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Forming Ganymede's grooves at smaller strain: Toward a self-consistent local and global strain history for Ganymede

Michael T. Bland *, William B. McKinnon

Department of Earth and Planetary Sciences and McDonnell Center for the Space Sciences, Washington University in St. Louis, Saint Louis, MO 63130, United States

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ABSTRACT

The ubiquity of tectonic features formed in extension, and the apparent absence of ones formed in contraction, has led to the hypothesis that Ganymede has undergone global expansion in its past. Determining the magnitude of such expansion is challenging however, and extrapolation of locally or regionally inferred strains to global scales often results in strain estimates that exceed those based on global constraints. Here we use numerical simulations of groove terrain formation to develop a strain history for Ganymede that is generally consistent at local, regional, and global scales. These simulations reproduce groove-like amplitudes, wavelengths, and average slopes at modest regional extensions (10–15%). The modest strains are more consistent with global constraints on Ganymede's expansion. Yet locally, we also find that surface strains can be much larger (30–60%) in the same simulations, consistent with observations of highly-extended impact craters. Thus our simulations satisfy both the smallest-scale and largest-scale inferences of strain on Ganymede. The growth rate of the topography is consistent with (or exceeds) predictions of analytical models, and results from the use of a non-associated plastic rheology that naturally permits localization of brittle failure (plastic strain) into linear fault-like shear zones. These fault-like zones are organized into periodically-spaced graben-like structures with stepped, steeply-dipping faults. As in previous work, groove amplitudes and wavelengths depend on both the imposed heat flux and surface temperature, but because our brittle strength increases with depth, we find (for the parameters explored) that the growth rate of topography is initially faster for lower heat flows. We observe a transition to narrow rifting for higher heat flows and larger strains, which is a potential pathway for breakaway margin or band formation.

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1. Background

1.1. Ganymede's surface strain

Ganymede's iconic "grooved terrain" consists of tens- to hundreds-of-kilometers-wide swaths of parallel, periodically spaced ridges and troughs that form a complex tectonic patchwork across the surface. Dominated at the smallest scales by apparent normal faults, and at larger scales by periodic ridges and troughs (or horst and graben, see below), the grooved terrain almost certainly formed via lithospheric extension. In contrast, features formed in contraction have not been identified. Thus, Ganymede's surface is apparently dominated by extensional strain (Pappalardo et al., 2004; Collins et al., 2010). This observation has led to the suggestion that Ganymede has experienced a period of global expansion during either differentiation (Squyres, 1980; Mueller and McKinnon, 1988) or resonance passage (Showman et al., 1997; Bland et al., 2009). Differentiation yields the greatest areal expansion (up to ~6% (Mueller and McKinnon, 1988)) as high-density ice deep in the satellite's interior is brought up to lower pressure and converts to lower-density phases. The inferred age for the grooved terrain of 2 Ga (albeit with large uncertainty) (Zahnle et al., 2003) poses a challenge for the differentiation hypothesis unless it can be delayed until relatively late in Ganymede's history (e.g., Mueller and McKinnon, 1988). The timing problem is overcome by the resonance-passage hypothesis, which can yield up to ~2% areal expansion of Ganymede as both ice I and high-pressure ice phases melt and yield lower-density (overall) liquid water (Showman et al., 1997; Bland et al., 2009). However, such melting is only transient (current tidal heating in Ganymede is negligible), and it is unclear how global compression during the slow *refreezing* of Ganymede's ice mantle would affect its surface deformation. Furthermore, Ganymede's orbital evolution into the Laplace-resonance is far from certain (see, e.g., Peale and Lee, 2002; Malhotra, 1991; Greenberg, 1987; Yoder, 1979), and need

* Corresponding author. Fax: +1 (314) 935 7361.
E-mail address: mbland@levee.wustl.edu (M.T. Bland).

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not include passage through the paleo-resonances necessary for tidal dissipation to occur.

There are several independent constraints on Ganymede's global, regional, and local strain (see Fig. 1). McKinnon (1981) argued that the increase in Ganymede's surface area must be less than ~2% (i.e., less than 1% increase in radius) based on the observation that Galileo Regio, a large, roughly-circular region of dark terrain, retains its intact shape (the tectonic patterns associated with its furrow sets are generally ancient and not, in themselves, precursors to grooved terrain (Prockter et al., 2000)). Radial expansions larger than 1% should have resulted in obvious, radially striking, extensional deformation (e.g., graben) within the Regio (Fig. 1A). The constraint is consistent with the degree of global expansion suggested by the theoretical considerations described above.

In contrast, structural analyses of Ganymede's grooved terrain itself indicates larger regional and global strains (Collins, 2006, 2008). Collins et al. (1998) estimated strains of roughly 50% in a portion of the Uruk Sulcus region from structural reconstruction of grooved terrain swaths. More general estimates of the strain required to produce large-scale grooves suggested 25–100% extension may be typical (Collins, 2006); however, images with resolution sufficient to reconstruct pre-deformation surfaces are limited. Lower-amplitude grooves are presumed to require less strain to form (Collins, 2006). Extrapolation of these strain magnitudes to the rest of the satellite suggests that Ganymede underwent an areal increase of 6–20%, with a nominal value of 8% (Collins, 2008, 2009) (Fig. 1C and D). The low-end estimate may be consistent with strain magnitudes resulting from differentiation; however, these estimates are generally larger than those based on Galileo Regio, and exceed the global strains resulting from internal melting. To date these difference have not been fully reconciled.

At the smallest scales, surface strain on Ganymede can be quite large. Deformed craters on Ganymede, whose initially circular shape lends itself to strain analysis without requiring an assumption of tectonic structure, indicate that localized strains can exceed 100% (Pappalardo and Collins, 2005) (Fig. 1B). Many of these measurements were performed in craters 20–30 km in diameter with extensional zones ~10 km wide. Such large strains have only been measured at local scales, which may not be applicable across broad regions. In fact, the majority of Ganymede's grooves *must* have formed at lower extensional strain (Collins, 2008, 2009). Bubastis Sulcus near Ganymede's south pole is ~600 km across and includes large-amplitude grooves (Fig. 2). Forming the Bubastis grooves at 100% extension of the original surface would require a 300 km increase (1.8%) in Ganymede's circumference, or a 3.6% increase in Ganymede's surface area for Bubastis Sulcus *alone*. The strain magnitude exceeds that which can be produced by ice-mantle melting and is nearly half that produced by global expansion. Whereas Bubastis is one of Ganymede's widest groove swaths, invoking strains of 50–100% wherever large-amplitude grooves are observed would result in cumulative global strains that well exceed current estimates. This observation alone suggests that even large-amplitude grooves must be able to form at relatively small regional strains (~10%), or that large amounts of hitherto unrecognized crustal consumption has occurred. As demonstrated below, the observations of large local strain can be reconciled with the necessity of smaller regional strain if strain is not evenly distributed throughout the grooved terrain.

1.2. Salient features of the grooved terrain

Truly constraining Ganymede's strain history requires a detailed understanding of the formation of its dominant extensional tectonic feature: the grooved terrain. Nearly two-thirds of Ganymede is composed of bright terrain, much of which includes tectonic structures dubbed grooves (e.g., Patterson et al., 2010). The remaining third of the surface is heavily cratered, lower-albedo terrain. In generic terms, the grooved terrain consists of swaths of periodically spaced ridges and troughs with amplitudes of several hundred meters (Squyres, 1981; Giese et al., 1998; and Fig. 2). The salient

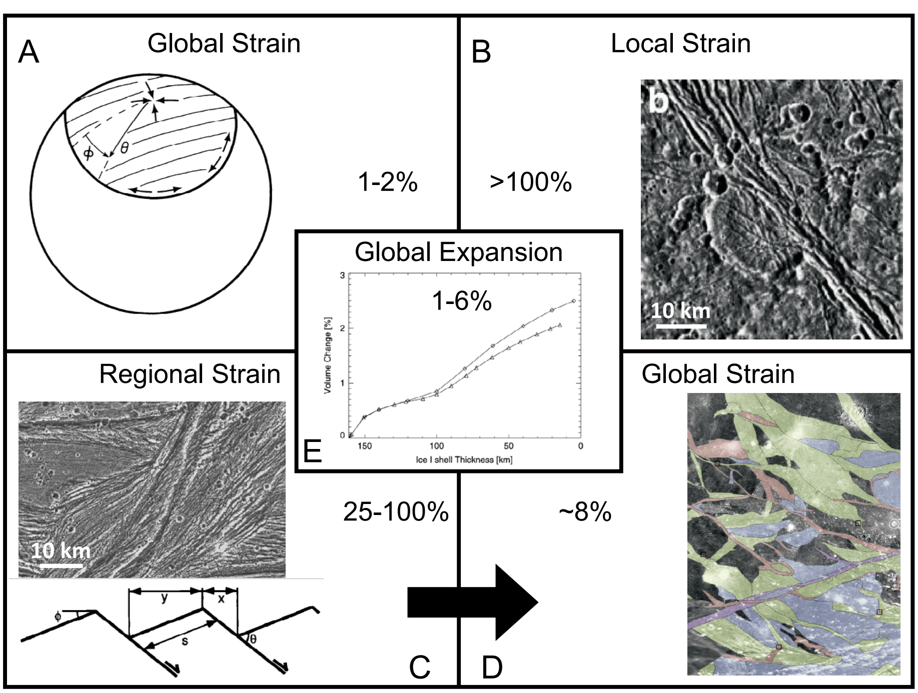

Fig. 1. Summary of independent constraints on Ganymede's areal strain. (A) The observation that Galileo Regio forms an intact spherical cap of dark terrain limits Ganymede's global expansion to ⩽2%. Figure modified from McKinnon (1981). (B) Measurements of deformed craters indicate local strains can exceed ~100%. Figure modified from Pappalardo and Collins (2005). (C) Structural reconstruction of grooved terrain suggest typical extensions of 25–100% for the formation of large amplitude grooves. Figures modified from Collins et al. (1998) and Collins (2006). (D) Extrapolation of regional strain estimates from (C) suggest global surface strain of 8%. Figure modified from Collins (2008). (E) Theoretical calculations of the global strain available from differentiation or melting indicate maximum surface strains of 1–6%. Figure modified from Bland et al. (2009).