Palimpsests on Ganymede: an endogenic origin?

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Introduction. One of the more enduring puzzles in the geology of the galilean satellites Ganymede and Callisto has been the interpretation and origin of the so-called palimpsests: quasi-circular light albedo patches with subdued interior topographic structure. Most hypotheses for the origin of palimpsests as a group have invoked some form of impact-related process, including: viscously relaxed "normal" impact craters (1), large, high velocity/high melt producing impacts (2), impacts with induced central endogenic diapirs (3), and impacts modified by cryovolcanism (4). Hypotheses of purely endogenic origin were proposed specifically for the Valhalla structure on Callisto soon after the Voyager Jupiter encounters (5,6). These specific models, however, could not be scaled to the observed dimensions of the palimpsests, and no further purely endogenic models have been considered. Reconsideration of the morphologies, classifications and statistical data of palimpsests, presented here, leads to inconsistencies with any kind of impact model for some palimpsests, prompting the proposal of a new, purely endogenic model for these features.

Morphologic classifications. One of the problems with interpretation of palimpsests has been the inclusion by various authors of different types of structures under the term "palimpsest." It is important to recognize different structure types, because different structures may be formed by entirely different processes. Based on a number of papers, features classed at times as palimpsests are differentiated as follows: 1) impact basins (e.g.: Gilgamesh, Nidaba, Hathor, 24N,182W on Ganymede) with a small central plain or dome, two (possibly 3) distinct concentric rings, secondary crater fields, and (sometimes) bright ejecta blankets, typically larger than about 150 km in diameter (1,2); 2) moat (7)/ anomalous pit (2)/ or (some) dome (3) craters (e.g.: Menhit on Ganymede) with subdued rims, prominent/oversize central pit rims with topographically prominent central domes, usually smaller than 100 km in diameter (2,3); ripple ring structures (e.g.: Valhalla and Asgard on Callisto, and 27S,153W on Ganymede [first described by (8), later rediscovered by (9)]) with rounded central smooth patches surrounded by inner annuli of concentric ridges and (only in the largest) outer annuli of concentric graben, usually larger than 300-400 km in diameter (8); and 4) "palimpsests" (e.g.: Memphis, Busiris, and Buto Faculae on Ganymede) with irregular central smooth patches surrounded by subdued, subconcentric ridges within a distinct, circular, sharp-edged light albedo patch, usually larger than about 100 km in diameter (1,2). [Hereafter, the term "palimpsest" will be restricted to class 4 features only.] Possible transition features between moat craters and small palimpsests exist, but the impact basins and palimpsests are distinctly different - one cannot be converted to the other by viscous relaxation (2). Ripple ring structures may be related to palimpsests, but only Valhalla has a bright albedo patch, and that is associated with the circular central plain. In contrast, the albedo patches of palimpsests extend considerably beyond any topographic structures, and they appear to be distinct deposits of non-negligible thickness overlying pre-existing terrain with sharp, raised, and sometimes slightly lobate edges. These characteristics led to their interpretation as ejecta blankets (1), melt sheets (2), or cryovolcanic flows (4).

Observations. Considering the [class 4] palimpsests as distinct features yields a number of interesting observational characteristics. A. The difference in crater statistics between large craters on Ganymede and Callisto is accounted for: if [class 4] palimpsests are assumed to be impact features and included in Ganymede crater counts (adopting a conservative rim diameter of 1/2 the diameter of the albedo patch), then the craters on Ganymede's dark terrain follow a roughly -2 differential slope between about 80 and 500 km in diameter. Over the same diameter range, there are actually fewer craters on Callisto (a much more heavily cratered object than Ganymede) and they follow a -4 differential slope. Removing the two dozen-odd palimpsests from the Ganymede statistics brings the crater counts on both bodies between 80 and 500 km into statistical coincidence - a result that might be expected for two bodies experiencing the same cratering flux (10). B. There are no unambiguous [class 4] palimpsests on Callisto. Except for Valhalla, virtually all of (1)'s proposed palimpsests turn out to be moat craters or fresh crater ejecta blankets. C. A few additional features (Siwah Facula, 19S,150W and 18S,156W) may be considered as palimpsests: they have the characteristic light deposit, but are irregular in shape. D. Palimpsests are not randomly distributed: they are concentrated in southern Galileo/eastern Marius Regio and eastern Barnard Regio. E. Palimpsests lack secondary crater fields and the sharp-edged bright deposit are difficult to interpret as ejecta. F. Palimpsests have a minimum diameter of 80-100 km; interior ridge systems and central patches (where identifiable) are, respectively, about 0.6-0.7 and 0.1-0.2 the diameter of the albedo patch.

Most of these observations are difficult to reconcile with any kind of impact model. The large impactor/high-velocity impact model of (2) is consistent with items E and F, but none of the rest, particularly the non-random areal distribution on Ganymede and the lack of palimpsests on Callisto. That palimpsests comprise the difference in large crater statistics between Ganymede and Callisto seems to be positive evidence that palimpsests are not crater-related, unless the putative crater is much smaller than any identifiable interior structure. On the other hand, the similarities in structure between palimpsests suggests that they were formed by a specific process. Therefore, consider a purely endogenic model.

Diapir/Plume Model. Several considerations motivate a diapir model: 1) Axisymmetric organization of most palimpsests are nominally consistent with expected isolated diapir shapes, yet diapir forms on Earth are flexible enough to account for irregular palimpsests. 2) Based on several studies (e.g.: 4,11), palimpsest bright materials are very thick (in excess of a few km) in the center near the central plain but much thinner (a few hundred meters) in and beyond the concentric ridges, suggestive of a massive upwelling of material in the center that flows viscously outward over the surface as might be anticipated from a large piercement diapir. 3) The existence of a lower diameter cut-off for palimpsests is consistent with diapirism, since diapirs have to be of some minimum size (dependent on mantle and plume viscosity and density relations) to reach and break through the lithosphere (12). 4) The edges of the bright material are sharp and slightly lobate and look like materials extruded from primary grooves (see groove at 15S,152W), suggestive of viscous flow. 5) The non-random area distribution of palimpsests is consistent with terrestrial analogs: diapirs form in groups where local conditions are favorable.

A scenario for palimpsest formation might be as follows: a large diapir, consisting of buoyant warm water ice or (more likely) mixtures of a number of low-melting point ices, nucleates at a boundary at depth (core-mantle, ice-phase change or ice-liquid?), rises through the mantle and pushes through the lithosphere to the surface. Near-surface materials buckle and fold, forming an incipient concentric ridge system (perhaps not unlike folds around Richat structure and Pilbara batholiths, see ref. 13). Viscous material then erupts from the central piercement and flows symmetrically outward. Collapse of the diapir "magma chamber" due to volume loss to the surface outflows would form concentric failure surfaces that may also contribute to the formation of the concentric ridge system. The irregular central plain marks the remnant of the central "vent", filled with cryovolcanic liquids or slushes. Ring dikes may also form, allowing local fracturing and flooding at large radial distances, forming some of the sharp, lobate boundaries and concentric depressions seen at the outer edges of some palimpsests (e.g.: Memphis Facula and 4S,222W). Alternatively, all of the flows may have originated from the central diapir, but a problem would be maintaining axial flow symmetry over such large distances.

Some comments can be made on the nature of the diapiric material. If Ganymede is only marginally differentiated (only a thin ice crust), the diapirs could consist of liquids and slushes. If Ganymede is largely differentiated (with a thick ice crust), then buoyancy considerations imply that liquids of likely composition would have difficulties reaching the surface and that the material should be warm, but solid, ice. The observed thicknesses (4) and distinct edges of the light deposits in the rugged terrain implies fairly viscous flows. Low viscosity liquid water or brine flows would be too thin and simply "get lost" in rugged terrain as they spread out from the source vent, unlike the observed deposits. Based on current understanding (14), the only icy magmas with viscosities high enough to form the observed deposits are liquids and slushes containing ammonia. Diapirs containing significant amounts of ammonia provide an additional plus for the model: depressurization melting (as occurs in terrestrial plumes) becomes possible. This allows the diapirs to buoyantly rise as warm solids and also provides a mechanism to initiate massive surface flows.

Light terrain formation on Ganymede was a distinct geologic episode. Based on morphology, light terrain emplacement may have been similar to dike swarm formation and flooding on the Earth. Dikes are now thought to propagate laterally from large diapir-like magma bodies (15). If Ganymede's grooved terrain was formed by a similar mechanism, then one would expect large diapirs in Ganymede's lower crust as well. Some of the diapirs should break through, forming surface features: I propose the palimpsests. Formation of the palimpsests as part of the same process as light terrain is supported by the similar appearance of materials forming some of the light terrain and palimpsest, and by their similar crater-count ages (1). This suggestion also accounts for the lack of both light terrain and [class 4] palimpsests on Callisto: it never went through the heating episode that produced both these features on Ganymede. The discussion of Ganymede's unique heating episode is beyond the scope of this paper, but possible explanations may come from special tidal heating mechanisms (16).

References. 1. Q. Passey & E. Shoemaker (1982) Satellites of Jupiter, U. of Arizona Press, p. 379. 2. S.K. Croft (1983)JGR (Suppl) 88:B71. 3. J. Moore & M. Malin (1988) GRL 15:225. 4. P.J. Thomas & S.W. Squyres (1990) JGR 95:19161. 5. W. Hale et al. (1980) Conf. Multiring Basins (Abs.), p. 30. 6. C.A. Wood (1981)Proc. Multiring Basins, p173. 7. USGS Ganymede Mapping Program standard designation. 8. S.K. Croft (1985) Rep.PGG Prog-1984, p.206. 9. P. Schenk & w.B. McKinnon (1987) Icarus 72:209. 10. S.K. Croft (1988) LPS XIX, p.227. 11. S.K. Croft et al. (1993) Geologic map of Tiamat Sulcus Quad, Ganymede, I-2328. 12. S.W. Squyres & S.K. Croft (1986) Satellites, U of Arizona Press, p. 293. 13. N.M. Short & R.W. Blair (1986) Geomorph. from Space, p. 98,124,158. 14. J.S. Kargel et al. (1991) Icarus 89:93. 15. H.C. Halls & W.F. Fahrig (1987) Mafic Dyke Swarms. 16. R. Malhotra (1991) Icarus 94:399.