On the origin of south polar folds on Enceladus

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**Abstract**

Recent high-resolution Cassini images of the south polar terrain of Enceladus reveal regions of short-wavelength deformation, inferred to be compressional folds between the Baghdad and Damascus tiger stripes (Spencer, J.R., Barr, A.C., Esposito, L.W., Helfenstein, P., Ingersoll, A.P., Jaumann, R., McKay, C.P., Nimmo, F., Waite, J.H. [2009b]). Enceladus: An active cryovolcanic satellite. In: Saturn after Cassini–Huygens. Springer, New York, pp. 683–722). Here, we use Fourier analysis of the bright/dark variations to show that the folds have a dominant wavelength of 1.1 ± 0.4 km. We use the simple model of lava flow folding from Fink (Fink, J. [1980]). Geology 8, 250–254) to show that the folds could form in an ice shell with an upper high-viscosity boundary layer of thickness <400 m, with a driving stress of 40–80 kPa, and strain rate between 10^{-14} s^{-1} and 10^{-12} s^{-1}. Such deformation rates imply resurfacing of the SPT in 0.05–5 Myr, consistent with its estimated surface age. Measurements of fold topography and more sophisticated numerical modeling can narrow down the conditions of fold formation and provide valuable constraints on the thermal structure of the ice shell on Enceladus.

\section{1. Introduction}

The south polar region of Saturn's small moon Enceladus (see Fig. 1a) is geologically active, with plumes of water vapor, dust, and other materials (Porco et al., 2006; Waite et al., 2006) erupting from four linear features dubbed the "tiger stripes" (Porco et al., 2006; Spitele and Porco, 2007). The SPT is also a region of high endogenic heat output, with 6–9 GW inferred from early short-wavelength Cassini Composite Infrared Spectrometer (CIRS) data (Spencer et al., 2006). More recent, long-wavelength CIRS data indicate that the total power output may be closer to 15 GW (Spencer et al., 2009b). The polar region is also an area of intense deformation. Initial mapping of the south polar terrain (SPT) suggests that the region is dominated by extensional tectonics with a component of right-lateral shear (Helfenstein et al., 2006). The terrain is bounded by a series of cycloidal arcuate fractures running close to 55°S with wedge-shaped regions of intense folding at their cusps (Helfenstein et al., 2006; Spencer et al., 2009a). The SPT is cross-cut by the tiger stripes Alexandria, Cairo, Baghdad, and Damascus sulci, which are roughly parallel, 130 km long, 2 km wide, and approximately 500 m deep (Porco et al., 2006). The SPT has few craters, and none larger than 1 km, suggesting a <0.5 Myr surface age (Porco et al., 2006).

The regions between the tiger stripes, in particular between Baghdad and Damascus sulci (see Fig. 1a), contain closely spaced linear features, dubbed the "ropy" terrain (Spencer et al., 2009a). High-resolution images of that portion of the SPT obtained in the August 11 and October 31, 2008 Cassini flybys reveal that the ropy terrain consists of many locally parallel features, inferred to be compressional folds (Spencer et al., 2009a). Initial mapping suggests that the Baghdad/Damasus region is deforming due to transpression, a combination of compression and right-lateral shear (Spencer et al., 2009a). The kilometer-scale folds are subparallel, and generally follow the direction of the tiger stripe, but appear to terminate on a fracture where Damascus sulcus forks at a Y-shaped junction (see overlap between footprints of Skeet Shoot 6 and Skeet Shoot 7 in Fig. 1a).

The morphologies of the SPT folds are distinctly different from other tectonic features observed on the icy satellites. Multi-kilometer-wavelength extensional ridges, analogous to the types of extensional subparallel features observed on Ganymede (see Pappalardo et al. [2004] for discussion), have been observed in the currently inactive and older regions of Enceladus (Bland et al., 2007). The extensional features in the equatorial Sarandib and Dijyar Planitia and the Cufa-Lahee region on Enceladus have wavelengths of 3–4 km, and 5–9 km, respectively (Bland et al., 2007), and consist of disjointed fault block segments, rather than remaining coherent over tens of kilometer distances like the SPT folds. The SPT folds appear to have a quasi-semi-circular cross-section and smooth top, rather than triangular-shaped cross sections characteristic of tilted extensional fault blocks (Pappalardo et al., 2004).

The inferred cross-section of the folds, their apparent short wavelength compared to other tectonic features on Enceladus, and the high regional heat flow motivate us to suggest that the SPT folds may form in a manner analogous to compressional folds on terrestrial lava flows (e.g., Fink, 1980). Here, we use high-resolution images of the SPT and Fourier transform methods to determine the dominant wavelength of folding in the Baghdad/Damasus region. We use the dominant wavelength and the Fink (1980) folding model to infer properties of the subsurface, including the thickness of the folded upper high-viscosity boundary layer and the strain rate associated with deformation.

\section{2. Dominant wavelength}

We use high-resolution images from the August 11, 2008 and October 31, 2008 Cassini flybys of Enceladus to obtain profiles of brightness (expressed as data number, or DN) as a function of distance across the ropy terrain. The images we use are ultra-high-resolution, unstaged snapshots of the surface of Enceladus referred to in press releases as the "Sheet Shoot" images. Table 1 summarizes information about each of the five images used. Radiometric calibration was performed using CIRS/CAL (Porco et al., 2005) and the images were imported into ISIS 3.1.20 (Anderson et al., 2004). Measurements were performed on polar stereographic projections of each image, necessary because the tiger stripes are very close to the south polar terrain. However, because the planet-spacecraft distance is so small, and the emission angle is low, projection of the images did not significantly alter the geometry of the ropy features.

We obtained a total of 127 profiles of brightness as a function of distance. The typical length of a DN profile is ~4 km, constrained by the image geometry. A one-dimensional discrete Fourier transform is used to determine the dominant wavelength of deformation from each DN profile. The Fourier transform allows an
arbitrary function \( h(x) \), which represents the DN values as a function of distance (Fig. 2a), to be decomposed into the sum of harmonic components (i.e., sines and cosines), each with a different spatial wavenumber \( k = 2\pi/\lambda \), where \( \lambda \) is the wavelength. The spectral frequency is \( k/2\pi \), or equivalently, \( 1/\lambda \). The power spectrum (Fig. 2b) describes the relative contribution of a harmonic function of frequency \( 1/\lambda \) to \( h(x) \). To find the dominant wavelength, the power-frequency spectrum is changed to a power-wavelength spectrum by inverting the frequency values (Fig. 2c). Similar methods have been used to infer topographic wavelengths of grooved terrain on Ganymede (Grimm and Squyres, 1985; Patel et al., 1999). A detailed description of these methods can be found in Patel et al. (1999).

Table 1

<table>
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<th>Image number</th>
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<th>Image time (2008)</th>
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Fig. 1. (a) Polar stereographic projection of a mosaic of images of Enceladus’ south polar terrain with 108 m/pixel resolution (PDS image SE_500K_90S_0_STEREO). Locations of Skeet Shoot images used in our study from the August 11, 2008 flyby are shown in yellow (#6 and #7), and locations of images from the October 31, 2008 Skeet Shoot are shown in green (#3, #5, and #8). (b) Skeet Shoot #6, with our study area highlighted in green. (c) Close-up of Skeet Shoot #6 showing locations of our brightness profiles.
We assume that DN scales with topography, likely a safe assumption because the images were obtained at high incidence angle (Patel et al., 1999). The profiles sample data from a swath 10 pixels wide, which helps eliminate high-frequency, short-wavelength noise arising from bright/dark variations due to boulders sitting on the surface of the folds (Spencer et al., 2009a). We compute the discrete Fourier transform of the topography using the built-in fast Fourier transform in IDL 7.0, implemented inside a publicly available subroutine designed for determining power spectra from topography, prof2psd.pro (Windt, 2000). It was not necessary to use zero-padding or spectral windows to remove high-frequency noise from the spectra (Patel et al., 1999) because the dominant wavelength of the folding is much larger than the size of a single pixel.

Fig. 2a–c illustrates a sample FFT result for folded terrain in the Damascus/Baghdad region. Spectra for each profile were inspected by hand to determine the dominant frequency and wavelength of deformation. In the vast majority of profiles, we find only a single dominant wavelength. Fig. 2d shows a histogram of the dominant folding wavelengths inferred from our measurements. The average dominant wavelength over the entire region is 1.1 km, with a standard deviation of 0.4 km. Measurements of DN profiles across ~10 km using lower-resolution images that cover a larger area on Enceladus reveal the same dominant wavelength. However, in the low-resolution profiles, the spectral peak at ~1 km is less pronounced; the spectrum contains more power in larger wavelengths than the high-resolution profiles.

3. Conditions of formation

Folds with an appearance similar to the ropy terrain on Enceladus are thought to form in response to compressional stresses acting on the cold upper surface of a lava flow. The classic terrestrial example is the formation of ropy pahoehoe on Hawaiian volcanoes (Fink and Fletcher, 1978).

The simplest folding model (Fink, 1980) represents the flow as two layers. The folded surface layer has thickness $H$, in which the viscosity decreases with depth as $\eta(z) = \eta_s \exp(-cz)$, where $\eta_s$ is the surface viscosity, $z$ is depth ($z < 0$), and $c$ describes the exponential decrease in viscosity. The bottom layer is a low-viscosity half-space with constant viscosity $\eta_s$. The viscosity of both layers is assumed to be Newtonian, so viscosity is independent of stress. The ratio between the interior viscosity and
surface viscosity $R = \eta_0/\rho$. Such a structure may be consistent with their formation atop a thick convecting ice shell with a weak upper surface (Roberts and Nimmo, 2008; Barr, 2008) or a thin conductive ice shell. Unlike more sophisticated techniques to constrain the deformation (Dombard and McKinnon, 2006; Bland and Showman, 2007; Bland et al., 2007), multiple-wavelength structures can also form on lava flows subjected to multiple convective events (e.g., Gregg et al., 1998). However, we detected only a single dominant wavelength in our analysis. If future analyses find multiple-wavelength structures, a more sophisticated analysis may be warranted.

Moreover, the Fink (1980) model uses a very simple rheological description for the ice shell. The rheology of the near-surface ice on Enceladus is poorly constrained, so we deemed it premature to include multiple deformation mechanisms and/or a viscoelastic/plastic description for the ice shell (e.g., Dombard and McKinnon, 2006). We note that this may be a promising avenue for future work and can yield tighter constraints on the conditions of fold formation and the subsurface thermal structure of the ice shell.

The folds between the tiger stripes and the folds at the cusps of the arcuate features bounding the SPT represent a rare detection of a compressional morphology on an icy moon. In fact, only one other unequivocal example exists: long-wavelength, low-amplitude folds on the surface of Europa, which have been observed in only one location on that moon (Prockter and Pappalardo, 2000). Measurements of the heat flux and geophysical modeling of the origin of the tiger stripes and compressional features in the SPT may shed light on the processes that accommodate convection on Enceladus and other tidally flexed icy satellites.

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References


