THE CONTRIBUTION OF ANCIENT TIGER STRIPES TO PLUME ACTIVITY AND ENERGY FLUX ON ENCELADUS.

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Introduction: The heavily fractured south polar region of Saturn's icy moon Enceladus is known for its eruptive plumes of water [1,2] and relatively large energy flux [3,4] emanating from the surface. Most of the observed plume activity and the warmest regions are associated with the four largest and most prominent fractures, the tiger stripes (Fig. 1) [1,4]. Previous studies have suggested this relationship is driven by diurnal tidal stresses which cause the tiger stripes to open (opening a pathway to a subsurface liquid layer) [5,6], close, and shear (generate frictional heat along the fracture wall) [7,8,9]. However, not all the higher heat sources and plumes can be tied to one of the four named tiger stripes. Here we model the effects of the diurnal tidal stresses on other fractures in the SPT with a focus on the ancient tiger stripes, identified in [10]. We compare the timing of the observed plume activity with predicted opening of the ancient tiger stripes to show that fractures other than the tiger stripes could be locations of plume activity or allow for plume activity to continue along, or near, a tiger stripe after the fracture is predicted to close.

Tidal Effects on the Ice Shell: Enceladus's eccentric orbit around Saturn generates diurnal tidal stresses on the surface of the moon. During the course of each orbit, the resulting principal stresses change in magnitude and orientation; south of the equator, the stresses will rotate 180° clockwise while north of the equator they rotate counterclockwise over the course of one Enceladus day [11]. The changing stresses cause every point on the moon's surface to experience periods of compression, tension, and shear (both left- and right-lateral) [5,7,8]. Fractures within the ice shell therefore experience the same changing stress field, and if the stresses are large enough, may cause the crack to open, close, or shear [5,7,8]. The possible shearing, and resulting frictional heat, along the tiger stripes has been suggested as a means to help account for the large heat flux observed by the Cassini spacecraft [3,7,8]. The periodic opening and closing of the tiger stripes could partially control the timing of the observed plume sources [5,6].

Ancient Tiger Stripes: The SPT contains numerous fractures, other than the tiger stripes, most of which are short (<30 km) and narrow (10–100s m) with a muted morphology. Most of these fractures can be grouped into one of four fracture sets based on orientation and relative age, with the youngest fractures sharing a similar orientation to the named tiger stripes [10]. However, some of the fractures in the older sets stand out from the other fractures within their sets and are morphologically similar to the present day tiger stripes, particularly in set 2 (yellow fractures in Fig. 1). These tiger stripe-like fractures (ancient tiger stripes) are longer and wider than adjacent fractures of similar orientation and age. Some of the fractures and can be linked across younger bisecting fractures resulting in a cumulative length and spacing that is similar to the four active tiger stripes. The ancient tiger stripes may have behaved analogously to the present day tiger stripes, before becoming less active and undergoing modification by later deformation.

The ancient tiger stripes suggest the SPT has experienced a long history of tiger-stripe-like activity where the older tiger stripes were similar in form and function to the current tiger stripes. The older tiger stripes may have had numerous plumes of water-ice erupting from the surface and contributed to Saturn's E-ring in a manner similar to the way the present day tiger stripes contribute to the modern E-ring [1]. Portions of the ancient tiger stripes, especially those of set 2, are warmer than other fractures [3] and are aligned with some of the identified plume source locations from [12] suggesting that ancient tiger stripes have the capability to be reactivated even after younger fracture sets have already developed. Three of the current tiger stripes (Damascus, Baghdad, and Cairo) appear to have utilized portions of the set 2 ancient tiger stripes as they evolved. The abrupt bends in the tiger stripes often occur where there is a junction between the younger and older tiger stripes. The junctions often correspond to plume source locations (Fig. 1) suggesting the ancient tiger stripes could partly control the locations of the water-ice plumes by helping to open a conduit to a subsurface liquid layer at the junction of the fracture sets [8]. Sources II, III, V, and VI all occur where ancient tiger stripes intersect the present day tiger stripes. The ancient tiger stripes could also help explain the seemingly forked ends to some tiger stripes where the fork is composed of an ancient tiger stripe and younger fracture.

Model: To calculate the diurnal stresses, we use the 2D numerical program SatStress [13] and its graphical user interface (SatStressGUI) developed at the University of Idaho [14], and which is being continually improved by us. The program uses a 4-layer viscoelastic model in which Enceladus is divided into an inner core, global liquid layer, and lower and upper ice shell layers. The 2-layer ice shell allows for the approximation of a colder rigid outer layer and less viscous, slightly warmer, inner ice layer. The water and ice layer parameters as well as the orbital constraints were approximated based on previous similar models of Enceladus [7,8,15]. We assumed an orbital eccentricity of Enceladus of 0.0047 with a semimajor axis of 2.38e8 m [6]. See Table 1 for the layer parameters used for this model.

Discussion: Previous studies have looked at the relationship between the diurnal tidal stresses along the tiger stripes and the plume sources I, II, III, and VI. Hurford et al. [6] found that the plumes were mostly observed to occur when the tiger stripe was predicted to be in tension, opening the crack. However, some of the plumes were observed to be active when the tiger stripe was predicted to be in compression. Hurford et al. [6] suggested an explanation for this could be that plume activity may occur while the fracture is experiencing shear or even compressional stress if the force is small enough to be overcome by the erupting water. Alternatively, we suggest other fractures, especially the ancient tiger stripes, could be in tension while the tiger stripes are in compression allowing for the conduit at the intersection of the two fractures to remain open.

Additional published plume source locations have been triangulated to be away from one of the named tiger stripes (e.g., sources IV and VIII in Fig. 1) [12]. Source VIII does, however, correspond to one of the ancient tiger stripes. Preliminary modeling suggests the ancient tiger stripe associated with source VIII was in tension during the observation of the plume, favorable for opening of the fracture and allowing for plume material to escape. The activity along this ancient tiger stripe suggests it may still be experiencing minor shear and opening displacements. The motions along the older fractures and ancient tiger stripes could contribute additional energy to the SPT and may help account for the large energy flux.

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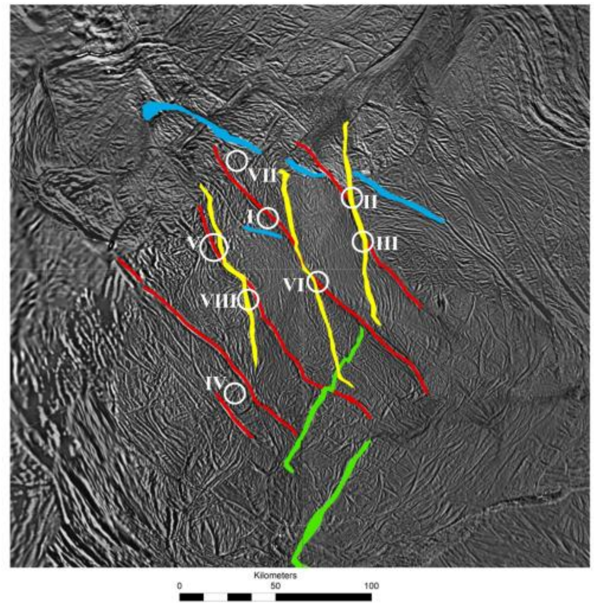

Fig 1: South polar projection of the ancient tiger stripes and plume sources. The youngest, and named tiger stripes, are shown in red with the ancient tiger stripes from [10] displayed (from younger to oldest) in yellow, green, and blue. White circles show the locations of plume sources from [12].

Table 1: Ice shell parameters. Values for our models were chosen based on previous similar studies [7,8,15].

Layer	Thickness (km)	Density (kg/m^3)	Shear modulus (Gpa)	Viscosity (Pa s)	Poisson's ratio
upper ice	3	920	3.5	10^{22}	0.33
lower ice	21	920	3.5	10^{13}	0.33
ocean	72	1000	0	0	0.5
core	156	3500	1000	10^{27}	0.002

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