TECTONIC AND VOLCANIC EVOLUTION OF DARK TERRAIN AND ITS IMPLICATIONS FOR INTERNAL STRUCTURE AND EVOLUTION OF GANYMEDE. Scott L. Murchie and James W. Head, Dept. of Geological Sciences, Brown University, Providence, RI 02912; Jeffrey B. Plescia, U.S. Geological Survey, 2255 N. Gemini Dr., Flagstaff, AZ 86001.

Introduction. Half of Ganymede's surface consists of heavily cratered dark terrain which contains sets of parallel to subparallel furrows [1,2]. The commonly accepted model of dark terrain evolution is developed around three central hypotheses [3,4,5,6]: (a) furrows were formed by large impacts on rapid time-scales; (b) dark terrain is the silicate-contaminated, impact-metamorphosed, primordial crust of a differentiated ice mantle; and (c) a dense, Callisto-like crater population was removed by viscous relaxation. In this study, we undertake a detailed analysis of dark terrain geology (a) to characterize the formation and evolution of dark terrain and (b) to determine any implications of dark terrain geology for Ganymede's internal structure and evolution. We utilize: (a) maps of both structures and resolvable dark-material units; (b) crater-density measurements; (c) calculations of crater-ages of different dark terrain surfaces and selected younger surfaces, using the impactor flux history and apex-antapex heliocentric flux gradient of [7]; and (d) testing of multiple hypotheses of furrow origin.

Geology of dark terrain. The most conspicuous dark-terrain structures are two hemispheric-scale furrow systems, designated systems I and III by [8,9]. System I is located in the anti-Jovian hemisphere, in Marius Regio and Galileo Regio. System I is dominated by arcuate furrows arranged approximately concentrically to a faint albedo feature that may be a giant crater palimpsest [3,4,8,9], and also contains furrows arranged sub-radially to the palimpsest and having variable lengths and age relations with the arcuate furrows [8,9]. System III is located in the sub-Jovian hemisphere, in Perrine Regio, Barnard Regio, and Nicholson Regio, and is dominated by arcuate furrows arranged approximately concentrically to a point in younger light terrain north of Perrine Regio [2,8,9]. No conspicuous ridges or obvious compressional features occur within either system I or III. Furrows in both systems crosscut extremely few older craters, yet within each system occur on material units with significantly different crater-ages ranging between 3.8 and 4.1 Gyr (Figure 1 in [10]). Many furrows are partly buried by smooth to hummocky dark materials that appear to have emanated from other furrows, most notably in northwest Nicholson Regio [10], Galileo Regio [11], and central Marius Regio [12]. Younger furrows cut both these resurfacing materials and also partially infilled craters, yet have morphologies and radial and concentric orientations similar to those of the older furrows. These relations suggest that systems I and III developed over 2-3 x 10^8 yrs by global extension, perhaps localized in preexisting radial and concentric fracture zones, and that furrow formation was closely related to emplacement of volcanic materials that buried preexisting topography.

The youngest furrow system, system II [8,9,11], contains troughs that are arranged radially to a point about 1700 km east of the center of system I. In dark terrain observed at high resolution, these radially-arranged troughs extend to a distance of 5500 km or more from the center of radial symmetry (i.e. 60% of the distance to the antipode). System II cuts all dark materials but is disrupted by reticulate terrain and buried by light terrain, and therefore has a crater-age of about 3.8 Gyr (see Fig. 1 in [10]).

Dark terrain structures and volcanic materials exhibit four types of global trends relative to the center of system II. First, the total thickness of accumulated dark-material deposits, estimated from (a) the areal extents of individual deposits of different age and (b) the thicknesses of the deposits that are required to bury preexisting topography (1-3 km), generally decreases from 4-8 km near the center of system II to 1-3 km near the antipode. The global *average* thickness of accumulated dark materials appears to be about 5 km. Second, almost all dark materials which bury system I furrows are circumscribed by a small circle 4000 km in radius that is centered on the center of system II. Third, surface crater-ages are youngest near the center of system II (3.8-3.9 Gyr) and increase to 4.0-4.1 Gyr toward the antipode. Fourth, the density of system I sub-radial furrows is greatest within 2500-3000 km of the center of system II.

Origin of the furrow systems. We tested nine models of furrow origin, by comparing predicted and observed furrow morphology, age relations, spatial organization, and association with impact and volcanic features. These models include: (a) impact-generation of a multiringed structure [13]; (b) fracturing driven by an impact-generated tsunami [14]; (c) fracturing of an isostatic, thermal uplift [15]; (d) fracturing of a dynamic uplift over an upwelling convection current [15]; (e) large-scale negative diapirism [16]; (f) reactivation of conjugate tidal fractures [17]; (g) reactivation of parallel zones of weakness created by tidal despinning [cf. 18]; (h) reactivation of fractures produced as in (a); and (i) reactivation of fractures produced as in (b).

Of these nine models, observational constraints on the origins of systems I and III (radial and concentric furrow patterns; variable furrow crater-ages; association of furrows with volcanic material) are satisfied only by reactivation of impact-generated, multiringed structures by volcanism and endogenic global extension over a period of 2-3 x 10^8 yrs. This inference is consistent with the observation that system I is centered on a possible giant, degraded palimpsest. System II is consistent only with fracturing of a circular, isostatic uplift in an environment of global tension. Thus furrows are interpreted to be endogenic features that developed on a time-scale of 2-3 x 10^8 yrs, although most of them reused preexisting impact-generated structures.

Dark terrain origin and crater removal. The considerable average thickness of dark materials suggested above ($\approx$5 km), their apparent volcanic mode of emplacement, their global extent [1,2], and evidence that light terrain buries downdropped dark blocks to a depth of only $\approx$1 km [19] together imply that Ganymede possesses a dark, volcanic "crust."

Dark terrain surfaces having significantly different crater-ages contain relatively undegraded furrows which are commonly associated with dark resurfacing materials [9,11]; such furrows crosscut older craters extremely infrequently. A significant number of craters is crosscut only in the second oldest dark terrain area, southeastern Nicholson Regio, and these craters retain significant relief. In areas possessing more degraded furrows (e.g. central Marius Regio [10,12], northwest Nicholson Regio [10]), large craters are flattened and commonly embayed by dark materials. These materials possess a lower cumulative crater-density than do adjacent surfaces with well-preserved furrows, and also a preferential depletion of craters <20 km in diameter, indicating that extensive resurfacing has occurred (see [10]). These observations support the hypothesis of [20], that volcanic infilling rather than viscous relaxation was the primary agent of removal of small- and intermediate-sized craters in dark terrain.

Possible implications for the state of internal differentiation. The scale of system II (5500 km from the center of radial symmetry to the most distant furrows), its radial symmetry, and the absence of any other analogous furrow system are consistent with deformation of a single, circular [21], hemispheric-scale isostatic uplift. Tidal deformation is not expected to have produced either such an uplift or radial fractures, but would have produced antipodal regions of deformation which are not observed. Global expansion, by itself, would have produced a global system of fractures with varying orientation, but not radial fractures or a large circular uplift. A plausible genetic mechanism for so *large* and *circular* an uplift is thermal uplift over a gradually warming, upwelling current of a single, global, axisymmetric convection cell. The concentrations of fracturing and young, thick volcanic materials around the center of system II are consistent with locally thinned lithosphere and high advective heat loss, and thus may support this hypothesis.

Theoretical studies [22] suggest that one-celled convection would require the radius of any convectively isolated core to be ≤ 0.27 times the global radius. Such a volume of silicate-enriched material could have been produced by partial accretional melting of a thin outer layer of the satellite, followed by sinking of the silicate-rich fraction through underlying, less dense material. The resulting clean-ice upper mantle would be ≤ 20 km thick, and the bulk of the satellite would have remained cold and undifferentiated. Hsui et al. [23] showed that long-term radiogenic warming of such a cold, homogeneous interior could have led initially to 1-celled convection (provided that convection through H_2O-ice phase transitions occurred). If such a convection pattern developed, then as the interior accumulated radiogenic heat the greatest temperature increase would have occurred in a single, axisymmetric, upwelling current [22,23]. Thermal expansion of this warm material would have created an isostatic topographic uplift, and radial extensional fracturing of its lithosphere may have occurred [12].

Long-term warming of an initially cold, undifferentiated interior is consistent with two major independent inferences about the early geologic history of Ganymede. First, global tension is interpreted to have occurred throughout furrow formation; such stress is a predicted consequence of the warming of an undifferentiated interior [24]. Second, the width of endogenic furrows and grooves decreased with time, suggesting a long-term decrease in the thickness of the mechanical lithosphere. Such a decrease in lithospheric thickness may imply an accompanying increase in the lithospheric thermal gradient [25], and presumably warming of an initially cooler mantle.

Conclusions. The results of this study present a new paradigm of dark terrain evolution: (a) furrows are endogenic and formed on a 2-3 x 10^8 yr time-scale, commonly by reactivation of preexisting, impact-generated zones of weakness; (b) dark terrain consists of a thick layer of volcanic materials; and (c) a dense, Callisto-like crater population was removed by volcanic infilling.

The furrows' endogenic origin implies that an observed decrease in the width of extensional tectonic features through the time of grooved terrain formation was the result of long-term thinning of the mechanical lithosphere. Such a decrease in lithospheric thickness may indicate an increase in the lithospheric thermal gradient, and warming of an initially cooler upper mantle.

Large-scale patterns of lithospheric fracturing and the distribution of volcanic materials are consistent with development of an axisymmetric thermal anomaly in cooler material, perhaps by long-term warming of the upwelling current in a single, global convection cell. The geometry of such a convection cell, if it existed, would require that very little growth of a silicate-rich core has occurred, and thus that the satellite is largely undifferentiated. This hypothesis is consistent with the independent inference that the interior was initially cool.

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