THE ANCIENT HEAT FLOW AND ELASTIC THICKNESS ON ENCELADUS: CONSTRAINTS FROM PHOTOCLINOMETRY AND NUMERICAL MODELING.

M. T. Bland[1], R. A. Beyer[2], and A. P. Showman[3], [1]University of Arizona (mbland@lpl.arizona.edu), [2]NASA Ames Research Center (rbeyer@arc.nasa.gov [3]University of Arizona (showman@lpl.arizona.edu).

Overview: Much of Enceladus' equatorial region is dominated by ridge and trough terrain that appears to be extensional in origin [1]. Fourier analysis of photoclinometric profiles taken within these terrains indicates that these ridges and troughs have strongly periodic spacings of 3-4 km. The periodic nature of the ridges and troughs suggests that they resulted from unstable extension of the lithosphere.

We numerically model unstable extension of an icy lithosphere under conditions appropriate to Enceladus. Comparison of these model results to our photoclinometric profiles suggests that the lithospheric thermal gradient was 15-30 K km^{-1} at the time the ridges and troughs formed. This implies heat flows of ~30-60 mW/m^2 and elastic thicknesses of 1 km to 3 km. These results support the idea that diapirs, such as that proposed by Nimmo and Pappalardo [2], have been active on Enceladus throughout its geologic history [3].

Background: It has been suggested that the thermal activity and young surface age observed at Enceladus' south pole is the result of a warm diapir in Enceladus' ice or silicate mantle [2]. The rise of such a diapir is capable of generating substantial extensional stress within Enceladus' lithosphere [4, 2], creating the long south-polar fractures known as the "tiger stripes". Terrains similar in geometry and scale to that of the south pole have also been observed in Enceladus' equatorial region. These terrains (Diyar and Sarandib Planitia) may record the location of ancient ice diapirs that are now inactive [3].

Among other features, both Diyar and Sarandib Planitia contain extensive regions of roughly parallel, periodically spaced ridges and trough of extensional origin (*Fig. 1*). This surface is consistent with having been formed by unstable extension of Enceladus' lithosphere. During such extension, perturbations in the thickness of the lithosphere are amplified, creating periodically spaced pinches and swells [5]. These pinches and swells are thought to correspond to the ridges and troughs found on many icy satellites [6, 7].

A salient feature of unstable extension is that the morphology (wavelength and peak to trough amplitude) of the deformation produced depends sensitively on the thermal gradient in the lithosphere. This fact has previously been used to determine heat fluxes in Ganymede's lithosphere during groove formation [8, 6]. By comparing the results of numerical models of unstable extension to observations of dominant deformation wavelengths within Diyar and Sarandib Planitia, we constrain the thermal state of the lithosphere during the extensional event that resurfaced the region. We then infer the elastic thickness of the surface. Knowledge of the elastic thickness helps to constrain the degree to which the rise of a diapir can reorient the satellite.

Photoclinometry: Point photoclinometry [9] was used to construct topographic profiles across several regions of Diyar and Sarandib Planitia (*Fig. 1*). These profiles confirm that the terrain in the Planitia consists of periodic ridges and troughs. These ridges and troughs generally have amplitudes between 100 m and 250 m, but can be as high as 450 m. On average, Diyar Planitia has slight higher peak to trough amplitudes then Sarandib Planitia.

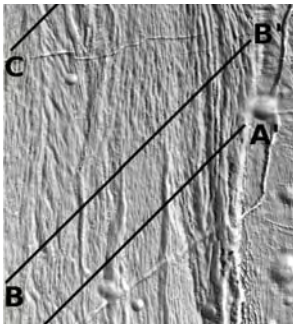
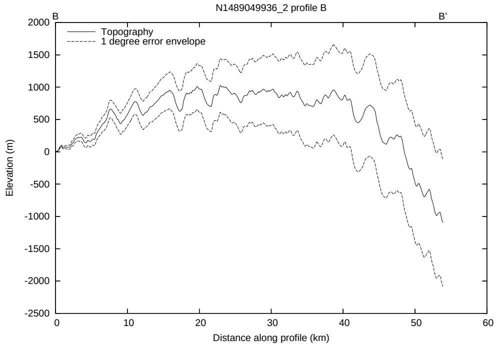


Figure 1: Left*) Image of Diyar Planitia indicating locations of photoclinometric profiles. Profiles are in the down-sun direction.* ***Below)*** *Profile* BB' *showing periodic ridges and troughs. The parabolic shape of the profile is an artifact of the technique.*



To determine whether the surface topography in these regions is truly periodic, a Fourier analysis was performed on each profile. The power spectra derived from this analysis (*Fig. 2*) indicates surprisingly strong periodicity in the terrain. Dominant topographic wavelengths in the Planitia are 3 km to 4 km. In several cases, multiple wavelengths are present in the topography (*Fig. 2*) suggesting a complex geologic history.

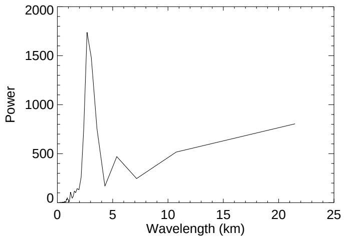


Figure 2: *Power spectrum of profile* BB' *(fig. 1), indicating that the terrain is strongly periodic with a dominant wavelength of 2.7 km. In this case, a second, longer wavelength is also observed.*

Modeling Unstable Extension: Following the methods of Bland and Showman [10], we use the two-dimensional, finite-element model TEKTON to simulate the extension of an icy lithosphere under conditions appropriate to Enceladus. The model includes elastic, viscous, and plastic deformation. We investigate strain rates ranging from 10^{-12} s^{-1} to 10^{-15} s^{-1} and thermal gradients between 2 K km^{-1} and 45 K km^{-1}. The surface temperature is assumed to be 70 K. A small initial perturbation (~10 m) is imposed on the domain to allow the instability to initiate. Such a perturbation is consistent with the expected topography that would exist before extension began.

Extension of the model domain generally produces periodic structures with a single dominant wavelength. The results of this model at small strains (3.15%) are shown in Figure 3. Instability growth (i.e. amplification of topography) occurs fastest at moderately high thermal gradients (30 K km^{-1}) and moderate strain rates (10^{-13} s^{-1}). Dominant wavelengths are roughly independent of the strain rate but depend strongly on the thermal gradient, increasing nonlinearly as the gradient decreases. It should be noted that the production of large amplitude deformation (100-200 m) requires imposing larger strains on the model (≥ 31.5%). In the large strain limit, the conditions for producing large amplitude deformation shift to lower thermal gradients. However, the dominant wavelength produced by extension is only moderately affected [10].

Discussion: Comparison of our numerical results to the photoclinometric profiles allows the thermal gradient of the lithosphere at the time extension occurred to be constrained. The 3-4 km wavelength deformation present in the Planitia suggests that thermal gradients were 15-30 K km^{-1}. This implies a large heat flux of roughly 30-60 mW/m^2 at the time of extension. While caution must be used in making comparisons, it is interesting to note that this heat flux is broadly consistent with the current average heat flux of 250 mW/m^2 measured at Enceladus' south pole [11]. The high heat flux we derive is unlikely to have existed globally and is instead more consistent with localized heating. These results therefore support the existence of a now-inactive diapir as suggested by Helfenstien et al. [3]. Such a diapir would provide a source of both strong localized heating and extensional stress.

It is also of interest to calculate the elastic thickness of Enceladus' lithosphere during the heating event. For an ice diapir to globally reorient the satellite an elastic thickness of at least 0.5 km must be maintained [2]. Using the Maxwell time and an expression for the temperature-dependent viscosity of ice, a relationship can be derived between the heat flux and the elastic thickness of the lithosphere [12]. Using this method we derive elastic thicknesses between 1 km and 3 km for the Planitia region. These elastic thicknesses are large enough to allow global reorientation of the satellite. It is therefore plausible that the reorientation of Enceladus proposed by Nimmo and Pappalardo [2] is but the latest in a series of reorientations that have occurred throughout Enceladus' history.

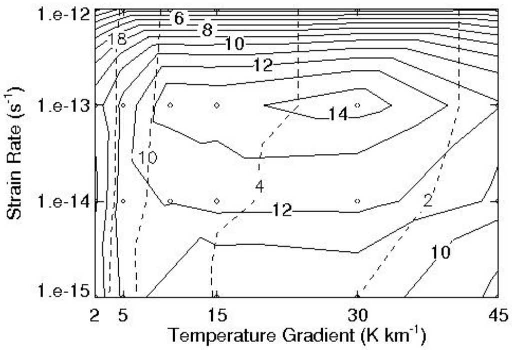


Figure 3: *Contours of exponential growth rate (solid) and dominant wavelength (dashed) as a function of thermal gradient and strain rate after 3.1% extension. The exponential growth rate describes the rate at which amplification occurs at small strains.*

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