FORMATION OF GANYMEDE'S CRATER PALIMPSESTS Paul J. Thomas and Steven W. Squyres, Center for Radiophysics and Space Research, Cornell University, Ithaca NY 14853

Crater palimpsests on Ganymede are circular features of very subdued relief that are apparently vestiges of ancient impact craters. Where they lie in dark cratered terrain, they are rendered easily visible by a high albedo relative to their surroundings. In the few cases where palimpsests lie in the brighter resurfaced terrain, no obvious albedo boundary is present, and they are visible only as subtle topographic forms. Some palimpsests in both settings are clearly observed to consist of broad, low, dome-like deposits of some small but finite thickness. Two models have been suggested for the origin of palimpsests. In one (1), the margin of the palimpsest is envisioned to be the rim of the original crater. In the other (2), the margin of the palimpsest is the limit of continuous ejecta. Both models face difficulties. For the first, several lines of evidence (discussed below) suggest that the margin of the palimpsest in fact extends well beyond the original crater rim. For the second, one must note that the limit of continuous ejecta on craters elsewhere in the solar system is typically quite ragged and irregular, while palimpsest margins are very clearly defined, smoothly curved, and nearly circular.

We have re-examined the distribution and dimensions of all the palimpsests on Ganymede, updating the original survey of Passey and Shoemaker (2). The base maps used were the fifteen USGS quadrangle maps of Ganymede. We measured four characteristics: palimpsest diameter, diameter of the smooth central region of the palimpsest, apparent diameter of the original crater rim where a vestige of it appears, and diameter of the secondary crater field. We find linear relationships between several of these parameters. Where a smooth central region is present, it typically has a diameter 1/4 to 1/3 that of the palimpsest. Where a vestige of the original crater rim appears to be present within the palimpsest, its diameter is typically about half that of the palimpsest. The smallest craters for which palimpsests are observed have diameters of about 40 km.

We have found three palimpsests that have sufficiently defined secondary crater fields for us to measure their dimensions with confidence. Assuming that the ratio of secondary field diameter to crater diameter is the same as is observed for the rest of Ganymede, we find again that the original crater diameter is about half that of the palimpsest. This observation strengthens our confidence in the identification of crater rims well inside the outer edge of the palimpsest.

As an alternative to the two hypotheses for palimpsest formation mentioned above, we suggest that the outer margin of a palimpsest instead represents the limit of a volcanic deposit triggered by a large impact event early in Ganymede's history. We suggest that palimpsest formation may be a straightforward result of cratering during an early period of intense activity within the satellite. Accretional heating of Ganymede would have led to substantial early warming of the satellite's outer layers, producing a thick, warm, mobile zone overlain by a relatively thin, rigid "lid". The material below the lid may have been solid, or might have even been liquid for a short time. In the case of solid but warm ice, the material would clearly have been buoyant relative to the cold lid above it. In the case of liquid, a small amount of silicates in the lid would be required for buoyancy. Small impacts would not have penetrated the lid, and would have produced normal craters. Larger impacts, however, would have penetrated it, allowing any buoyant, mobile material to ascend to the surface. Crater excavation depths for 40 km craters are expected to be ~10 km (3), comparable with estimates for the thickness of both the mechanical (4) and thermal lithospheres 4 Gy ago. As the lithosphere cooled and thickened, palimpsest formation would have ceased, consistent with the observed concentration of palimpsest formation in the earliest part of Ganymede's recorded geologic history.

Constraints on the nature of the extruded materials may be derived from the mechanics of their emplacement. We first consider the case of extrusion of solid ice. Extrusion would be driven by the density difference between the lithosphere and the underlying mobile material. We make the conservative assumption that this difference is that of pure ice at temperatures of 250 vs. 200 K (4.3 kg m^{-3}), although an increased silicate content in the lithosphere would increase this value, and hence the buoyancy of the ascending material. For ice at a plausible sublithospheric temperature of 250 K (corresponding to a viscosity of 10^{15} Pa s (5,6)), extrusion through a 40 km diameter conduit will extrude what we believe to be a typical palimpsest volume ($\sim 10^{13}$ m^3) in $\sim$3 My, comparable to the conductive cooling time for the flow. Because the flow is much thinner than the conduit, cooling of the palimpsest will control extrusion.

We are able to determine the aspect ratio γ (maximum height divided by radius) of palimpsests in only one case. The value is about 0.02, but this palimpsest may be an unusually thick one. The smallest values may be in the vicinity of 0.005 (typical thickness of 500 m for a 100-km radius palimpsest), but accurate measurements cannot be made from Voyager data. A simple model for axisymmetric spreading of a Newtonian viscous material (7) and the requirement that the flow is emplaced in one cooling time for a layer of appropriate thickness would imply a bulk viscosity for the flow of 10^{15} Pa s for $\gamma = 0.02$. For $\gamma = 0.005$, however, the value would be about 10^{12} Pa s.

While the former viscosities are consistent with glacial viscosities of ice (and the assumed extrusion viscosities), the latter values are too low for subsolidus flow. If typical aspect ratios really are as low as 0.005, we must then instead consider flow in a partially liquid state. In this case, the behavior of the spreading material might best be described by a Bingham rheology (8,9). Using the simple model of Paterson (10) we can determine the yield strength of such a partial melt from the dimensions of the palimpsest. For a 100 km radius palimpsest with $\gamma = 0.005$, the yield strength would be 1.7 kPa. This is lower than is typical for the yield strength of even very mobile silicate lavas, but may be reasonable for an H_2O water/ice slush.

We believe that formation of crater palimpsests by volcanic extrusion of buoyant, mobile subsurface materials is the model most consistent with their morphology. It also readily explains the concentration of palimpsest formation in the early part of the satellite's history. In order to better constrain the mode of emplacement (solid or liquid) of palimpsest deposits, an important objective for the Galileo mission will be to obtain accurate measurements of the aspect ratios of the deposits.

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