LIMITS ON THE EXPANSION OF GANYMEDE AND THE THICKNESS OF THE LITHOSPHERE

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The suface of Ganymede is composed of ∿50% low-albedo, heavily cratered terrain and 50% higher-albedo, less cratered grooved terrain. Grooved terrain contains many parallel sets of narrow linear to curvilinear troughs or depressions that separate various sized polygons of cratered terrain. Most workers have concluded that grooves probably result from some type of extensional tectonic and resurfacing process that changed ancient cratered terrain into younger grooved terrain (1). Numerous truncated craters, as opposed to rifted craters, indicate that some form of "sea-floor spreading" was not responsible for the formation of grooves, but rather cratered terrain was converted in situ into grooved terrain (2). Thus, most models suggest shallow flooding of grabens with water ice and subsequent refracturing of the ice to form grooves (3, 4, 5).

In general, the geometry and kinematics of a fault or a group of faults must be known to determine the extension. Even though neither of these is known for grooves on Ganymede, geologically reasonable end members of the dip, displacement, and extension of faults bounding graben can be made. These estimates place valuable constraints on the possible surface area increase, radius increase, and thickness of the lithosphere of Ganymede.

The extension across a fault is equal to the vertical displacement divided by the tangent of the angle of dip; the greater the displacement and shallower the dip of the fault, the greater the extension. Naturally, an upper limit to the fault dip is 90°, in which case no extension is required to form grooves. This somewhat unlikely situation will be numerically approximated by 89.5° dipping normal faults. A minimum normal fault dip is probably 60°. 60° dipping normal faults would form in a completely unannealled ice-sand lithosphere with an angle of internal friction equal to that of loose sand. This end member is mechanically similar to the moon where faults bounding grabens dip 60° in the poorly consolidated megaregolith (6). Note that if the lithosphere of Ganymede is cemented or coherent, then the angle of internal friction would be greater and steeper normal faults would be expected.

The vertical displacement across a fault on Ganymede must be at least as great as the surface scarp. Photoclinometric profiles of grooves indicate topographic relief of a few hundred meters or less and a maximum of 700 meters (7). However, because the grooved terrain formed in stages and fractures associated with early stages represent more fundemental breaks than later-stage fractures (1), the vertical displacement across early grooves is assumed to be greater than later grooves (in accord with minima imposed by measured topographic relief). Thus, the vertical displacement will be overestimated (to arrive at a secure upper limit) as follows: stage 1 primary grooves - 1 km; stage 2 secondary grooves - 0.75 km; stage 3 tertiary grooves - 0.5 km. These overestimates can account for a greater than 1 km thickness of resurfacing material for most groove sets. Furthermore, to obtain a maximum extension, grooves in each stage are assumed to be grabens, each bounded by 2 normal faults of equal displacement. Finally, because of only partial photographic coverage of the surface of Ganymede and the hiearchy of faults found by Golombek and Allison (1), a specific area will be analyzed where the sequence of groove formation is well understood and high resolution images exist (Fig. 1 in 1). This area has a high density of grooves in the grooved terrain and therefore should yield a secure upper limit to the extension of grooved terrain elsewhere on Ganymede.

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The extension associated with groove formation can be expressed as an increase in surface area scaled to the 50-50% mix of cratered and grooved terrain on Ganymede. Results are: stage 1, 0.5-0.01%; stage 2, 0.8-0.02%; stage 3, 0.7-0.01%; where the first and second numbers equal the percent surface area increase assuming 60° and 89.5° dipping faults, respectively. Thus, the total increase in surface area required for all grooved terrain is limited between 2 and 0.04%. This corresponds to a radius increase of 1-0.02% and is substantially less than the 5-7% surface area increase calculated by Squyres (8) based on theoretical calculations of internal melting and differentiation of the planet. The upper limit of 1% agrees exactly with that calculated independently by McKinnon (9) from the limit of expansion imposed by the relatively undisturbed lithospheric shell of Galileo Regio. The radius increase of 1% probably is a maximum because of the low strength of Ganymede's ice crust.

The width of grabens and the dip of faults bounding grabens on Ganymede contain potentially useful information about the thickness of the lithosphere. McGill (10) argued that for simple graben the depth at which the bounding faults intersect below the surface marks the contact between crustal materials with different mechanical properties. Without other supporting information it is not possible to know a priori what mechanical units the contact separates. On Ganymede and Callisto, which are thought to have very thin lithospheres, this intersection depth has been assumed to be the base of the lithosphere for concentric or ringed furrows surrounding impact basins in the heavily cratered terrain (11). Like simple grabens on the terrestrial planets, concentric furrows have similar widths and similar spacing between adjacent members of a set. If ringed furrows are grabens and if faults bounding these grabens intersect at the base of the lithosphere, it seems prudent to place some end member limits on permisible thicknesses of the lithosphere. Naturally, this thickness is critically dependent on the angle of dip of the bounding fractures. If faults bounding furrows dip 60°, the lithosphere thickness, T = 9 km (as calculated by 11); nevertheless, for 80° dipping faults T = 28 km, and for 85° dipping faults T = 57 km (however, mechanically T cannot exceed the spacing between furrows (50 km) if furrows are rings, 11). Therefore, the 10 km thickness of the lithosphere suggested by McKinnon and Melosh (11) and Fink and Fletcher (12) is a minimum at the time of furrow formation.

This analysis is also possible for grooves in the grooved terrain which formed after the furrows. Grooves like simple grabens, also have similar widths (roughly 4-5 km) and similar spacings between members of a set. Assuming that faults bounding grooves intersect at the base of the lithosphere, T = 4 km for 60° dipping faults, T = 13 km for 80° dipping faults, and T = 26 km for 85° dipping faults. The lithosphere thickness of 2 km suggested by Fink and Fletcher (12) is not possible because it is mechanically impossible for faults bounding a graben to initiate and propogate upwards from a point below the lithosphere. Therefore, the minimum lithosphere thickness at the time of groove formation is 4 km.

In conclusion, geologically reasonable estimates of the dip, displacement, and extension of faults bounding graben place valuable constraints on the maximum planetary expansion (1%) and the minimum lithosphere thickness at the time of furrow formation (9 km) and groove formation (4 km) on Ganymede.

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