A PRE-GALILEO REVIEW OF MAJOR GEOLOGIC QUESTIONS ABOUT GANYMEDE;
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Fifteen years of analysis of Voyager images has led to a broad understanding of several aspects of the geology of Ganymede. These include the gross morphology and distribution of tectonic features in dark and light terrains, the emplacement of light terrain by high albedo cryovolcanism, and variations in the form and albedo of impact features as a function of size. However, there is substantial disagreement about the origin and evolution of dark terrain, the detailed evolution of light terrain, and crustal stratigraphy. These issues are all essential to understanding how the evolution of the surface has been influenced by internal thermal evolution and exogenic processes. Here we review the observations and interpretations from Voyager images pertinent to these issues and identify observations from Galileo that will help to resolve them.

(1) Mode of emplacement of dark terrain: The canonical model for the origin of dark terrain is that it is a nearly primordial, impact generated surface. The lower density of impact craters than on Callisto is attributed to viscous relaxation in an early warm lithosphere [1-3]. However, geologic mapping and studies of crater size frequency distribution have revealed evidence for widespread, thin resurfacing by low albedo cryovolcanism. This evidence includes smooth patches in topographic lows, embayed large craters, and depleted density of small craters [4-8]. Some estimates of the abundance of low albedo cryovolcanic deposits suggest that they may account for a greater amount of resurfacing than light terrain deposits [6,8]. If correct, this would place major constraints on the evolution of Ganymede and the mechanism for subsequent formation of light terrain. Also, if volcanic infilling as well as viscous relaxation has modified the topography of dark terrain craters, estimates of early heat flow based on crater topography [1] may be seriously overestimated. An accurate estimate of the extent and abundance of low albedo cryovolcanism in dark terrain is critical to understanding the early evolution of Ganymede.

(2) Global structure of furrows: Measurements of orientations and arrangements of furrows have shown that they are organized on regional and probably global scales, into three "systems." The earliest studies [2,9,10] recognized that the first system, the "arcuate furrows" in the anti-Jovian hemisphere, are concentrically arranged. Later studies [8,11,12] showed that these are associated with perpendicular, sub-radially arranged furrows having varying crosscutting relations with the arcuate furrows. The second furrow system consists of narrow, linear troughs of extreme length (up to >1000 km), which are spaced widely and arranged radially to a point somewhere east of Marius Regio. They are consistently superposed on the arcuate furrows and are therefore younger. Their extent in the western part of the sub-Jovian hemisphere is unknown. The third system, which is currently exposed in the sub-Jovian hemisphere, consists of a widespread group of roughly concentric furrows [8,12] or alternatively two overlapping sets [11]. Absence of these features in the anti-Jovian hemisphere suggests that they predate the other systems of furrows.

There is controversy regarding whether furrow systems are in their initial configuration or if they were disrupted early in the history of groove formation. It was originally suggested that Galileo Regio has been rotated by about 500 km of left-lateral shear relative to Marius Regio, based on a discontinuity in the trend of arcuate furrows across the intervening light terrain (Uruk Sulcus) [2,13]. Examination of furrow concentricity and search for strain indicators in light terrain led to the conclusion that there has been no shear offset since the formation of the light terrain [14]. Reexamination of this issue using improved coordinate control led to the conclusion that the furrows are concentric and that there is no evidence for disruption [11]. Others [12] also used the improved control but mapped furrows in regions additional to [11]. They [12] agreed with the earlier work which suggested ~500 km of left-lateral shear offset, and supplemented this evidence with the identification of other offset structural features indicating the same magnitude and sense of shear. Improved mapping of the region between eastern Galileo and Perrine Regio will provide independent evidence for the occurrence, sense, and magnitude of shear offsets.

(3) Global structure of grooved terrain: Like furrows, grooves show systematic orientations over a variety of scales. Several groups [2,15-17] noted coherent organization of grooves at both local and regional levels. Preferred orientations within light-terrain regions of the same scale has also been noted [18-20]. Organization of grooves on a global scale has also been documented [21]; many grooves are oriented parallel to two great circles, leading to suggestions that either internal convection or inheritance of the fracture pattern from global despinning may be responsible for the coherent organization of the grooves. Alternatively, it has been shown [22] that the globally preferred orientations discovered by [21] correspond to orientations of furrows in the three large dark-terrain systems, supporting the idea of inheritance of older structures. Documentation of groove orientation on the widest possible basis is necessary to constrain the global structure of grooved terrain.

(4) Formation of grooves and furrows: Individual tectonic troughs in light and dark terrains, loosely grouped as grooves and furrows, may have originated as graben, modified tension fractures, or ductile necking features [2, 23-25]. Voyager images have insufficient resolution to resolve this issue. However, they show variation in furrow morphology between different regions of dark terrain, and between different furrow "sets" in the same dark terrain [8,14]. Grooves sometimes exhibit morphologic differences between regions in which they have different geometric interrelationships ("terrain types"), and those few that occur in dark terrain are irregular. These morphologic differences could arise from mass wasting, differences in strain rate or thickness of lithosphere [24,25], constructional cryovolcanism, or surface deformation due to plutonism in underlying fractures [26]. More thorough investigation into this issue requires new data on the detailed morphology of grooves and furrows representative of those occurring in different areas of Ganymede.

(5) Emplacement of light material: Evidence of emplacement of light terrain as a fluid includes occurrence of large smooth patches and apparent structural confinement by fault scarps [9,13,24]. In some places, smooth light material has been emplaced with a feather edge on surrounding terrain whose appearance contrasts enough that it may be possible to see a flow front, and from its morphology infer the rheology of ice-lava [27]. In other places, light material appears to have been emplaced as a very thin mantle on older, rough topography without infilling its low spots. This mode of occurrence [16,17] is the clearest indication of explosive cryovolcanism predicted to accompany eruption of aqueous melts [28]. High resolution images will help to constrain the nature of eruption mechanisms and the rheology of the erupted material.

(6) Sequence of events during light terrain formation: Complicated stratigraphic relations of different light terrain morphologic features record a history of resurfacing and deformational processes. Study of these relationships can potentially provide insights into the basic geologic processes that formed light terrain and grooves, but doing so requires clear understanding of exactly how to interpret the stratigraphic relationships. This issue has been investigated carefully by several groups [15,16,29]. These groups agree on the basic concept of the breakup of older dark terrain into progressively smaller blocks, but they disagree on the stratigraphy of grooves and light materials. One study [15] suggests that breakup preceded a later stage of resurfacing which somehow preserved the older, throughgoing grooves outlining the lithospheric blocks. Other studies [16,29] agree that a more complicated history most have occurred, in which resurfacing and groove deformation were interspersed; many of the oldest throughgoing grooves were later reactivated and occupied by younger tectonic features. The main reason for this divergence in views is that most of the critical morphologic details which are essential to determining stratigraphic relations were at the limit of Voyager image resolution.

(7) Impact basins as indicators of crustal stratigraphy: Palimpsests are flattened impact structures which occur in a variety of degradation states. The freshest contain remnant basin rings and central smooth patches; the most degraded are nearly flat. Most palimpsests exhibit an elevated albedo, but in some of the freshest ones this is confined to the central smooth patch. The exact mechanisms for the formation of palimpsests are not agreed upon. Important roles have been suggested for prompt collapse of impact basin topography [30], slow viscous relaxation [1,2], subsequent resurfacing by fluid light material [31], and extrusion of a more viscous melt [32]. Still others [33,34] noted a continuity of form and albedo pattern with smaller craters, suggesting that central smooth patches and domes represent frozen impact melt. Origin of palimpsests has a critical bearing on interpretation of crustal stratigraphy. The presence of higher-albedo material in palimpsests has been used as evidence for impact excavation of a relatively "clean" ice mantle underlying a crust which is richer in low albedo, non-ice materials [2,3]. In contrast, if the higher albedo is due to impact melting or to resurfacing, the occurrence of high-albedo materials in palimpsests has nothing to do with crustal stratigraphy and instead is related to the impact process. High resolution images of palimpsests exhibiting a variety of morphologies and albedo patterns will help to test these hypotheses.

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