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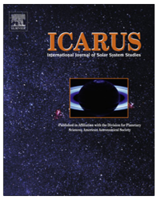

Role of fluids in the tectonic evolution of Titan

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ABSTRACT

Detailed analyses of slopes and arcuate planform morphologies of Titan's equatorial mountain ridge belts are consistent with formation by contractional tectonism. However, contractional structures in ice require large stresses (4–10 MPa), the sources of which are not likely to exist on Titan. Cassini spacecraft imagery reveals a methane-based hydrological cycle on Titan that likely includes movement of fluids through the subsurface. These crustal liquids may enable contractional tectonic features to form as groundwater has for thrust belts on Earth. In this study, we show that liquid hydrocarbons in Titan's near subsurface can lead to fluid overpressures that facilitate contractional deformation at smaller stresses (<1 MPa) by significantly reducing the shear strength of materials. Titan's crustal conditions with enhanced pore fluid pressures favor the formation of thrust faults and related folds in a contractional stress field. Thus, surface and near-surface hydrocarbon fluids made stable by a thick atmosphere may play a key role in the tectonic evolution of Titan.

1. Introduction

Titan, the largest moon of Saturn, has a thick atmosphere, surface fluids (Stofan et al., 2007; Lorenz et al., 2008), subsurface liquids (Hayes et al., 2008), and a methane-based hydrologic cycle that likely includes a ground 'methane' system similar to Earth's groundwater system (Lunine and Lorenz, 2009). The stability of fluids on and near the surface makes Titan unique among the satellites that have icy lithospheres. Since the Cassini spacecraft (2004–present) began imaging Titan's surface, many studies have examined the Earth-like geological processes involving surface fluids (e.g., Hayes et al., 2008; Lunine and Lorenz, 2009; Burr et al., 2013). It is also possible to examine the role of subsurface fluids in the tectonic evolution of the lithosphere, despite the fundamental rheological differences between materials of Earth and Titan (i.e., liquid hydrocarbon in water ice crust).

The general understanding of icy satellite tectonics is that most bodies exhibit evidence for extensional tectonism (e.g., fractures, grabens, normal faults), whereas evidence for contractional tectonism (e.g., folds, thrust faults) is rare (Collins et al., 2009). The stress required to form contractional structures in ice on Ganymede and Europa is estimated at 10–25 MPa (Dombard and McKinnon, 2006; Pappalardo and Davis, 2007), 3–8 times that required to form extensional features in ice. Generating such large stresses on icy satellites is difficult. The dominant source of stress for brittle-frictional faulting, which is diurnal eccentricity, can only generate stresses of 0.1 MPa on Europa and <0.1 MPa on Ganymede and Titan (Collins et al., 2009). It is possible that other mechanisms may produce larger stresses, such as despinning, nonsynchronous rotation, polar wander (e.g., Dombard and McKinnon, 2006), or volume change (Mitri et al., 2010a,b), but in the absence of these mechanisms, sources of contractional stress sufficient for thrust faulting probably do not exist on most icy satellites, including Titan.

Nevertheless, there is strong evidence that contractional features do exist on Titan. The Cassini RADAR instrument, operating in Synthetic Aperture Radar (SAR) mode, has obtained images at ~350 m resolution of many landforms on Titan (Elachi et al., 2005; Lunine et al., 2008), including E–W oriented, long, narrow mountain ridges (Fig. 1) (Radebaugh et al., 2007; Cook-Hallett et al., 2015; Liu et al., 2016). Their long, curvilinear morphology (Paganelli et al., 2010; Radebaugh et al., 2011; Solomonidou et al., 2013; Liu et al., 2016), their low slopes and relief (Radebaugh et al., 2007; Liu et al., 2012; Mitri et al., 2010a), comparisons of these morphologies with Earth's tectonic features (Solomonidou et al., 2013), and structural and stress field analysis (Paganelli et al., 2010; Cook-Hallett et al., 2015; Liu et al., 2016) are all consistent with formation by contraction. However, the source

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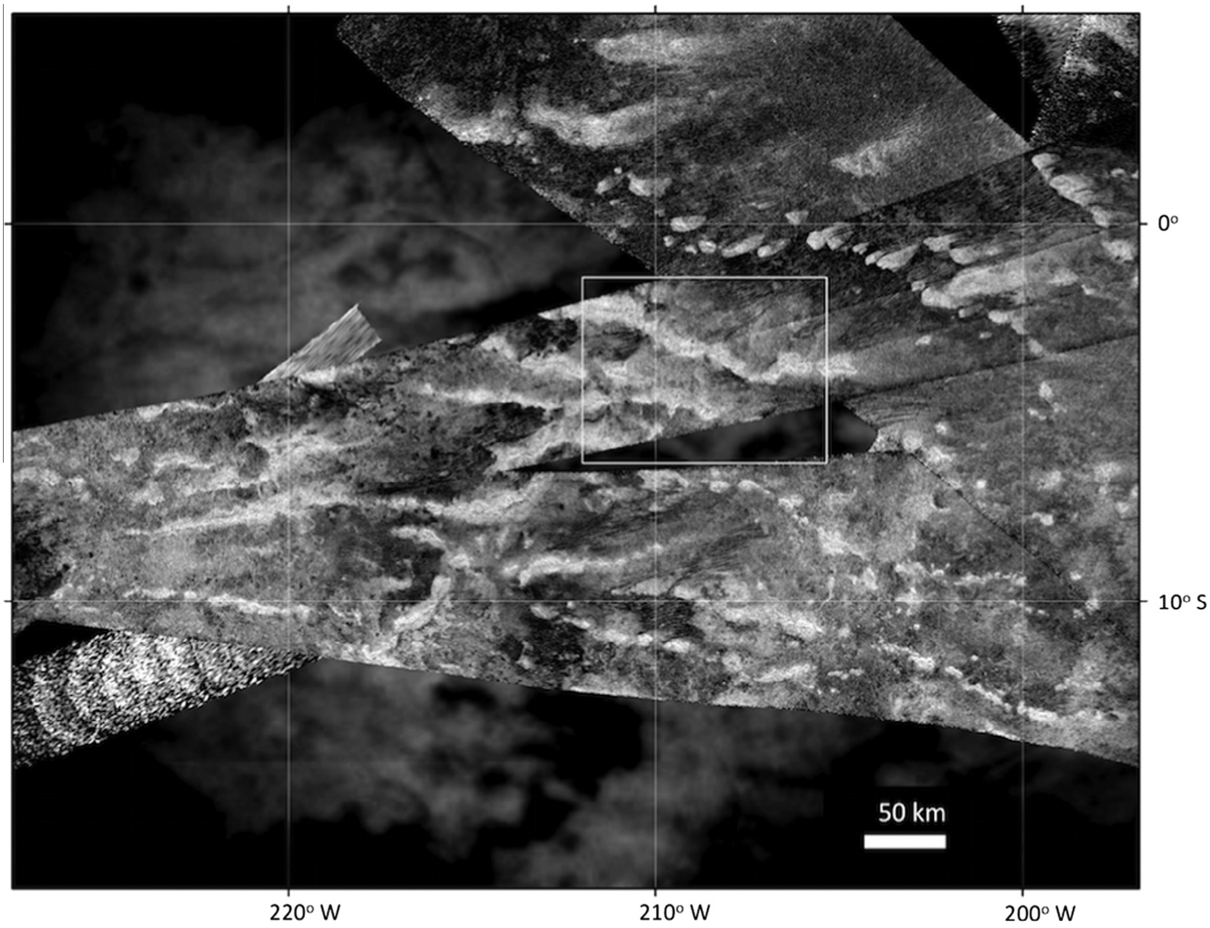

Fig. 1. Mountain ridge belts on Titan. Bright linear ridges at 200–230°W, 5°N–15°S are apparent on this image, which is a Cassini SAR (Synthetic Aperture Radar) mosaic (T8, T61 and T41 flyby swaths) processed using Imaging Science Subsystem (ISS). SAR image brightness represents the normalized microwave energy backscattered from the surface, which is a function of surface slope, dielectric properties, roughness, and the amount of volume scattering. Ridge belts are elevated, SAR-bright features with curvilinear margins morphologically similar to terrestrial fold belts. White rectangle shows the location of the image in Figs. 2 and 6.

of stresses large enough to produce the contractional structures is not obvious.

1.1. The origin of Titan's tectonism

Both Cook-Hallett et al. (2015) and Liu et al. (2016) documented Titan's global tectonic pattern by mapping outlines of mountains and traces of ridges, respectively. Both studies revealed a pattern of E–W oriented mountains and ridges within 30° of the equator. Cook-Hallett et al. (2015) found mountains oriented N–S between 60° latitude and the poles, while Liu et al. (2016) contend the ridges trend E–W globally. Both studies concluded that Titan's global tectonic pattern could be caused by contractional tectonism. Liu et al. (2016) suggested global contraction with initial lithospheric thinning in the equatorial regions (Beuthe, 2010) could explain the global tectonic pattern. Cook-Hallett et al. (2015) suggested that either global contraction coupled with spin-up or global expansion coupled with despinning could explain the pattern if coupled with a thin lithosphere in Titan's polar regions. However, the magnitude of stress calculated from their model is <0.1 MPa (Cook-Hallett et al., 2015), which is much lower than would be expected for thrust fault formation. A model for contraction on Titan by Mitri et al. (2010a,b) revealed that volume change resulting from internal cooling may possibly provide enough stress to form contractional folds on Titan, but their model does not account for the global tectonic pattern. Therefore, current geophysical models cannot explain both the global tectonic pattern and the source of large stresses to produce the contractional structures.

1.2. Goal of this study

This study explores the role of fluids and their effect on Titan's tectonic evolution, specifically on contractional tectonism. We report that fluid pressures associated with liquid hydrocarbons in Titan's subsurface significantly reduce the shear strength of the icy crust and enable contractional structures to form without the requirement of large stresses. Although the thermal model constructed by Mitri et al. (2010a,b) suggested that the volume change mechanism may possibly provide enough stress to form contractional structures on Titan, the fluid overpressures model extended in this study provides a way to significantly reduce the strength of Titan's crust and allow contractional deformation at much lower stresses.

In this paper, we first discuss new evidence supporting the model of contractional tectonism having built the equatorial ridge belts on Titan (Section 2). We then estimate the strength of Titan's icy lithosphere and the differential stress necessary for failure in the brittle and ductile regimes (Section 3). Finally, we discuss the role of fluid pore pressure on Earth and how it reduces the stress needed for contraction and address its application to Titan's unique crustal environment (Section 4). Notably, since the effect of fluid pore pressure in Titan's tectonic evolution has never been explored in previous studies, the initial first-order modeling we present here