PATTERNS OF FRACTURE AND TECTONIC CONVERGENCE NEAR THE SOUTH POLE OF ENCELADUS.

P. Helfenstein[1], P. C. Thomas[1], J. Veverka[1], J. Rathbun[1], J. Perry[2], E. Turtle[2], T. Denk[3], G. Neukum[3], T. Roatsch[4], R. Wagner[4], B.Giese[4], S. Squyres[1], J. Burns[1], A. McEwen[2], C. Porco[5], TV. Johnson[6] and the ISS Science team. [1]Center for Radiophysics and Space Research, Cornell University, Ithaca NY 14853 USA (helfenst@astro.cornell.edu). [2]Dept. of Planetary Sciences, University of Arizona, 1629 East University Boulevard, Tucson, AZ 85721. [3]Institut für Geologische Wissenschaften, Freie Universität, 12249 Berlin, Germany. [4]Institute of Planetary Research, German Aerospace Center, Rutherfordstrasse 2, 12489 Berlin, Germany. [5]Space Science Institute, 4750 Walnut St., Suite 205, Boulder, CO 80301. [6]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109.

Introduction: Cassini's Imaging Science Subsystem (ISS) coverage obtained to date shows that the Saturnian moon Enceladus has evolved through a long and complex tectonic history[1]. The most recent episodes of major tectonic activity are identified by a peculiar hemispheric pattern of fractures and lineations that exhibit a remarkable symmetry relative to the satellite's spin-axis. These tectonic patterns appear to be closely tied to a unique, geologically active region known as the South Polar Terrain (SPT) province, where ongoing eruptions of water plumes were recently discovered by Cassini[2]

The detailed shapes and symmetry of the young tectonic patterns, detailed below, suggest that they formed in response to a global change in rotational figure. We investigate the extent to which the morphology, geographic placement, and orientations of these tectonic patterns are consistent with axial shortening of Enceladus' spin axis, as suggested by Porco et al.[2].

Predicted Stresses: The predicted orientations and relative magnitudes of surface stresses arising from uniaxial elastic deformation of a thin lithospheric shell and also of a solid sphere are described by previous workers [3,4]. These models predict that orthogonal horizontal principal stresses are aligned E-W (parallel to circles of latitude), and N-S (along meridian lines), respectively. For axial shortening, the N-S principal stresses are always compressional. The predicted E-W oriented "hoop"stresses are tensile over latitudes from the equator to about 50° to 55°, with the maximum tensile stress at the equator. Closer to the poles, the predicted hoop stresses become more compressive with increasing latitude, but the compressive stress magnitude is less than that of meridional stresses (except exactly at the poles where they are equal.)

Geographic Placement and Morphology: The SPT province is separated from other Enceladus terrains by a conspicuous cycloidal chain of arcuate scarps that appear to encircle the south pole at ~55ºS latitude. The convex faces of the arcuate scarps uniformly point southward. At longitudes where the arcs bound ancient heavily cratered terrains to the north, they intersect to form cusp-shaped "kinks" that crudely resemble the dihedral cusps of intersecting terrestrial island arc systems. At longitudes where the arcuate scarps bound pre-existing fractured terrains to the north, they to not intersect in a sharp cusp. Instead, they bend northward through about 90° in azimuth to form the parallel, tapered ends of unusual Y-shaped discontinuities (Fig. 1) that interrupt the otherwise continuous circumpolar outline.

The Y-shaped discontinuities transition northward toward the equator into sub-parallel networks of N-S trending rifts and cracks. The cracks are most closely spaced at the tapered end of the Y-shaped discontinuities from which they appear to emerge and they progressively fan-out as they extend toward equatorial latitudes.

The broad south-facing openings of both the Y-shaped discontinuities and the cycloidal cusps confine prominent, curved belts of laterally folded ridges and troughs. The hinge-points of the lateral folds generally bend northward in line with the discontinuities and cusps (Fig. 1). ISS stereo images and oblique views of the confined fold-belts show that they are hundreds of meters higher than surrounding terrain.

The SPT is distinguished from other terrains on Enceladus by its youthful age (as implied by the virtual absence of unambiguous impact craters), active cryovolcanic venting of water ice particles and vapor, and a family of unique ~7-km-wide fractures, called "tiger stripes"[2]. Tiger stripes are flanked by 100m high upturned ridges with distinctive albedo and color contrasts caused by the presence solid or coarse-grained ice. Crosscutting relationships and their close proximity to sites of active plume eruptions [2] imply that they are geologically young and active. Tiger stripes are roughly parallel with a spacing of approximately 35 km. They have similar orientations and shapes and strike approximately 45° from the plane of Enceladus' tidal axis (longitude 0°) and spin-axis.

Physical Interpretation: The N-S trending fractures and rifts that extend northward from the Y-shaped discontinuities to the equator appear to be tension cracks that have formed largely in response to horizontal extensional stresses aligned approximately parallel to circles of latitude. The fact that these fractures are most densely-spaced at and appear to emanate from the tapered ends of Y-shaped discontinuities suggest that some mechanism has locally focused stresses where the fractures emerge from the SPT boundary.

The resemblance between the pattern of cycloidal arcs making up the circumpolar SPT boundary to the outline of terrestrial island arc systems is not coincidental. In terrestrial island arc systems, this distinct pattern arises from the geometry of a spherical lithospheric shell that buckles under a convergent oceanic plate boundary at the onset of subduction [5]. The convex face of the island arc points toward the direction of convergence. By analogy, the southward facing arcs of the circumpolar SPT boundary may have formed in response to compressive stresses oriented parallel to meridian lines as predicted by the axial deformation models. In this case, the arcuate scarps are best interpreted as south-facing thrust-faults, but not necessarily as terrestrial-style subduction zones.

Additional evidence that the SPT margin represents a convergent tectonic boundary comes from studying the geometry and morphology of laterally folded ridges and troughs near the Y-shaped–discontinuities and strike-slip offsets observed in adjacent older fractured terrains (Fig. 1). The most conspicuous of these folds are bent in the direction of Y-shaped-discontinuities. The fold deformation appears to have been caused by N-S compressive stresses. The fact that the steep ridges in the fold belts rise hundreds of meters in elevation above the surrounding terrain suggest that they are thrust faults that formed in a manner akin to terrestrial accretion wedges along island arcs [6]. That is, the south polar fold belts appear to represent relatively thick wedges of lithospheric ice that have been pushed against the SPT boundary and thrust-faulted by N-S aligned compressive stress. As shown in Fig. 1, some prominent right-lateral shear offsets can be mapped along pre-existing fractures in the older terrain northward of the SPT boundary. These offsets are consistent with the resolved stresses arising from convergence of the wedge on the SPT boundary.

The proposed accretion wedge hypothesis also provides a possible mechanism for focusing stresses at the tapered end of the Y-shaped discontinuities and may explain why the N-S trending tension fractures that extend to the equator appear to emanate from the SPT discontinuities. In particular, the pressure of the wedge against the margins of the discontinuties (yellow arrows in Fig. 1) may be sufficient to progressively cleave apart the tapered end at their tips and initiate northgoing tension fractures

Cycloidal cusps at the boundary of ancient cratered terrain and SPT are likely examples of incompletely-developed Y-shaped discontinuities. Such arrested development might occur if the lithospheric thickness of ancient cratered terrains is greater than for fractured plains, through which the Y-shaped discontinuties penetrate. Because the north pole of Enceladus is occupied mostly by ancient cratered terrains, the genesis of a corresponding province of active tectonism and volcanism there might have been inhibited by the greater mechanical strength and smaller deformational stress magnitudes in a thicker lithosphere.

Tiger Stripes do not define a pattern that is consistent with uniaxial shortening models. Their orientations relative to the sub-Saturn direction suggest that tidal stresses may have affected their formation.

Conclusions: The placement, morphology, and orientations of the SPT boundary is consistent with its interpretation as a convergent tectonic boundary arising from global deformation due to a recent episode of axial shortening along Enceladus' spin axis. Youthful systems of N-S tending fractures extending from Y-shaped discontinuities to the equator are also consistent with this deformation mechanism.

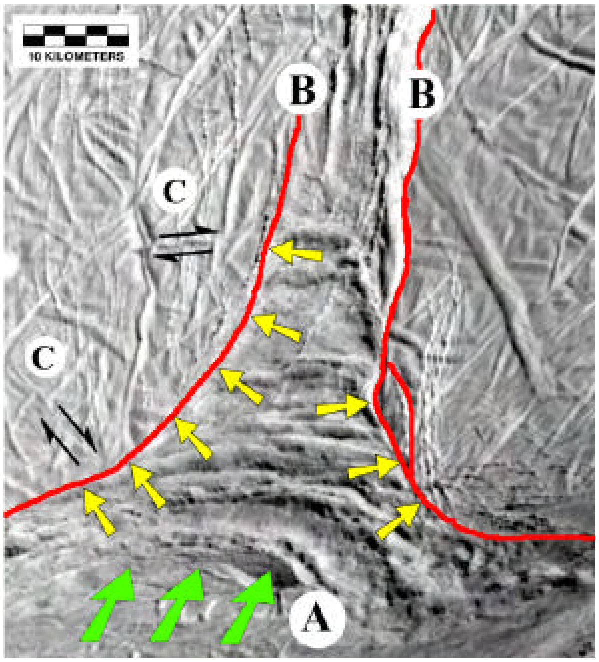

Figure 1: Cassini ISS GRN filter mosaic showing a Y-shaped discontinuity at 50°S, 280°W (north is up). Green arrows (A) show proposed direction of tectonic convergence. A wedge-shaped assemblage of lateral folds, perhaps analogous to a terrestrial accretion wedge, appears to be compressed against arcuate sections of the SPT boundary (B) shown in red. Yellow arrows suggest how the compression forces are likely directed at the margins of the wedge. Right-lateral strike-slip offsets (C) resolved along fractures in pre-existing fractured plains terrain, to the north, are consistent with the proposed transfer of compressive stress from the convergent accretion wedge.

References. [1] Helfenstein et al. 2005, *Bull. Amer. Astron. Soc.* **37**, abstract #36.01. [2] Porco, C. et al. 2006. *Science*, submitted. [3] Melosh, H.J.1977. *Icarus* **31**, 221-243. [4] Helfenstein, P. and E.M. Parmentier 1980, *Proc. Lun. Planet. Sci. Conf. 11th*, 1987-1998 [5] Bayly, B. 1982, *Geology* **10**, 629-632. [6] Ben-Avram et al. 1981. *Science* **213**, 47-54.