CO_2-DRIVEN WATER VOLCANISM ON GANYMEDE AND ITS IMPLICATIONS FOR VOLCANIC AND TECTONIC STYLES. Scott L. Murchie and James W. Head, Dept. of Geological Sciences, Brown University, Providence RI 02912.

About 50% of the surface of Ganymede consists of areas resurfaced by about 1 km of relatively clean light icy material, and cross-cut by tectonic troughs called grooves (1,2,3). Lucchitta (4) showed that large areas were apparently resurfaced by flooding, but more recently Helfenstein (5) concluded that pyroclastic volcanism preceded flooding in many areas. The grooves or troughs, especially where developed in flooded areas, commonly have raised rims (6), and average about 4 km in width (7). Elongate groove lanes (8) are bounded by prominent deep grooves in their wider portions, and taper at propagating tips to dark raised-rimmed troughs with associated patchy resurfacing material resembling pyroclastics (5).

Previous models of the planet's volcanotectonic evolution are based on phase changes in a water-ice mantle overlying a silicate core, and melting of a dense ice phase (9,10,11,12). However, the ice component of the satellite may contain salts mobilized from silicates by aqueous activity (13), and CO_2, whose cosmic abundance is 20% that of H_2O. A large fraction of the ice mantle could be in a stable form of CO_2-clathrate (CO_2*5-3/4H_2O) (14), which contains only 15 mole-% CO_2. Excess CO_2 could occur in liquid or solid form.

A preliminary chemical and physical model of CO_2-driven water volcanism and mantle evolution was developed, based on an assumed cosmic abundance of CO_2 in the ice. It was also assumed that melting and differentiation into a silicate core and liquid mantle would have occured due to heating by accretion and decay of short-lived isotopes, and that the same fraction of soluble elements would be removed from the silicates by aqueous activity as is removed from CI chondrites (13). The early liquid would thus have been a highly carbonated 2-3 M Na_2SO_4-K_2SO_4 solution. Freezing would have begun with the formation of a 20-km dominantly ice-I crust, because of the low CO_2 content of the brine at low pressures (15). Crustal density would have increased from near 0.92 to 1.0 g cm^{-3} at the base of the crust as the clathrate fraction rose to about one-fourth. Density would continue to increase slowly with depth; however, the densities given here are lower bounds because ice-I may have been altered to clathrate by the action of CO_2 gas. Because of the 1.2 g cm^{-3} brine density, the clathrate-contaminated ice-I would float. Further freezing of the brine would lead to exsolution at depth of solid CO_2, which would settle to form a higher density lower mantle (cf. 15). Most precipitating salt would also settle, but briny pods could have been trapped in solidifying, relatively brine-free ice. Complete freezing of the mantle could have occurred in <500 m.y. (16).

The internal structure of the satellite at the time of grooved terrain formation was estimated, to constrain processes that could have caused resurfacing and tectonic activity (Fig. 1). For a temperature of 150K at the base of the regolith, a thermal gradient of 1.5° km^{-1} (10), and a density of the silicate fraction of 3.5 g cm^{-3}, a five-layer stratification would have existed. The two uppermost layers, forming the lithosphere, would have been an ice-I dominated crust from 2610-2630 km radius, and an upper mantle of ice-I and at least one-third clathrate from 2590-2610 km. The middle mantle, from 1550-2590 km, would consist of convecting clathrate formed both by freezing of the initial liquid and by reaction of water ice with liquid or solid CO_2. Excess CO_2 would form a solid lower mantle from 1400-1550 km, underlain by the silicate core. Temperature would approach the melting point of salt-contaminated clathrate at the base of the lithosphere and at the boundary of the lower mantle. The core would heat the icy mantle over 2 b.y. or more, resulting in a few tenths of a percent global expansion from thermal expansion of the mantle (17) and possible partial melting of the solid CO_2 lower mantle. The warming lower mantle with possible plumes of liquid CO_2 could induce partial melting of the overlying clathrate. Resulting CO_2-H_2O brine would rise buoyantly through the middle mantle, and possibly the lower lithosphere where low-density liquid CO_2 would exsolve due to decompression. If it reached the low density ice crust, the CO_2-rich melt could continue to migrate upwardly through fractures as described by (18).

At a depth of 3-4 km, exsolved liquid CO_2 would vaporize, expanding violently and freezing entrained liquid to clathrate to produce an initial pyroclastic volcanic style. This rapid gas expansion would freeze about 40% of the melt, conceivably trapping temporarily some plutons at that depth by the formation of ices in conduits. Degassed brine remaining in the pluton would expand as it froze to ice-I, driving floods to the surface by hydraulic pressure. If the initial melt contained the same bulk chloride fraction as calculated for the mantle (about $10^{-1.4}$ M), and had reached equilibrium during its rise with carbonate and sulfate salts suspended in the mantle, freezing of the extruded liquid would precipitate sulfates, about 80% Na_2SO_4 with lesser K_2SO_4, plus carbonate and chloride salts from the last few percent of residual liquid.

The results of this model lead to the prediction of four classes of phenomena that may be observed at the surface. First, local volcanic styles would progress through pyroclastic and flood stages. Second, there may be topographic evidence of the emplacement of buoyant magma bodies in the lithosphere. Third, global extensional tectonics would have resulted from the small amount of global expansion. Fourth, degassed magma that may be trapped at a 3-4 km depth by rapid expansion of vaporizing CO_2 would have expanded upon later freezing, causing tension in the overlying crust. Grabens overlying such magma bodies, if the grabens are modelled as having bounding faults dipping at 60° and meeting at the top of the bodies (7), would commonly be 3-4 km wide. These predicted phenomena closely resemble some of the major geologic patterns and features on the satellite. Local progression from pyroclastic to flood volcanic styles has been proposed by (5) and (19). Large topographic domes have been documented by (20), who proposed that they may have originated by the intrusion of buoyant material. Global expansion has widely been cited as an explanation for the global dominance of extensional tectonics, and (19) noted that elongate bands of parallel grooves (groove lanes) with their bounding lows resemble rifts predicted to occur from passive stretching of the lithosphere. The grabens suggested to have been formed by the freezing of shallow ice plutons are similar to grooves, which are commonly about 4 km in width (7).

In summary, a preliminary chemical and physical model of mantle evolution and volcanism was constructed for Ganymede, based on the presence of a differentiated silicate core and briny ice mantle with cosmic abundances of H_2O and CO_2. The model predicts a Na_2SO_4-dominated salt chemistry of resurfacing material, local progression of volcanism through pyroclastic and flooding styles, global expansion, and possible surface expressions of rising or freezing plutons.

References: (1) Smith, B.A. and the Voyager Imaging Team (1979a) The Jupiter system through the eyes of Voyager 1. *Science* 204:951-972. (2) Smith, B.A. and the Voyager Imaging Team (1979b) The Galilean satellites and Jupiter: imaging science results from Voyager 2. *Science* 206:927-950. (3) Schenk, P. and McKinnon, W.B. (1985) Dark halo craters and the thickness of grooved terrain on Ganymede. *Journal of Geophysical Research* 90:C775-C783. (4) Lucchitta, B.K. (1980) Grooved terrain on Ganymede. *Icarus* 44:481-501. (5) Helfenstein, P. (1986) Derivation and analysis of geologic constraints on the emplacement and evolution of terrains on Ganymede from applied differential photometry. Ph. D. thesis, Brown University, 414p. (6) Squyres, S.W. (1981) The morphology and evolution of Ganymede and Callisto. Ph. D. thesis, in *Advances in Planetary Geology,* NASA TM-84412, 365-718. (7) Golombek, M.P. (1982) Constraints on the expansion of Ganymede and the thickness of the lithosphere. *Journal of Geophysical Research* 87:A77-A83. (8) Murchie, S.L. and Head, J.W. (1985) Global tectonic mapping of Ganymede: a preliminary report. *Lunar and Planetary Science* 16:599-600. (9) Squyres, S.W. (1980) Volume changes in Ganymede and Callisto and the origin of grooved terrain. *Geophysical Research Letters* 7:593-596. (10) Shoemaker, E.M., Lucchitta, B.K., Plescia, J.B., Squyres, S.W., and Wilhelms, D.E. (1982) The geology of Ganymede. in *The Satellites of Jupiter,* Morrison, D., ed., Univ. of Arizona , 974 p. (11) Parmentier, E.M., Squyres, S.W., Head, J.W., and Allison, M.L. (1982) The tectonics of Ganymede. *Nature* 295:290-293. (12) Parmentier, E.M. and Head, J.W. (1984) A model for the emplacement and solidification of bright terrain on Ganymede. *Lunar and Planetary Science* 15:633-634. (13) McSween, H.Y. and Richardson, S.M. (1977) The composition of carbonaceous chondrite matrix. *Geochimica et Cosmochimica Acta* 41:1145-1161. (14) Takenouchi, S. and Kennedy, G.C. (1965) Dissociation pressures of the phase CO_2*5-3/4H_2O. *Journal of Geology* 73:383-390. (15) Quinn, E.L. and Jones, C.L. (1936) *Carbon dioxide.* Reinhold, 294 p. (16) Consolmagno, G.J. and Lewis, J.S. (1978) The evolution of icy satellite interiors and surfaces. *Icarus* 34:280-293. (17) Zuber, M.T. and Parmentier (1984) Lithospheric stresses due to radiogenic heating of an ice-silicate planetary body: implications for Ganymede's tectonic evolution. *Journal of Geophysical Research* 89:B429-B437. (18) Crawford, G.D. and Stevenson, D.J. (1985) Gas-driven water volcanism and resurfacing Europa. *Lunar and Planetary Science* 16:148-149. (19) Murchie, S.L., Head, J.W., Helfenstein, P., and Plescia, J. (1986) The sequence of grooved terrain formation in Uruk Sulcus, Ganymede. *Lunar and Planetary Science* 17, this volume. (20) Squyres, S.W. (1980) Topographic domes on Ganymede: ice vulcanism or isostatic upwarping. *Icarus* 44:472-480.

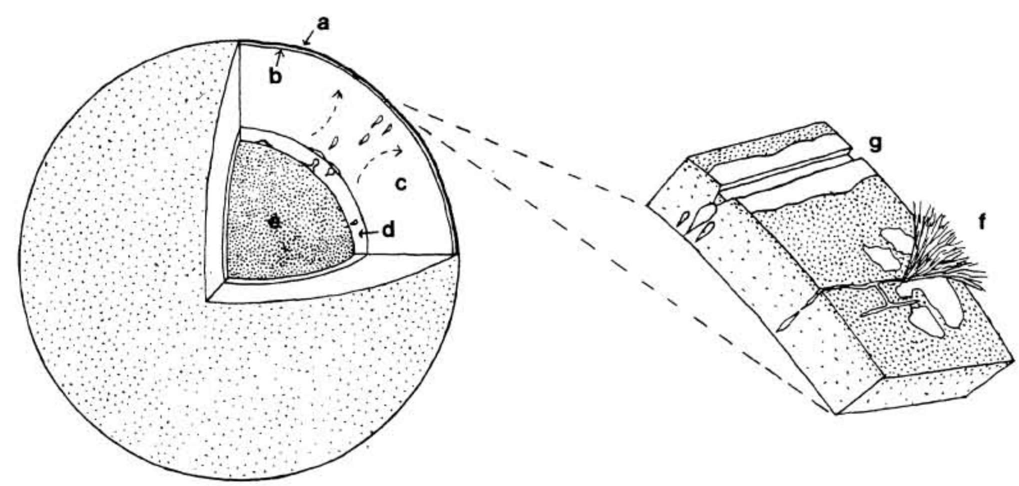

Fig. 1. Hypothetical cut-away view showing the generalized internal structure of Ganymede. The layers are (a) an ice-I dominated crust; (b) a lower lithosphere of CO_2-clathrate and ice-I, where the lower boundary of the lithosphere is marked by the isotherm equal to 0.8 of the melting temperature of clathrate; (c) a middle mantle dominated by CO_2-clathrate; (d) a lower mantle of solid CO_2 possibly with a small portion of liquid; and (e) a silicate core. The segment of the lithosphere shown in detail contains rising plutons initially degassing and partially freezing at shallow depths (f), and later expanding and discharging liquids under hydraulic pressure during freezing (g).