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Tectonics of Icy Moons: A Tale of Oceans and Orbital Dynamics

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Icy moons of the outer solar system commonly experience eccentric orbits that impart daily tidal stresses to the outer ice layer. Depending on the orbital dynamics and configuration of the moons and their host planets, these stresses may or may not be sufficiently large to deform the ice layer. Although the stresses are typically very small, many icy moons exhibit pervasively tectonized surfaces, replete with fractures, faults, and significant topography (e.g., Europa, Ganymede, Enceladus, Dione, Titan, Miranda, Ariel, Titania, Triton). Deformation may be driven by various means (e.g., orbital recession, polar wander, ice shell thickening), but tidal deformation is particularly important and is enhanced if an outer ice layer is decoupled from an underlying liquid ocean. The tidal response of the ocean creates tidal bulges in the ice layer that oscillate longitudinally and in amplitude during the orbital period. The resultant diurnal tidal stress field (perhaps 10s of kPa) rotates throughout the orbit. Any fractures growing in this time frame should thus be curved (e.g., Europa's cycloidal cracks, which have been cited as the smoking gun for a subsurface ocean). Long lineaments should accumulate strike-slip offsets in such a stress field, as occurs on Europa and perhaps Enceladus. The progressive development of ice ridges to either side of central cracks may result from this shearing process. A decoupled ice layer also permits faster than synchronous rotation of the ice layer, which may allow several MPa of stress to accrue, perhaps explaining long lineaments on Europa. It is unclear if Europa continues to be tectonically active, especially given apparent ice shell thickening that would have muted the tidal response through time. Nonetheless, subtle troughs across Europa's surface crosscut all other features and may indicate some degree of ongoing activity. In contrast, active tectonics on Enceladus is implied by ongoing geyser-like eruptions of water-ice from cracks clustered around the south pole. These eruptions do not necessitate a liquid ocean, which seems difficult to sustain through tidal heating on such a small body. Nonetheless, a prolonged history of fracturing in the south-polar area created successive sets of fractures that imply the ice shell of Enceladus gradually rotated across the extant stress field, creating multiple fracture sets of different ages and in different orientations. These fractures may be the smoking gun for a subsurface ocean on Enceladus, with associated nonsynchronous rotation stresses having allowed successive fracture sets to form when sufficiently high stresses had accrued in the ice shell.