Icarus 260 (2015) 232–245

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Constraining the heat flux between Enceladus' tiger stripes: Numerical modeling of funiscular plains formation

Michael T. Bland [a,b,*], William B. McKinnon [b], Paul M. Schenk [c]

[a] U.S. Geological Survey, Astrogeology Science Center, 2255 N. Gemini Dr., Flagstaff, AZ 86001, United States
[b] Department of Earth and Planetary Sciences and McDonnell Center for the Space Sciences, Washington University in St. Louis, 1 Brookings Dr., Saint Louis, MO 63130, United States
[c] Lunar and Planetary Institute, 3600 Bay Area Blvd., Houston, TX 77058, United States

ARTICLE INFO

Article history:
Received 13 March 2015
Revised 10 July 2015
Accepted 15 July 2015
Available online 22 July 2015

Keywords:
Enceladus
Tectonics
Satellites, surfaces
Thermal histories

ABSTRACT

The Cassini spacecraft's Composite Infrared Spectrometer (CIRS) has observed at least 5 GW of thermal emission at Enceladus' south pole. The vast majority of this emission is localized on the four long, parallel, evenly-spaced fractures dubbed tiger stripes. However, the thermal emission from regions between the tiger stripes has not been determined. These spatially localized regions have a unique morphology consisting of short-wavelength (~1 km) ridges and troughs with topographic amplitudes of ~100 m, and a generally ropy appearance that has led to them being referred to as "funiscular terrain." Previous analysis pursued the hypothesis that the funiscular terrain formed via thin-skinned folding, analogous to that occurring on a pahoehoe flow top (Barr, A.C., Preuss, L.J. [2010]. Icarus 208, 499–503). Here we use finite element modeling of lithospheric shortening to further explore this hypothesis. Our best-case simulations reproduce funiscular-like morphologies, although our simulated fold wavelengths after 10% shortening are 30% longer than those observed. Reproducing short-wavelength folds requires high effective surface temperatures (~185 K), an ice lithosphere (or high-viscosity layer) with a low thermal conductivity (one-half to one-third that of intact ice or lower), and very high heat fluxes (perhaps as great as 400 mW m^{-2}). These conditions are driven by the requirement that the high-viscosity layer remain extremely thin ($\lesssim$200 m). Whereas the required conditions are extreme, they can be met if a layer of fine grained plume material 1–10 m thick, or a highly fractured ice layer >50 m thick insulates the surface, and the lithosphere is fractured throughout as well. The source of the necessary heat flux (a factor of two greater than previous estimates) is less obvious. We also present evidence for an unusual color/spectral character of the ropy terrain, possibly related to its unique surface texture. Our simulations demonstrate that producing the funiscular ridges via folding remains plausible, but the relatively extreme conditions required to do so leaves their origin open to further investigation. The high heat fluxes required to produce the terrain by folding, which equate to an endogenic blackbody temperature near 50 K, should be observable by future nighttime CIRS observations, if funiscular deformation is occurring today.

Published by Elsevier Inc.

1. Background

Despite its small size and icy composition (its mean density is 1600 kg m^{-3}, and its surface area of ~800,000 km^2 is comparable to the country of Turkey), Saturn's satellite Enceladus is one of the most geologically active bodies in the Solar System. Extensive tectonic deformation in the mid-latitudes (Bland et al., 2007; Giese et al., 2008), and the presence of viscously relaxed craters within both tectonized and heavily cratered terrains (Bland et al., 2012) indicate that elevated heat flow and geologic activity were spatially extensive in Enceladus' past. Now, however, all of the current activity is apparently located in a quasi-circular region of very young terrain ($\leqslant$1 Ma) within ~55°S of the satellite's south pole (the south polar terrain (SPT), Fig. 1; e.g., Porco et al., 2006). In many localities, the terrain is bounded by a curvilinear band of high-relief ridges and troughs of uncertain origin (see, e.g., Porco et al., 2006; Spencer et al., 2009; Schenk and McKinnon, 2009; Crow-Willard and Pappalardo, 2015 and references therein), which separates the SPT from older terrains to the north (Fig. 1).

The SPT itself is a heavily tectonized region dominated by sets of extensional fractures (Patthoff and Kattenhorn, 2011). In particular, four roughly-parallel fractures, each ≈130 km long, and

* Corresponding author at: USGS, Astrogeology Science Center, 2255 N. Gemini Dr., Flagstaff, AZ 86001, United States. Fax: +1 (928) 556 7014.
E-mail address: mbland@usgs.gov (M.T. Bland).

http://dx.doi.org/10.1016/j.icarus.2015.07.016
0019-1035/Published by Elsevier Inc.

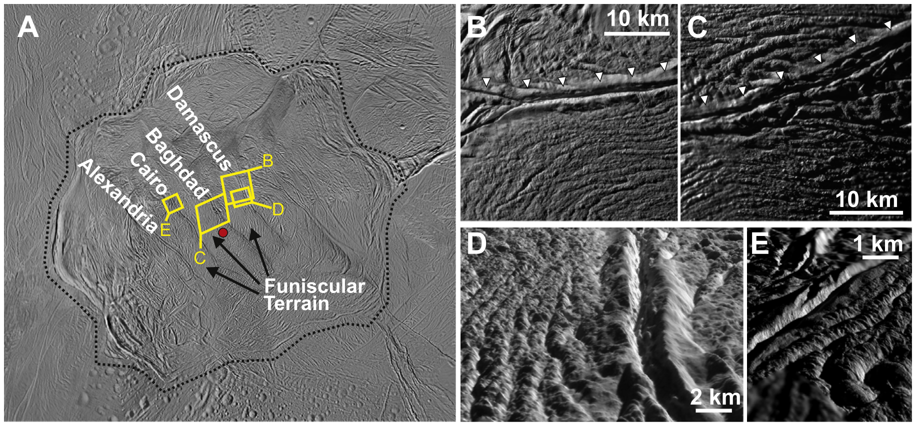

Fig. 1. A. Cassini-ISS mosaic of Enceladus' south polar terrain (SPT). The red dot indicates Enceladus south pole, and the black dotted line outlines the inferred boundary of the SPT. White labels indicate specific "tiger stripes." Yellow boxes correspond to locations of images in B–E. B. Funiscular terrain south of Damascus Sulcus (sulcus indicated by white arrows). Cassini ISS image N1604167158. C. Funiscular terrain adjacent to Baghdad Sulcus (sulcus indicated with white arrows). Cassini ISS mosaic from sequence 91E. D. Oblique view of funiscular terrain near Damascus Sulcus (see B). E. Oblique view of funiscular terrain near Cairo Sulcus. Image credit: NASA/JPL/Space Science Institute. Oblique views produced by Paul Schenk. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

spaced ≈35 km apart, dominate the region (Porco et al., 2006). Dubbed "tiger stripes," the fractures are the source of both Enceladus' dramatic jets (Spitale and Porco, 2007; Porco et al., 2014), and its surprisingly high thermal emission (e.g. Spencer et al., 2006; Howett et al., 2011). *Cassini's* Composite Infrared Spectrometer (CIRS) instrument has detected 5–15 GW of power being emitted from the SPT (Spencer et al., 2006, 2013; Howett et al., 2011). The vast majority of this thermal output is localized precisely on the tiger stripes themselves (e.g. Spencer et al., 2009, 2013; Howett et al., 2011; Abramov et al., 2015), an observation independently supported by *Cassini's* Visual and Infrared Mapping Spectrometer (VIMS) images (Goguen et al., 2013).

Nimmo et al. (2007) proposed that frictional heating (both viscous and brittle) along the tiger stripes during tidally driven shearing was the ultimate source of the thermal anomaly, with a substantial component of the thermal emission due to latent heat advected with the plume vapor and deposited within cold, porous ice around the shear zone. The detection of salt- and bicarbonate-rich ice grains in Enceladus' plume by *Cassini's* Cosmic Dust Analyzer (CDA), along with CO_2, NH_3, and other volatiles in plume vapor (Waite et al., 2009), implies the plumes originate from a liquid water reservoir at depth (Postberg et al., 2009, 2011). If the tiger stripe fractures act as conduits that extend to the ocean, liquid water could ascend toward the surface, partially driven by gas bubbles (e.g., CH_4 or CO_2), which reduce the density of the water column and eventually produce the observed vapor plume (Crawford and Stevenson, 1988; Matson et al., 2012; Porco et al., 2014). The rising ocean water advects heat toward the surface, and as in Ingersoll and Pankine (2010) and Porco et al. (2014), vapor deposition along tiger-stripe fracture walls provides strongly localized heat sources.

The thermal emission from the tiger stripes themselves is constrained, but the current thermal contribution from regions adjacent to them has not been firmly established (cf. Abramov and Spencer, 2009; Abramov et al., 2015 and see later discussion). A moderately elevated thermal emission, if it exists (i.e., higher than background but considerably lower than the tiger stripes) in these regions would be difficult to distinguish from thermalized sunlight in current CIRS data. We return to the point in Section 4.

Much of the terrain adjacent to and between the tiger stripes has a unique morphology consisting of tightly spaced (short wavelength) ridges and troughs oriented roughly parallel to the tiger stripes themselves (Figs. 1–3). The ridges are generally linear to gently curving. Individual ridges can be traced along strike tens of kilometers, but frequently anastomose with adjacent ridges in complex patterns (Fig. 2A and B). Ridge orientations generally follow the orientation of adjacent tiger stripes, often bending as the tiger stripes bend. Occasionally this causes the ridges to briefly orient orthogonal to an adjacent tiger stripe or intersect a tiger stripe at low angles, although in such cases the ridges tend to remain parallel to the other, adjacent tiger stripes (Fig. 2A). The morphology is reminiscent of pahoehoe lava flows (Barr and Preuss, 2010), although the scales are obviously different. Because of its ropy appearance, the terrain type has been classified as "funiscular terrain" (Spencer et al., 2009).

Fig. 3 shows two topographic profiles across a tiger stripe (Damascus Sulcus) and adjacent funiscular terrain. The profiles were created from stereo-controlled photoclinometery (shape from shading) and have a horizontal resolution of 30 m. Vertical uncertainties are less than 10 m. The ridges and troughs have relatively rounded crests and v-shaped troughs (see also Fig. 2C and D), with peak-to-trough amplitudes of ~100 m. Topographic wavelengths (peak-to-peak distances) are $\lesssim$1 km, consistent with previous measurements (Barr and Preuss, 2010).

A striking characteristic of the funiscular terrain is its limited spatial extent (Helfenstein et al., 2011). Whereas ridge and trough terrains are found across Enceladus, terrain with this unique morphology is formally recognized only between the tiger stripes themselves, and does not extend beyond the ends of the fractures. Possibly similar ridges or ridge segments have been identified on Enceladus' leading hemisphere (Crow-Willard and Pappalardo, 2015), but this terrain type appears to be unique among the icy satellites of the outer Solar System. The geographic correlation between the funiscular terrain and the tiger stripes, along with their similar orientation (i.e., strike direction) strongly suggests either that the formation of one has affected the other (either kinematically or thermally), or that both features formed by the same larger-scale process. Hence, understanding the origin of the funiscular terrain may provide substantial insight into the formation of the tiger stripes, and the SPT more generally.

The mechanism of formation for the funiscular terrain ridges remains uncertain. Barr and Preuss (2010) suggested that the ridges form by folding of a very thin, high-viscosity surface boundary layer. Conventionally, this boundary layer might be identified with the lithosphere (the portion of the ice shell that deforms brittlely (Collins et al., 2010)). Using observations of funiscular ridge spacing (roughly 1 km based on DN profiles – topography was assumed to correlate with pixel brightness) and a model for the