PINWHEEL RIFTS EMANATING FROM THE SOUTH POLAR TERRAIN OF ENCELADUS.
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Introduction: The highly tectonized south polar terrain (SPT) of Enceladus displays prominent structural features, including the eruptive tiger stripe fissures, numerous tectonic fracture sets in different orientations, and an encircling belt of complex deformation called the dichotomy boundary. A system of narrow rifts (or chasmata [1]) extends ~260 km northward from this boundary up to and beyond the equator (Fig. 1), implying that the tectonic reach of SPT deformation processes may extend far beyond the SPT itself. North of the dichotomy boundary and adjacent to the SPT, there are additional terrains of relatively less-defined troughs and ridges with contrasting patterns of structural reworking, encircled by a second dichotomy boundary-like feature (labeled as the outer deformation boundary in Fig. 1) that could be an indication of a past northern extent of the SPT. This boundary does not fully circumscribe the SPT, but extends outward from the SPT dichotomy boundary into the trailing hemisphere. Hence, we hypothesize that both the locus of activity and the boundary of the SPT may have receded poleward over time, possibly in response to a change in the size of the south polar thermal anomaly.

The rifts radiate out from the tips of northward-pointing cuspate protrusions along the inner dichotomy boundary and appear to curve in a clockwise fashion as they extend across the outer terrain boundary, producing geometries that inspired our descriptive term pinwheel rifts. These relationships indicate that pinwheel rift development is strongly linked to the evolution of the dichotomy boundary and hence recent SPT activity. The curved clockwise geometry of the rifts may signify a shift in the regional stress fields beyond the influence of the SPT, possibly in response to nonsynchronous rotation related stresses or some other global stress field. By characterizing the geometries of these large structural features that interact with the SPT, we can elucidate the rift evolution process on Enceladus and the possibility of ongoing rift-formation away from the SPT.

Rift Systems: All three of the identified pinwheel rift systems emanate northward from the cuspate protrusions along the dichotomy boundary (Fig. 1). These cuspate protrusions have distinct internal morphologies reminiscent of folds which are convex toward the direction of the pinwheel rifts and appear to have been caused by N-S compressive stresses induced by activity near the center of the SPT [2]. Cuspate protrusions occur intermittently along the outer edge of the dichotomy boundary; however, only three of these protrusions have developed into rift systems. Folds within the cuspate protrusions that are not associated with pinwheel rift systems are relatively far less arcuate and numerous compared to the protrusions which lead into the three rifts, suggesting that compressional stresses from the SPT are greater in the direction of the pinwheel rifts or that the crust is weaker in this direction.

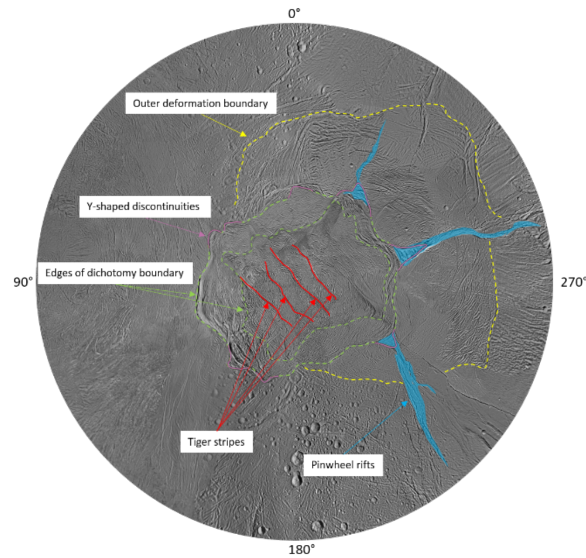

Figure 1: SPT and related features in south polar projection. Latitude along the edge of the map is 0°. The light blue shaded areas highlight the three rift systems emanating from the dichotomy boundary. The dark purple lines represent the outer edges of the cuspate protrusions. Red lines mark the tiger stripes. The dashed green lines are drawn along both the outer and inner edges of the dichotomy boundary encircling the SPT. The dashed yellow line represents an outer deformation boundary.

Little is currently understood about the processes or driving mechanisms for rifting on Enceladus. Enceladus could potentially initiate and drive rifts utilizing mechanisms similar to those responsible for terrestrial rift propagation through thick lithospheric mantle. The tidally heated ice-shell and subsurface ocean of Enceladus allows for the possibility of solid-state convection or perhaps cryomagmatism or the migration of ice-water material within Enceladus' icy shell, which may drive rifting [3]. Intrusive dikes of warmer ice or cryomagma could play a major role in the propagation of the pinwheel rifts. Since these rifts appear to originate from the thermal anomaly that gave rise to the active SPT, there is a possibility that subsurface fractures filled with water-ice are emanating outward/northward from this thermal anomaly, providing the extensional driving stresses at depth needed to begin the process of rifting in overlying cold ice. This process has been invoked to explain rift evolution in magmatic rift zones on both Earth and Mars [4, 5]. Enceladus' icy crust has been interpreted to have a brittle/ductile transition zone at ~4 km depth [6], perhaps creating a mechanical interface above which rifts are able to develop. Cuspate protrusions along the dichotomy boundary have been interpreted in past work to drive apart the pinwheel rifts like a wedge [2]; however, no mechanism has been described to explain how this process drives rifting as far north as is observed. Dike intrusion thus provides a potential mechanism to drive rift propagation for hundreds of kilometers away from the SPT.

Outer Deformation Boundary: The three identified pinwheel rifts of Enceladus appear to be disrupted throughout their extent by an abrupt, deep fracture that originates from the dichotomy boundary and curves northward into the trailing hemisphere, eventually rejoining the dichotomy boundary, and referred to here as the outer deformation boundary. This boundary appears to divide older terrain from younger terrain much like the dichotomy boundary does (Fig. 2). Younger, or transitional [7], terrain located between the dichotomy boundary and the outer deformation boundary is characterized by sets of 1–3 km wide, curvilinear troughs that are subparallel to slightly oblique, crosscutting at small (20°–30°) angles [7]. North of the outer deformation boundary, older striated plains are characterized by numerous small (0.6–2km wide) ridges and troughs oriented approximately N-S.

The outer terrain boundary appears to mimic the general shape of the dichotomy boundary and also contains cuspate protrusions much like the cuspate protrusions located along the outer edge of the dichotomy boundary [7]. All three pinwheel rifts propagated exclusively into this transitional terrain, perhaps implying a lower brittle thickness than elsewhere around the SPT. The largest pinwheel rift appears to gently rotate clockwise where it intersects the outer deformation boundary, which thus either formed after the rifts or the stress field is perturbed by the outer deformation boundary which affected the geometry of the developing rifts.

Conclusions: The apparent relationship between the SPT, dichotomy boundary, and pinwheel rifts leads us to posit that the pinwheel rifts began to form on Enceladus in response to an outward push of the SPT. Deformation patterns and geometries of both the SPT and the pinwheel rifts imply that the rifts formed sometime after the formation of the SPT in response to ice-shell convection [e.g., 8]. Processes such as dike-fed cryomagmatism could have aided in the propagation of these rifts by playing the role that an intrusive igneous body normally plays in terrestrial graben models [9]. The outer deformation boundary shares similar morphologies with the dichotomy boundary, more notably the cuspate protrusions, raising the possibility that the outer deformation boundary and the dichotomy boundary were formed through related processes. Separation of relatively young and old terrains by the outer deformation boundary leads us to speculate that this outer boundary marks the abandoned former extent of a nascent, older and larger SPT before a change in the thermal anomaly in the ice shell caused it to recede to its current state and create an even younger terrain south of the dichotomy boundary.

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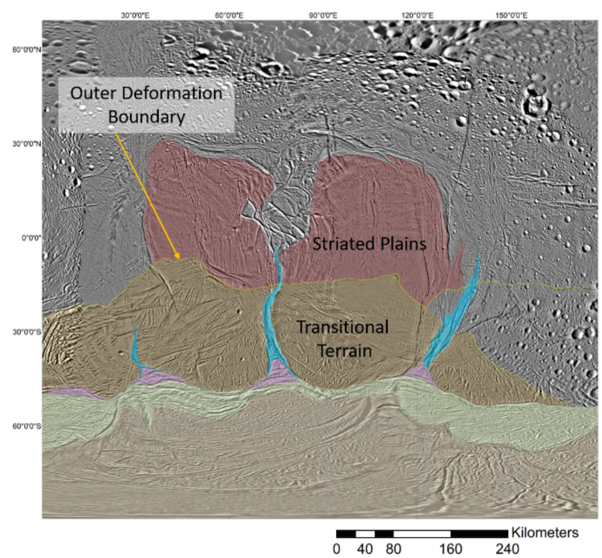

Figure 2. Outer deformation boundary on Enceladus base map, cylindrical projection. The area shaded in red marks the older terrain separated from the gold-shaded younger transitional terrain by the outer deformation boundary, represented by a yellow line. The pinwheel rift systems are shaded in light blue. The longest rift system rotates clockwise just before intersecting the outer deformation boundary, then changes orientation again just past the outer deformation boundary. Cuspate protrusions are highlighted in purple. The dichotomy boundary is shaded in light green just north of the SPT, which is shaded in a light brown.