GLOBAL EXPANSION OF GANYMEDE DERIVED FROM STRAIN MEASUREMENTS IN GROOVED TERRAIN. G. C. Collins, Physics and Astronomy Dept., Wheaton College, Norton MA 02766; gcollins@wheatonma.edu.

Introduction: Grooved terrain on Ganymede records an episode of extensional tectonics and possibly cryovolcanism [1], but the cause of groove formation remains uncertain. With little evidence for surface contraction to balance out extension, various mechanisms have been proposed to increase the interior volume of Ganymede and thus cause global expansion. Global expansion may be caused by the interior differentiation of Ganymede, which could produce as much as 3.2-3.6% expansion in radius [2,3], though Galileo gravity data [4] appears to constrain this maximum radial expansion to < 3%. Volume expansion of up to 2% (radial expansion of 0.7%) may also occur as a result of melting and warming Ganymede's ice mantle during an eccentricity-driven thermal runaway event [5].

Observational constraints derived after the Voyager encounters set the maximum areal expansion of Ganymede at 1% (corresponding to a radial expansion of 0.5%). McKinnon based his estimate on Galileo Regio being an intact spherical cap [6] and Golombek based his estimate on the strain represented by the grooved terrain [7]. In the latter study, a portion of Uruk Sulcus was examined and extensional strains were assigned to the different ages of grooves to calculate the percent area increase. The assumed strains of a few percent were based on the assumption that the grooves are graben with small displacements. Golombek then applied the areal expansion from Uruk Sulcus to the whole body, assuming a 50-50 mix of bright and dark terrain.

The simple graben model does not describe the characteristics of grooved terrain at high resolution [1]. Strain measurements in grooved terrain based on fault geometry [8] and deformed impact craters [9] show that tens of percent extension is not uncommon in grooved terrain. This begs the question of just how common large extensional strains are, and whether they imply either (a) global expansion in excess of that possible through volume change mechanisms, or (b) the existence of large-scale contractional deformation which has so far eluded observation. I will address this question by combining recent strain measurements with a global database of grooves on Ganymede [10].

Linking strain to groove morphology: Because of the limited extent of Galileo high-resolution observations, there are only a few areas in which we can measure the strain across swaths of grooved terrain. The challenge in estimating global strain is to link local strain observations from images at the 10 - 100 m/pixel scale with groove morphology observable in the available global image coverage at ~1 km/pixel. At the global scale, bright terrain may be divided into several types: (I) densely-packed, high relief grooves; (II) alternating subdued and prominent grooves; (III) grooves characterized by fine, subtle lineations; (IV) polygons of smooth bright terrain; and (V) narrow linear swaths of smooth material.

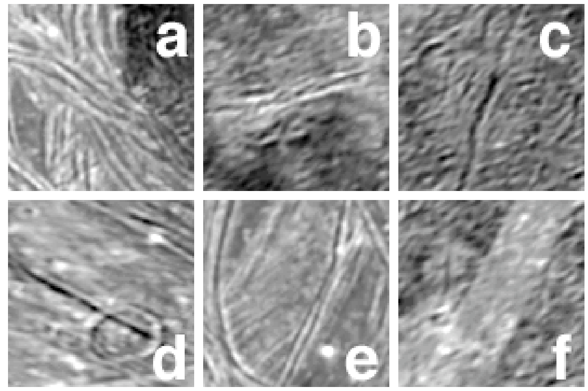

Figure 1: Example global-scale images of grooved terrain where the strain has been constrained. Each image is 100 km on a side. Morphological types include (a) type I, (b,c) isolated type I grooves in dark terrain, (d) type II, (e) type III, and (f) type V.

In the G1 Uruk Sulcus target area, high resolution stereo image coverage enabled strain measurement based on fault geometry, with the result of ~50% extensional strain in the type I grooves shown in Figure 1a [8]. In Nicholson Regio, prominent isolated grooves matching the type I morphology cut across impact craters in the dark terrain (Fig. 1b,c). Strain measurements of these craters indicate >100% extension within the grooves [9]. In Nun Sulci, the impact crater Nefertum has been stretched by faults in an area of type II grooved terrain (Fig. 1d), and this crater exhibits 15% extensional strain [9]. Attempts to measure strain in craters cut by structures typical of type III or IV terrain (Fig. 1e) show either statistically insignificant extension or extension up to 5% [9]. The smooth terrain in type V may be volcanically resurfaced and behave like type IV [11], or it may represent separation and spreading of the crust, like gray bands on Europa [12].

Observations: Initial global expansion estimates have been obtained by examining the expansion of Ganymede's circumference along great circles. Along each great circle, the bright terrain is classified by morphology, and the azimuth difference is measured between the great circle and the trend of each small packet of grooves. Ignoring (for now) the possible role of strike-slip deformation, we can take the length of a packet of grooves L along the great circle, the extensional strain ε represented by that groove morphology, the angle α between the grooves and the great circle, and derive the change in circumference along the great circle represented by the groove packet:

$$\Delta C = L\left(1 - \frac{1}{1+\varepsilon \sin\alpha}\right).$$

Two transects around Ganymede have been completed so far. The first transect follows the equator, and the second transect is perpendicular to the equator, following the 50°W and 230°W lines of longitude. Both transects have good image coverage and avoid large impact structures. As a portion of length along the great circle, the equatorial transect contains 6.0% type I grooves, 8.5% type II grooves, 12.3% type III grooves, 13.4% type IV grooves, 0.5% type V grooves, 6.6% undivided bright terrain (due to low resolution or high emission angle image coverage), 6.6% craters which obscure bright terrain morphology, and 46.1% dark terrain. The 50°-230°W transect contains 1.9% type I grooves, 17.9% type II grooves, 8.6% type III grooves, 10.1% type IV grooves, 2.0% type V grooves, 7.1% undivided bright terrain, 5.0% bright terrain craters, 43.2% dark terrain, and 4.2% with no image data. Though the equatorial transect has a greater proportion of type I grooves along it, they more closely parallel the great circle on average, and thus they don't contribute as much extension per unit length along the transect.

What are reasonable values of ε? Strain measurements indicate 50% to >100% extension in type I grooved terrain, though this type of groove morphology may develop with as little as 25% strain [13]. Only one strain measurement has been made in type II grooved terrain, showing 15% extension; values from 10% to 20% are considered. Structures in type III and IV may represent 5% extension down to negligible strain; I will consider values from 5% to 1% for these terrains. I will consider two cases for type V, either it represents crustal spreading, or it behaves like types III and IV. Strain estimates for undivided terrain are made from 1% to 15%, recognizing that the terrain will be composed of all types, weighted toward types III and IV.

Results: The results of measurements along the two transects, combined with the strain assumptions outlined above, are summarized in Table 1. Shown are one high and one low estimate for the limits of the strain assumptions, and one moderate estimate showing a current "best guess" in the middle of the strain assumption ranges. Though they pass through very different regions of Ganymede, both transects show remarkable agreement in circumference change (except for the high estimate, which is dominated by the spreading of type V terrain in the 50-230°W transect). Despite large strains in some areas of grooved terrain, the moderate estimate gives less than 3% global expansion, consistent with models of interior differentiation. All of the top three estimates show more global expansion than is possible from melting Ganymede's interior (0.7%) and more than previous observational estimates (0.5%). For comparison, the strain estimate labeled "lowest" in Table 1 shows how ~0.5% expansion can be accommodated by lowering the strain estimates for type I and II terrain, though this would bring the strain far out of agreement with measurements from high resolution observations.

Continuing work: This project is part of a larger effort to code morphology and time sequence [14] into a global database of grooves on Ganymede [10], synergistic with the effort to produce a global geologic map of Ganymede [15]. Ultimately the circumferential expansion estimates produced above will be checked against estimates of surface area expansion once all grooved terrain has been outlined and classified.

References: [1] Pappalardo R. T. et al. (2004), Geology of Ganymede (book chapter), in *Jupiter*, Cambridge; [2] Mueller S. and McKinnon W. B. (1988) *Icarus 76*, 437-464; [3] Squyres S. W. (1980) *GRL 7*, 593-596; [4] Anderson J. D. et al. (1996) *Nature 384*, 541-543; [5] Showman A. P. et al. (1997) *Icarus 129*, 367-383; [6] McKinnon, W. B. (1981) *LPSC XXII*, 1585-1598; [7] Golombek, M. P. (1982) *LPSC XXIII*, 269-270; [8] Collins G. C. et al. (1998) *GRL 25*, 233-236; [9] Pappalardo R. T. and Collins G. C. (2005) *J. Struct. Geol. 27*, 827-838; [10] Collins G. C. et al. (2000) *LPSC XXXI*, #1034; [11] Schenk, P. M. et al. (2001) *Nature 410*, 57; [12] Head, J. W. et al. (2002) *GRL 29*, 2151; [13] Sims, D. W. et al., this meeting; [14] Martin, E. S. et al., this meeting; [15] Patterson, G. W. et al. (2005) *LPSC XXXVI*, #1068.

Strain estimate	*Type I ext. strain*	*Type II ext. strain*	*Type III ext. strain*	*Type IV ext. strain*	*Type V ext. strain*	*Undivided ext. strain*	***Equatorial ΔC***	***50-230°W ΔC***
High	100%	20%	5%	5%	Spreading	15%	**4.3%**	**5.9%**
Moderate	50%	15%	3%	3%	3%	5%	**2.6%**	**2.8%**
Low	25%	10%	1%	1%	1%	1%	**1.4%**	**1.6%**
Lowest	5%	3%	1%	1%	1%	1%	**0.58%**	**0.53%**

Table 1: Effect of variations in strain estimates on the change in circumference around the two great circle transects.