GROOVED TERRAIN ON GANYMEDE: SCIENCE ISSUES TO BE ADDRESSED THROUGH GALILEO IMAGING; Robert Pappalardo, James W. Head, and The Galileo Imaging Team, Depart. Geol. Sci., Brown University, Providence, RI 02912.

Grooved terrain on Ganymede consists of sets of subparallel ridges and troughs, typically organized in structural cells within broader swaths of bright terrain. Morphological evidence generally indicates an extensional-tectonic origin for the ridges and troughs, likely as normal fault blocks. However, the detailed emplacement mechanism, stratigraphy, deformation style, and evolution of grooved terrain remain uncertain. Here we examine some of the outstanding questions regarding the origin and evolution of grooved terrain and discuss how planned Galileo observations will address these issues.

Nature and origin of grooved terrain

Grooved terrain on Ganymede consists of sets of curvilinear, subparallel ridges and troughs, which can be continuous along their trend for hundreds of kilometers [1]. Spacing of ridges and troughs within a single set tends to be regular, with a mean trough spacing of about 8 km [2]. Crosscutting and termination relationships among troughs identifies them as tectonic structures [3,4]. A continuum of forms from single troughs to ridge-and-trough sets suggests a genetic relationship [5]. Individual troughs are generally indicative of tensional stresses, arguing an extensional-tectonic origin; similarly, an extensional origin is implied by observations that some grooved terrain lies lower than surrounding terrain and that relatively deep primary troughs commonly define the margins of sets [1].

An extensional-tectonic origin implies that troughs are either normal fault blocks (tilt blocks and/or graben), or crevasse-like fractures due to tensional failure. Morphological arguments, including large trough widths, favor a normal faulting origin [6,7]. Viscous relaxation [5] and mass wasting may have affected the form of grooved terrain, but to an uncertain extent. A regular spacing of graben can be accounted for by invoking an extensional instability in the ductile lithosphere [8]. Alternatively, grooved terrain faults may relieve stress in their vicinity, promoting a regular fault spacing [7]. If troughs are graben, their spacing and geometry permits estimate of the thickness, strength, and thermal profile of Ganymede's lithosphere during their formation [2,6,8,9].

Swaths of grooved terrain on Ganymede are considered to be broad graben that have been infilled [5] by extrusion of relatively clean (i.e. silicate-poor) liquid water, warm ice, or icy slush [10,11]. Dark halo craters in regions of bright terrain confirms that bright terrain overlies older dark terrain [12].

Stratigraphy and emplacement history

A formation sequence has been suggested for grooved terrain, consisting of primary groove formation, secondary groove formation, and flooding and tertiary grooving of the intervening polygons [4]. A different analysis [13] similarly suggests a sequence of lithosphere dissection by throughgoing grooves, deformation of the intervening blocks, and widespread resurfacing accompanied by continuing deformation, but with reactivation of earlier structures being a vital component of the emplacement sequence. The resulting morphological types of grooved terrain have been classified as narrow groove lanes (individual elongate grooves), groove polygons (polygonal domains of grooves), and complex grooved terrain (cross-cutting groove sets) [13]. Galileo will observe examples of each stage and type of grooved terrain to allow for their characterization to test models of grooved terrain emplacement. Criteria have been established for determining detailed grooved terrain stratigraphy and the technique applied to Uruk Sulcus [13]. A portion of Uruk Sulcus will be observed by Galileo on Encounter G1 at 70 m/pixel; on Encounter G2 a 50 m/pixel observation will be nested within the G1 observation, providing stereo. This will enable detailed examination of the stratigraphy, small-scale structure, and degree of modification of this region.

Detailed mapping shows that grooves have preferred orientations, typically trending parallel to nearby dark terrain furrows [13,14], supporting the notion that grooves are influenced by pre-existing structures. To allow evaluation of the global structural trends of grooves and groove lanes, Galileo will image the leading and trailing hemisphere image gaps of Ganymede on orbits C9 and E6, respectively.

Deformation style and strain

The style of normal faulting--whether as horsts and graben or domino-style tilt blocks--is important in that these normal faulting styles imply very different amounts of extensional strain for a similar observed topographic wavelength [7]. Previous assumptions that ridges and grooves are horsts and graben implies <1% global expansion is necessary to form all grooved terrain [6]. But the presence of tilt blocks is suggested by the morphology of some Ganymede ridges and troughs, and this may imply greater amounts of strain. Galileo images across Erech Sulcus on Encounter G8 (resolution 145 m/pixel) will allow for an estimate of the strain across this morphologically typical groove set which cuts across dark terrain.
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Furthermore, during Encounter G8 Galileo will observe a pit crater (resolution 150 m/pixel) with a rim that appears to have been disrupted by grooved terrain formation; the observed rim displacement may allow for a direct estimate of strain across this region.

Small-scale structures can contribute significantly to total extension across a region [15]. The contribution of small-scale faults to strain on Ganymede can be estimated from very high resolution Galileo images, especially the 11 m/pixel sample on Encounter G1. Furthermore, high resolution images will allow assessment of whether primary fault surfaces are preserved in grooved terrain and the degree of post-faulting modification that scars have experienced.

Additional models for ridges and grooves

Other mechanisms may have operated at least locally to create ridges and troughs of grooved terrain. The detailed morphological predictions of a variety of candidate processes has been compiled [16], and Galileo high-resolution observations can test these predictions to reveal the processes that have shaped grooved terrain.

No evidence has been found for consistent asymmetry of ridges and troughs, as might be expected if they originated as thrust faults [5]; however, if thrusting or folding occurs above a weak basal detachment, such as a fractured regolith or a ductile icy substratum, then the resulting compressional structures can be symmetrical in cross-section [16]. Moreover, there is speculation that some grooved terrain, for example in the Nun Sulci region, may contain transpressional folds [17]; this region will be observed at 165 m/pixel during Encounter G7. Distributed deformation in response to strike-slip motion may have produced some grooved terrain sets as transpressional or transtensional fault duplexes [16], and reticulate terrain also might be related to large-scale shearing [17]. A spreading model for grooved terrain structural cells has been suggested based on observations of central ridges and regions of apparent axial symmetry [18]; however, limited evidence has been found overall for the large-scale extension and shear expected to accompany this lateral motion [19]. A Galileo observation of Tiamat Sulcus on Encounter G7 will help to determine whether this process is a viable one, or whether the boundary of Tiamat and Kishar Sulci instead is analogous to a terrestrial accommodation zone [20].

Fissure-style extrusion of icy material has been suggested as a means to create isolated positive-relief ridges on Ganymede [1,7,21]. Intrusion of tabular bodies to create anticlinal cryptodomes might also produce subparallel ridges and troughs [16].

In distinguishing formational processes from high resolution images, among the most important parameters to characterize are ridge and trough cross-sectional shape, termination style, and incipient morphology [16]. Many of the diagnostic predictions of geological processes that can produce ridge and troughs will be observable in Galileo high resolution images of Ganymede, making grooved terrain formation processes distinguishable.

Grooved terrain on Ganymede is a vital constraint on models of surface tectonism and volcanism as well as the satellite's interior history [1,6,10,13,14,19]. While most of Ganymede's grooved terrain is likely of extensional-tectonic origin, its precise nature, formation mechanism, relationship to the resurfacing process, implied strain, and reason for the regular spacing of its constituent structures remain unresolved issues. Moreover, ridge and trough terrain that is morphologically similar to grooved terrain occurs on the Enceladus, Miranda, and Ariel. Therefore, understanding the origin and evolution of grooved terrain is critical to understanding not only the history of Ganymede, but the general geological evolution of icy outer planet satellites.