THE EVOLUTION OF VOLCANISM ON GANYMEDE: POSSIBLE IMPORTANCE OF A LOW MELTING-POINT VOLATILE. Scott L. Murchie and James W. Head, Department of Geological Sciences, Brown University, Providence, RI 02912.

Volcanic materials on Ganymede. Light terrain cut by pervasive grooves is the most conspicuous surface on Ganymede that has been widely interpreted to be ice-volcanic in origin. Light materials cover half of the satellite [1,2] to a depth thought to average 1-2 km [3], and have crater-densities [4,5] suggesting that they were emplaced 3 to 3.8 Gyr ago. On a local scale light materials generally exhibit embayment relations which suggest emplacement as low-viscosity flows [6,7], but restricted areas of light material appear to have been deposited from above, suggesting a "pyroclastic" mode of emplacement [8,9]. Light materials appearing to have been emplaced in either mode also typically appear to have emanated from grooves.

Recent studies [5,10,11,12] suggest that older dark terrain, covering the remaining half of the satellite, is also ice-volcanic in origin. Large, smooth to hummocky dark deposits partially to completely cover older, furrowed materials, embaying some large craters and preferentially burying small ones [5,10,11,12]. Separate large regions of furrowed dark material have significantly different crater-ages, ranging from 3.8 to 4.1 Gyr (Fig. 1 in [5]). The furrows within each region crosscut extremely few or no large craters, however, suggesting that furrows formed approximately contemporaneously with emplacement of dark-material deposits over a period of 2-3 x 10^8 yrs [5,12]. An initial attempt to determine the stratigraphy and layering of dark materials suggests a total thickness averaging about 5 km globally [12].

Albedos of volcanic materials. The most conspicuous albedo variation of materials interpretd here to be volcanic is the higher albedo of light material than dark material. However, the two materials occupy a continuous range of albedo variation. This observation is apparent in many *Voyager* images of Ganymede, and has previously been documented quantitatively by Helfenstein [8]. These materials form three general albedo classes: "low-albedo" materials, including those forming dark terrain in Galileo, western Marius, and southeastern Nicholson Regio; "intermediate-albedo" materials, including those forming dark terrain in central Marius, Barnard, and northwestern Nicholson Regio, plus flank materials of furrows in southern Galileo and eastern Marius Regio; and "high-albedo" materials, including virtually all light materials and the material forming "dark" terrain of extreme western Marius Regio. Contacts of albedo units typically coincide with contacts of materials of different ages, most obviously at light terrain-dark terrain boundaries. Within dark terrain, the coincidence of albedo and material units is conspicuous where smooth to hummocky, intermediate-albedo material of central Marius Regio embays furrowed, low-albedo material of western Marius Regio, and where intermediate-albedo material of northwestern Nicholson Regio embays furrowed, low-albedo material of southeastern Nicholson Regio.

Possible origins of albedo variations. Both light and dark materials are generally thought to be relatively pure ice which has been darkened by time-dependent processes, primarily the intimate intermixing of darker meteoritic material by impact gardening [4,13,14]. Spencer [15] has suggested, alternatively, that intimately mixed regoliths would develop surfaces consisting of frost patches on a silicate-rich lag, on a time-scale much shorter than that of impact gardening. If Spencer's hypothesis is correct, then albedos of different materials are controlled less by time-dependent processes and more by substrate properties and the local availability of H_2O-ice to form frost patches. If the time-dependent darkening hypothesis is correct, then lower-albedo materials should have greater ages of emplacement.

When the two most basic groups of volcanic materials (light and dark) are taken as a whole, then the lower-albedo (dark) material has a greater age as indicated by crater-densities and stratigraphy [1,2]. However, crater-ages of different large dark-material units (Figure 1 in [5]) reveal an inconsistent relationship of albedo and crater-age. Of surfaces whose crater-densities were measured, those nominally 4.0-4.1 Gyr in age (western Marius, Nicholson Regio) are low-albedo. Surfaces with a nominal 3.9 Gyr age (central Marius, Barnard, northwest Nicholson regio) are intermediate-albedo. However, the youngest dark materials (Galileo Regio, 3.8 Gyr in age) have as low an albedo as do the 4.0-4.1 Gyr-old materials. Furthermore, some of the oldest light materials ("complex grooved terrain" of [9]) are within several hundred kilometers of young, low-albedo dark material in Galileo Regio, and have only a slightly lesser crater-age of about 3.7 Gyr (Fig. 1 in [5]). This "complex grooved terrain" is distinctly high-albedo, however, and not obviously darker than nearby, younger light terrain. These observations are inconsistent with the hypothesis that time-dependent darkening processes were the *primary* determinant of albedo differences of volcanic materials.

Surface composition and albedo of volcanic materials. If albedo differences of volcanic materials are not due primarily to time-dependent darkening processes, then they may result from compositional or textural differences of the volcanic materials or from differences in the lag deposits that formed on these materials [cf. 15]. Three types of differences in substrate composition are possible: (a) differences in the fraction of silicates entrained in ice-lavas [11]; (b) differences in the composition of silicates entrained in ice-lavas; or (c) differences in the contents of salts or low melting-point volatiles in ice-lavas. Model (a) is plausible, but the reason for temporal evolution of the fraction of entrained silicates is unclear. There is no clear reason to expect temporal variation of the composition of entrained silicates (model b). Evolution of the volatile and salt contents of ice-lava (model c) is plausible, and could be expected to result from evolution of the temperature and composition of the magma source region. We thus investigate this possibility in detail.

Influence of a low melting-point volatile on Ganymedean volcanic history. We first assess candidates for low melting-point volatiles in the Ganymedean environment. *In situ* measurements of cometary gases [16] suggest that CO, CO_2, CH_4, and NH_3 are the most abundant non-aqueous volatiles in the outer solar system. In the presence of H_2O-

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ice, at pressures appropriate to Ganymede's interior, and at abundances relative to H_2O of <15 mole-%, CO, CO_2 and CH_4 form a clathrate whose melting temperature is higher than that of H_2O-ice [17]. Any of these compounds is therefore unlikely to have been a low-melting point volatile. However, under similar conditions, NH_3 forms a dihydrate which yields eutectic melt at $\geq 40°K$ less than the melting point of pure H_2O-ice, and more H_2O-rich melt at higher temperatures [18]. If dark material erupted as cool, near-eutectic melt containing about 15 mole-% NH_3, and if light material erupted as a higher-temperature liquid containing only 0-5 mole-% NH_3 [cf. 18], then the global inventory of "ice-igneous" materials described earlier could have been derived by mobilization of a global NH_3 volume fraction of only $\leq 0.2\%$. We therefore conclude that NH_3 is a primary candidate for a low melting-point volatile that could have produced melting, volcanism, and volcanic deposits early in Ganymede's history.

Three properties of low-temperature, NH_3-rich volcanic material could have led to its development of a lower albedo than higher-temperature, more H_2O-rich material. First, the low-pressure NH_3 phase (monohydrate) [18] ablates three orders of magnitude more rapidly than does pure H_2O-ice [19]. If materials of different NH_3 content contained similar silicate fractions at the times of their eruption, then the more NH_3-rich material would have developed a comparatively silicate-rich lag surface. Second, the NH_3-rich material may contain a greater concentration of easily mobilized salts, which have been darkened by radiation [4]. Third, extrapolation from the experimental data of [20] suggests that near-eutectic melt (15 mole-% NH_3, $T=180°$-$200°K$) would have erupted with a vapor pressure of about 10^{-3} bars; higher-temperature, more H_2O-rich material (5 mole-% NH_3, $T=250°K$) would have erupted with a vapor pressure of about 10^{-2} bars. Therefore, a flow of NH_3-rich material would have boiled to a depth of around 6 cm, whereas a flow of H_2O-rich material would have boiled to a depth of around 60 cm. This difference in eruption style might have led to differences in the materials' porosities and textures that influenced the evolution of their albedos.

On the basis of the considerations above, we propose a simple model for a two-stage evolution of volcanism on Ganymede which assumes an initially cold satellite interior [cf. 12]. First, as the interior accumulated radiogenic and/or tidal heat, dark material erupted as a low-temperature, NH_3-rich liquid that removed most of the NH_3 inventory from the magma source region. Second, after greater internal temperatures had been achieved, light material erupted as a higher-temperature, more H_2O-rich liquid that extracted much of the remainder of the NH_3.

Discussion. This model of Ganymedean volcanism would account for the increase of the albedo of volcanic material from "dark" to "light" as a result of long-term decrease in the NH_3 content of erupted ice-lavas, due to its depletion from the interior by prolonged internal warming. The transitional nature of this albedo difference is consistent with variability of the NH_3 fraction of erupted lavas. The model requires no previous, large-scale internal melting or ice-silicate differentiation, and so is consistent with the inference of [12] based on tectonic patterns that Ganymede's interior warmed from a cold, undifferentiated state. Finally, the model has two additional important implications for the nature of albedo variations on Ganymede and Callisto. First, Croft [21] has suggested that the subdued topography of crater palimpsests, whose albedos are commonly similar to that of light materials, is the result of incorporation of large amounts of impact-melt of bulk lithosphere within these features as they formed. Such bulk melt probably would have been H_2O-rich, so if it migrated to the surfaces of palimpsests its albedo may have evolved similarly to that of H_2O-rich light material. Second, volcanic material observed on Callisto within the Valhalla ring system [22] is all "dark material". Callisto's lower silicate fraction and perhaps lesser tidal heating than Ganymede [e.g. 23] should have resulted in lower internal temperatures having been achieved, if both it and Ganymede accreted as cold, NH_3-bearing bodies. If they both did accrete cold, Callisto would have been less likely than Ganymede to have achieved the internal temperatures necessary for production of more H_2O-rich light material.

Summary. Volcanic materials on Ganymede do not exhibit a consistent relationship of albedo to crater-age, suggesting that inherent material properties as well as time-dependent processes (intermixing of meteoritic material) controlled the evolution of observed albedo differences. We propose that old, "dark" volcanic materials erupted as a relatively cool, silicate-bearing, near-eutectic H_2O-NH_3 liquid, and that younger "light" volcanic materials erupted as a higher-temperature, silicate-bearing, H_2O-rich liquid. The much higher ablation rate of low-pressure ammonia monohydrate than pure H_2O-ice led to formation of a darker, more silicate-rich lag on the older, more NH_3-rich volcanic material. This hypothesis is consistent with independent inferences about the thermal history of Ganymede [12], and with other albedo properties of both Ganymede and Callisto.

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