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Morphotectonic features on Titan and their possible origin

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ABSTRACT

Spectro-imaging and radar measurements by the Cassini–Huygens mission suggest that some of the Saturnian satellites may be geologically active and could support tectonic processes. In particular Titan, Saturn's largest moon, possesses a complex and dynamic geology as witnessed by its varied surface morphology resulting from aeolian, fluvial, and possibly tectonic and endogenous cryovolcanic processes. The Synthetic Aperture Radar (SAR) instrument on board Cassini spacecraft, indicates the possibility for morphotectonic features on Titan's surface such as mountains, ridges, faults and canyons. The mechanisms that formed these morphotectonic structures are still unclear since ensuing processes, such as erosion may have modified or partially obscured them. Due to the limitations of Cassini–Huygens in the acquisition of *in situ* measurements or samples relevant to geotectonics processes and the lack of high spatial resolution imaging, we do not have precise enough data of the morphology and topography of Titan. However we suggest that contractional tectonism followed by atmospheric modifications has resulted in the observed morphotectonic features. To test the possibility of morphotectonics on Titan, we provide in this work a comparative study between Cassini observations of the satellite versus terrestrial tectonic systems and infer suggestions for possible formation mechanisms.

1. Introduction

Tectonic or structural geology is the field of geological research that focuses on the study of features observed on the crust of the Earth and that of other planets investigating the processes, forces and movements that resulted in them. Tectonism encompasses geological events not caused by exogenous processes such as erosion and meteoritic impacts. Tectonism being compressional or extensional is related with important endogenous processes such as terrestrial volcanism and most probably with extraterrestrial cryovolcanism. Morphotectonics correlate landscape morphology to tectonism (Rosenau and Oncken, 2009; Scheidegger, 2004; Lidmar-Bergström, 1996) by studying landform evolution and degradation, since tectonic features are subsequently subjected to exogenous processes. Major morphotectonic features on Earth are represented by mountains, ridges, faults and escarpments, as well as by significant types of linear features such as rifts, grabens and other linear terrestrial terrains that are subjected to erosion subsequently to deformational events (e.g., Scheidegger, 2004). However, geology on Earth is dominated by active plate tectonics where rigid lithospheric plates float and move on a plastic asthenosphere.

Although the other planetary bodies in our Solar System possess different surface and internal conditions, bodies like Titan, Europa and Enceladus may possess a liquid water layer underneath their icy crust. If confirmed, then similarly to rocky plate tectonics on Earth, rigid ice plates may rupture and collide, floating over such a liquid substrate layer, resulting in surficial features, which may be reminiscent of terrestrial edifices. It is therefore possible that other planets and moons in the Solar System harbor "tectonic activity" in varying degrees and even exhibit morphotectonic features on their surfaces, which are subsequently modified by exogenous processes.

Venus appears to have no plate tectonics due to a high surface temperature and a higher density of its lithosphere compared to that of the mantle, which prevents a subduction regime, despite the fact that the mantle is convecting (Nimmo and McKenzie, 1998). However, the planet shows deformation and morphotectonic features such as faults, mountain crests and rifts, which probably originated from lithospheric movements in association with volcanism (Jull and Arkani-Hamed, 1995; Nimmo and McKenzie, 1998). In the case of Mars, two major regions are known to display morphotectonic features: the Tharsis volcanic plateau, which was possibly formed after crustal deformation in

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association with active diapirism from the mantle (Mège and Masson, 1996) and the Elysium region, which was a result of volcanic activity (Hall et al., 1986). Io, Jupiter's moon, presents morphotectonic features with no apparent association to plate tectonic activity. The mountains of Io are formed by stresses at the bottom of the lithospheric layer and subsequent uplift through thrust faulting system (Schenk and Bulmer, 1998).

A good candidate for the study of morphotectonic features in the Solar System appears to be Titan. With a diameter of 5150 km (1/3 that of the Earth), Titan is the largest satellite of the Saturnian System and the second in the Solar System, after Ganymede the moon of Jupiter. The temperature and pressure conditions at the surface near the equator are 93.65 ± 0.25 K and 1.467 ± 1 hPa, as measured by the Huygens probe Atmospheric Structure Instrument (HASI) (Fulchignoni et al., 2005). Titan is recognized as a world bearing several resemblances to our own planet, with respect to its atmosphere and to its surface morphology. Titan's dense atmosphere consists mainly of nitrogen ($\sim$97%), methane (1.4%) and hydrogen ($\sim$0.2%) with traces of hydrocarbons, nitriles, oxygen compounds and argon (see table 6.4 in Coustenis and Taylor, 2008). This complex atmosphere renders the surface difficult to access and analyze, apart from within a few methane spectral windows in the near-infrared where the methane absorption is weak (Griffith et al., 1991). Thirty-two years after the Voyager encounter in 1980, Cassini is today able to probe Titan's surface with a spatial resolution reaching a few hundred meters per pixel (RADAR), while the Huygens probe achieved the first *in situ* measurements in 2005 (for instruments and resolutions see Section 2). Even though Titan's surface morphology resembles that of the Earth, it is made of materials and subjected to surface conditions very distinct from the terrestrial ones. Indeed, morphotectonic features such as mountains (e.g. Radebaugh et al., 2007; Lopes et al., 2010), ridges (Soderblom et al., 2007b; Mitri et al., 2010), faults (e.g., Radebaugh et al., 2011), rectangular drainage patterns and cryovolcanic structures are most likely controlled, at least in part, by tectonism (Burr et al., 2009).

Atmospheric processes, like cloud formation and precipitation create extensive fluvial features on the surface, as observed by Huygens near its landing site and constitute the visible part of an active methane cycle (Atreya et al., 2006; Coustenis and Taylor, 2008; Lorenz and Mitton, 2008; Raulin, 2008; Brown et al., 2009; Coustenis and Hirtzig, 2009; Lebreton et al., 2009). The preservation limit of 100 Myr for this atmospheric methane requires a reservoir that would replenish occasionally the atmosphere (Lunine and Atreya, 2008). One of the most predominant theories suggests that methane sources exist in Titan's interior (e.g., Tobie et al., 2006; Fortes et al., 2007). Since volcanism is a major process associated with the terrestrial carbon release (Bolin, 1981), cryovolcanism may play a similar role in the methane supply (Sotin et al., 2005), as well as significantly influence Titan's surface morphology.

Geophysical models suggest that Titan's partially differentiated interior consists of a silicate core ($\sim$1800 km thick), a high-pressure ice mantle ($\sim$400 km), a liquid layer of aqueous ammonium sulfate (50–150 km thick), and an external icy shell 100–170 km thick that possibly contains clathrate hydrates (Tobie et al., 2005; Fortes et al., 2007; Grindrod et al., 2008). Castillo-Rogez and Lunine (2010) suggested possible dehydration of the core's hydrated silicates, which impacts the geophysical structure of the satellite as well as the possible internal ocean. Regarding the icy shell, the methane stored as clathrate hydrates within the ice shell is a plausible methane reservoir that can replenish the atmosphere via cryovolcanism (Sotin et al., 2005). Indeed, surface discontinuities such as faults and fractures, which are probably the result of tectonic and volcanic-like processes, could provide the pathways of internal methane release to the atmosphere. The morphotectonic structures on Titan's surface provide good evidence of such a mechanism, in the same way as, over extensive zones of geological weaknesses, magma and volatiles are released on the Earth's surface.

In the last eight years, despite continuous observations by Cassini and the development of models and interpretations based on them, we still lack long-term *in situ* measurements and geophysical data of Titan's interior, in order to be in a position to accurately evaluate its endogenetic potential and how it affects morphotectonic features. However, in this work we attempt to use similarities between the surficial morphotectonic features on Titan and on Earth as the key for deciphering Titan's endogenetic processes, in spite of the fact that our understanding of Earth's endogenetic processes is rather recent (Wilson, 1973).

2. Titan surface observations

From the interpretation of Voyager 1 recordings, a global ocean of dissolved ethane and nitrogen, several kilometers deep, was first assumed to cover the entire surface of Titan (Flasar, 1983; Lunine et al., 1983). However, ground- and space-based observations refuted this assumption by unveiling, within the methane "windows" of weaker methane absorption (centered at 0.94, 1.08, 1.28, 1.59, 2.03, 2.8 and 5 μm), a solid surface with heterogeneous bright and dark features (Muhleman et al., 1990; Griffith, 1993; Smith et al., 1996; Gibbard et al., 1999; Meier et al., 2000; Coustenis et al., 2001). The Cassini orbiter arrived at the Saturnian System in 2004 equipped with two spectro-imagers capable to probe down to the surface via several of the near-infrared windows: the Visual and Infrared Mapping Spectrometer (VIMS—with a typical resolution of 10–20 km/pixel) and the Imaging Science Subsystem (ISS—with a typical resolution of 1 km/pixel). In the scope of this paper we also make use of the RADAR data from Cassini with a spatial resolution from 300 m to 1.5 km/pixel. In addition, Huygens probe measurements and observations by the Descent Imager Spectral Radiometer (DISR—Tomasko et al., 2005), the Surface Science Package (SSP—Zarnecki et al., 2005), and the Gas Chromatograph Mass Spectrometer (GCMS—Niemann et al., 2005, 2010) provided additional information of Titan's geology. The actual landing site on the Saturnian satellite appears to be a relatively soft surface similar to tar or dry sand, tinted by methane ready to evaporate and providing ample evidence for fluvial and aeolian processes.

2.1. Surface expressions

2.1.1. Geological features formed by non-tectonic processes

Endogenous, as well as exogenous dynamic processes have created diverse terrains with extensive ridges and grooves, impact units, icy flows, caldera-like structures, layered plains and stable liquid lakes (Mitri et al., 2007; Stofan et al., 2007). In addition, Cassini's radar has partially revealed the topography of Titan's surface, indicating several types of surficial expressions, which are non-tectonic. Features like dunes, lakes and drainage network are attributed solely to fluvial, aeolian and impact processes (Fig. 1). Thus, their formation is the result of exogenous processes with no influence of internal activity.

2.1.2. Morphotectonic features

Cassini's remote instrumentation and the Huygens lander brought evidence of many features on Titan's surface, which were probably formed by extension or compression of parts of the planetary solid crust due to endogenetic geological and geophysical processes (Radebaugh et al., 2007; Soderblom et al., 2007b;