GROOVED TERRAIN ON GANYMEDE: A GALILEO-BASED SYNTHESIS. Robert T. Pappalardo[1], Geoffrey C. Collins[2], James W. Head[3], Jeffrey M. Moore[4], and Paul M. Schenk[5], [1]LASP, University of Colorado, Box 392, Boulder, CO 80309 (robert.pappalardo@colorado.edu), [2]Astronomy and Physics Dept., Wheaton College, Norton, MA 02766, [3]Brown University, Box 1846, Providence, RI 02912, [4]Ames Research Center, MS 245-3, Moffett Field, CA, 94035, [5]Lunar and Planetary Institute, 3600 Bay Area Blvd, Houston, TX 77058.

Introduction: Swaths of bright "grooved terrain" (sulci) on Ganymede are 10s to 100s of kilometers wide and cross-cut the older dark terrain, forming an intricate patchwork across 2/3 of Ganymede's surface. The view of grooved terrain developed from Voyager images is that bright cells are broad graben infilled by extrusion of relatively clean (silicate-poor) liquid water, warm ice, or icy slush, and then extended and faulted [1]. Galileo imaging has greatly improved understanding of the emplacement history and geological implications of grooved terrain, supporting a rift-like model for its formation.

Grooved terrain characteristics: Intersecting grooved terrain sulci can exhibit complex stratigraphic relationships. From regional-scale Voyager imaging, it was suggested that newer grooved terrain structures commonly end against older, more prominent grooves in T-terminations [2]. High resolution images show that newer grooved terrain typically cross-cuts and can destroy older terrain instead, creating the observed complex array of crosscutting swaths [3]. In some locations, there appears to be an inheritance of structural patterns at the boundaries between dark terrain and grooved terrain [e.g. 4, 5], suggesting that prominent grooved terrain structures have utilized pre-existing zones of structural weakness in dark terrain.

High resolution images reveal the extent of albedo heterogeneity in grooved terrain [6]. Stereo imaging confirms a close correlation of albedo to topography, with the darkest material concentrated in local topographic lows [6, 7]. Bright material is generally located on ridge crests, and dark material concentrates in the topographic lows between ridges. There is a tendency those slopes which receive the least total insolation during the day to be brighter, implying cold-trapping of ice [8]. At high resolution, any albedo contrast between "bright" and "dark" terrain can be elusive, exemplified by Galileo imaging of Philae and Anshar Sulci.

Fourier analysis on several sites imaged by Galileo reveals multiple superposed wavelengths of topography [9]. Multiple small-scale wavelengths (~1 to a few km) are generally superimposed on longer wavelength topography (~5 to 10 km). This result is confirmed by limited high-resolution stereo imaging, which shows that small-scale ridges and troughs are superimposed on larger-scales swells and valleys. Extensional necking of Ganymede's lithosphere can account for multiple topographic wavelengths, and suggests a brittle lithosphere ~1 to several kilometers thick at the time of stretching [10].

High resolution stereo imaging reveals the detailed topographic characteristics of grooved terrain. In Uruk Sulcus, topographic amplitudes reach ~500 m and the resolved (long wavelength) slopes are ≤19° [11]; smaller-scale ridges are probably ≤ 200 m high. These results are consistent with photoclinometric profiles from Voyager images [12].

Tectonism: High resolution Galileo images support an extensional tectonic model of grooved terrain formation, with roles for strike-slip faulting and possibly lithospheric spreading.

Styles of extensional tectonism. Grooved terrain within some polygons has a morphology resembling flat-floored graben and intervening flat-topped horst ridges, but the more common morphology of grooved terrain is kilometer-scale blocks, with ridges that appear triangular to rounded in cross-section, suggestive of domino (tilt-block) style normal faulting [6]. Boundary relationships give strong support to an extensional tectonic origin, as incipient fractures immediately adjacent the grooved terrain commonly have the same spacing as grooved terrain structures, suggesting that tectonic structures propagated into and imbricated preexisting terrain. Hanging wall rollover is commonly associated with tilt block normal faulting, and could explain for prominent bounding troughs alongside some lanes of grooved terrain [6, 13].

Amount of extension. Based on the geometry of domino-style fault blocks inferred from high-resolution Uruk Sulcus images, a minimum extensional strain of ~50% has been estimated [14]. Strained craters offer valuable insight into the degree of extension across groove sets, suggesting that highly strained grooved terrain (10s to >100% strain) may be common [15]. The high strain implied by tilt-block style normal faulting in bright and dark terrains poses a challenge for constraints on the total expansion of Ganymede.

Tectonic Resurfacing. The high degree of strain in zones of tilt block normal faulting suggests that preexisting surface features may be altered beyond recognition through tectonic resurfacing [16]. This does not rule out volcanic resurfacing early in grooved terrain formation, to brighten the terrain overall and produce relatively smooth materials. However, destruction of older grooved terrain and the formation of subsequent units does not require volcanism to erase pre-existing terrain; instead, intense tectonism alone has apparently resurfaced some grooved terrain units without new icy volcanic resurfacing.

It is noteworthy that dark terrain which has undergone a high degree of tectonic deformation appears somewhat brighter than the surrounding terrain, despite there being no evidence for icy volcanism affecting the terrain [9, 13]. Moreover, the transition from some dark terrain to grooved terrain regions shows no direct evidence for icy volcanism, as in Anshar Sulcus [13]. It is intriguing to consider whether tectonism alone can not just resurface older terrain, but brighten it as well. At least some brightening of initially dark terrain is expected where tilt-block faulting has occurred, revealing brighter icy material beneath, with loose dark material moving downslope into topographic lows. However, it remains to be demonstrated whether fine-scale faulting can effectively smooth and brighten pre-existing terrain.

Strike-slip faulting. Voyager imaging suggests that strike-slip tectonism has operated on Ganymede, notably based on the sigmoidal shapes of some grooved terrain sets and candidate strike-slip offsets along major fault zones [17, 18]. At higher resolutions, strong evidence is found for strike-slip faulting in grooved terrain, specifically based on en echelon structures, sigmoidal fault-bounded regions suggesting fault duplexes, and offsets of pre-existing features (e.g. Dardanus Sulcus) [19]. Small amounts of horizontal shear appear to be an integral part of the grooved terrain formation process.

Lithospheric spreading? A spreading-analog model for grooved terrain was suggested based on Voyager observations [17], but little evidence was found for cut and separated older features or the large-scale horizontal shear expected to accompany lateral motion. Galileo observations of Arbela Sulcus suggest that pre-existing structures may have been offset and displaced laterally, presents the intriguing possibility that limited lithospheric spreading might have occurred on Ganymede [20].

Volcanism: Though the extent of icy volcanism in bright terrain formation remains somewhat enigmatic, indirect evidence for volcanism is inferred.

Volcanic landforms. Most high resolution images have lacked clear and abundant morphological evidence for icy volcanism such as lava flow fronts, source vents, or embayment relationships [6]. Such features may generally have been destroyed by fracturing, impact erosion, or mass wasting, may be too low in relief to be resolved, or perhaps did not form in volcanic terrains on Ganymede.

At least 18, and probably more than 30 scalloped depressions (provisionally termed "paterae" by the IAU) are observed on Ganymede, and could represent caldera-like source vents for icy volcanism [17, 21]. High-resolution Galileo images show that the largest patera of several within Sippar Sulcus is associated with a ridged deposit interpreted as an icy flow [22].

Smooth terrain in central Sippar Sulcus exhibits topographic characteristics consistent with icy volcanic resurfacing, lying at roughly constant elevations over great longitudinal extent and depressed 250 to 1000 meters below surrounding terrains [23]. In this volcanic resurfacing scenario, downfaulted regions are flooded by aqueous lavas and then tectonized by groove formation, while only the youngest smooth bands escaped tectonization.

Smooth terrains. Embayment relationships and truly smooth regions indicating icy volcanism have been elusive at high resolution. Limited embayment is suggested in Sippar Sulcus [22, 23]. Moreover, low-relief patches seen at 16 m/pixel within Harpagia Sulcus [20] might be examples of plains emplaced by low-viscosity icy volcanic flows.

Virtually all smooth bright terrains on Ganymede exhibit some degree of tectonic overprinting [20]. The apparent intimate association of tectonism and volcanism suggests that icy volcanic extrusions and tectonic extension operate in concert. The search for pristine and unambiguous icy volcanic landforms may be confounded by near-simultaneous tectonism which has highly modified them.

Summary: Overall a rift-like model of grooved terrain is supported by Galileo imaging, with important modifications from previous scenarios including: overprinting by cross-cutting of groove lanes; multiple superimposed length scales of deformation; a significant role for tilt-block style normal faulting; locally high extensional strains; the potential for tectonism alone to resurface some groove lanes; abundant evidence for minor strike-slip faulting; the possible occurrence of local lithospheric spreading; and limited direct evidence for smooth terrains and implied icy volcanism.

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