ENCELADUS AND MIRANDA: SIMILAR HISTORIES OF LOW-ORDER CONVECTION AND REORIENTATION DURING DIFFERENTIATION. R. T. Pappalardo[1] and G. Schubert[2], [1]M/S 321-560, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, [2]Department of Earth, Planetary and Space Sciences, University of California, Los Angeles, CA 90095-1567.

Summary: *Voyager 2* imaging of Miranda and *Cassini* imaging of Enceladus reveal a striking similarity between these comparably sized satellites: each shows two antipodal, hemispheric-scale, relatively young regions of tectonic deformation encompassing its leading/trailing (b-) axis and its south pole, surrounded by cratered ancient terrain. Such similar occurrences on the only two geologically active satellites in this size class seems more than coincidental. We propose that low-order convection could account for these tectonized regions on each satellite, implying formation while the satellites' rocky cores were small. The relative youth of these regions compared with surrounding ancient cratered terrains implies near-homogenous accretion, then late-stage differentiation potentially triggered by tidal heating events. Convective upwellings in differentiating satellites would be relatively silicate-free, promoting reorientation.

Geological Observations: Of the four icy satellites in their size class (~250 km radius), Miranda at Uranus and Enceladus at Saturn are the only two with signs of geological activity, and they show strikingly similar large-scale patterns of deformation.

In the hemisphere illuminated during the *Voyager 2* encounter, Miranda (236 km average radius) shows three hemispheric-scale "coronae," ovoidal to trapezoidal regions of tectonic deformation and cryovolcanism, up to 300 km across (Figure 1). Each has an outer belt of roughly concentric structures surrounding an inner belt of less organized structures. Extensional tectonism is inferred as predominant [1,2] (though other mechanisms have been suggested [3,4]). In accordance with tectonic models [3,5], this suggests formation of each corona above an upwelling region as a manifestation of convection and/or satellite differentiation [6]. Miranda's three known coronae are positioned on each of the larger-inertia axes: encompassing the south pole (illuminated c-axis), and the leading and trailing regions (b-axis). It is inferred that Miranda has reoriented to position the coronae along the larger inertia axes, consistent with their being relatively low-density regions [1,3,4,7]. The inferred crater ages of the coronae depend upon models of impactor flux and of reorientation, but are nominally ~0.1 to 2 Ga [8].

Geological mapping [9,10] of *Cassini* images of Enceladus (252 km average radius) shows that, in addition to the well-known and geologically active South Polar Terrain (SPT), there are two additional hemispheric-scale regions of tectonic deformation encompassing the leading and trailing hemispheres (Figure 1). These areas were active in the geologically recent past, nominally 30 Ma to 2 Ga for the trailing hemisphere tectonized terrain [11]. Regional-scale mapping shows that each tectonized region has an outer belt of subconcentric structures and an inner zone of less organized structures [10], implying applicability of vertical loading models [3,5]. A two-stage history has been suggested [10], in which upwelling plumes created inferred extensional structures of the leading and trailing hemisphere tectonized terrains, then downwelling (perhaps by cooling) produced inferred contraction.

Low-Order Convection during Differentiation: Convection driven by endogenic heating is a likely means to produce upwellings in an icy satellite. We consider that degree-2 convection is the most plausible means of producing large-scale, antipodal, tectonized terrains on Miranda and Enceladus, if these indeed formed above interior upwellings. Low-order convection cannot have occurred after the satellites' cores have fully formed, because convection in the relatively thin ice shells implied by full differentiation of Miranda and Enceladus (each ~90 km) would instead produce numerous upwellings of similar dimension [e.g. 12], rather than large-scale degree-2 upwellings. Moreover, a very small core would imply degree-1 convection, producing downwelling and contraction over one hemisphere and upwelling and extension over the opposite hemisphere. For degree-2 convection, the core should be about 0.2 to 0.3 of the satellite radius [13]. But recent modeling shows that degree-1 convection could occur in Enceladus for cores up to 120 km radius, depending on assumptions of internal heating rate and viscosity [14]. Moreover, [14] find that the same size core can permit transition from degree-2 to degree-1 convection as heating rate increases, suggesting that transition to a single plume is plausible.

If an icy satellite accreted as near-homogenous, then a simple model of Stokes flow suggests that silicate particles sink through ice as a function of their size and ice viscosity [15]. The model of [15] predicts the gradual advance of an unmixing front to clean out the ice mantle, above a core with growing rock fraction, which even after 2 Ga is below the rock close-packing limit. For Enceladus and Miranda, differentiation by gravitational settling is very similar to the model of [15] when scaled by satellite radius, with ice rheology expected to control convection into their latter histories. Maintenance of an incompletely differentiated interior until late geological activity implies cold satellite accretion and a lack of short-lived radioisotopes. A late heat pulse is also implied, such as passage through a temporary tidal resonance [e.g. 4].

Reorientation: Reorientation of Miranda and Enceladus could have placed negative mass anomalies along the satellites' larger inertia axes [1,3,7,16,17]. Negative mass anomalies will tend to reorient the satellites to place negative anomalies along the polar (c-) axis if they can overcome both the fossil triaxial shape and any strong pre-existing anomalies (presumably then to be rotated to the equator upon subsequent formation of the tectonized region that is currently located at the pole) [cf. 17], or otherwise could reorient to the leading/trailing (b-) axis [cf. 18] (implying independent earlier formation of the polar terrain, potentially applicable to Miranda). Although the low density contrast between warm and cold ice is problematic for triggering significant reorientation [12,16,17], the density contrast between silicate-contaminated ice and warm ice can be hundreds of times greater, considerably aiding reorientation in response to convective upwelling. On Miranda, reorientation to the leading/trailing axis may have opened Verona Rupes [1]; on Enceladus, we speculate that analogous reorientation may have caused the inferred contraction within the leading and trailing tectonized regions.

Formation of the polar terrain of each satellite is somewhat problematic. For Miranda, we do not know if a fourth corona lies near the satellite's north pole, perhaps implicating a second degree-2 convection event. For Enceladus (at least), degree-1 convection [14] or tidal heating above a south polar sea [19] is implicated for the polar terrain. A degree-1 convection model may be plausible for each polar terrain if: 1) its formation occurred during differentiation soon before or after the leading and trailing terrains, 2) the core was smaller and/or heating rate was larger, promoting degree-1 convection, *and* 3) for Enceladus, it remained active to the present day or reactivated recently.

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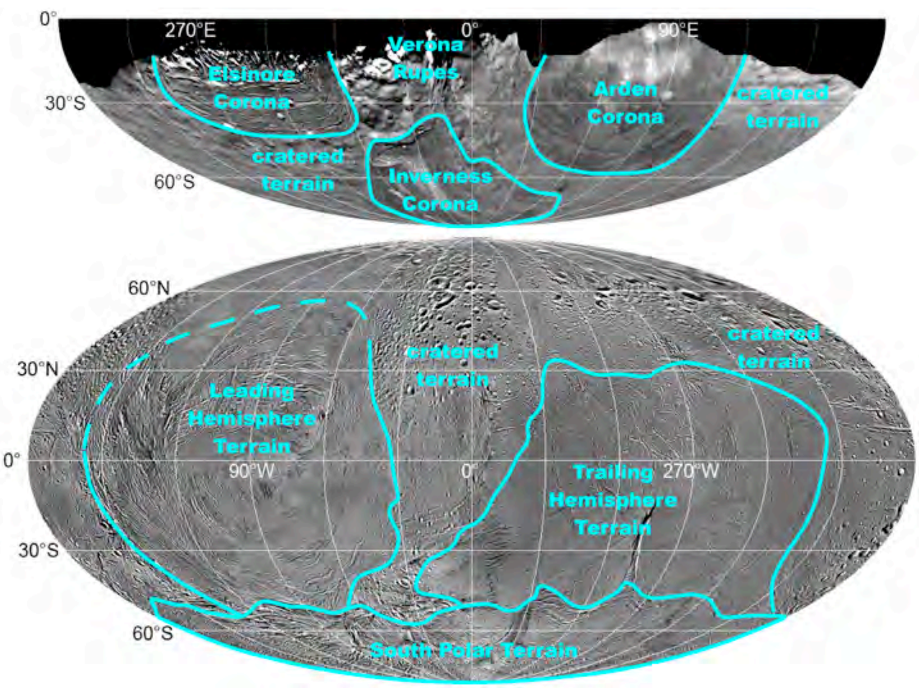

Figure 1. Both Miranda (top) and Enceladus (at the same scale) display hemispheric-scale regions of tectonic deformation (outlined), encompassing the leading and trailing regions and south pole. The satellites' longitude systems are defined oppositely (Miranda east-positive, Enceladus west-positive), so the leading (0°, 90°) and trailing (0°, 270°) points are displayed on opposite sides of these Mollewide projections. We propose that the antipodal leading and trailing tectonized regions were formed contemporaneously by degree-2 convection during differentiation.