Impact Through the Layered Icy Crusts of Europa, Ganymede and Callisto: Or, I Know How Thick Europa’s Ice Shell is (Maybe)!  

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Introduction: Abundant but circumstantial geologic evidence implies that a subcrustal ocean of liquid water exists (or existed) on ice-covered Europa close to the surface [e.g., 1]. Chaotic and ovoid features on the European surface may be evidence for melt-through of a very thin ice shell [2] or for ductile convection in a thicker crust [1]. Convection requires that the shell be some significant thickness [3] (on the order of 10 km or so), but in reality there are no firm observational constraints on the thickness of the ice shell.

Impact craters serve as direct interplanetary drilling rigs, in that they excavate and uplift material from a range of depths (typically up to a few 10’s of kilometers). Turtle and Pierazzo [4], for example, use numerical modeling to find a minimum shell thickness of 3 km on Europa based on the presence of central peaks, but this minimum does not constitute a definitive test of the thin-crust, thick-crust debate.

Depths and morphology of impact craters are influenced by both the planets surface gravity [5] and by the compositional or thermal stratigraphy of planetary interiors [6, 7]. Surface gravity on the three icy Galilean satellites are all similar and differences in morphology can be attributed to compositional or rheological differences alone. Moore et al. [8], in their initial analyses of Galileo observations of crater morphologies on Europa, found that the largest European craters are morphologically distinct and shallower than similar sized craters on Ganymede and Callisto. They concluded that craters on Europa may be excavating into either a global subcrustal ocean or a ductile zone in the deep crust.

Photoclinometry, Photogrammetry, and Shadowgrammetry: Systematic and abrupt differences in the shapes of craters on the three icy Galilean satellites have been detected using all new depth-diameter measurements. Depths of fresh, unrelaxed, craters have been measured using three techniques: shadows, stereo digital elevation models (DEMs), and 2-dimensional photoclinometry. Stereo DEMs resolve only the large craters Pwyll, Manannan, and Cilix. Photoclinometry (PC) can be used for single low-sun images to map topography from relative brightness. I use a new, rapid, stable, 2-D PC technique, which also allows the user to model local albedo during each run. Shadow measurements are used for all craters < 15 km across. Galileo-based depth/diameter statistics for craters on Ganymede and Callisto supercede Voyager-based measurements [6, 9].

Data: Depth/diameter curves on rocky terrestrial planets are linear (and always sloping positive) but feature two breaks in slope. These breaks, or transitions, correlate with the morphologic transitions from simple bowl-shaped to complex morphologies and from complex craters to large ringed basins [5, 10].

Depth/diameter ratios of simple craters average ~0.21 and ~0.19 on Ganymede and Callisto. Thus, simple craters are deeper than reported by Schenk [7] based on low-resolution Voyager data, but similar to depths on rocky terrestrial planets [5]. Measured depth/diameter ratios on Europa average slightly lower, ~0.17, although numerous craters have depth/diameters of ~0.2. The depths of complex craters 2 to ~35 km on Ganymede and Callisto are shallower than lunar craters by 40-50%. These values are similar to those reported by Schenk [7], who attributed them to an enhanced degree of floor rebound on the icy satellites.

Between 26 and ~110 km diameters, crater depths on Ganymede and Callisto are essentially constant (~1.1 ±0.2 km) and hence are shallower than predicted from extrapolation of the depth/diameter curve for complex craters. This coincides with the morphologic transition from complex craters with central peaks to those with central pits and domes [6, 9]. Beyond ~110 km, craters on Ganymede are characterized by anomalous morphologies. Most notably, rim scarps are barely or not discernable. Low-sun images of several of these craters suggest that their floors are domed above surrounding plains, as confirmed by limited stereo and photoclinometry data. Rim-to-floor depths are less than 500 m.

Europa: There are at least three transitions on each of the three icy Galilean satellites, but two of these occur at different diameters on Europa. Simple-to-complex transition diameters appear to be the same or similar on all three satellites. For Callisto and Ganymede, the depth/diameter transitions occurs at 2.6 ±0.5 and 1.9 ±0.5 km., respectively, consistent with the morphologic transition on Ganymede of 2.1 ±0.2 km. These values are less than half that reported by Schenk [6] for Ganymede, but this is attributed to the small sizes of such craters in the Voyager images.

The depth/diameter intercept on Europa for simple and complex craters occurs at 3.9 km, but this is misleading as the complex crater curve has a negative slope. The 8 smallest classical complex craters on Europa (between 3 and 9 km diameter) for which we have data have depths comparable to similar-sized complex craters on Ganymede and Callisto. The depth/diameter transition diameter for simple craters and for complex craters ~9 km across on Europa is 3.3 km, more similar to Ganymede and Callisto.

At crater diameters >9 km, Europa begins to diverge from its Galilean siblings. Beyond this, complex crater depths on Europa are all shallower than their counterparts on Ganymede, and consistently decrease...
with diameter, a trend not observed on any other planet. The topography of the two largest impact features, the multiring Callanish and Tyre basins (D=33 and 41 km, respectively) is difficult to determine due to the lack of discreetly identifiable rim scarps. Maximum relief across individual scarps of both structures does not exceed ~100 meters (from 2-D PC). As these graben-like rings cannot be attributed directly to rim slumping or rim uplift, I assume that true crater depth is between 0 and 100 m.

**Interiors:** The rollover and precipitous drop in crater depths with diameter for the Galilean satellites, and especially Europa, is unprecedented among the planets. That this is not due to post impact modification is suggested by the misshapen central structures and degraded or absent rim structures of the largest craters. Relaxation or volcanism may flatten or bury features but is unlikely to disrupt or structurally modify them. Also, larger projectiles are unlikely to differ radically in construction or velocity from smaller ones. Thus, differences in internal structure between the icy satellites and the Moon, and between the icy Galilean satellites themselves, are the most plausible explanation for the observed crater shapes.

Impact events involve not only the crater bowl but a quasi-hemispherical zone around it roughly 1.5 times as large [11]. Any compositionally or rheologically anomalous material within or beneath this zone will influence the collapse process and alter its final shape. On Ganymede, Schenk [9] proposed that central dome craters were shallow because larger craters were excavating (or sensing) more deeply into a relatively ductile layer. I propose that the new depth/diameter measurements reveal at least two such rheologic transitions with depth on the icy Galilean satellites, and that these transitions are much shallower on Europa.

**Layered Crusts:** The stratigraphic depths of these any anomalous layers must be estimated from the observed crater dimensions at the associated transition diameters. We use the McKinnon and Schenk [12] crater scaling relationships to estimate transient (pre-rim-slumping) crater depths and diameters for each transition. The depth of the anomalous layer being sensed by the impact must be at least as deep as the smallest transient crater and its surrounding zone ~1.5 times as deep that senses it, i.e., the transition diameter. Recent numerical modeling by Turtle and Pierazzo [4] suggests that crater morphology begins to change when the transient crater depth is roughly half that of the rheologically anomalous layer. I take this as a reasonable first approximation.

On Europa, the transition from normal to shallow complex craters occurs at 5-6 km, which by [12] scales to ~3 km depth for the first anomalous layer. The second transition, corresponding roughly to the change in morphology from complex craters to modified central pit craters occurs at 17-18 km diameter. This scales to a depth of 7.5 to 8 km for the second layer. These depths appear to reflect the beginning of the influence of at least two rheologically distinct zones at depth within Europa, although in reality these transitions are probably gradual.

The last observable transition, from complex craters to ringed basins, occurs at ~28 km diameter. This may be the beginning of the influence of a global ocean, as suggested by the multiple rings and flattened topographic [7, 8]. This scales to a depth of ~12 km for the inferred base of Europa’s ice crust.

On Ganymede and Callisto, the transition and associated depths all occur at larger values than on Europa. The transition from complex craters to central pit and dome craters at 26-km diameters corresponds to a depth of 12 km, and may be equivalent to either of the first 2 transitions on Europa. The transition to the highly flattened impact morphologies at 110 km scales to a depth of ~40 km, roughly 4 times as deep as on Europa. Whether this transition is related to an ocean at depth is less clear, as the thicker crust may result in different ring morphologies on Ganymede and Calisto than on Europa.

The identical depth/diameter statistics and transition diameters for craters on Ganymede and Callisto indicate that the internal composition and thermal structure have been similar over time. Gravity data suggest that the interior of Ganymede is probably strongly differentiated with an ice-rich crust while Callisto is apparently less differentiated but may have a water-ice rich outer crust of unknown thickness [13]. Our data support the interpretation that the upper 100 km or so of Callisto is also ice-rich, consistent with the geologic conclusion of Schenk [14], otherwise, crater depths and morphologies might more closely resemble those on the Moon. While this does not allow us to determine how water-rich the outer layers of Callisto are, it is apparent that the water-rich zone extends a few 10’s of kilometers. For Titan, studies of the shapes of the larger impact craters, if any and if unmodified, could provide valuable insights into the crustal structure and state of that similarly large icy body.