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LITHOSPHERIC STRENGTH OF GANYMEDE: CLUES TO EARLY THERMAL PROFILES FROM EXTENSIONAL TECTONIC FEATURES; M.P. Golombek and W.B. Banerdt, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109

Introduction

While it is generally agreed that the strength of a planet's lithosphere is controlled by a combination of brittle sliding and ductile flow laws, predicting the geometry and initial characteristics of faults due to failure from stresses imposed on the lithospheric strength envelope has not been thoroughly explored. In this abstract we will use lithospheric strength envelopes to analyze the extensional features found on Ganymede. This application provides a quantitative means of estimating early thermal profiles on Ganymede, thereby constraining its early thermal evolution.

Extensional Tectonics on Ganymede

Ganymede is the third and largest of the four Galilean satellites. Although it is larger than the planet Mercury, its low density indicates it is roughly one-half silicates and one-half water with a gravitational acceleration similar to the moon. About one-half of its surface is covered by low-albedo heavily cratered terrain and the other half by higher albedo, less cratered grooved terrain (1). Grooved terrain consists of numerous parallel sets of narrow linear to curvilinear troughs or depressions that separate various sized polygons of cratered terrain. Most photogeologic evidence suggests that the grooves formed by some extensional tectonic and resurfacing process involving shallow flooding of wide grabens with high-albedo water ice and subsequent refracturing of the ice to form grooves (1,2,3,4). Given that the grooved terrain probably formed from extensional faulting of one-half of the surface, grooves may be a result of planetary expansion. Attempts to estimate the amount of expansion suggest that a maximum of one percent is needed to form all the grooved terrain (5,6,7).

The largest remnant of cratered terrain on Ganymede is Galileo Regio, upon which a well preserved system of arcuate troughs called rimmed furrows can be found. These furrows which mark the first tectonic event preserved on Ganymede (well before the beginning of the formation of grooved terrain) have been interpreted as grabens (5,8), perhaps resulting from a large impact (8).

A number of attempts have been made to estimate the thickness of the lithosphere from the width or spacing of these extensional tectonic features. To first order, two independent lines of evidence suggest a thin lithosphere early in Ganymede's history. The theory of ringed basin formation (8) and the early high heat flow inferred from crater relaxation studies (9) both imply thin lithospheres (less than a few tens of km). The simplest model for determining lithosphere thickness from furrows and grooves suggests that both structures are simple grabens with flat floors and two exactly equal bounding faults that converge downward (5,8). These simple grabens probably form when normal faults initiate at the base of a brittle layer and propagate up yielding grabens with similar widths, similar displacements, and similar distances between members of a set. Assuming the bounding faults have the most probable 60° dips suggests lithospheric thickness of about 10 km for the furrows on Galileo Regio (5,8) and about 4 km average for the grooves. A more complicated model for extensional instabilty of a brittle plastic surface layer overlying a ductile interior (10) yields ~10 km brittle layer for the ~50 km spaced furrows and ~2 km for the ~8 km (11) spaced grooves. Given the various uncertainties (and the narrower furrows on Marius Regio) the brittle lithosphere thickness was probably 5-10 km at the time of furrow formation and

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2-7 km at the time of groove formation. With these geologic constraints on the thickness of the brittle surface layer in mind we now explore possible lithospheric strength envelopes to quantitatively evaluate temperature profiles for these times of deformation in Ganymede's history.

Lithospheric Strength of Ganymede

To calculate the lithospheric strength on Ganymede we use a combination of Byerlee's law and the ductile flow law for ice (see Banerdt and Golombek, this volume, for more thorough discussion of lithospheric strength envelopes). At low pressures we use the sliding friction as determined by Byerlee, which has been found to hold for a wide variety of geologic materials. At higher confining pressures we have used the friction data for ice (12). At higher temperatures deformation in the outer few tens of km of Ganymede is controlled by creep of ice I_h. We have used the flow law of Durham et al. (13) with modifications (Durham, written communication) for pure ice extrapolated to geologic strain rates of 10^{-15}/sec (~3%/m.y.). Because the mantle of Ganymede is probably also water-ice, the lithosphere has only one strength peak. A surface temperature of 100°K and a thermal gradient of 1.5°/km yield the strength envelope shown in Fig. 1. It has been shown at high temperatures that the inclusion of a small amount of silicates into the ice will greatly increase the creep strength of ice I_h (14). However, quantitatively determining the amount of hardening for our application is not possible because the creep processes that control the deformation of ice are not well known for the temperatures and strain rates of interest on Ganymede. For lack of a better constraint we will assume that the hardening resulting from the addition of less than a few percent of silicates in Ganymede's lithosphere can be bracketed by an order of magnitude increase in creep strength.

Predicting the type of failure from the lithospheric strength envelopes is straightforward. With increasing stress, elastic strain will be built up in the elastic part of the lithosphere until its strength is exceeded (roughly the yield stress of the brittle-ductile transition). At that time major throughgoing faults will initiate near the depth of the transition between the brittle and ductile deformation regimes (the brittle-ductile transition) (e.g., 15). Thus the brittle lithosphere defined by the simple graben and extensional instability models is dependent on the depth to the brittle-ductile transition. This depth is most dependent on the temperature gradient. Fig. 2a shows the relationship between brittle-ductile transition depth and thermal gradient for clean and simulated dirty ice. As a result we can quantitatively determine the thermal gradient at the times of furrow and groove formation on Ganymede.

It is important to note that the "brittle" lithosphere defined by the strength envelope is delineating areas of brittle versus ductile behavior at stresses exceeding the yield strength. As such it is inherently different from a "thermal" lithosphere derived from convection models, an "elastic" lithosphere derived from dynamic bending or membrane stress models, or a "seismic" lithosphere defined from discontinuities in seismic properties. Care must be used in selecting the properly defined lithosphere for interpreting specific structural features observed on a planet's surface.

The 10 km thick brittle lithosphere on Galileo Regio at the time of furrow formation indicates a thermal gradient of 1.5°/km for clean ice and a little above 2°/km for dirty ice. On Marius Regio the 5 km thick brittle-ductile transition requires respective thermal gradients of 4 and 6°/km. An average 4 km brittle lithosphere at the time of groove formation yields thermal gradients of 6.5 and 8.5°/km for clean and dirty ice. The given variations in groove width and spacing (implying brittle lithospheres of 2-7 km) yield thermal gradients of 2.5 - 15°/km and 3.5 - 20°/km for clean and dirty ice, respectively.

Variations in thermal gradient, through their effects on the depth to the brittle-ductile transition, also significantly affect the total strength of the lithosphere (defined as the integral of the yield stress versus depth curve (16,17)). Figure 2b shows the relationship between lithospheric strength and brittle lithosphere thickness for Ganymede. For example, the lithospheric strength under extension for a thickness of 10km (corresponding to a gradient of 1.5°/km) applicable to Galileo Regio is about 0.15 in units of 10^6 MPa-m. Marius Regio had lower strengths of 0.05. Lithospheric strengths for grooves varied locally from 0.02 to 0.07 with an average of about 0.03. Note that these strength estimates are insensitive to assumptions regarding the ductile flow law; they are determined almost solely from the inferred thickness of the brittle lithosphere.

Brittle extensional tectonic features on Ganymede indicate a significant lateral variability in thermal gradient and lithospheric strength at the times of their formation. Galileo Regio's long life as a relatively undisturbed remnant of cratered terrain is likely a result of its low temperature gradient and thus increased lithospheric strength. By comparison Marius Regio was fractured and fragmented to its current small size due to its weakness (lithospheric strength 2.5 times lower than for Galileo Regio at the time of furrow formation) imposed by its higher thermal gradient. The thermal gradient during groove formation could have varied from place to place by as much as a factor of 6 and was an average 4 times greater than earlier gradients during furrow formation. This increase in thermal profile is at least partly a result of local heating due to the water ice volcanism that accompanied groove formation and may not indicate a whole-satellite heating event. Nevertheless the variations in temperature gradient shown by the variations in furrow and groove thickness indicate that the cooling of Ganymede was highly inhomogeneous with significant lateral thermal anomalies.

Conclusions

Brittle lithospheric thicknesses estimated from tectonic features formed during the two periods of extensional tectonism during Ganymede's history allow the quantitative determination of thermal gradients because the thickness to the brittle-ductile transition is a function of the temperature gradient. Lithospheric thicknesses inferred from for furrow spacing, 10 and 5 km, indicate temperature gradients of 1.5 - 2°/km and 4-6°/km respectively. An average lithosphere thickness for the grooves of 4 km suggests thermal gradients of 6.5 - 8.5°/km; local variability in the thickness of 2-7 km implies wide variations in temperature profile, 2.5 - 20°/km. This increase in thermal gradient may be a result of local heating during water-ice volcanism accompanying groove formation and may not indicate whole satellite heating. The stability of large remnants of cratered terrain (e.g., Galileo Regio) can be understood in terms of a lower temperature gradient which resulted in an increased lithospheric strength.

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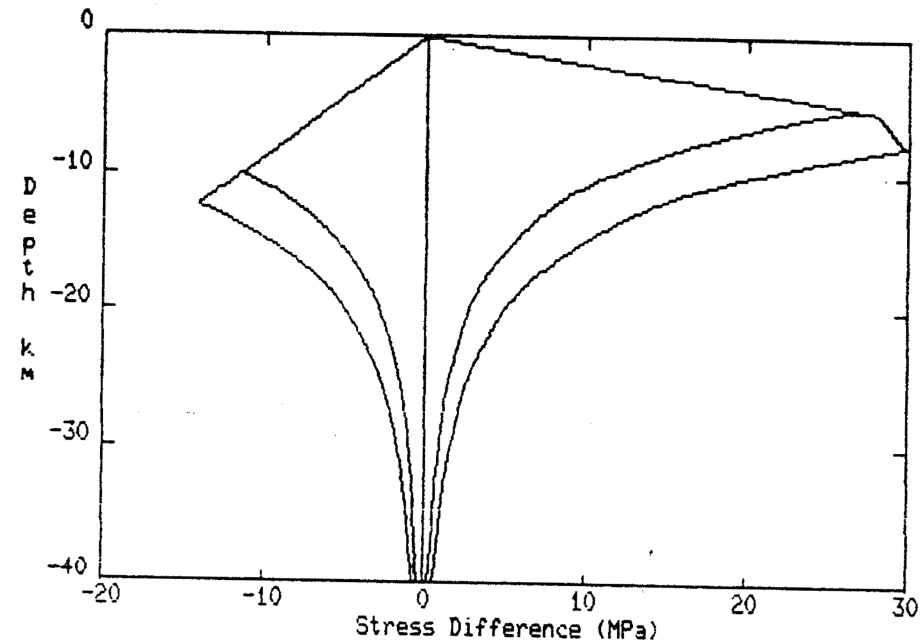

Figure 1. Lithospheric strength envelope as a plot of yield stress versus depth for compression (to the right) and extension (to the left). Linear part of curve is for brittle deformation at shallow levels. Ductile flow of ice I_h for a thermal gradient of 1.5°/km and a surface temperature of 100°K occurs at deeper levels. The upper flow curve is for clean ice deformed at 10^{-15}/sec. The lower curve is an order of magnitude stronger to simulate strengthing due to inclusion of silicates. The intersection between the brittle and ductile fields is the brittle-ductile transition.

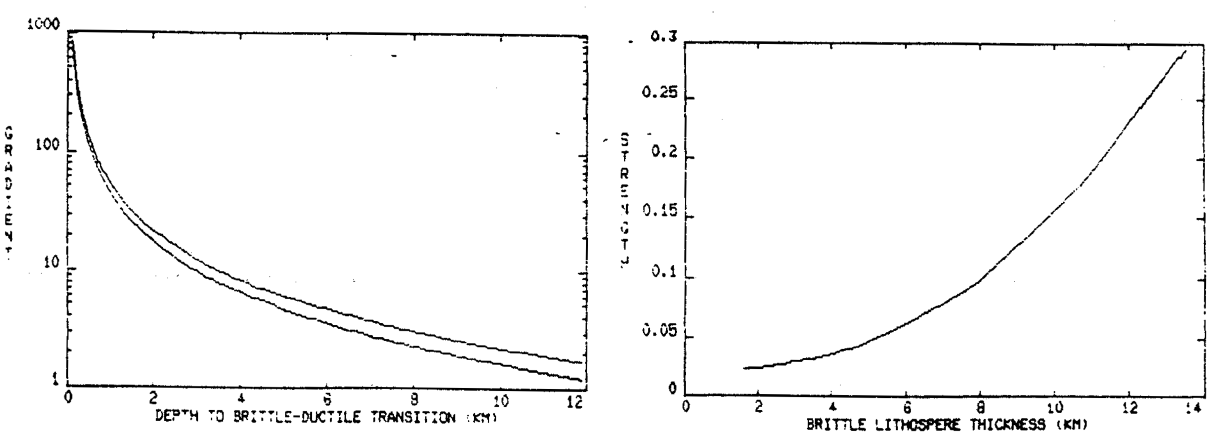

Figure 2. a) Plot of thermal gradient in degrees per km (surface temperature = 100°K) versus depth to the brittle-ductile transition for clean (lower curve) and dirty ice (upper curve). b) Plot of lithospheric strength (integral of yield stress versus depth) in units of 10^6 MPa-m versus brittle lithosphere thickness under tension. Strength under compression is roughly 50% greater.