HYDRAULIC FRACTURE AND FLOW: AN ALTERNATE DRIVING MECHANISM FOR VOLCANISM ON ICY SATELLITES

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Landforms suggesting volcanic processes on Ganymede--a primarily icy body--include two very dissimilar dome-like structures (1), small diapir-like domes in the central pits of certain craters (2, 3), and the smooth and grooved terrains indicative of extensive resurfacing and fracturing. The lack of traditional volcanic landforms such as volcanoes and lobate flows is evidence for the very low viscosity of the "magma" on Ganymede, which is most likely liquid water (4). A density contrast between the liquid water and the icy crust has been suggested as the driving mechanism for diapirism and volcanism (1, 3, 4, 5). Because liquid water is denser than water ice, the density-contrast driving mechanism requires a substantial silicate component in the crustal ice. This in turn implies that the outermost layers of Ganymede never melted. However, comparisons of spectra from the surfaces of Ganymede and Callisto with laboratory spectra of mixtures of ice and silicates (6) indicate that the surfaces of these satellites contain less than 10% silicate by weight, and perhaps as little as 0.1%. This implies a low-silicate crust on Ganymede with a density less than 0.99 g/cm^3 (10% silicate at 3.5 g/cm^3, the maximum silicate density probable in the Jovian system), and perhaps as low as 0.92 g/cm^3. That these low densities apply to the entire crust is implied by thermal history models of Ganymede (7, 8) which incorporate solid state convection. These models indicate that (probably) only the outer few hundred kilometers of the crust melted due to accretional heating, allowing the silicate component to sink toward the center and leaving a primarily pure ice crust. The inferred range of crustal densities is less than the density of liquid water and thus is insufficient to drive volcanism or diapirism on Ganymede by density contrast.

An alternate driving mechanism--hydraulic pressure generated by progressive freezing of trapped water pockets--is proposed. Positive topographic landforms on Earth such as pingos (9, 10) and ice mounds on frozen lakes (11, 12) result from hydraulic pressure where water is trapped by re-freezing in periglacial regions. Hydraulic pressures attained in trapped water pockets commonly exceed local lithostatic pressures, and cases of explosive rupture of ice mounds indicating very high hydraulic pressures have been reported (9). Holes drilled into pingos become hydraulically driven water fountains that endure several days before cessation of flow by infreezing of the hole (9). Assuming that at least the outer few hundred kilometers of Ganymede were melted (the results would be the same if the entire planet melted), thermal modeling (13, 14) indicates that the re-freezing liquid is trapped between freezing planes advancing simultaneously up from the core and down from the surface. The net volume change during the final stages of freezing is negative until the very last stage (the Final Freeze) when a small net volume expansion equivalent to a planetary surface area increase of 0.05%-0.1% occurs (14). This final expansion was originally suggested as the mechansim of groove formation (15), but was subsequently dismissed as being negligible compared to the expansion obtained by any initial melting and differentiation (14). During the Final Freeze, however, the remaining liquid water will be trapped under conditions of increasing hydraulic pressure similar to conditions occurring in terrestrial periglacial zones. The maximum depth of the pressurized water is the top of the ice III stability field, about 180 km deep on Ganymede, so the source depth is relatively shallow. Temperatures in the lower crust during the Final Freeze were probably inhomogenous--due possibly to residual accretional heat or solid-state convection patterns--so that the last liquid

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could be in an interconnected network or in isolated pockets. With continued freezing, the pockets will become smaller and more isolated, implying that any surface effects will at first be global (?), then regional, and finally local. Based on this scenario, it is suggested that grooved terrain may form as a result of the Final Freeze. Hydraulic fractures are quasi-planar and may extend great distances compared to the source (16). Initial fracturing may occur at pressures as low as 0.6 times the lithostatic pressure (17). Thus large cracks may appear without surface flow during the early part of the Final Freeze. Later, as the water pockets become more isolated and hydraulic pressures increase, cracks with flows similar to the Great Crack in the Southwest Rift zone in Hawaii may form, resurfacing large areas. Grabens may form as pressure is relieved in the underlying pockets, their orientation being increasingly determined by local stresses. Fracture, flow, and graben formation would continue until freezing is complete, thus the duration of groove formation by this mechanism is less than, but comparable to, the total crustal freezing time of 10^8 years (18). If, as implied by the thermal histories which include solid-state convection, melting on Ganymede was primarily due to accretional heating, then any tectonic features resulting from the very large expansion resulting from differentiation occurred very early, and were probably destroyed by the accretional bombardment long before the oldest currently observed lithosphere was formed. Thus the amount of planetary areal expansion represented by the grooved terrain may only be due to the 0.05% to 0.1% expansion (14) resulting from the Final Freeze. This range of expansion is well within the upper limit of 2% set on planetary areal expansion that occurred after the formation of the lithosphere in Galileo Regio (19). Indeed, the amount of expansion due to the Final Freeze is within the limits of the total expansion estimated for the grooved terrain assuming the grooves are grabens (20). Though much detailed work needs to be done, this hypothesis of grooved terrain formation is at least compatible with the geologically late occurrence and duration of grooved terrain formation, groove morphology and structure, the sequence of groove and smooth terrain formation (21), and the ranges and limits of planetary expansion. Finally, it is suggested that the domes on Ganymede are produced by pingo-like hydraulics associated with the Final Freeze. The diapir-like structures in pit craters may be formed similarly, but because of their dimensions, range in age, and occurrence in impact craters, it is suggested that these are ice mounds formed by re-freezing of impact melt lakes. In summary, hydraulic fracture and flow during final refreezing of the icy crust is proposed as a viable driving mechanism for volcanism and tectonism on Ganymede and other icy satellites experiencing at least partial melting.

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