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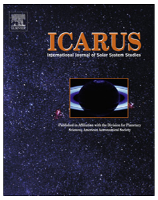

The tectonics of Titan: Global structural mapping from Cassini RADAR

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ABSTRACT

The Cassini RADAR mapper has imaged elevated mountain ridge belts on Titan with a linear-to-arcuate morphology indicative of a tectonic origin. Systematic geomorphologic mapping of the ridges in Synthetic Aperture RADAR (SAR) images reveals that the orientation of ridges is globally E–W and the ridges are more common near the equator than the poles. Comparison with a global topographic map reveals the equatorial ridges are found to lie preferentially at higher-than-average elevations. We conclude the most reasonable formation scenario for Titan's ridges is that contractional tectonism built the ridges and thickened the icy lithosphere near the equator, causing regional uplift. The combination of global and regional tectonic events, likely contractional in nature, followed by erosion, aeolian activity, and enhanced sedimentation at mid-to-high latitudes, would have led to regional infilling and perhaps covering of some mountain features, thus shaping Titan's tectonic landforms and surface morphology into what we see today.

1. Introduction

The Cassini spacecraft's 2.17 cm RADAR instrument has revealed that Titan has diverse geological processes, in many ways like Earth (Elachi et al., 2005; Lopes et al., 2010a). These include aeolian (Lorenz et al., 2006; Radebaugh et al., 2008, 2010; Savage et al., 2014), fluvial (Lorenz et al., 2008; Burr et al., 2009, 2013; Langhans et al., 2012), lacustrine (Stofan et al., 2007; Hayes et al., 2008; Lorenz et al., 2014), cryovolcanic (Lopes et al., 2007, 2013), and tectonic processes (Radebaugh et al., 2007, 2011; Solomonidou et al., 2013). These processes have formed and shaped ubiquitous, Earth-like surface features on Titan. The features that are RADAR bright as seen by Cassini's Synthetic Aperture RADAR (SAR) with relatively high topography have been called mountains (Radebaugh et al., 2007; Barnes et al., 2007; Mitri et al., 2010) and hummocky terrains (Lopes et al., 2010a). Some mountainous areas, in particular mountain ridge belts that are long and curvilinear in morphology, have been interpreted to be related to tectonic processes (Radebaugh et al., 2007, 2011; Mitri et al., 2010; Paganelli et al., 2010; Solomonidou et al., 2013; Liu et al., 2016). Possible tectonic landforms can be examined in geomorphological and structural mapping through analysis of the highest-resolution (350 m/pixel) Cassini SAR images, obtained beginning in 2004 (Elachi et al., 2005). These images can be used to determine the origin of the mountains, as contractional fold and thrust belts, normal or reverse faults.

Analyzing topographic data and undertaking global mapping of surface features are the keys to testing a possible tectonic contribution to shaping Titan's surface (Moore and Pappalardo, 2011). Although few researchers have undertaken geomorphologic mapping of Titan's mountain ridges (Paganelli et al., 2010; Moore et al., 2014; Cook-Hallett et al., 2015), no previous work has focused on the quantitative analysis of ridge structure, orientation, and distribution at the global scale. In addition, the driving forces of tectonism and the tectonic evolutionary history of Titan remain unclear. Thus, the purpose of this study is to: (1) analyze the distribution and orientation of mountain ridges to reveal their global tectonic pattern, and (2) explore the correlations between ridges and their regional elevations (Lorenz et al., 2013) and (3) consider the implication of these mountains for Titan's surface evolution history. In this paper, we first discuss current understanding of geological process related to Titan's mountains. Then, we describe our global structural mapping procedure on SAR images and pre-

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sent the results of ridge distribution and orientation. Finally, the distribution of ridge elevations are evaluated and tested statistically.

2. Geological background

2.1. Titan's interior structure

To be able to generate the observed mountain ridge belts through tectonism, sufficient internal energy is required to produce solid-state convection within the ice shell. This is believed to occur, in the stagnant lid regime (Tobie et al., 2006; Mitri and Showman, 2008). Furthermore, measurement of the tidal Love number k_2 reveals a relatively large response of the gravity field to the tidal field of Saturn, indicating the presence of a subsurface ocean (Iess et al., 2012). The onset of convection depends mainly on the rheology of the water ice and the composition of subsurface ocean. Mitri and Showman (2008) demonstrated that for the expected heat flux from the interior, thermal convection in the ice shell of Titan could cause repeated episodes of extensional and compressional tectonism. However, Titan's tectonics may alternatively be driven by tidal forces and the change of the satellite's figure through the mechanisms of internal cooling and rotational and orbital evolution (e.g., despinning, polar wander) without requiring a high heat flux produced in the interior (Collins et al., 2009; Moore and Pappalardo, 2011). Mitri et al. (2010) developed a thermal model of Titan's interior showing that Titan probably experienced global contraction during its secular cooling, which can produce tectonic features on the surface.

Titan's relatively low moment of inertia (MoI $\sim$ 0.34) measured by the Cassini spacecraft (Iess et al., 2010) indicates that Titan's interior may be only partially differentiated. This would indicate that Titan hasn't undergone strong internal heating. Nimmo and Bills (2010) established a model for Titan's long-wavelength topography consistent with the observed tidal Love number and moment of inertia (Zebker et al., 2009); they suggest that Titan's ice shell has thickness of $\sim$100 km and is conductive today, significantly limiting the amount of present-day geological activity expected. In addition, the strong inverse correlation between gravity and topography at long wavelengths led. Hemingway et al. (2013) to conclude Titan's ice shell is rigid and that relatively small topographic features on the surface are associated with large roots extending into the underlying ocean. They suggest that Titan's geological activity is limited at present day and Titan may be even less centrally condensed than previously thought. However, O'Rourke and Stevenson (2014) found that thermal convection couldn't realistically remove all of Titan's radiogenic heating to present day, so a partially differentiated Titan is unstable over geologic time. They concluded that Titan must be internally differentiated, and the discrepancy in the MoI could be explained by Titan having a mantle of serpentinized (hydrated) rock. Moreover, Baland et al. (2014) demonstrated that the measured obliquity of Titan (Stiles et al., 2008) indicates a higher degree of internal differentiation than expected from the moment of inertia inferred by the quadruple moment of the gravity field measurement (Iess et al., 2010). In sum, the hypotheses related to Titan's internal structure, crustal thickness, the degree of differentiation, and thermal evolution are still debated. Thus, an analysis of their structural and geographic patterns would help us understand Titan's evolutionary and geological history.

2.2. Titan's mountains

Titan's mountains have a variety of morphologies, described by four general categories: (1) *ridges*: chains of hills with elongate, curvilinear/linear crests that are higher than the surrounding areas (Fig. 1a). In many regions, ridges occur in parallel groups; we call these ridge belts. (2) *Isolated blocks*: elevated blocks with rough, SAR-bright surfaces that are generally isolated (Fig. 1b). (3) *Rugged or crenulated terrains*: rough mountains that have likely experienced erosion and have hummocky morphologies, wherein multiple adjacent peaks extend across vast regions (Fig. 1c). The crenulated nature observed in SAR is likely from the great relative elevations of these features, typically at least several hundred meters (Fig. 1c). Moore et al. (2014, 2015) pointed out that crenulated terrain generally occurs in closely spaced discrete patches, often with significant linear elongation that might be associated with tectonic deformation. Rugged and crenulated terrains are mainly located in the Xanadu region (centered at 5°S, 100°W) (Lopes et al., 2010a; Radebaugh et al., 2011; Moore et al., 2014), the first surface feature of Titan seen from Earth (Lemmon et al., 1993; Smith et al., 1996). Xanadu stands out globally as a bright feature on Titan's leading hemisphere and this brightness is the result of either compositional or textural differences in this region compared with other areas on Titan (Radebaugh et al., 2011; Langhans et al., 2013; Janssen et al., 2009, 2016). The last morphological category is (4) *massifs*: compact groups of mountainous peaks with rough, SAR-bright surfaces (Fig. 1d).

Note that Cassini RADAR altimetry, SARTopo (absolute topography with respect to the 2575 km radius sphere obtained from overlapping SAR images; Stiles et al., 2009) (Fig. 1), stereo DTM (digital terrain model) (Kirk et al., 2013), and radarclinometry data (Radebaugh et al., 2007; Liu et al., 2011) show that radar-bright mountains generally have a positive relief of several hundreds meters (Mitri et al., 2010; Kirk et al., 2013). Impact craters are also SAR bright (Fig. 1e) but have highly curved, rugged rims in contrast with the broad, open curvilinear shapes of ridges and ridge belts. Based on this difference in morphology, one can distinguish impact craters from mountainous terrains on Titan. There are only a few named impact craters, far fewer than would be expected compared to other bodies in the Solar System (Lorenz et al., 2007; Wood et al., 2010; Neish and Lorenz, 2012). The scarcity of impact craters, likely due to resurfacing inclusive of erosion and deposition or formation in marine environments (Neish and Lorenz, 2014), indicates that Titan's surface is very young, on the order of a few hundred million years old (Wood et al., 2010; Neish and Lorenz, 2012; Neish et al., 2016).

2.3. Degradation of Titan's surface

Degradation through erosion by methane rainfall plays an important role in altering Titan's surface landscapes (Collins, 2005; Burr et al., 2006; Perron et al., 2006), including mountains (Radebaugh et al., 2007). In addition, Cassini's Imaging Science Subsystem (ISS) has shown evidence that seasonal precipitation (e.g., methane rainfall) has facilitated erosion on Titan's surface (Turtle et al., 2011a, 2011b). Thus, interpreting the morphology of mountains must include the consideration of the effects of erosion.

The extent of erosion on Titan is not precisely known, but experimental work and observations suggest erosion rates somewhat slower than those on Earth. Collins (2005) originally suggested that the erosion rates on Titan were similar to those on Earth, even when the different materials and gravitation accelerations were taken into consideration. More recent work (e.g., Collins et al., 2011), however, suggests that the erosion rates are slower on Titan, perhaps by up to an order of magnitude. This experimental work is supported by observations of the degradation states of Titan's coastlines and impact craters (Black et al., 2012; Tewelde et al., 2013; Neish et al., 2016). Black et al. (2012) undertook a quantitative analysis of the shape of drainage networks on Titan,