deposition, the depth anomaly is a measure of the fill thickness. Most of the observed anomalies are positive, implying that the dominant fill material is denser than the surrounding crust. An alternative location for high density material would be super-isostatic uplift of the crust-mantle interface. The latter mechanism is thought to explain most mascon gravity anomalies at large lunar impact basins [11, 12].

As an aid to interpretation, Figure 1 includes lines showing the gravity anomaly $2\pi G h \delta\rho$ due to a depth anomaly h of uncompensated fill that is $\delta\rho$=+300 (solid line) or -300 kg m^{-3} (dashed line) different in density than the surrounding crust. These calculations treat the fill as an infinite slab. Because of the degree 72 cut-off in the spherical harmonic model, the actual gravity anomaly due to the crater fill will in general be somewhat less than predicted by the infinite slab model and numerical modeling of specific impact structures (e.g., [13]) is necessary. Nevertheless, the lines in Figure 1 do divide the structures into three broad categories: (1) structures with large positive anomalies (above the solid line), (2) structures with small positive anomalies (below the solid line but > 0), and (3) structures with negative anomalies.

We have modeled selected structures using the DISKGRAV gravity model [14]. In class 1, Newton crater has virtually no floor fill and requires at least 9 km of super-isostatic uplift of the mantle. The QCD at 50° S, 294° E can have only about half of its gravity anomaly explained by dense floor fill. The remainder of the anomaly requires at least 4 km of super-isostatic uplift. Huygens crater requires at least 5 km of super-isostatic uplift. Viscous relaxation has been proposed as an important process in the evolution of early martian impact basins [4]. If viscous relaxation has degraded the surface relief, it should also have destroyed super-isostatic mantle uplift. Thus, for these class 1 craters, we do not believe that viscous relaxation has been important, but we can not rule it out for other classes of impact structures. Structures in class 2 can be explained solely or primarily by dense crater fill, such as volcanic material. Structures that are predominantly filled by low density impact ejecta should have negative residual gravity anomalies (class 3). Only 3 such structures are evident in our data. These include the crater Herschel and the first QCD ever observed ([1], labeled "MOLA Hole" in Figure 1). These structures can be explained by post-impact fill that is 250-350 kg m^{-3} less dense than the surrounding crust. The limited importance of impact ejecta as fill material is consistent with the morphometric observations Rosenburg et al. [10], who found that QCD depth anomaly is virtually independent of distance from the young Hellas and Argyre impact basins, indicating that ejecta from these basins was not the primary cause of QCD degradation.

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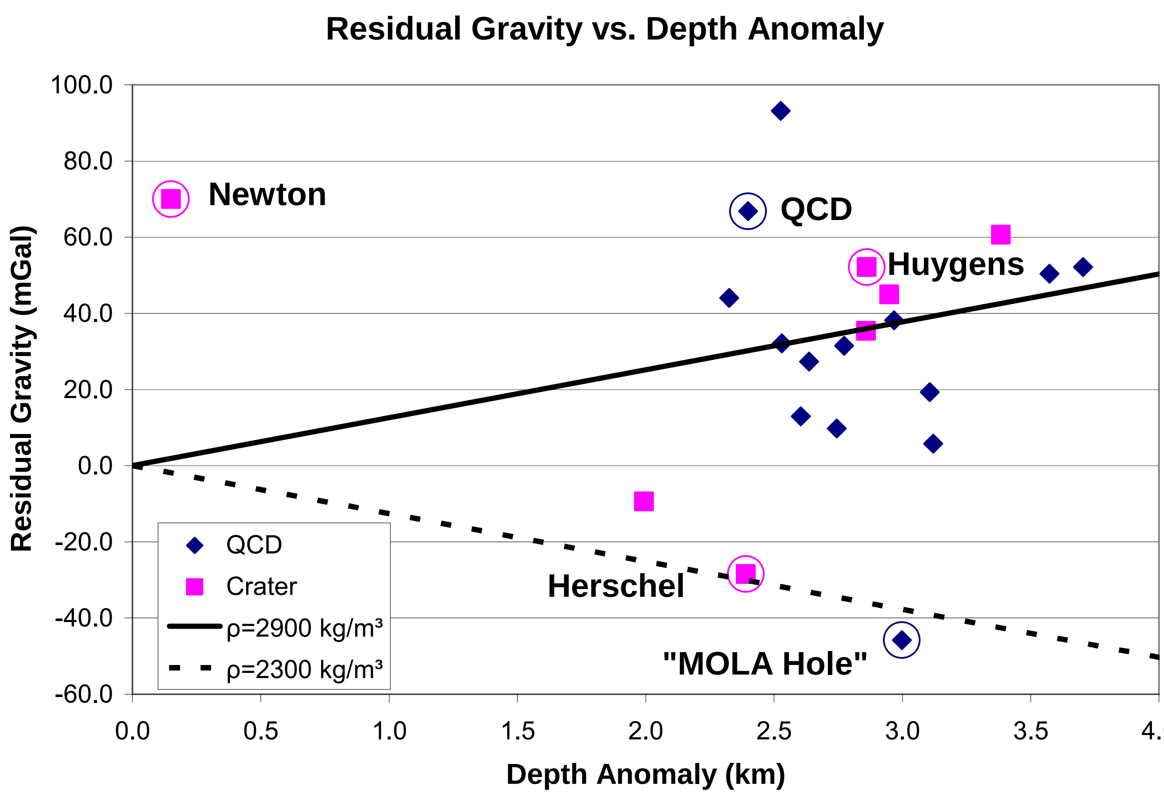

Figure 1. Scatter plot of residual gravity anomalies for 7 visible impact craters (pink squares) and 14 large QCDs (blue diamonds) as a function of depth anomaly. Assuming the depth anomaly is due to crater fill, the solid and dashed lines are gravity anomalies calculated for fill whose density δρ is +300 (solid line) and -300 kg m^{-3} (dashed line) relative to the surrounding crust. Detailed numerical models have been developed for the circled structures.