TECTONIC DETERMINATIONS OF LITHOSPHERIC THICKNESSES ON GANYMEDE AND CALLISTO.
Steven K. Croft, Lunar and Planetary Laboratory, University of Arizona, Tucson, Arizona 85721

Introduction. Thermal lithospheric thicknesses provide fundamental constraints on planetary thermal histories that complement the constraints provided by dateable surface deposits of endogenic origin. Lithospheric constraints are of particular value on the icy satellites where our understanding of both rheology and surface ages is considerably poorer than it is for the terrestrial planets. Certain extensional tectonic features can and have been used to estimate lithospheric thicknesses on Ganymede and Callisto (1,2). These estimates, however, refer to the depth of the elastic lithosphere defined by the zone of brittle failure. The relation between the elastic lithosphere and the thermal lithosphere (generally defined by the zone of conductive heat transport, 3) is not straightforward, because the depth of brittle failure depends not only on the thermal profile, but also on rheology and strain rate (or the characteristic time over which stresses build towards failure). Characteristic time considerations are not trivial in this context because stresses generating brittle failure on the icy satellites may be produced by impacts, with characteristic times of seconds to days, or by "geologic" processes (e.g., convection, differentiation) with time scales of millions to hundreds of millions of years. In this abstract, the concept of the Maxwell time, tm, of a viscoelastic material (4,5) is used in conjunction with calculated thermal profiles to evaluate the significance of tectonic estimates of lithospheric thickness.

Maxwell Time Profiles. The definition adopted here for the Maxwell time is $tm = 2\mu/E$ (5), where μ is the local viscosity and E is Young's modulus. The viscosity is both temperature and depth dependent:

$$\mu = \mu o \exp(A[(Tm - k\rho gZ)/T - 1])$$

where μo is the viscosity at the melting temperature, Tm, at zero pressure. A is an empirical constant related to the activation energy, ρ is density, g is the local gravity, Z is depth, k is a constant set to yield Tm = 252°K at a pressure of 2.08 kb (the pressure at melting where ice I changes to ice III), and T is the local temperature. The temperature dependence of Young's modulus, a minor effect, is also included: E=144.7-0.177 T kb (derived from 6). The nominal temperature profiles used in this calculation are shown in figure 1. They are calculated assuming the mass and density of Ganymede, chondritic radioactive abundances, whole-planet, heated-from-within convection, and viscosity parameters $\mu o=10^{15}$ and A=25. A Maxwell time is calculated at each depth Z using the appropriate temperature along each temperature profile.

The resulting Maxwell time profiles are shown in figure 2. Stresses building towards failure over times short compared to the Maxwell time cause the material to fail in a brittle manner, while stresses building over times long compared to the Maxwell time cause the material to deform viscously. Thus, each profile divides the brittle field above the curve from the ductile field below the curve. Following the thermal profiles (temperature is by far the dominant variable), each curve exhibits a similar Maxwell time dependence: little change in the depth of the brittle field over a large range of "geologic" characteristic times grading into a sharp increase in brittle depth at time scales of less than a year or so. The general increase in the depth of the brittle field with age represents the thickening of the lithosphere as the radioactive heat flux declines. These curves result from a particular thermal calculation. Thermal models assuming different input parameters will yield slightly different Maxwell profiles. Choosing a "stiffer" viscosity relation, for instance, forces temperatures at depth to rise in order to deliver the same heat flux at a given age (forcing the steep portion of the Maxwell profile to shorter times), but simultaneously thickens the brittle layer at "geologic" time scale. Thus, the relative insensitivity of the brittle depth for geologic time scales means that if a set of structures can be established as having "geologic" origins and an approximate age derived, then the inferred lithospheric depth constrains the rheology.

Tectonic Features on Ganymede and Callisto. The structures of interest on Callisto are the graben-like depressions forming a concentric network around the Valhalla basin, a large impact structure. The widths and spacing between the graben where best developed are, respectively, 15-20 km and about 70 km (1,7). The structures on Ganymede are the graben-like furrows with raised edges that permeate several of the large blocks of dark terrain. First recognized in Voyager 2 imagery (8), the furrows generally occur in enormous sub-parallel systems in which furrow width and spacing are remarkably regular. The best developed furrow systems are located in Galileo Regio and neighboring Marius Regio. The planform of each system is broadly arcuate, and both are crudely consistent with a single concentric pattern (9). This, plus some similarities to the graben system around Valhalla have led to the common suggestion that they are both parts of a single tectonic system, possibly of impact origin (1,7,8,9). However, the width and spacing of the furrows in Galileo Regio are about 10 km and 50 km, respectively, whereas they are only about half that, about 6 km and 22 km (9) respectively, in Marius Regio. These characteristics are consistent within each Regio, yet the regiones are separated by a strip of grooved terrain only about 300 km wide. Less well developed furrow systems are found in other blocks of dark terrain on Ganymede, as indicated in table 1, each with characteristic widths and separations either roughly equal to or equal to about half the dimensions of the furrows in Galileo Regio. Again, the blocks of differing furrow dimensions are separated by relatively narrow strips of bright terrain.

Interpretation. For the furrow systems on Ganymede, the rheology is presumably everywhere uniform to first order. Also the crater counts on the dark terrain are similar, particularly between Galileo and Marius Regiones, hence the furrow systems all date to the same geologic era - at most several hundred million years long. For a given rheology, the factor of 2 in lithospheric thickness inferred from the variations in furrow widths implies a comparable variation in heat flux. Variations by factors of 2 in heat flux due to planetary cooling are difficult to achieve over a period as short as several hundred million years for an object as large as Ganymede. However, variations of 2 to 3 in heat flux are commonly obtained in convective heat transport calculations between areas over upwelling warm material and areas over down flowing cold material (10). In a new scenario of differentiation on Ganymede (11), light terrain emplacement occurs in regions over warm rising mantle material. Thus, the geometric pattern of light and dark terrain, which bears a resemblance to theoretical geometrical patterns of rising and sinking material convecting in a spherical shell (12), is interpreted as reflecting a convection pattern with the cool sinking plumes under the large regiones: Galileo, Perrine, and Nicholson (13). By inference, the theoretical thermal lithosphere is 2-3 times thicker within the large regiones than elsewhere, a variation consistent with the observed variations in elastic lithospheric thicknesses inferred from furrow widths. Thus, the overall light-dark geometry, the emplacement mechanism of bright terrain, and the regional variation in furrow dimensions are all consistent with their interpretation as geologic elements reflecting the global convective heat flow pattern on Ganymede between 3 and 4 billion years ago.

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Even given this interpretation of furrow origin, it is not suggested that the furrows are the direct result of convective stress. If such were the case, furrow systems unassociated with impacts would be found on Callisto (where convective stresses are only slightly less), but they are not. Thus the furrows may be due to a slight expansion caused by marginal differentiation (13). This interpretation of the variation of furrow dimensions does not, as yet, eliminate an impact origin for the furrows because: 1) the Maxwell profiles resulting from more realistic thermal calculations may drop farther into the short impact time scales (they may also go higher), and 2) the type of impact induced, sub-lithospheric restorative flow envisioned by (14) as the cause of the Valhalla graben system may persist from months to years, yielding shallower brittle layers. The slightly thicker inferred lithosphere around Valhalla compared to that on Ganymede may be due simply to a months-years time scale restorative flow around the Valhalla basin compared to a much longer building endogenic stress source for furrows on Ganymede (see figure 2), rather than differences in global heat flux or rheology. Since the local thickness of the brittle layer depends on the local heat flux, a single impact-induced restorative flow passing through areas of differing heat flux may produce extensional surface features of differing dimensions. Such a flow could have produced the Galileo-Marius system; asymmetries in the Valhalla system (15) may also be due to local variations in heat flux.

The characteristics of the Maxwell time profiles and their sensitivity to rheology and calculated thermal profiles implies that detailed analysis of furrow dimensions (in progress) on Ganymede and ring structures on Callisto can provide significant constraints on model thermal histories (in progress) and estimates on two-dimensional heat flow patterns on planets other than the Earth. They may also ultimately provide the decisive clues to whether the enigmatic furrow systems on Ganymede are of impact or endogenic origin.

References

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Figure 1. Ganymede Thermal Profiles. Ages are in billions of years before the present; e.g., age=0 is present time.

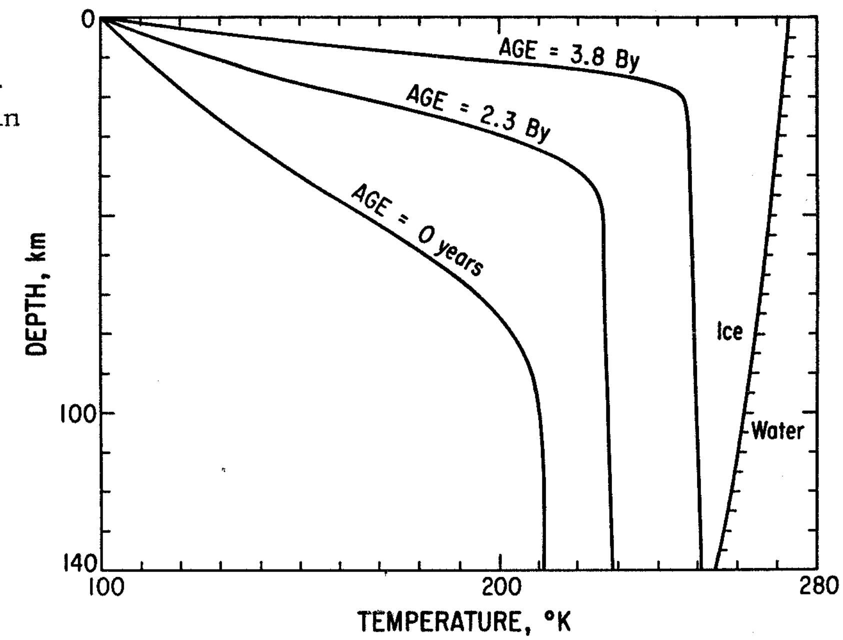

Figure 2. Maxwell Time Profiles. Each profile corresponds to thermal profile in figure 1 of the same age.

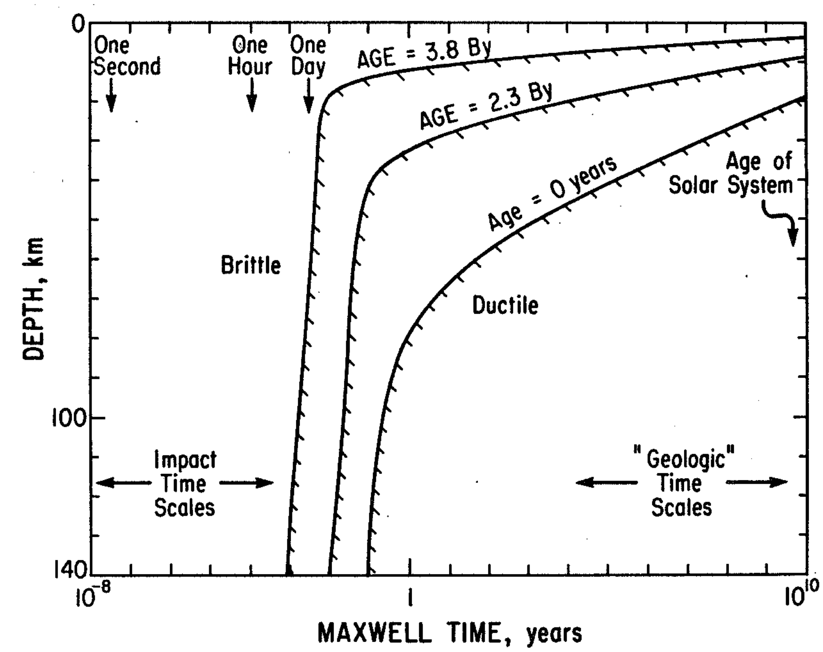

Table 1. Furrow Widths and Spacing

Area	Image FDS#	Width (km)	Spacing (km)	Comments
Galileo Regio	-	8-10	30-50	Refs. 1,7,8
Marius Regio	-	~6	~22	Ref. 9
NE Perrine Regio	16405.46	7-8	~33	Low resolution
NW Perrine Regio	16402.02	7-9	~38	Low resolution
E Central Barnard Regio	16405.18	5-6	20-25	
Central Nicholson Regio	16405.02	10-13	40-50	Few furrows