TECTONIC DEFORMATION OF GALILEO REGIO AND LIMITS TO THE PLANETARY EXPANSION OF GANYMEDE. William B. McKinnon and John Spencer, Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721

Galileo Regio is the largest and most prominent unit of dark, ancient heavily cratered terrain on Ganymede (1,2). Its major tectonic feature, an arcuate system of rimmed furrows (3), formed very early as nearly the entire cratering record post-dates it (2). However, Galileo Regio has undergone very little subsequent structural alteration, as opposed to the rest of the planet (i.e., replacement by grooved and smooth terrain). It will be shown that the survival of Galileo Regio as an intact lithospheric unit during the era of grooved terrain formation constrains the amount of concomitant planetary expansion, if any. Furthermore, a comparison of tectonic features (both endogenic and impact produced) on Ganymede and Callisto suggests that the ultimate source that powered the creation of grooved terrain lies in the Ganymedean core.

The rimmed furrows comprise the first recorded tectonic event in the history of Ganymede, and are best interpreted as ring graben created in response to the prompt collapse of a large impact basin (4,5). A lower limit for the lithosphere thickness at the time of formation is set at \( \approx 10 \) km (4,5). Grooved terrain formation occurred later, as indicated by abrupt transection relationships between the two units (4,6). This terrain was created on a planet-wide basis, and is responsible for the destruction of most of the ring system of which Galileo (and Marius) Regio are remnants of. It is widely believed that the ridges and grooves that make up grooved terrain represent a form of extensional tectonics (eg.,6).

Various versions of an expanding Ganymede have been proposed (7,8) to account for this extension. However, it is difficult to reconcile any major planetary expansion with the survival of Galileo Regio as a coherent unit. Incipient wedges of grooved and smooth terrain are not observed, and there is very little evidence of tectonic deformation other than the rimmed furrows. Planetary expansion can potentially result in large tensions in the lithosphere of a planet. Once faulting takes place, however, stresses are greatly relieved. The vast extent of grooved terrain (faulting) implies that if extension driven by expansion was important, it became less and less so as more of the terrain formed. The lithospheric unit that would best express expansional stress will be the largest, Galileo Regio.

Galileo Regio can be simply modeled as a thin spherical shell of approximately 3200 km diameter (Fig. 1). Planetary expansion and grooved terrain forming at its periphery will insure that its lithosphere can be decoupled from the rest of the planet. As Ganymede expands its curvature decreases, and Galileo Regio will relax to accomodate the new 'geoid'. As the edges of the shell are free (\( \sigma_{\theta \theta} = 0 \)), it should deform to minimize membrane stress (9). In the simplest approximation, the area of the shell will be conserved. This leads to compression in the center and circumferential tension at the edge. As the planetary radius grows, the angle Galileo Regio subtends must decrease. Overall, the circumference of the shell increases. Strain is given by

\[
\varepsilon = (1 + \frac{\Delta r}{r}) \sin \left\{ \arccos \left[ 1 - (1 - \cos \theta) \left( \frac{r}{r + \Delta r} \right)^2 \right] / \sin \theta - 1 \right\}
\]
where $r$ is the planetary radius (2600 km) and $\theta = 35^\circ$. This is plotted as a function of $\Delta r/r$ in Fig. 2. As $\sigma_{\phi\phi} \sim E\varepsilon$, for $E \sim 10^3 - 10^4$ MPa ($10^4 - 10^5$ bars) (10,11), tensional stresses of tens to hundreds of bars will be generated for an increase in planetary radius of one percent. $10 - 20$ bars is a good upper limit for the uniaxial tensile strength of ice (10,11). Therefore if the radius of Ganymede had increased by 1%, the effects of large tensional stress (cracks, normal faults, and graben) would be manifest at the boundary of Galileo Regio (and perpendicular to it). They are not, and 1% can serve as a prudent upper limit for the expansion of Ganymede since the formation of the lithosphere late in terminal bombardment (5). (There are a few furrows unrelated to the ring graben system, but as they are randomly oriented, they are not related to the expansion stress system either).

Global differentiation results in $\Delta r/r \sim 3.5\%$ (8) and thus would have to have taken place prior to lithosphere formation. A more refined approach to thermal evolution (12) results in late stage inversion of a primordial core and a predominantly silicate lower mantle. The radius increase in this scenario would be smaller but probably at least 1%.

Mechanisms of grooved terrain formation that require large planetary expansion would seem to be ruled out. In addition, grooved terrain is probably not simply the result of a dying planetary tectonic engine, a natural consequence of thin lithospheres and solid state convection (13). The preservation of a large ancient cratered unit such as Galileo Regio attests to the ability of even very thin lithospheres to survive convection in the mantle. The Valhalla multiringed system on Callisto has many aspects in common with the ring graben in Galileo Regio. Lithosphere thicknesses on the two bodies at the time of impact were the same to within a factor of two (4). The solid state convection that would be required to maintain such a thickness on Callisto did not disrupt the crust there to form grooves. It appears that grooved terrain formation was a distinct episode on Ganymede, not directly attributable to gross planetary expansion or "normal" mantle convection.

Thermal models and hypotheses on the grooved terrain have evolved from mantle freezing (7) to global differentiation (8) to core/lower mantle differentiation (12). It is proposed that this trend of thought be pursued to the core itself. The segregation of hydrous silicates in the core allows for dehydration and eventual magmatic processes. Interaction between magma and water ice at the core/mantle boundary could have profound effects on the surface.

References
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Fig. 1. Ganymede and Galileo Regio lithospheric shell. Coupled arrows denote expansion stress.

Fig. 2. Circumferential extension, ε, as a function of increase in planetary radius.