CRYOVOLCANISM ON GANYMEDE: EVIDENCE IN BRIGHT TERRAIN FROM GALILEO SOLID STATE IMAGING DATA.
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Introduction and background: Pre-Voyager observations revealed that the surface of Ganymede consisted largely of water ice [1] and Voyager analyses concluded that the bright terrain on Ganymede was emplaced by cryovolcanism and then tectonically deformed, with terrain smooth at Voyager resolution often representing least deformed to undeformed cryovolcanic deposits [2-4]. Galileo Solid State Imaging high-resolution data have provided important new information about the nature of bright terrain on Ganymede that raise questions about the significance of the role of cryovolcanism [5, 6]. Here we outline Galileo observations related to resurfacing processes [6] and describe specific evidence for the nature and style of cryovolcanism in bright terrain [7] from Galileo data.

General evidence for cryovolcanism and the nature of other resurfacing processes: Over the vast majority of bright terrain imaged, little evidence has been found for volcanic source vents, embayment relationships, flow fronts, or associated structures [8]. Boundaries between bright terrain and dark terrain are typically very sharp and appear to be of tectonic origin [9]; in most places, no evidence is seen for embayment of bright terrain material into dark terrain topography, even where furrows or depressions are oriented normal to bright terrain [e.g., 10]. This could be due to high-viscosity cryovolcanism, but this is not consistent with the very widespread development of bright terrain, its regional very flat topography, and the lack of constructional edifices. Central domes in impact craters, previously interpreted to be volcanic, appear diapir-like in origin [11]. Highly tectonized portions of dark terrain, and regions of transitional terrain, often appear to be brightened by tectonic deformation (tilt-block faulting, shear, etc., causing shedding of dark material off highs and deposition in adjacent lows, revealing more ice-rich material beneath), rather than volcanism [12]. Tectonic resurfacing may thus be an important alternative to cryovolcanism for the formation of some bright terrain deposits on Ganymede [6].

Evidence for cryovolcanic activity on Ganymede has been found in the form of: 1) relatively smooth plains that do not appear to have originated from tectonic resurfacing at least at a resolution of several tens of meters [e.g., 10], 2) features described previously as 'caldera-like' in Voyager images [13], and imaged at high-resolution in orbit G8 [14], and 3) dark smooth plains that appear to fill extensive low-lying areas and may embay adjacent higher older areas in dark terrain [15].

Bright Smooth Plains: A narrow strip of relatively smooth plains about 15 km wide is seen extending for several hundreds of km in Voyager data [16] in Nippur Sulcus, and Galileo data shows its characteristics (Fig. 1). Grooved terrain in the lower left is clearly cross-cut and truncated by the smooth band. Grooved terrain in the upper right appears also to predate the smooth terrain but has been deformed by shear as well as extension [10]. This lane of bright material is one of the smoothest observed at Voyager scale and is a good candidate for cryovolcanic resurfacing. Note, however, that the smooth plains do not embay the parallel troughs in either unit of the adjacent grooved terrain, and that the smooth plains themselves are deformed. This could be due to high-viscosity cryovolcanism, or the possibility that the flooding never reached the level of the lows in surrounding terrain topography, but this is not consistent with the very widespread development of bright terrain, and its regional flat topography. Clearly the terrain is not completely flooded and resurfaced, because tectonic fabric similar to that seen to the northeast is observed, and there is a faint hint of the orthogonal fabric of the southwest trend in the smooth plains. One possibility is that the surface is recently tectonically resurfaced but that this resurfacing is at a much finer scale than the Galileo resolution. Another possibility is that the region is partially flooded and resurfaced, leaving the structural fabric as kipukas of preexisting deformed grooved terrain. A third possibility is that the smooth area has been extensively resurfaced by cryovolcanism and then modestly deformed in its latest stages, following cryovolcanic emplacement. This would require that the deformation influence only the interior of the smooth plains as the margins are not modified. If these smooth plains have been emplaced partially or wholly cryovolcanically, as suggested by a possible ghost crater that may have been partially flooded, then one must explain why the cryovolcanic flows did not enter into the adjacent terrain (near-orthogonal furrows to the lower left and tangential furrows to the upper right). One possible explanation for this might be the levee-like raised margins of the smooth plains unit. If these represented chilled margins of the flow unit or deposit, than this could provide a mechanism to keep the lavas from flowing into the adjacent terrain. Some other areas of narrow smooth strips imaged by Galileo are associated with caldera-like features [14] and are judged, by this association, to be better candidates for cryovolcanic resurfacing.

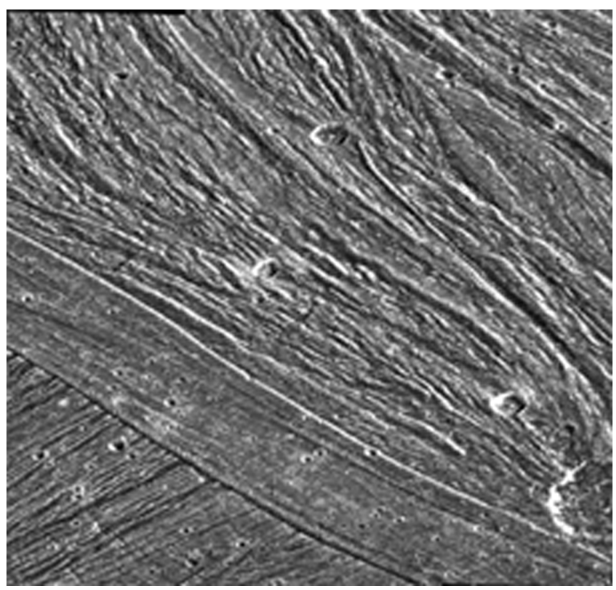

Fig. 1: Portion of the G2 Nippur Sulcus region. Image width is 75 km.

Central Crater Domes: Central domes in impact craters, previously interpreted to be candidates for volcanic extrusionon the basis of Voyager data [13,17], appear diapir-like in origin in Galileo data [11]. Instead of lobate lava flows emanating from the dome structure on the floor, the central dome appears to be more viscously extruded, and the floor as a whole broadly upbowed (11). This is much more consistent with impact penetration to depths that expose more ductile ice in the central regions of the crater, and the subsequent upbowing, diapiric rise, and extrusion of this material into the central part of the crater floor. We consider this as a crater modification process, rather than melting or volcanism associated with crater formation or evolution.

Calderas: Some of the most convincing features indicative of volcanic activity on Ganymede are multiple caldera-like features imaged in Voyager [13,18]. Their morphology is similar: a single inward facing scarp forming a broad arc which is unclosed and truncated or breached by a lane of brighter material. On the basis of Voyager data, these features were hypothesized to form similarly to terrestrial calderas; e.g., partially drained magma chambers resulted in subsidence and faulting of blocks of the crust. The formation of bright terrain lanes in the vicinity are thought to be associated with these caldera-like features. The Galileo G8 Ganymede encounter data included a region (30S, 183W) which has a cluster of eight of these features [14]. Morphologically, the caldera-like features observed in G8 data (Fig. 2) are thought to be non-impact related because of the steepness of their walls, the irregularity of their shapes and the lack of evidence for ejecta deposits; some even show similarities to rille-like channels, suggesting the possibility of thermal erosion [21]. The candidates for caldera-like features are concentrated along the swaths of the freshest, smoothest grooved lanes [14].

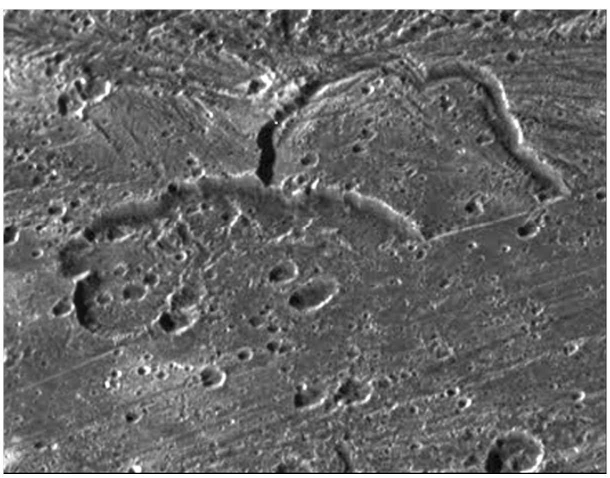

Fig. 2: Portion of G8 Sippar Sulcus region. Image width is 60 km.

The most prominent of these caldera-like features is a scalloped, internally-terraced depression about 55 km in length and 17-20 km wide and oriented tangential to a groove lane (Fig. 3). There is a smooth terrace a few km wide on both sides of the depression, and the floor of the inner depression is occupied by a lobate flow-like deposit 7-10 km wide with parallel ridges oriented convexly toward a cross-cutting groove lane. The morphology of this structure suggests the possibility of multiple eruptions and thermal erosion creating a channel and downcutting into the substrate. The central deposit appears to flow out into the adjacent terrain (there is a scarp-like flow margin where it turns the corner into the groove lane) but the flow is cut by superposed grooves of the groove lane that run parallel to the strike of the lane and almost orthogonal to the direction of the flow as it enters the groove lane area. This feature is the best evidence for cryovolcanic emplacement of at least portions of the bright terrain revealed by Galileo.

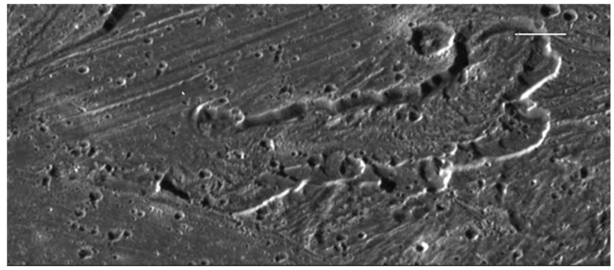

Fig. 3: G8 Sippar Sulcus flow-like feature. Image width is 95 km.

The theory of flow emplacement on Ganymede [19] has recently been reassessed on the basis of data on the admixture of various impurities in water ice [20]; this analysis [21] shows that cryovolcanic eruptions are plausible and should be characterized by high to very high effusion rates. Even modest amounts of gas will result in pyroclastic deposits spread up to about 5 km from the vent and very high effusion rates may lead to thermal erosion and formation of circular depressions around the vent. Lava flows tens of meters thick and many hundreds of km long are plausible, and turbulent motion near the vent may result in eroded channels up to a few hundred meters deep. Thus, we are investigating the possibility that some of the caldera-like cuspate to circular depressions and near-vent channels may be formed or heavily modified by thermal erosion.

Summary and Conclusions: Galileo data have shown that several features cited as evidence for volcanism from interpretation of Voyager images may have alternate explanations (e.g., mass wasting [12]; tectonic resurfacing [6]; viscous flow and diapiric rise[11]). High-resolution data also show evidence for young smooth plains of possible cryovolcanic origin and scalloped depressions, one of which is the source of a lobate cryovolcanic flow that has been emplaced into adjacent bright lanes. This strongly suggests that at least in these regions, crovolcanism is important in the formation of the bright terrain, and that similar scalloped features adjacent to bright terrain elsewhere may be remnants of caldera-like features that mark the location of cryovolcanic extrusions. Thermal erosion may play an important role in the formation of these features [21].

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