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Gravitational spreading, bookshelf faulting, and tectonic evolution of the South Polar Terrain of Saturn's moon Enceladus

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ABSTRACT

Despite a decade of intense research the mechanical origin of the tiger-stripe fractures (TSF) and their geologic relationship to the hosting South Polar Terrain (SPT) of Enceladus remain poorly understood. Here we show via systematic photo-geological mapping that the semi-squared SPT is bounded by right-slip, left-slip, extensional, and contractional zones on its four edges. Discrete deformation along the edges in turn accommodates translation of the SPT as a single sheet with its transport direction parallel to the regional topographic gradient. This parallel relationship implies that the gradient of gravitational potential energy drove the SPT motion. In map view, internal deformation of the SPT is expressed by distributed right-slip shear parallel to the SPT transport direction. The broad right-slip shear across the whole SPT was facilitated by left-slip bookshelf faulting along the parallel TSF. We suggest that the flow-like tectonics, to the first approximation across the SPT on Enceladus, is best explained by the occurrence of a transient thermal event, which allowed the release of gravitational potential energy via lateral viscous flow within the thermally weakened ice shell.

1. Introduction

Enceladus, a small moon of Saturn with a diameter of ~500 km, is geologically active as expressed by eruption of gas and water–ice particles in plumes sourced from the parallel "tiger-stripe" fractures (TSF) in Enceladus' South Polar Terrain (SPT) (Porco et al., 2006, 2014) (Figs. 1A and 2A). The flux of the erupting plumes varies with time, possibly related to the diurnal variation of tidal stress that controls TSF opening and closing (Hurford et al., 2007; Hedman et al., 2013; Nimmo et al., 2014). The estimated surface age of the SPT is <0.5 Ma, which contrasts with 1–4 Ga surface ages of the surrounding terranes (Fig. 2) (Porco et al., 2006; Kirchoff and Schenk, 2009). Active geologic processes concentrated along the TSF are expressed by ejection of plumes (Porco et al., 2006; Spencer et al., 2009; Spencer and Nimmo, 2013). Because of this, understanding how the TSF were initiated and evolved is essential for determining the controlling mechanisms of active geologic processes and plume eruptions on Enceladus. In addition, as the SPT shares similarities in first-order structural style to that of the Trailing Hemisphere and Leading Hemisphere Terrains, which are both characterized by the development of circumferential belts (Crow-Willard and Pappalardo, 2015), establishing how the most dominant structures (i.e., TSF) in the SPT formed has important implications for global resurfacing processes of this icy moon.

Existing work attributes TSF initiation to formation of tensile cracks as a result of (1) the presence of a rectangular or elliptical thermal anomaly of an unspecified origin below the SPT that led to surface extension (Gioia et al., 2007), (2) icy-shell flexing induced by tidal stress (Nimmo et al., 2007), (3) true-polar wander of the satellite (Matsuyama and Nimmo, 2008), (4) non-synchronous rotation of Enceladus' ice shell above a global ocean relative to its solid rocky core (Patthoff and Kattenhorn, 2011), and (5) formation of a large rift basin (Walker et al., 2012). The subsequent kinematic evolution of the TSF after their initiation has been related to processes similar to those operated along divergent plate boundaries (Helfenstein et al., 2008) or strike-slip faulting with alternating senses of motion driven by cyclic tidal stress (Nimmo et al., 2007; Smith-Konter and Pappalardo, 2008). Extension along the proposed spreading centers at the TSF may be accommodated by deformation along the SPT margin (Helfenstein et al., 2006, 2008), which has been generally inferred to be entirely contractional (Porco et al., 2006; Spencer and

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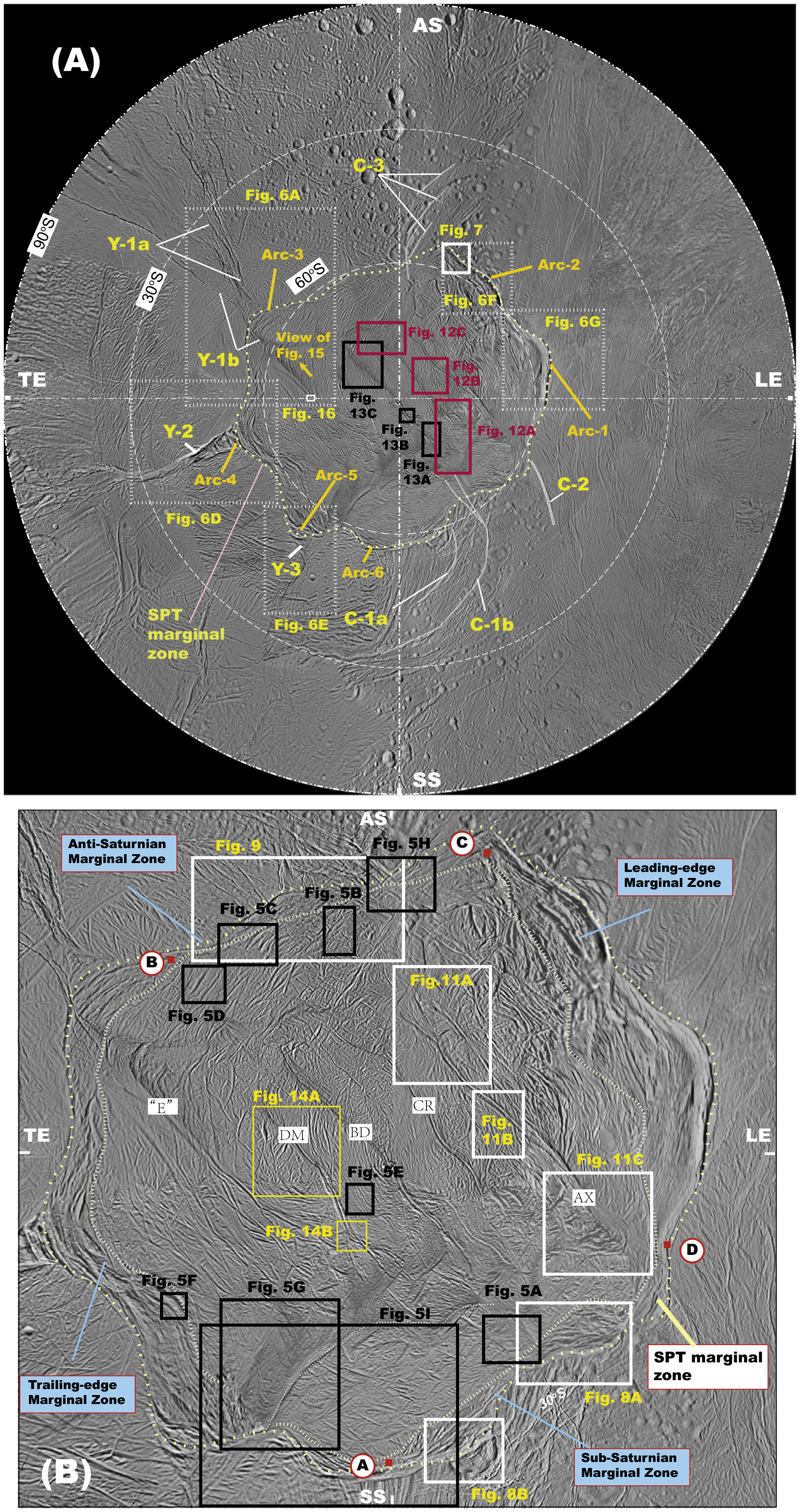

Fig. 1. (A) Image mosaic of the southern hemisphere of Enceladus collected by the Cassini orbiter's Imaging Science Subsystem (ISS) and constructed by the CICLOPS team (i.e., Cassini Imaging Team); the mosaic is in the south polar projection. This composite image serves as a context map for the South Polar Terrain (SPT) shown in (B) and Fig. 2A. Also shown are locations of figures mentioned in the text. Y-1 to Y-3 and C-1 to C-3 are Y-shaped and C-shaped fractures discussed in the text. (B) A close-up view of the SPT. Points A, B, C and D marked by red dots delimit the segmental ends of the SPT marginal zone (i.e., the sub-saturnian, anti-saturnian, leading-edge, and trailing-edge margins). Coordinate points SS, AS, LE, and TE are longitudinal directions from the south pole pointing toward the sub-saturnian (0° longitude), anti-saturnian (180°W), leading-edge (90°W), and trailing-edge (270°W) points on the equator of Enceladus, respectively. Abbreviations: AX, Alexandria fracture; CR, Cairo fracture; BD, Baghdad fracture; DM, Damascus fracture; "E", a newly designated fracture in this study. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)