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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;

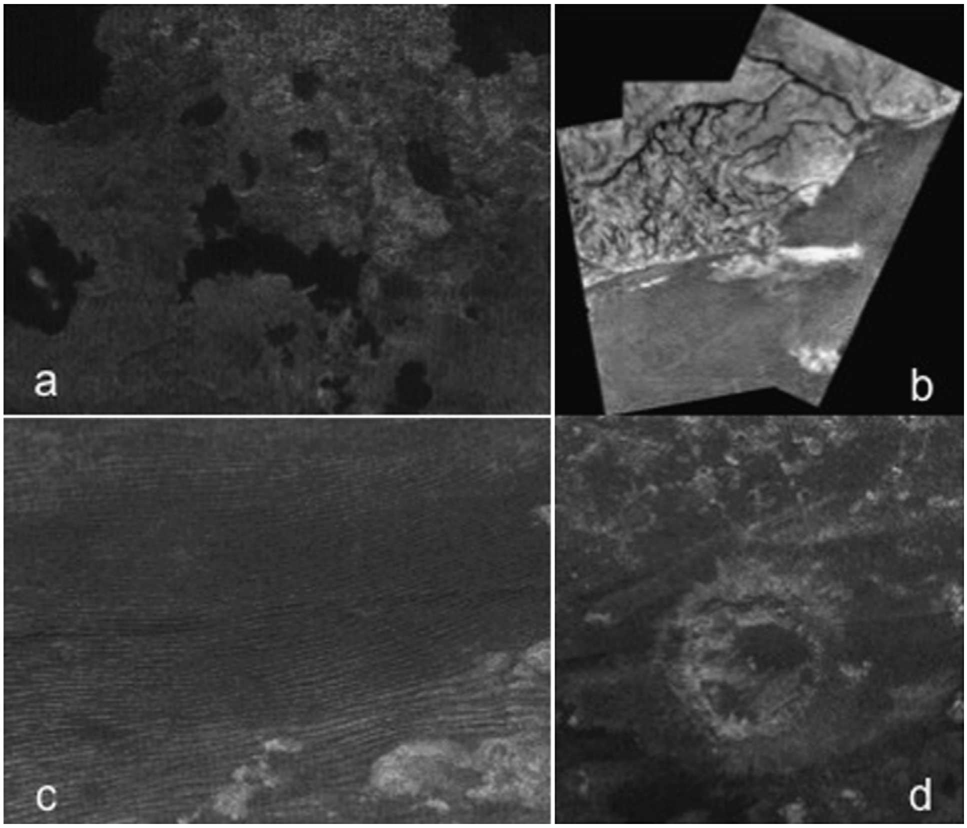

Fig. 1. Surface features on Titan. (a) Hydrocarbon liquid lakes at the North pole (Cassini Radar Mapper, JPL, ESA, NASA). (b) Complex network of narrow drainage channels formed by fluvial processes near the Huygens probe landing site (NASA/JPL). (c) Sand dunes formed by aeolian processes (NASA). (d) Afecan (26°N, 200°W) impact crater, discovered in 2008 (NASA/JPL).

Lopes et al., 2010). Furthermore, these features can be modified under the influence of exogenetic processes: the resultant morphotectonic structures are mainly mountains, ridges, faults, and structures of probable cryovolcanic origin as we will argue further down. Titan, despite its small size, displays surface features that resemble the structure of terrestrial volcanic fields albeit they are much more extensive. For example, Hotei Regio (see Section 4.2) covers an area of 140,000 km^2, which is an order of magnitude larger than Harrat Khaybar (14,000 km^2) in Saudi Arabia, which represents one of the most extensive volcanic fields on Earth (Camp et al., 1991).

2.2. Silicate and icy tectonism

A surface feature largely owes its shape to the material composing the planetary body's crust and to the forces that formed it. The response of the crustal material to the applied stresses, defines to a large extent the main topographic terrain of an area, along with the atmospheric conditions. Even though geological features such as mountains, faults and rifts on Titan present similar visual characteristics, the type of material that builds the features plays an important role. Indeed, the properties of the source material such as viscosity, elasticity and density in addition to the geological forces control the structural characteristics of the feature such as height, expansion and gradient slope.

On Titan, the surface should probably be composed mainly of mixtures of water and other ices, organics–tholins, nitriles (e.g. Soderblom et al., 2007a), while, most likely, its interior is composed of rock and high-pressure ice (Tobie et al., 2005). Since the well-known tectonic features of Earth are closely linked to silicate geology, we must first assess the similarities and differences between water ices and silicates, so that our comparative study can be based on reasonable assumptions. The icy crust of the outer system satellites possibly reacts in a brittle fashion to the application of stresses, similarly to the Earth's rocky upper crust (Collins et al., 2009). Both on Titan and Earth this reaction changes in proportion with depth. However, while water ice and silicate rock exhibit similar frictional strength (Beeman et al., 1988), when ductile yielding becomes important, ice is about ten times weaker than silicate rock (Melosh and Nimmo, 2011). The major differences and similarities between water ice and silicates are noted in Collins et al. (2009) and summarized in Table 1.

Table 1 shows that silicate materials, when compared to water ice, exhibit higher viscosity, Young modulus i.e. the ratio of linear stress to linear strain and melting temperature, but display lower density. As a result, the homologous temperature, on which rheology depends, is reached at greater depths in silicate environments while silicate magma eruptions are statistically more possible to occur than eruptions of ice (Collins et al., 2009). Nevertheless, both icy and silicate systems seem to follow some similar general deformation principles and mimic each other's behavior. Also, since ice topography could viscously relax over geologic time (e.g. Dombard and McKinnon, 2006) and elastic, brittle and ductile deformation could occur in the icy crust, tectonic-like movements, resembling the silicate plate behavior, are plausible.

3. Morphotectonic observations of mountains

3.1. Mountains and ridges

RADAR, VIMS as well as DISR data have provided some details of the characteristics of Titan's mountains and ridges. The term mountain describes large uplifted localized landforms while the term

Table 1
Comparison between silicate and ice properties.

Properties	Water ice	Silicate	Similarity
Homologous temperature	0.4	0.4	Yes
Melting temperatures	273.15 K	950–1500 K	No
Density	Low (in solid state)	High	No
Young Modulus	~10 GPa	~100 GPa	No
Low stress and strain	Elastic deformation	Elastic deformation	Yes
High strain, low temperature	Brittle deformation	Brittle deformation	Yes
Low strain, high temperature	Ductile deformation	Ductile deformation	Yes

Table 2a
Major mountain and ridge features on Titan.

Location	Orientation	Heights	Characterization	Flyby/Time	Instrument (reference)
10°N, 15°W 15°N, 45°W		380–570 m	Blocks of mountains	T3/February 2005	RADAR (Radebaugh et al., 2007)
20°N, 87°W	E–W	~300 m	Ridges	T3/February 2005	RADAR (Williams et al., 2011)
40°S, 340°W			Hills	T7/September 2005	RADAR (Lunine et al., 2008)
5°S, 12.5°S 63°W, 67°W	E–W	~860–2000 m	Curvilinear mountains/Ridges	T8/October 2005	RADAR (Radebaugh et al., 2007; Mitri et al., 2010; Lopes et al., 2010)
10°S, 210°W		~400 m	Mountainous region	T9/December 2005 T13/April 2006	VIMS/RADAR (Barnes et al., 2007)
10.4°S, 192.4°W	W–E	100–150 m	Ridges	Huygens/January 2005	DISR (Tomasko et al., 2005; Soderblom et al., 2007b)
30°S, 315°W	NW–SE	~1500 m	Mountain ranges	T20/October 2006	VIMS (Sotin et al., 2007)
52°N, 347°W	E-W	~1400 m	Mountain block	T30/May 2007	RADAR (Stiles et al., 2009; Mitri et al., 2010)
30°S, 107°W	S–W	~800 m	Mountains	T43/May 2008	RADAR (Mitri et al., 2010)
2°S, 127°W	E–W	1930 m	Ridges	T43/May 2008	RADAR (Mitri et al., 2010)

Table 2b
Proposed mechanisms for the formation of mountains and ridges of Titan.

Proposed mechanism	Description	Observations	Terrestrial analog
Lithospheric shortening (Mitri et al., 2010)	Folding of the upper crust due to past high heat flux from the interior and high temperature gradients in the ice shell	Curvilinear mountains/ Ridges T8, T30, T43	Folded mountains: Rocky Mountains, North America
Tectonic stresses of the ice shell (Mitri and Showman, 2008)	Transitions of the ice shell over a liquid subsurface ocean, from a conductive state to a convective state, causes tectonic stresses and movements that influence the surface	Model	Rocky Mountains, North America
Crustal compression/ upthrust blocks (Radebaugh et al., 2007—scenario 1)	Localized compression due to thickening of the crust linked with the cooling of Titan at areas where fault structures exist	Linear mountains T8, T3 (15°N, 45°W)	Eroded mountains: Acadian Mountains, USA Mountain-building due to Sevier/Laramide Orogeny
Crustal stresses/upwelling of material (Sotin et al., 2007)	Generation of extensive stresses that penetrate the icy shell and create pathways for the internal material	High-standing mountain ranges T20	Tectonic and magmatic aspects on geological terrains: Mid Atlantic Ridge, Atlantic Ocean Ahaggar Mountains, North-central Sahara Desert
Crustal extension (Tobie et al., 2006; Radebaugh et al., 2007—scenario 2)	Recent crustal thickening due to localized extension	Blocks and grabens T8	Mountains due to extension: Basin and Range Province (Harcuvar Mountains, Gila Mountains, Maricopa Mountains) (Radebaugh et al., 2007)
Blocks of impact ejecta (Radebaugh et al., 2007—scenario 3)	Deposition of ejecta blocks around craters in a radial manner	Blocks of mountains T3	Ejecta patterns: Meteor crater, Arizona
Dissection and erosion (Radebaugh et al., 2007—scenario 4; Lunine et al., 2008)	Erosion and incision of terrains that form regional uplifted structures	Mountainous region T13	Erosional geomorphological structures: Colorado Plateau, USA (Lorenz and Lunine, 2005; Radebaugh et al., 2007). It is dissected by a number of long north–south trending normal faults while deep entrenchment of streams and differential erosion have formed high standing crustal blocks

mountain ridges (in this paper we will refer to mountain ridges as ridges), chains of elevated (uplifted) ground that extend for some distance. The major mountains and ridges on Titan are listed along with their location and observational characteristics in Table 2a.

Table 2a points at two intriguing aspects: mountain-like edifices exist at almost all latitudes on Titan; however, they are concentrated in the equatorial region at latitudes between 30°S and 30°N (Lopes et al., 2010). Their height is significantly lower than that of the terrestrial mountains ranging from 100 to 2000 m (Barnes et al., 2007; Radebaugh et al., 2007; Soderblom et al., 2007b; Sotin et al., 2007; Mitri et al., 2010). This may be partly due to erosional processes, as it is suggested by the blanket-like

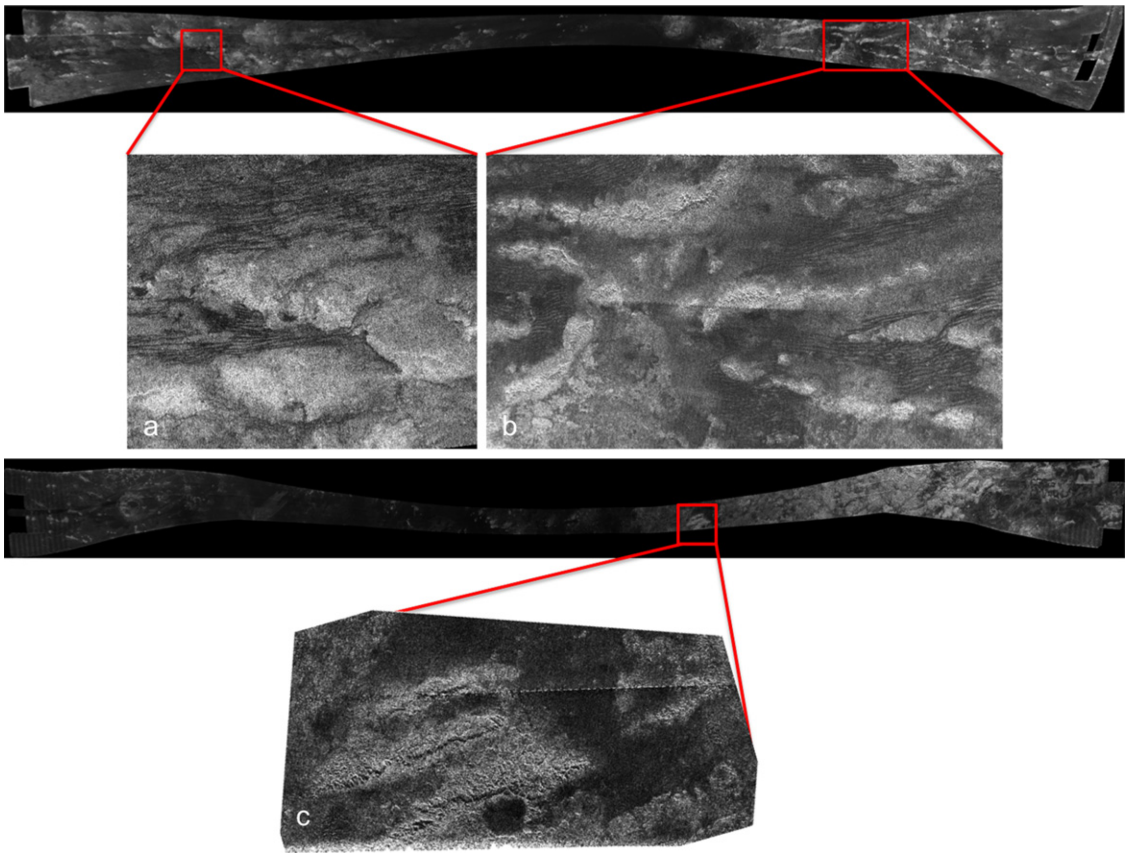

Fig. 2. Major mountainous regions on Titan. (a) Mountain extends for almost 240 km (NASA/JPL). (b) Long bright ridges with multiple mountain peaks were observed in T8 on October 28, 2005 (linear mountains extend from 13-5°S to 198-225°W) (e.g., Radebaugh et al., 2007; Lopes et al., 2010), and extend over 480 km (NASA/JPL). (c) Three radar bright parallel ridges (2°S, 127°W) within the mountainous area of Xanadu from T43 of May 12, 2008, the length of the image is almost 400 km (e.g,. Mitri et al., 2010) (NASA/JPL/Space Science Institute).

materials that surround these structures (Radebaugh et al., 2007). Alternative hypotheses include the construction of Titan's mountains with materials with properties preventing height growth (Radebaugh et al., 2008) and the effects of high temperature gradients on the ice shell which, according to the calculations of Mitri et al. (2010), result in mountains from 100 to 2700 m high. Similarly to Earth where terrain topography is defined by the interaction of tectonism and erosion (Montgomery and Brandon, 2002), we suggest here that there is a strong connection between slope morphology and erosional rates on Titan due to its extreme conditions of hydrocarbon rainfall and/or winds.

Fig. 2 presents three portions of the T8 and T43 RADAR swaths that provide the most reliable evidence so far for the existence of mountains and ridges on Titan.

3.2. Related mechanisms and terrestrial analogs

The mechanisms for mountain formation on Titan are summarized in Table 2b and include pure extension (Tobie et al., 2006; Sotin et al., 2007; Radebaugh et al., 2007—scenario 2), pure compression (Radebaugh et al., 2007—scenario 1; Mitri et al., 2010) and transitions between compressional and extensional stresses (Mitri and Showman, 2008). Extensional deformation is observed on all icy moons, but if orogenesis on Titan can be attributed to compressional forces this will render Titan unique.

Orogenesis in the terrestrial analog is predominantly a compressional event due to the coming together of the lithospheric plates floating on the plastic asthenosphere. The phenomenon is attributed to global convection initiated from the liquid external core and might not be random but with peaks related to the orbit of our Solar System around the galactic center. Terrestrial orogenesis results in forms and tectonic structures such as folds and thrust faults. Such compressional structures are represented by the mountain chains of the Rocky Mountains, the Andes and the Himalayas. Fig. 3 shows the Rocky Mountains, an almost 5000 km long mountain chain, extending from Canada to the western United States. This region was formed by subduction of the Pacific plate beneath the North American plate (Bird, 1998), when two tectonic plates of different densities sank one beneath the other inducing internal compressive forces within the plates. Mitri et al. (2010) argued for Titan that ice floes of altered densities, moving on a liquid layer, could reproduce structures and simulate phenomena similar to subduction. If this hypothesis is confirmed in the near future by geophysical measurements and modeling, and under the assumption that ice floes would react exactly like silicate plates to the stresses simulating subduction, something not impossible as shown in Table 1, then we may infer that what we see on Titan is an Earth-like mountainous terrain with peaks and extensive ranges.

Formation of mountains due to extension on Earth is represented by the classical example of the Basin and Range area and other examples listed in Table 2b. The geomorphology of Basin and Range (Hawkesworth et al., 1995) consists of separate and semi-parallel mountain ranges as seen in Fig. 4. The formation of the area is attributed to crustal extension and associated development of large faults along which mountains were elevated and valleys have submerged. These endogenous tectonic processes resulted in a geological terrain characterized by morphotectonic

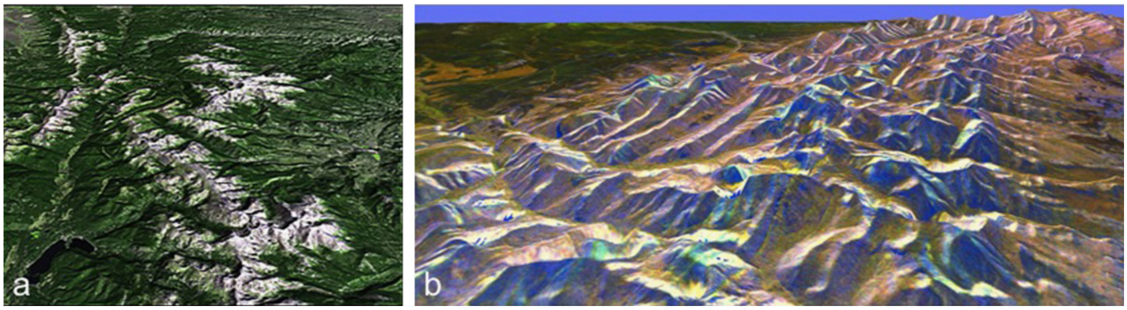

Fig. 3. Rocky Mountains, USA (a) in Landsat TM scene with DEM data (Credit: Federation American Scientists FAS). (b) 3-D perspective view by combining two spaceborne radar images (PIA01840 NASA/JPL).

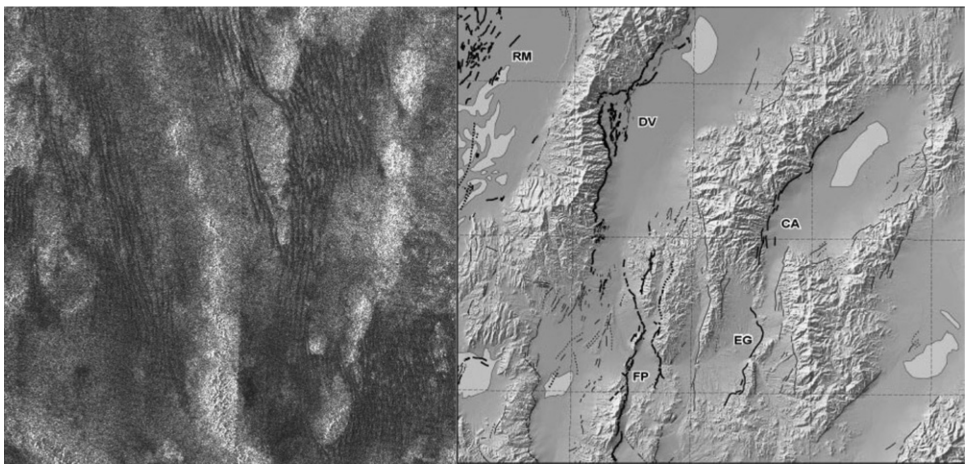

Fig. 4. (left) Fault-block mountains on Titan (portion of Fig. 2b) (PIA03566 NASA/JPL) formed possibly through crustal extension (Radebaugh et al., 2007). (right) Relief map of the Basin and Range province in west-central Nevada (USGS) displaying the parallel ranges and valleys created by crustal thinning and fracturing by extensive stresses.

features such as linear mountain ranges and valleys. Fluvial, aeolian and other exogenous processes subsequently modified these features.

However, convective stresses on silicate bodies tend to be larger and their rheological length scales are typically greater (Table 1). In Titan therefore it is essential to note that local/regional rather than global stress mechanisms are commonly suggested in the models for mountain building. Regional or local stress mechanisms invoked in these models include (a) convection, which depends in the ice shell thickness, (b) local gravity, and (c) ice viscosity, which depends on the temperature and mostly on the grain-size (Barr and Pappalardo, 2005; Collins et al., 2009). Indeed, on large icy satellites, layers of high- and low-pressure ice may convect separately (McKinnon, 1998).

Among the local stress mechanisms presented above, one can include lateral pressure gradients that may have as a consequence the lateral flow of floating ice shells on their low viscosity base. Rigid ice floes rupturing and colliding are reminiscent of plate tectonics albeit in a random fashion. This could lead to the creation of blocks of high-standing topography that would subsequently be subjected to erosional processes. Such elevated morphotectonic features on Titan, as mountains, ridges, hills and ranges, indicate a formation preference around the equatorial zone of the moon (Barnes et al., 2007; Radebaugh et al., 2007; Mitri et al., 2010).

4. Morphotectonics of faults and transverse processes

In this section, we describe Titan's morphotectonic features as a combination of a formation process and one or more superimposed "transverse processes" that occurred at the same time or subsequently, modifying the initial shape of the feature.

4.1. Tectonic control on Titan's linear features: Faults, fractures, canyons and drainage networks

In geology, a fault is a rupture that separates a rock unit into two parts, moving one relatively to another, in a microscale or a whole field in a macroscale. A variety of geological processes are associated with faults and therefore their analysis is very important. For instance, geologists consider the direct relation of earthquakes with faults, or the penetration of igneous rocks on Earth's crust along faults, or also the interaction of faults in the development of sedimentary basins. On the other hand, canyons are another type of crustal scars, formed on Earth by the accelerated erosion by rivers entrenched after tectonic activity and trying to reach base-line elevation (Schumm et al., 2002). On Titan the observed faults, fractures, canyons and ground lineaments are most likely the results of crustal movements due to tectonic and/or volcanic processes as well as structures associated with fluvial networks controlled by tectonism (Table 3). An investigation of canyon formation can augment our understanding of Titan's geology. A study in 2009 by Burr et al. (2009) provided evidence on the influence of subsurface tectonic activity on drainage patterns as observed by SAR data. Based on that, we can infer that these fluvial networks are morphotectonic features since there are indications that both tectonic and fluvial processes operate for their formation. Titan studies based on observations and mapping, have suggested the presence of fault formations. Table 3 summarizes their major observations by Cassini.

As expected from the study of other icy satellites, the majority of formation mechanisms suggest extensional style tectonism. In the areas where fluvial networks seem to be controlled by tectonic patterns, the surface material seems to have the proper elasticity to create linear fractures. At the Huygens landing site, as proposed by Soderblom et al. (2007b), the linear structures can function as the ideal path for the hydrocarbon liquids to escape towards the surface. Furthermore, the observed radial fault system around the possible calderas of Hotei Regio (Soderblom et al., 2009), argue in favor of cryovolcanism since the identification of radial faults around caldera formations also on Earth, are indicators of ground elevation due to volcanic activity.

Fig. 5 displays a complex feature on Titan (71°S, 240°W), which — even if it is not confirmed by radar data processing yet — it appears to be a canyon-like morphotectonic feature since it consists of a sinuous dark, rather narrow feature with tributary-like off shoots and it is limited on all sides by high albedo i.e. elevated terrains (e.g. Radebaugh et al., 2007). The morphology of the bright and the dark shape of this region resembles the terrestrial analog, which is the Grand Canyon in the United States. This terrestrial feature is adjacent to the Basin and Range Province that was mentioned earlier. The formation of the Grand Canyon on Earth is the end result of the extensional tectonics that formed the Basin and Range Province and of continuous rifting and erosion (Sears, 1990).

From Table 3 we can distinguish a tendency for preferential formation of these features between 10°S and 26°S, that is, within the zone where mountains are formed. Such observations imply crustal movements are more frequent within this zone than around the poles, including compressional and extensional stresses. However, Titan's limited-coverage observations (less than 50% of the surface), with instruments incapable of precisely unveiling its geology, make this aspect a subject for future exploration.

4.2. Cryovolcanism and association with morphotectonics

Plate tectonics and volcanism are strongly associated on Earth (McDonald, 1982) and this can also be the case on Titan in the presence of tectonic features overlying a liquid water ocean. These can function as leading 'pathways' for the ammonia–water cryomagma to reach the surface and for the release of methane. Liquid pockets with methane clathrates and with a high ammonia mass concentration in a water solution can dissociate in the ice shell and eventually exsolve on the surface and in the atmosphere (Tobie et al., 2006; Mitri et al., 2008). Hence, cryovolcanism can also act as the dynamic force that deforms tectonic features. Cryovolcanism is believed to represent an important geological process in the history of several icy Saturnian satellites and other icy satellites, such as Triton (Kargel, 1994; Fagents, 2003; Lopes et al., 2007a). Gaidos (2001) stated that tectonic extension could trigger cryovolcanic eruptions by reducing the minimum normal stress in an aquifer to a value

Table 3
Major fault, fracture and canyon formations on Titan.

Location	Characterization	Proposed mechanism	Flyby/Time	Instrument (reference)
15°S, 155°W	Conjugate-like faults	i. Large scale tectonic modification of bedrock material. ii. Fluvial sapping of bedrock that enlarges tectonic zones of weakness.	T0/July 2004 TA/October 2004 TB/December 2004	ISS (Porco et al., 2005)
10°S, 145°W 0°N, 180°W	Joints and/or faults	Control by a subsurface tectonic structural fabric due to orbital processes (diurnal tides, non-synchronous rotation: tensional stresses)	T13/April 2006 T44/May 2008	RADAR (Burr et al., 2009)
10°S, 192°W	Linear fault patterns/ canyon-like formations	Preexisting faults reactivated from cryovolcanism and filled with deposited material and formed canyon-like systems	Huygens DISR/ January 2005	DISR (Soderblom et al., 2007b)
15°S, 100°W	Lithospheric fault-blocks	Extensional crustal stresses	Model	(Radebaugh et al., 2011)
26°S, 78°W	Radial fault system	i. Hot plume uplift and crust elevation-fault formation due to extension stresses. ii. Large ancient impact crater.	T47/November 2008	VIMS (Soderblom et al., 2009)

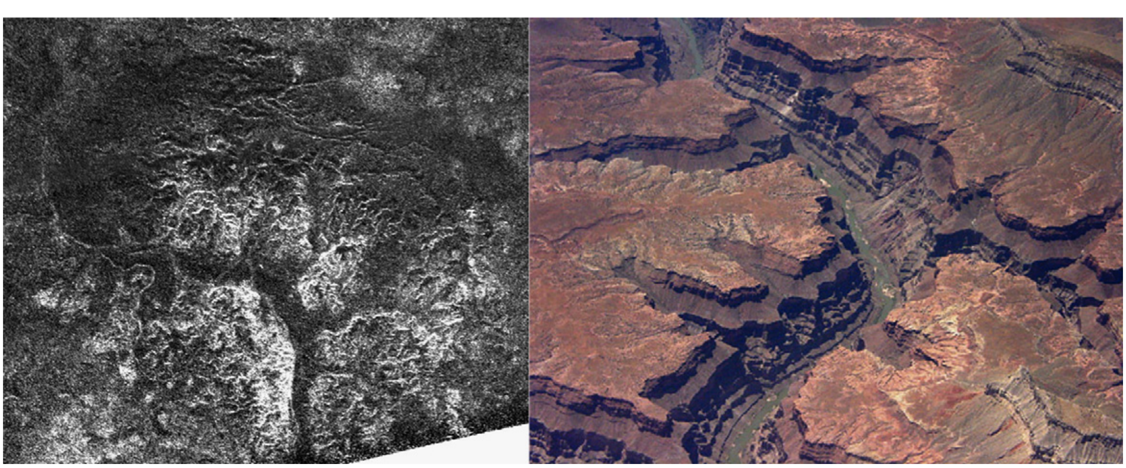

Fig. 5. (left) Radar image showing canyon-like systems on Titan (71°S, 240°W) (PIA12036 NASA/JPL). (right) Massive canyon formation on Earth, Grand Canyon, USA (USGS).

below the pore pressure. On Titan, a few topographic features are candidates for large volcanic edifices (Table 4).

The mechanism of cryovolcanism resembles terrestrial type volcanism, however the cryomagma differs from the terrestrial magma in composition, texture and temperature. Indeed, the cryomagma i.e. aqueous solutions of ammonia, methane, salts, etc., can be found at temperatures well below the freezing point of pure water and degassing replaces the traditional silicate volcanism. Cryovolcanic structures are openings, or ruptures, on a planetary surface or crust, allowing for various internal products like water, other chemical components, gases and cryoclastic ash to escape from the planet's interior (Fortes et al., 2007).

On Titan, internal heating due to radiogenic decay and tidal forces along with pressure fluctuations may trigger cryomagma eruptions. The cryolava deposition would then happen at temperatures much lower than the terrestrial ones (Davies et al., 2010). In general, the temperatures of most terrestrial magma types range from 1150 to 1470 K while a plausible range of the Titan cryomagma temperatures is between 177 and 239 K (Mitri et al., 2008). Besides predictions from theoretical modeling we also have surface features indicating possible cryovolcanism on Titan. Indeed, lobate and fan shaped features seen in radar images have been interpreted as cryovolcanic in origin, as for instance, the lobate circular structure of Ganesa Macula (50°N, 87°W) (Lopes et al., 2007a). The structure contains bright rounded features, interpreted as cryovolcanic flows, while the curved or linear shapes are lineaments that could be caused by elevation of the crust due to cryovolcanic activity (Lopes et al., 2007a). Other such features like Tui Regio, Hotei Regio and Sotra Facula are more extensively discussed hereafter. The identification of cryovolcanic structures is rendered difficult mainly for two reasons: firstly, the masking of cryovolcanic features by the interaction with major exogenetic processes, e.g. by fluvial or aeolian deposits (Lopes et al., 2010). As an example of the latter case, Lopes et al. (2010) report in the Winia Fluctus (45°N, 30°W) a dune field, which has partially covered a cryovolcanic edifice. Secondly, the Cassini instrumentation with relevance to cryovolcanic investigations (SAR and VIMS) is not adequate on terms of spatial and spectral resolution (Elachi et al., 2004; Brown et al., 2004).

However, we have currently some cryovolcanic candidate features. The most probable ones are three areas located close to the equator. Tui Regio, as well as Hotei Regio, lie within the bright region of Xanadu (100°N, 15°S), a large, reflective equatorial area. Tui Regio presents relatively high 5-μm reflectivity and its size is 1500 km long and 150 km wide (McCord et al., 2006). It is a massive flow-like terrain, which resembles flow fields in volcanic areas on Earth. In 2006, Barnes et al. (2006) noted that there are two bright and long areas within Tui Regio that are filled with a material darker than the surrounding terrain, forming a trench. These areas, located within the northwestern portion of Tui Regio's flow and including the trending dark linear marks (Fig. 6), may have a regional tectonic origin (Barnes et al., 2006). Additionally, the latter authors pointed out a linear dark feature with similar spectral behavior which surrounds the southern bright region, suggesting that it might also be formed by regional tectonics. A recent and very reliable candidate for cryovolcanic activity is Sotra Facula; an area 235 km in diameter including a 1 km high mountainous peak next to a 1.5 km wide crater-like feature from which lobate flows seem to originate (Kirk et al., 2010; Lopes et al., 2010). Indeed, this area displays varying topography with adjacent uplifts and pit features suggesting probable tectonic control. Hotei Regio is also another candidate for the presence of tectonic features within a probable cryovolcanic region (Wall et al., 2009). Hotei Regio extends over 700 km and includes a 1 km wide topographic depression, characterized as a basin filled with flow-like features, a ridge-like mountainous terrain that surrounds the basin, dendritic channels, two caldera-like structures, dark blue patches (as seen in VIMS infrared images; a color that suggests enrichment in water ice), and possible alluvial deposits (Soderblom et al., 2009). Hotei Arcus, a bright arc in the southern margin of Hotei Regio, may represent a heavily eroded crater (Barnes et al., 2005). This assumption reinforces the hypothesis of interplay among the different types of processes. Soderblom et al. (2009) correlated VIMS and RADAR images in order to unveil the geological history of this area. Their interpretation suggests that a wide range of processes occurred — or are still occurring — in this varied terrain, including tectonism. Furthermore, they suggested that impact-induced faults created

Table 4
Candidates of major cryovolcanic features on Titan and their association with volcanotectonic processes.

Location	Name	Description	Possible tectonic features
20°S, 130°W	Tui Regio	Flow-like region	Trending dark linear marks on VIMS data (Barnes et al., 2006)
26°S, 78°W	Hotei Regio	Volcanic-like terrain	Circular tectonic features (Soderblom et al., 2009)
15°S, 42°W	Sotra Facula	Volcanic-like terrain	Topographic elevation, mountain-like structures (unidentified) (Lopes et al., 2007b)

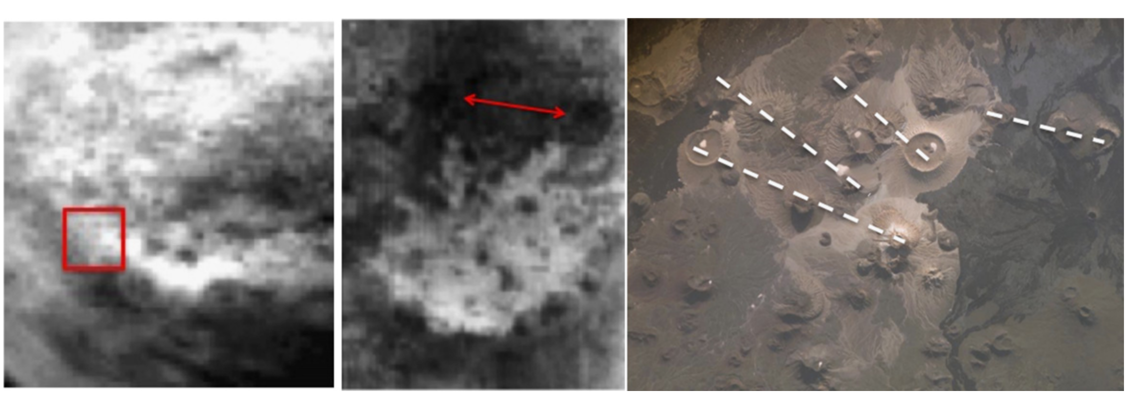

Fig. 6. Area on Tui Regio (left) with possible tectonic influence; two dark patches on Hotei Regio (middle) assumed to be volcanic caldera ridges (NASA/JPL/University of Arizona); Harrat Khaybar (right), massive volcanic terrain in western Saudi Arabia on Earth; the dashed lines indicate the linear trend of the volcanic vents suggesting tectonic control (NASA).

zones of weakness on which volcanism and tectonism occurred. The two dark morphotectonic features (Fig. 6) north of Hotei Regio, are interpreted as cryovolcanic calderas by Soderblom et al. (2009).

A terrestrial region that appears to resemble the evolution of Hotei Regio is Harrat Khaybar, located in north of Medina in Saudi Arabia. It is a 14,000 km^2 volcanic field that was formed by eruptions along a 100 km N–S linear vent system. The area contains multiple volcanic rock types, lava flows, and volcanic structures such as calderas and domes (e.g., Baker et al., 1973). The internal mechanism that most likely formed the terrain is a mantle plume causing diffused lithospheric extension (Chang and Van der Lee, 2011). The association of the volcanic centers that lie over a linear zone of weakness with the Red Sea transform fault i.e. conservative plate boundary—where plates slide past each other along transform faults, characterizes them as geological structures that are presently active (Rehman, 2010). This suggests that local movements of parts of the crust, probably affect areas of great extent like Hotei Regio and Harrat Khaybar, even if they are not located precisely in the center of the active area. In the case of Harrat Khaybar, the adjacent Red Sea fault continues to propagate: its rifting causes seafloor spreading, triggering the volcanic centers of the region (Camp et al., 1991). Such a process illustrates the relation between the terrestrial volcanic terrains and tectonism, a relation that seems possible for Titan's case as well.

Tui Regio, Hotei Regio and Sotra Facula are all located in the 15°S–30°S latitudinal zone which is close to the southern margin of Xanadu (Soderblom et al., 2009), implying that the region might be an extensive zone of crustal weakness. The existence of possible volcanic and tectonic features within a specific area seem to be manifestations of the most active region of Titan like the boundaries of tectonic plates on Earth. Although still under investigation in Titan's case, the definite identification and understanding of morphotectonic features in these regions is crucial in order to determine the presence and origin of zones of crustal weakness, which will in turn impose additional constraints on cryovolcanism on Titan. Indeed, on Earth, as well as on other planetary bodies, the interplay of volcanism and tectonism causes the formation of extensive and distinct geological terrains.

The moons of Jupiter, Europa and Ganymede, possibly also display similarities with the morphotectonics of Earth (volcanism–tectonism) and of the Saturnian icy satellites (cryovolcanism–tectonism). Fig. 7a shows Europa's ridges, junctions and domes, as seen by the Galileo instrument Solid State Imager (SSI), which are typical geological expressions on this moon. The ridges are most likely formed by cryovolcanic processes probably causing deposition of subsurface materials over surface units, accompanied by tectonic movements, that formed the lineaments (Figueredo and Greeley, 2004). This extensional volcano-tectonic mechanism is similar to the terrestrial mid-oceanic rifting (Prockter et al., 2002). On Ganymede, volcanic processes may have occurred in the past, but current evidence suggests the presence of tectonic processes (e.g., Head et al., 2002). The linked tectonic–cryovolcanic hypothesis suggests graben rupture (depressed block of ice bordered by parallel faults) due to lithospheric extension and cryovolcanic deposition caused by flooding of the internal material (cryovolcanic resurfacing) (e.g., Schenk and McKinnon, 1985; Murchie et al., 1986). Also fault blocks operating as zones of weakness can act as pathways for the bright material onto the surface while the crustal movements could produce the bright ridges (e.g., Head et al., 1997, 2002) (Fig. 7b).

Ganymede, and partially Europa, are the targets of a future mission proposal to the Jovian system, which will, among others, could explore the icy moons' interior heat potential, as well as, the surface motion and morphology, with improved and enhanced instrumentation in order to better understand their surface composition, internal structure, dynamics and the morphotectonics. Further investigation and comparison of the morphotectonic features of many of the icy satellites will shed light on the potential different internal mechanisms that operate in the Solar System.

5. Discussion

The morphotectonic structures presented here are related to the most elevated, as well as the most fractured features observed on Titan. Major mountainous regions are concentrated in mid-latitudes between 30°S and 30°N and probable cryovolcanic areas are located within the same zone (20°S–30°S). Linear features are displayed also within the same region (10°S–26°S). Fig. 8 represents a location map of the major morphotectonic features presented in this study.

We have argued here that all these features are related to surface stress fields. In analogy with terrestrial morphotectonic structures, the shape, size and morphology of Titan's observed mountains, ridges, hills and linear features such as faults, major fractures and canyons probably originate through some form

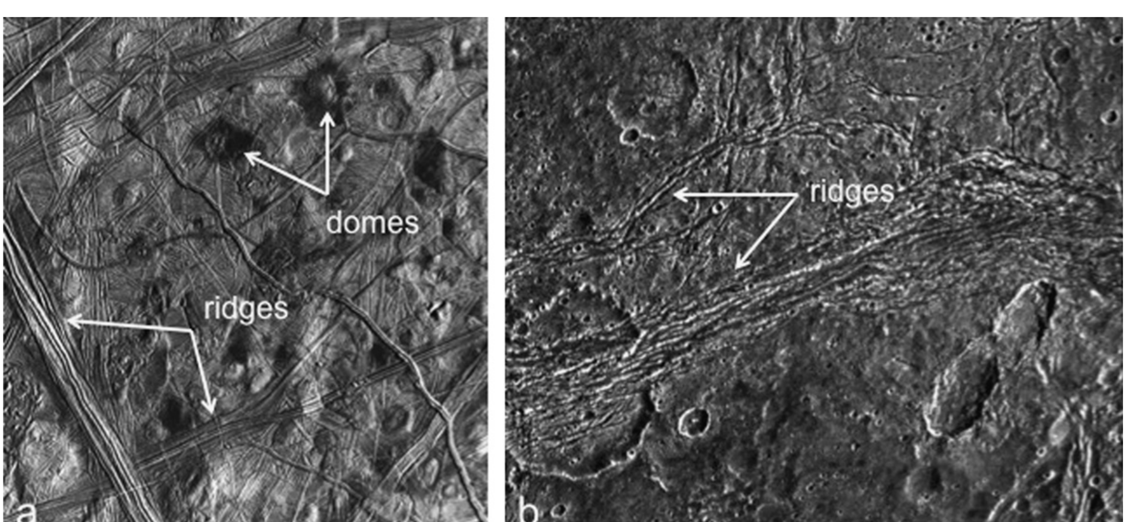

Fig. 7. (a) Europa's major geo-structures that may have formed due to volcanic and tectonic processes acting together (NASA/JPL-Caltech). (b) Ganymede's grooved and tectonic terrain (NASA/JPL/Brown University).

compressional and extensional tectonic activity. Titan's rigid crust and the probable existence of a subsurface ocean create an analogy with terrestrial, at least surficial, plate tectonics.

If in future missions a number of Titan's surface features are definitely identified as a result of compressional processes, as it has been proposed here, and despite the fact that large stresses are required to form compressional features (Pappalardo and Davis, 2007), then this will render Titan unique among the rest of icy satellites where extensional features are dominant (Jaumann et al., 2009) and will ratify the thesis of Mitri et al. (2010) that some of Titan's mountains represent folds and/or thrusts.

On the other hand, in regard to the extensional features on Titan as compared to their terrestrial analogs one may question if there are some essential differences in the development and propagation of fractures in the icy crusts vis-à-vis the silicate crusts.

However, before addressing these questions, one should initially examine which factors control tectonism on a planetary body; essential stress mechanisms that can be either global, regional and local. Global stress mechanisms include tides, non-synchronous planetary rotation, polar wander, despinning, orbital recession and radiogenic decay. One major stress mechanism is provided by *convection*. Another array of mechanisms is due to volume changes up to the large density contrast between ice-I and water and is applicable to icy satellites (Collins et al., 2009). Finally, ''impacts'' represent another local stress mechanism. To global, regional or local stresses, Solar System bodies and particularly their crusts may react in a brittle, ductile or more rarely elastic fashion, producing corresponding landforms. In this respect it is essential to compare and contrast the mechanical properties of icy and silicate crusts, as well as, the order in which stress mechanisms occur, to find correlations between the morphotectonic features on Earth and those on Titan (Radebaugh et al., 2007; Collins et al., 2009).

Thus, a question arises: is there some essential difference in the development and propagation of faults in the icy crust with respect to a silicate crust? As indicated in Table 1, ice and silicates mainly share a similar crystal structure, differ in melting temperature but when ice involves water and methane, an additional similarity with the silicates is found in the three physical states of the material (solid, liquid, gas).

Earth and Titan share all the global stress mechanisms and sources of internal heat such as radiogenic decay, heating by applied tidal forces and primordial heat.

However the analogy probably stops here since Earth has preserved a capital of its primordial heat. The outer core of the Earth with a thickness of 2890–5150 km has a temperature range of 4400–6100 °C, similar to the photosphere of the Sun. Furthermore the total heat flux from Earth's interior ranges from 0.08 to 0.4 W m^{-2} (Pollack et al., 1993; Davies and Davies, 2010). Due to the state (liquid) and composition (Fe–Ni) of Earth's outer core, *thermal runaways* occur at the core–mantle interface and resurface as hot spots, causing local mantle convection and induce plate motion which implies the breaking of continents (Africa) or supercontinents (Pangea).

Hot spot volcanism is found in the middle of lithospheric plates and on the margins of extensional plates. Volcanism also occurs in compressional plate margins followed by orogenesis (mountain building). Titan's primordial heat flux from the satellite's interior is of the order of 0.02–0.06 W m^{-2} and Mitri et al. (2010) proposed that it can similarly result in crustal fold processes and mountain building.

On Titan, stress mechanisms even if global, as in the case of tides, can have very local effects: for instance Saturnian tidal forces result in a concentration of morphotectonic structures mainly around Titan's equator. It is not a random event that all the three candidates for cryovolcanic areas are concentrated in Titan's equatorial zone. Actually, it will be surprising if future detailed observations refute the case for cryovolcanism on Titan in this area, given positive indications from current studies (Lopes et al., 2010; Solomonidou et al., in preparation). Morphotectonic features resulting from tidal-induced convection have different ages, as can be shown from superposition and cross-cutting relationships. Mountains are old (20–100 million years—Radebaugh et al., 2007) and probable cryovolcanic areas are younger (less than 10,000 years for Hotei Regio—Soderblom et al., 2009). This is to be expected since tidal-induced convection will cause ice elevations with subsequent breaking of the surface ice and formation of fractures (extension). The ice floats may collide

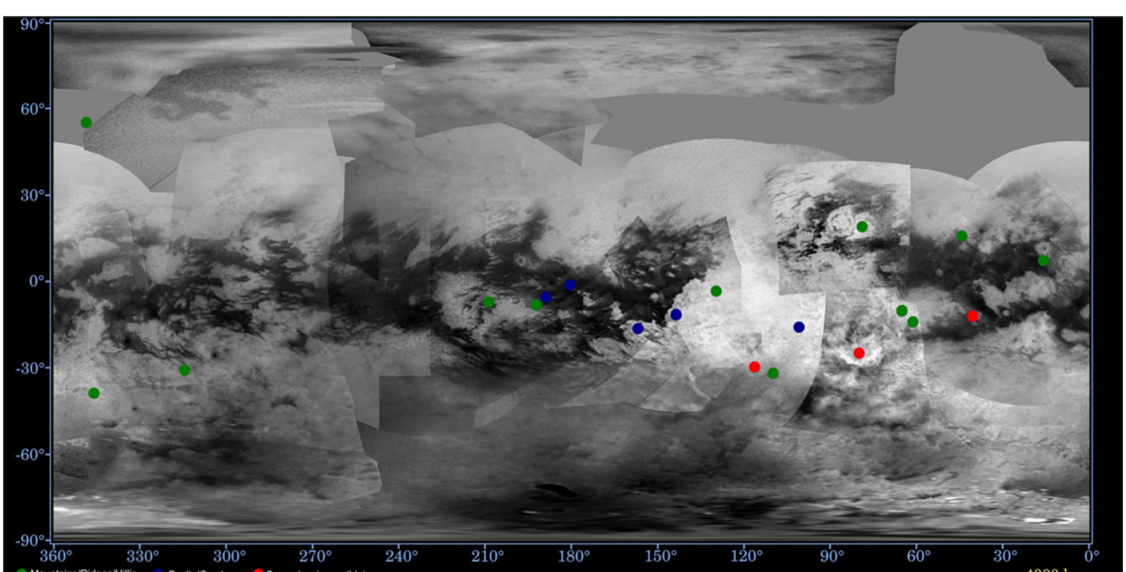

Fig. 8. Location map of the major morphotectonic features on Titan (background map credit: NASA/JPL). In green: mountains, ridges and hills; in blue: linear features, faults, fractures, canyons; in red: probable cryovolcanic regions. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

against each other (compression) forming mountain- or ridge-like features. Subsequent extension of the so-formed fractures will provide the pathways for cryovolcanism, which will be the younger event.

Primordial heat, as well as, heat produced by radiogenic decay and heat induced by tidal forces can be dissipated both by conduction and/or convection. It has been shown that transitions from a conductive to a convective state for an ice shell, overlying a pure liquid ocean (Tobie et al., 2005), can have major effects on surface morphotectonics (Mitri and Showman, 2008). The same authors have shown that thermal convection can occur under a range of conditions in the ice-I shells of Titan and two possible scenarios can follow. A thin ice with a low viscosity base (I) and a thick ice with a high viscosity base (II). Thus, Mitri and Showman (2008) proposed oscillations in the thermal state of the ice-I shell of the Saturnian satellites, which may cause repeated episodes of extensional and compressional tectonism. Similarly on Earth, a current widely accepted internal evolution model suggests that expansion and contraction processes are due to internal thermal runaway cycles and can be important in controlling geotectonic mechanisms (Rice and Fairbridge, 1975; Fowler, 1986; Baumgardner, 1994, 2003; Benn et al., 2006).

Thermal stresses are responsible for updoming, weakening and subsequent fracturing of the crust of a planetary body. On Earth, such a paradigm is provided by the continent of Africa where hot spot activity has resulted in updoming, fracturing and volcanism (East African Rift, Ahaggar Mountains, Table 2a). On Titan, zones of tectonic weakness have probably formed in an analogous manner i.e. as a consequence of thermal stresses and weakening of the crust with concomitant formation of open fissures, which act as pathways for the ejection of material from the interior (cryovolcanism) as it has already been proposed for Enceladus and Europa (Manga and Wang, 2007).

Localized compression and crustal thickening can also lead to mountain building on Titan. Linear mountains in T3 and T8 swath, seen in radar data, probably have formed this way (Fig. 3a and b; Table 2b). A terrestrial analog can be provided by the Laramide Orogeny. The Laramide event that affected Western-North America during Late Cretaceous and Early Paleogene time, involved compressive forces, conductive heating and crustal thickening that eventually led to mountain building (orogeny) (Dickinson and Snyder, 1978). A similar example is provided by the Acadian Orogeny during middle Paleozoic, which has affected the Eastern-North America as the result of collision of Baltica plate with the Laurentia.

The proposed formation mechanism for Titan's mountains, mainly the ones observed during T8, T30 and T43 flybys (Fig. 2c), concerns folding of the upper crust due to high heat flows from the interior and high temperature gradients in the past (Table 2b). A terrestrial analog, the Rocky Mountains chain in Western-North America (Fig. 3), was formed over an area where high values of mantle heat flow occur (Bird, 1998).

For the high-standing ranges of the T20 radar swath a formation mechanism has been proposed by Sotin et al. (2007) involving the generation of stresses by tectonic extension that penetrate the icy shell and create pathways for the internal material. This finds a terrestrial analog in the formation of the Mid Atlantic Ridge in Atlantic Ocean where divergent tectonic plates are associated with magma upwelling due to partial melting of the upper mantle in the interior.

Other surface features on Titan that seem to be the result of intense forces of tectonic extension are the probable blocks and grabens seen in T8 radar swath (Tobie et al., 2006; Radebaugh et al., 2007). On Earth, the Basin and Range Province in USA (Fig. 4; Table 2b) is such a large terrain subjected to forces of tectonic extension. As it can be seen from Fig. 4 a striking structural similarity exists in the morphology of the T8 mountain range on Titan and the Basin and Range Province on Earth. Alternative proposed mechanisms for *mountain formation* on Titan do not involve crustal movements: Radebaugh et al. (2007) argue that blocks of mountains viewed in T3 swath could have been formed by *impact ejecta*. Such deposits resemble those of Meteor Crater in Arizona, USA where blocks of ejecta deposited 1200 m away from the rim create hilly features (Ramsey, 2002). Furthermore, two terrestrial analogs presented and described in this study that seem to have a major resemblance with *canyon-like* and *cryovolcanic* features seen on Titan, are the Grand Canyon (Fig. 5) and the Harrat Khaybar (Fig. 6). Both terrestrial terrains consist of a number of geological features that have been subject to multiple processes. Titan's surface seems to be as complex as the Earth's and may be the end result of the action of multiple processes as well.

The fact that the mountains and ridges seem to be concentrated around Titan's equatorial band is a very strong argument for tidal forces shaping these morphotectonics features. However, Lopes et al. (2010) showed that mountains exist at other latitudes, a possible sign for a global source of stress as well. It is plausible that radiogenic decay would heat uniformly the entire satellite, similarly to what occurs on Earth (Dickin, 1995), and lead to morphotectonic structures evenly distributed all over the body's crust. We argue, nevertheless, that mountain ranges are more extensive at the equator of the satellite as a result of tidal forces since the very geometry of tides causes local stresses larger at the equator than anywhere else, inducing convection and therefore enhancing mountain formation. This mountain formation can be contrasted with that on Earth where mountains occur globally along collisional plate boundaries. Furthermore, as noted hereabove, radiogenic heat production on small bodies like Titan or even Mars has significantly decreased over a long period of time (e.g., Schubert et al., 1986; Grasset and Sotin, 1996; Grott and Breuer, 2008). It should be noted here that Saturn's tides are still heating up Enceladus' interior (Hurford et al., 2007).

The existence of tectonism on Titan can provide significant insights on the internal structure of the Saturnian satellite. In reference to the terrestrial paradigm, where rigid lithospheric plates '*float*' on a weaker asthenosphere, it could provide indirect evidence for the existence of a subsurface ocean on Titan. The importance of deciphering morphotectonic features on Titan that can be linked to tectonism has also consequences in elucidating the methane cycle on Titan in analogy with the link between terrestrial tectonics and the global terrestrial carbon cycle (Bolin, 1981; Ruddiman, 1997). More specifically, Titan's tectonic activity can probably be directly related to the replenishment of the atmosphere in methane (Sotin et al., 2005; Atreya et al., 2006; Tobie et al., 2006; Coustenis and Taylor, 2008; Lunine and Atreya, 2008; Mitri et al., 2008).

Finally, the origin of some morphological features can be attributed to exogenous processes such as *meteorite impacts* (Moore and Pappalardo, 2011), *aeolian processes* (Stofan et al., 2006; Radebaugh et al., 2009) and *fluvial erosion* (Porco et al., 2005; Tomasko et al., 2005), especially *monsoonal rainfall* causing flooding mainly in the equatorial region (Tokano, 2011).

The Cassini–Huygens mission has significantly improved our understanding of Titan and the coupling of its atmosphere and surface. Since 2004 and for another five years, Titan is investigated by Cassini's flybys. However, only limited surface coverage will be achieved at high spatial resolution. Therefore, the composition and evolution of its diverse surface features will still demand extensive future investigation.

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