Crater Depth/Diameter/Morphology Relationships on the Icy Satellites: Implications for Ice Rheology

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Introduction: Ever since serious thought was given to possible geological forms and processes on the icy satellites, consideration of the relative ease of viscous creep of ice as compared to rock has pushed modification by viscous relaxation to the forefront. Indeed, early pre-Voyager calculations suggested that virtually no topography at all would be seen on satellites like Ganymede and Callisto (1). Contrariwise, actual observation showed preservation of significant topography of considerable age. However, virtually all unusual morphologies and the relative shallowness of craters on Ganymede and Callisto relative to lunar craters were interpreted as the result of viscous relaxation (2,3). This interpretation was challenged (4,5) based on: a) better experimental data on ice creep which indicated that the previously adopted creep relations were too "soft", b) morphometrical comparisions of "unusual" with more "usual" crater forms which indicated that the former could not be obtained from the latter by simple relaxation, and c) preliminary measurements of depth/diameter/morphology (d/D/M) relations on Ganymede which indicated that lunar crater depths were not the correct standards of reference. This last argument is based on the empirical correlations of complex crater depths with the diameter of the simple/complex morphology transition found on the terrestrial planets: smaller transition diameters corresponding with shallower initial complex crater depths. This correlation is not based on viscous relaxation, but is related to conditions of crater modification that leads to the formation of complex craters. The transition diameter on Ganymede was observed to fall between those of Earth and Mars, thus based on d/D/M relations, fresh complex craters on Ganymede should have depths intermediate between those on the Earth and Mars, which was also observed to be the case, precluding significant relaxation for craters smaller than $\sim$ 80 km in diameter. However, the d/D/M relations were poorly defined for the icy satellites, and new creep measurements of ice at low temperatures (6) indicated very strong non-newtonian behavior and a change of mechanism near 190K that predicted higher than expected creep rates at temperatures appropriate to Ganymede's crust. Theoretical relaxation calculations based on the new ice creep data (7,8) indicated non-relaxation of craters up to 20-30 km in size, but initial crater dimensions and properties remained poorly defined. This study presents the completed measurements of d/D/M's for fresh craters on the icy satellites which define initial crater properties as completely as possible. A comparison between observation and current theory is also given.

Observational Measurements and Results. Crater diameters, shadow depths and morphologies were determined for fresh (and some degraded) craters on Ganymede, Callisto, Mimas, Enceladus, Tethys, Dione, Rhea, Miranda, Umbriel and Titania. Simple craters were found to be geometrically similar on all the icy satellites and similar to simple craters on the terrestrial planets with the exception that the depth/diameter ratios on the icy satellites are between 0.1 and 0.15 (3) compared to the $\sim$ 0.2 on the terrestrial planets. Complex craters exhibit depth/diameter dependencies of the form $d=aD^b$, with values of b between 0.3 and 0.5. These exponents are similar to those for complex craters on the terrestrial planets, though the average exponent is somewhat higher for complex craters on icy than on rocky surfaces. The transition diameters range from about 7 km on Ganymede to ~ 35 km on Mimas and show the approximate inverse dependence on gravity noted previously (9, 10). Most importantly, however, the absolute depths of complex craters on the icy satellites correlate with the transition diameters in a manner completely analogous with the terrestrial planets, verifying a consistent d/D/M relationship for all crater populations on all well-imaged surfaces.

Model Calculations. To evaluate evidence for viscous relaxation in the depth/diameter data, a Monte-Carlo simulation was developed in which craters of random size were formed at random within a specified time interval. Variables in the simulation include fresh crater geometry parameterizations, surface gravity, time- dependent temperature profiles and parameters governing the stress and temperature dependence of the ice. The relaxation of each crater was followed to the present using e-folding relaxation times normalized to the model calculations of (8). Plots of the computed present crater depths were then compared to the observed data for each satellite. The calculated plots showed characteristic shapes: largely unrelaxed simple and complex craters up to a "bend" beyond which crater depths dropped off systematically to a minimum near 100 m. The "bend" is fairly sharply defined in spite of the random formation times because of the extremely high inverse dependence of e-folding time on crater diameter due to the highly stress-dependent nature of creep in ice. The characteristic "bend" is seen only in the data for Ganymede, Callisto and Enceladus, implying that significant relaxation has occurred only on these satellites and then only above crater diameters of about 60, 65, and 15 km, respectively. The presence of a few anomolously shallow craters may be indicative of unusual conditions of local heat flow in time or space, or may be the result of some form of volcanic modification. An enormous observational/theoretical discrepancy remains, however, for the vast majority of craters as determined by comparison between the observed "bend" for craters on Ganymede near 60 km and the "bend" of ~ 20 km based on the best theoretical data. A match between observation and theory may be obtained by arbitrarily increasing crater e-folding times by a factor of about 300-500. Based on the current model, this factor may be obtained by: a) shortening the interval (set at 4 b.y.) of crater formation, b) lowering the thermal gradient, or c) assuming much larger "field" viscosities than are indicated by laboratory measurements, or some combination of the three. Choice of any of these alternatives does violence to one aspect or another of the current picture of icy satellite evolution. Based on all the related arguments, the most likely resolution seems to be an effective "stiffening" of ice by silicate or other impurities, but a quantitative reconciliation remains difficult.

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