Imaging of potentially active geological regions on Saturn's moons Titan and Enceladus, using Cassini-Huygens data: With emphasis on cryovolcanism*

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ABSTRACT: Since 2004, investigations, measurements and data analysis by the Cassini-Huygens mission showed that Titan, Saturn's largest satellite, presents complex, dynamic and Earth-like geology. Endogenous, as well, as exogenous dynamic processes, have created diverse terrains with extensive ridges and grooves, impact units, caldera-like structures, layered plains and liquid hydrocarbon lakes. Observations by the Cassini Visual Infrared Spectrometer instrument (VIMS) have indicated possible cryovolcanic terrains in the areas called Tui Regio (20°S, 130°W) and Hotei Regio (26°S, 78°W). In addition, Cassini's investigation over another icy moon of Saturn, Enceladus, identified its cryovolcanic activity and partially revealed its unique topography indicating several types of surface expressions. We present a comparative study of volcanic analogues from Earth and Enceladus that derive insight on the origin of some of these features. In this work, we focus on the analysis of VIMS data using the Principal Component Analysis technique in order to identify regions of altered chemical composition on Titan. The analysis of VIMS data suggests that possible cryovolcanic activity formed both the Tui Regio and the Hotei Regio.
Key-words: *Planetary geology, icy satellites, Titan, Enceladus, cryovolcanism, spectroscopy.*

ΠΕΡΙΛΗΨΗ: Μακροχρόνιες έρευνες, μετρήσεις και αναλύσεις δεδομένων από την αποστολή Cassini-Huygens από το 2004, έδειξαν ότι ο Τιτάνας, ο μεγαλύτερος δορυφόρος του Κρόνου, παρουσιάζει περίπλοκη, δυναμική και παρόμοια με τη Γη γεωλογία. Ενδογενείς, όσο και εξωγενείς δυναμικές διεργασίες, έχουν δημιουργήσει ποικίλα γεωλογικά πεδία με εκτεταμένες ράχες και αύλακες, κρατήρες πρόσκρουσης, δομές καλδέρας, πεδιάδες με στρωμάτωση καθώς και λίμνες υδρογονανθράκων. Παρατηρήσεις από το Cassini Visual Infrared Mapping Spectrometer (VIMS) όργανο, έχουν δείξει πιθανές κρυοηφαιστειακές εκτάσεις στις περιοχές Tui Regio (20 ° Ν, 130 ° Δ) και Hotei Regio (26°Ν, 78°Δ). Επιπλέον, η έρευνα του Cassini στον παγωμένο δορυφόρο του Κρόνου, Εγκέλαδο, επιβεβαίωσε την κρυοηφαιστειακή του δραστηριότητα και αποκάλυψε μερικώς τη μοναδική του τοπογραφία, παρουσιάζοντας ποικίλους τύπους επιφανειακών εμφανίσεων. Παρουσιάζουμε μια συγκριτική μελέτη, δείχνοντας ηφαιστειακά ανάλογα της Γης και του Εγκέλαδου, που παρέχουν πληροφορίες για τη δημιουργία κάποιων σχηματισμών. Σε αυτή τη μελέτη, επικεντρωνόμαστε στην ανάλυση δεδομένων VIMS, χρησιμοποιώντας τη μέθοδο Ανάλυσης Κύριων Συνιστωσών σε περιοχές με διαφορετική χημική σύσταση. Οι αναλύσεις των VIMS δεδομένων των προαναφερθέντων εκτάσεων δείχνουν ότι τόσο η περιοχή Tui Regio όσο και η περιοχή Hotei Regio πιθανά σχηματίστηκαν από κρυοηφαιστειακή δραστηριότητα.
Λέξεις-κλειδιά: *Πλανητική Γεωλογία, Παγωμένοι δορυφόροι, Τιτάνας, Εγκέλαδος, κρυοηφαιστειότητα, φασματοσκοπία.*

INTRODUCTION

Icy moons are small celestial bodies whose surfaces are partially, if not principally, covered by ice, mostly water ice (Johnson, 2004). The most remarkable icy moons around the giant planets are Jupiter's Ganymede, Neptune's Triton, Uranus's Miranda and Saturn's Titan and Enceladus in a variety of sizes, composition and temperatures. It was thought that due to the abundance of water ice, the large distance from the Sun, the absence of internal energy sources and of an atmosphere in most cases, the geology of these bodies would be simple, or rather simpler than the geology of Earth; however, subsequent images have shown complex surfaces with several notable morphological formations. Furthermore, the composition, as well as, the structure of the surfaces of the icy moons depends on geological and geophysical factors (Johnson, 2004).

Titan is the second largest moon in the Solar system after Jupiter's Ganymede, with a radius of 2,575 km (Lindal *et al.,* 1983) and spherical geometry. Titan has a unique atmosphere, in that it is dense and consists mainly of N_2 (98.4%), as on Earth. CH_4 (1.4%), H_2 (0.1%) and traces of argon, ethane, acetylene, propane and more complex hydrocarbons and nitriles, as well as condensates and organic aerosols (Coustenis & Taylor, 2008) constitute the rest of the atmosphere. The identification of such atmospheric compo-

* Απεικόνιση των πιθανών ενεργών γεωλογικών περιοχών στους δορυφόρους του Κρόνου Τιτάνα και Εγκέλαδο: Μελέτη για την κρυοηφαιστειότητα με τη χρήση υπέρυθρων φασματικών δεδομένων

nents endorse theories suggesting that even though Titan is far out of the habitable zone, it is one of the most likely worlds in our solar system of astrobiological interest (RAULIN, 2008). Except for the new atmospheric discoveries such as the organic chemistry in the ionosphere, new components in the neutral atmosphere and the properties of the troposphere, Cassini-Huygens' most surprising discovery was Titan's complex and Earth-like geology (COUSTENIS & TAYLOR, 2008). As far as the surface is concerned, one of the moon's exceptional characteristics is the existence of surface liquid bodies that resemble terrestrial lakes (STOFAN *et al.*, 2007). Other surface formations, were captured both by the Cassini orbiter's *remote sensing* instrumentation such as the Synthetic Aperture Radar (SAR) (ELACHI *et al.*, 2005); the Visual and Infrared Mapping Spectrometer (VIMS) (BROWN *et al.*, 2004) and the Imaging Science System (ISS) (PORCO *et al.*, 2004; MCCORD *et al.*, 2006), as well as by the Huygens probe's *in situ* instruments i.e.: the Surface Science Package (SSP) (ZARNECKI *et al.*, 2005), the Descent Imager and Spectral Radiometer (DISR) (TOMASKO *et al.*, 2005) and the Gas Chromatograph Mass Spectrometer (GCMS) (FULCHIGNONI *et al.*, 2005). The surface discoveries include extensive mountains, ridges, dendritic networks, dunes, lakes, channels, canyons and riverbeds. Of even higher importance is the possible existence of active zones on the satellite due to past or recent cryovolcanic and tectonic activity (e.g. SODERBLOM *et al.*, 2007; LORENZ *et al.*, 2008; SOLOMONIDOU *et al.*, 2010). Caldera-like edifices characterized by radial faults, features resembling lava flows and other possible volcanic structures and deposits, within large areas of volcanic-like terrains, in addition to spectral data indications, suggest that Titan is a world that once suffered cryovolcanic activity which could possibly still be active. The suggestion of an active cryovolcanic interior that supplies the atmosphere with methane is compatible with the current level of methane in Titan's atmosphere. According to calculations, the lifetime of atmospheric methane is limited to 10-100 Myrs (WILSON *et al.*, 2004). If we assume that methane in the atmosphere should be replenished, then Titan needs a reservoir that would supply the atmosphere with enough methane to maintain the atmospheric abundance. The requirement of sufficient supplies of methane in combination with the volcanic-like expressions did trigger the theory of active cryovolcanism on Titan (TOBIE *et al.,* 2006).

Other than Titan, the Cassini mission unveiled another unique world among Saturn's icy moons. Enceladus is a significantly smaller satellite than Titan (500 km in diameter), it presents however, extremely interesting surface features including cratered as well as smooth terrains, extensive linear cracks, scarps, troughs, belts of grooves in addition to the spectacular phenomenon of volcanic geysers that Cassini instrumentation captured in 2005 in the south pole (PORCO *et al.*, 2006). High-resolution data from Cassini magnetometer (MAG) (DOUGHERTY *et al.,* 2006), ISS (PORCO *et al.,* 2006) and the Ultraviolet Imaging Spectrograph (UVIS) (HANSEN *et al.,* 2006), reported cryovolcanic activity in the form of jets in the southern Polar region, at the geological surface expressions called "Tiger stripes''. The accumulation of multiple jets resulted in the formation of a massive fountain that reached over 435 km in height (PORCO *et al.,* 2006).

Our work provides: i/ an overview of the geology of Titan and Enceladus, ii/ terrestrial analogues and iii/ the results of our data analysis regarding Titan's potentially active regions. This study implicates the presence of cryovolcanism on Titan's surface.

GEOLOGY AND CRYOVOLCANISM ON TITAN & ENCELADUS

Cryovolcanism

Cryovolcanism is considered to be one of the principal geological processes that have shaped several of the icy moons' surfaces. This activity can be described as ice-rich volcanism, while the cryovolcanic ejecta are referred to as cryomagma. The cryomagma appears in the form of icy cold liquid and, in some cases, as partially crystallised slurry (KARGEL, 1994). The possibility of volcanic resurfacing on icy moons was first noted by LEWIS (1971, 1972) and subsequently addressed by CONSOLMAGNO & LEWIS (1978), but it was not until after the Voyager flybys of Jupiter and Saturn that evidence for past and present tectonic and volcanic activity on moons such as Europa, Ganymede, and Enceladus was brought to light. In our Solar system the only observed recent eruptions are limited to Earth and three other locations: 1) Io, moon of Jupiter; 2) Triton, moon of Neptune; and, 3) Enceladus, moon of Saturn. Titan is also major candidate for past and/or present cryovolcanic activity awaiting for a definitive evidence.

Subsequent to the Cassini-Huygens findings, the term 'cryovolcanism' has been associated with Titan more than any other Saturnian moon (SODERBLOM *et al.*, 2009). Even though, for the case of Enceladus the cryovolcanic origin of the plume is now confirmed (PORCO *et al.*, 2006), the cryovolcanic activity on Titan presents a controversial scientific issue within the scientific community. However, some facts are in favor of such processes like the theory of cryomagma being relevant to the formation of prebiotic compounds (e.g. FORTES, 2000).

The composition of the material called cryomagma on Titan's surface is still unknown, due to the lack of *in situ* measurements and in depth investigations, which may reveal its properties. Cryovolcanic features on Titan's surface are believed to be a significant source of the methane present in the atmosphere (LORENZ & MITTON, 2008). Considering this, a model has been suggested regarding the evolution of Titan, indicating that the methane supply may be trapped in a methane-rich ice and episodically released by cryovolcanic phenomena (TOBIE *et al.*, 2006). However, the definite answer of the composition of Titan's cryomagma is still a subject of research.

According to TOBIE *et al.* (2006) the methane could have originated through three distinct episodes: the first following the silicate core formation, accretion and differentiation period; a second episode approximately 2000 million years ago when convection commenced in the silicate core; and finally, a geologically recent period, circa 500 million years ago, where subsequent cooling and crystallization of the outer layer occurred. FORTES *et al.* (2007) suggested that ammonium sulphate is the possible origin of cryovolcanism. Titan's interior is broadly described by these authors, from the core to the crust, in distinct layers: a serpentinite core, a high-pressure ice VI mantle, where ice VI has a differentiated crystalline structure ordering and density than typical water ice, a liquid layer of aqueous ammonium sulphate and an externally heterogeneous shell of methane clathrate with low-pressure ice Ih (similarly as ice VI) and solid ammonium sulphate (FORTES *et al.*, 2007).

The geological map below (Fig. 1) has been derived from albedo and texture variations and indicates that the circular feature shows signs of several series of flows, as shown by the black lines (SOTIN *et al.*, 2005). The black circle indicates a caldera, similar to vents that appear above reservoirs of molten material associated with volcanoes on Earth. The colours of the map are representative of the brightness of the features where yellow-green to light brown are the bright patches; blue are the dark patches, red the mottled material and finally the yellow area marks the location of the volcano (SOTIN *et al.*, 2005).

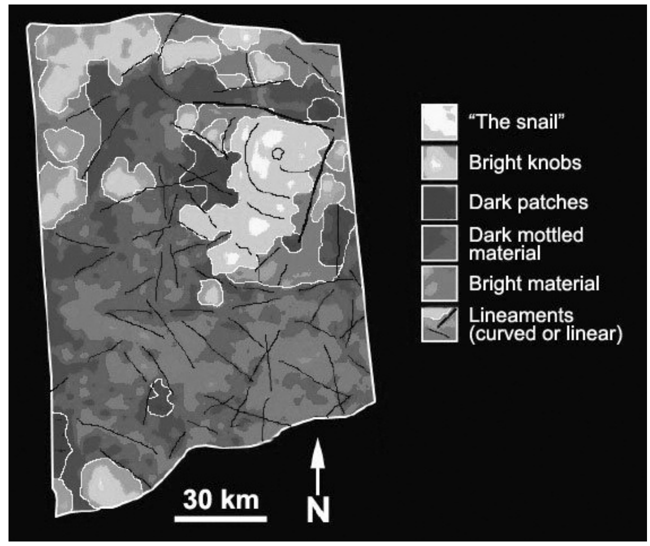


Fig. 1. Geological map of Titan possible volcano (SOTIN *et al.*, 2005).

Enceladus

Cassini's observations on Enceladus did reveal distinct geological features. The surface of Enceladus is covered by smooth and cratered terrains, ridges, grooves, escarpments and extensive linear fractures (JOHNSON, 2004). The most interesting and youthful terrain seen on this moon called "Tiger Stripes" and presents a very complex structure and evolution. The Tiger Stripes (Fig. 2) are tectonic structures consisting of four sub-parallel, linear depressions located in the south polar region (PORCO *et al.,* 2006). In 2005 Cassini's instrumentation and especially the ISS experiment provided evidence of active cryovolcanism (Fig. 3), emanating from a series of jets located within the Tiger Stripes (PORCO *et al.,* 2006).

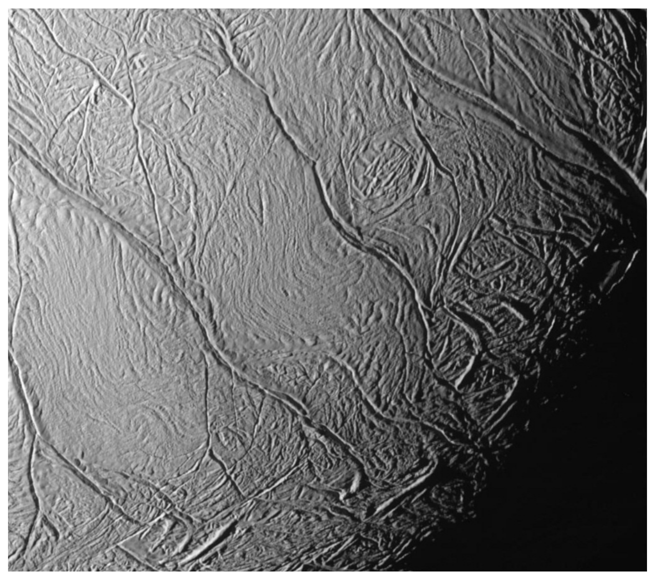


Fig. 2. Tiger Stripes on Enceladus (NASA).

The jets of water ice from the fractures of Tiger Stripes produce a plume of gas and particles like NH_3, Na, K salts (WAITE *et al.,* 2009). These tectonic fractures, discharge material by endogenic dynamic and most probably hydrothermal activity. The source of the jets is a controversial issue as extensive internal stratification as well as dynamic modeling, is required for the source to be identified. The recent discovery of salts in Saturn's E-ring composition, which is fed from Enceladus' plumes (POSTBERG *et al.,* 2009), suggests that the source of jets is possibly a "chamber" of liquid water that lies underneath the ice shell (TOBIE *et al.,* 2008). Alternatively, the material could derive from originally warm ice that is heated and explodes by the dissociation of clathrate hy-

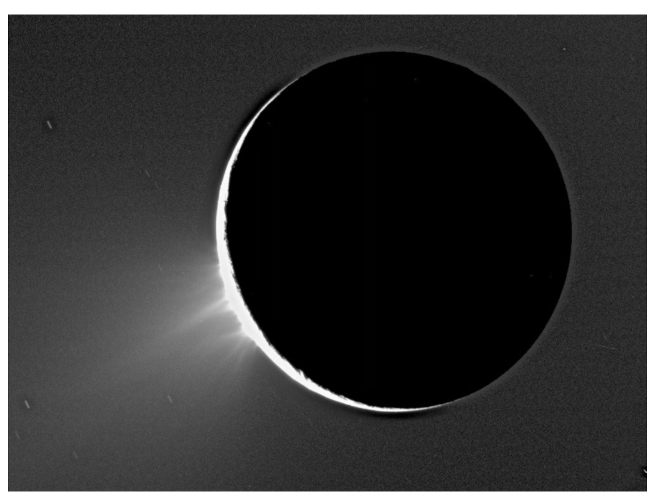


Fig. 3. Enceladus' Plume from Cassini/ISS (PORCO *et al.*, 2006).

drates (Kieffer *et al.,* 2006). The clathrate hydrates are crystalline water-based ices where the host molecule is water and the trapped-guest molecule is typically a gas. The VIMS instrument detected simple organic compounds in the Tiger Stripes. Such chemical composition which consists of liquid water, ammonia, carbon dioxide, Na and K salts, benzene and other hydrocarbons (Waite *et al.,* 2009), has not been found in any other region on Enceladus (Brown *et al.,* 2006). The presence of liquid water might also make it possible for Enceladus to support life (Lammer *et al*., 2009).

Recent data from Cassini reported pockets of heat that appear along a fracture named Baghdad Sulcus (Fig. 15), one of the Tiger Stripes that erupt with jets of water vapor and ice particles (Hurford *et al*, 2009). The temperature along Baghdad Sulcus exceeds 180 Kelvin (Waite *et al.,* 2009). As is the case for Titan's Hotei Regio, Tiger Stripes on Enceladus and in particular Baghdad Sulcus represent tectonic zones of weakness from which the internal materials find their way to the surface. The idea of a subsurface sea becomes all the more compelling since Enceladus' south polar region (Tiger Stripes area) is actually a half-kilometer deep basin distinguishing from the surrounding expressions (Collins & Goodman, 2007). Such figure, like the deep basin in Tiger stripes, resembles Titan's Hotei Regio which is a basin lying one kilometer deeper than the surrounding area (Soderblom *et al.,* 2009). This basin could be the surface expression of a subsurface sea (Collins & Goodman, 2007).

Titan

Titan's geology has been extensively studied using Cassini image data. In this research, we investigate and process data acquired from VIMS in order to identify areas of cryovolcanic deposition.

The most intriguing problem in regard to the decoding of Titan's surface is the atmospheric veil that covers the surface. This veil prevents any direct observation from Earth and space-based telescopes. However, VIMS on board Cassini has the ability to acquire partial surface images, taken within the so-called "methane windows" centered at 0.93, 1.08, 1.27, 1.59, 2.03, 2.8 and 5 µm, where the methane atmospheric absorption is weak (McCord *et al*., 2008; Coustenis

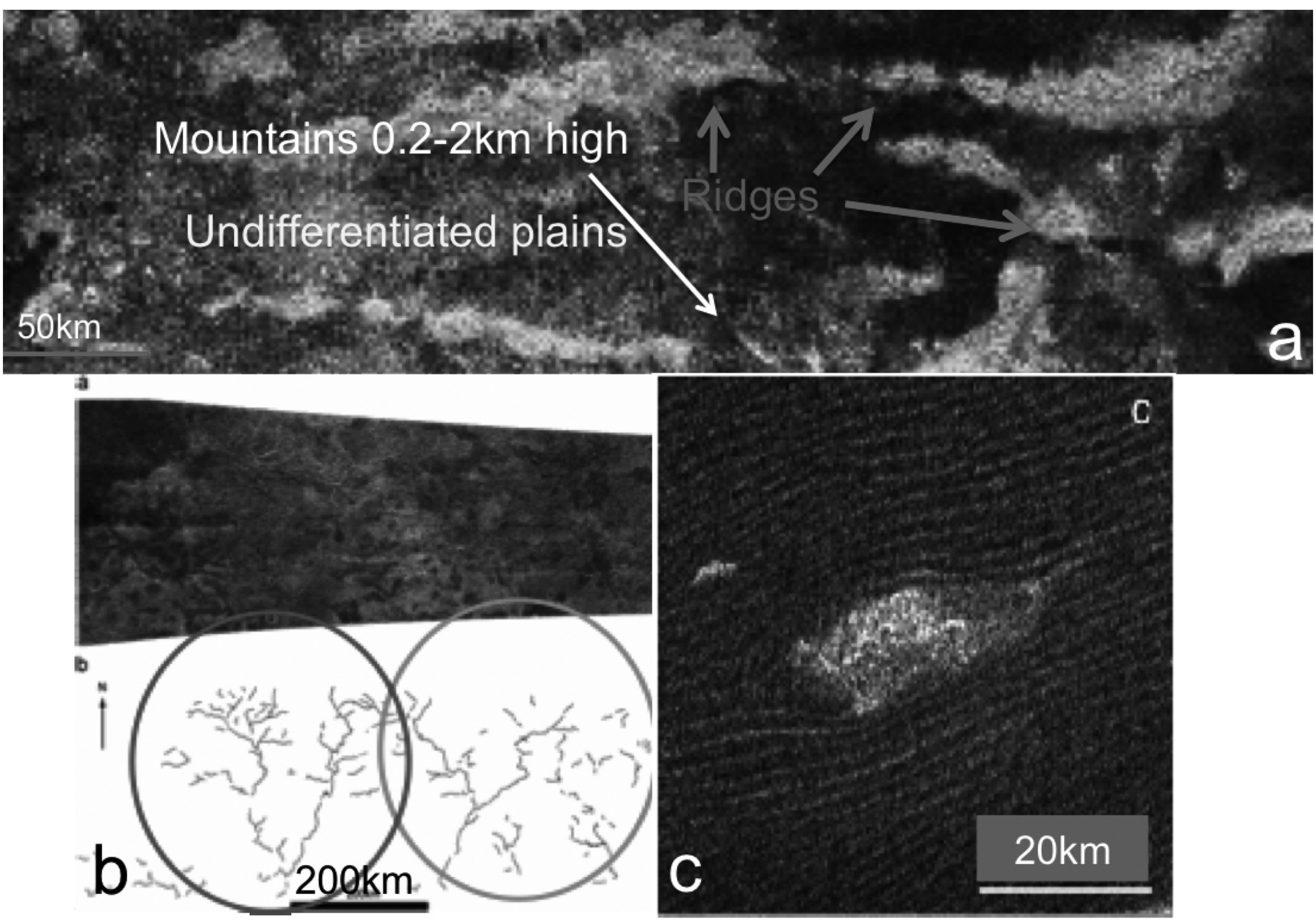


Fig. 4. (a) Ridges and mountains on Titan's surface. The radar bright features are part of the undifferentiated plains (Lopes *et al*., 2010). The proposed processes that formed this terrain have possibly tectonic origin. (b) Dendritic networks as seen with SAR and morphological map (Lorenz *et al*., 2008). The system is located at the western end of Xanadu close to our area of interest, Tui Regio. (c) Sand dunes around the Belet sand sea on Titan. The dunes are formed due to Aeolian processes. The bright figures are topographic obstacles that advance the formation of the dunes (Radebaugh *et al*., 2009).

et al., 2005). In general, Titan's surface appears to have smooth and rough areas of various altitudes which include extensive mountains and ridges (Fig. 4a) (Lopes *et al.*, 2010), longitudinal dunes (Fig. 4c) (Radebaugh *et al.*, 2009), dendritic networks (Fig. 4b) (Lorenz *et al.*, 2008), liquid lakes (Fig. 6) (Stofan *et al.*, 2007) and impact craters that are intermittently filled by atmospheric precipitations (Elachi *et al.*, 2005). Radebaugh *et al.* (2008) suggests that mountains on Titan range from 200 m to 2000 m in height (Fig. 4a). Erosional processes that operate at the area where mountains lie, are probably the reason of the significant short height of the mountains. However, there is also the assumption that the mountains are built by material with properties that prevent the altitudinal growth (Radebaugh *et al.*, 2008). Radebaugh *et al.* (2007) mentioned that the notably SAR bright features on Titan's surface most probably correspond to mountains and tectonic ridges which represent mountain chains (Fig. 4a). In particular, the tectonic ridges could have suffered atmospheric precipitation (i.e. hydrocarbon rain) acquiring a rough and fractured surface (Soderblom *et al.*, 2007). Rivers are common on Titan, while in some cases a few craters are traversed by them (Wood *et al.*, 2009). The observation of river systems with dendritic patterns (Fig. 4b) (Lorenz *et al.*, 2008), in addition to the observation of storm clouds (Porco *et al.*, 2005), suggest that rainfall may be a continuing erosional force erasing impact craters. Other surficial structures observed on Titan are impact craters. Of particular importance is the small number of impact craters which has been observed by the Cassini/Radar which suggests that the surface of Titan is relatively young (i.e. Wall *et al.*, 2009).

The consideration of Titan's young surficial age indicates the possible existence of active regions among the satellite. Contrary to impact craters, surficial structures that are seen commonly on Titan are the dunes (Fig. 4c). The dunes are generally smooth surfaces that diverge around topographic obstacles resembling terrestrial dunes (Radebaugh *et al.*, 2009). Moderately variable winds that either follow one mean direction or alternate between two different directions have formed the observed longitudinal dunes (Lorenz *et al.*, 2006).

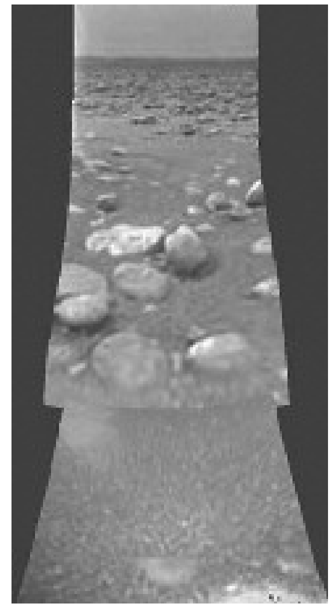


Fig. 5. Titan's surface from the Huygens probe (Tomasko *et al.*, 2005).

Our knowledge regarding Titan's surface deposits is limited to the data acquired from Huygens' landing site. The Huygens captured image was that of a dark plain covered in pebbles mainly composed of water ice (Fig. 5) (Tomasko *et al.*, 2005). The size of pebbles is estimated to be roughly 10-15 cm. There is evidence of erosion at the base of the icy rocks, indicating possible fluvial activity (Tomasko *et al.*, 2005). The surface is darker than originally expected, consisting of a mixture of water and hydrocarbon ice. It is believed that

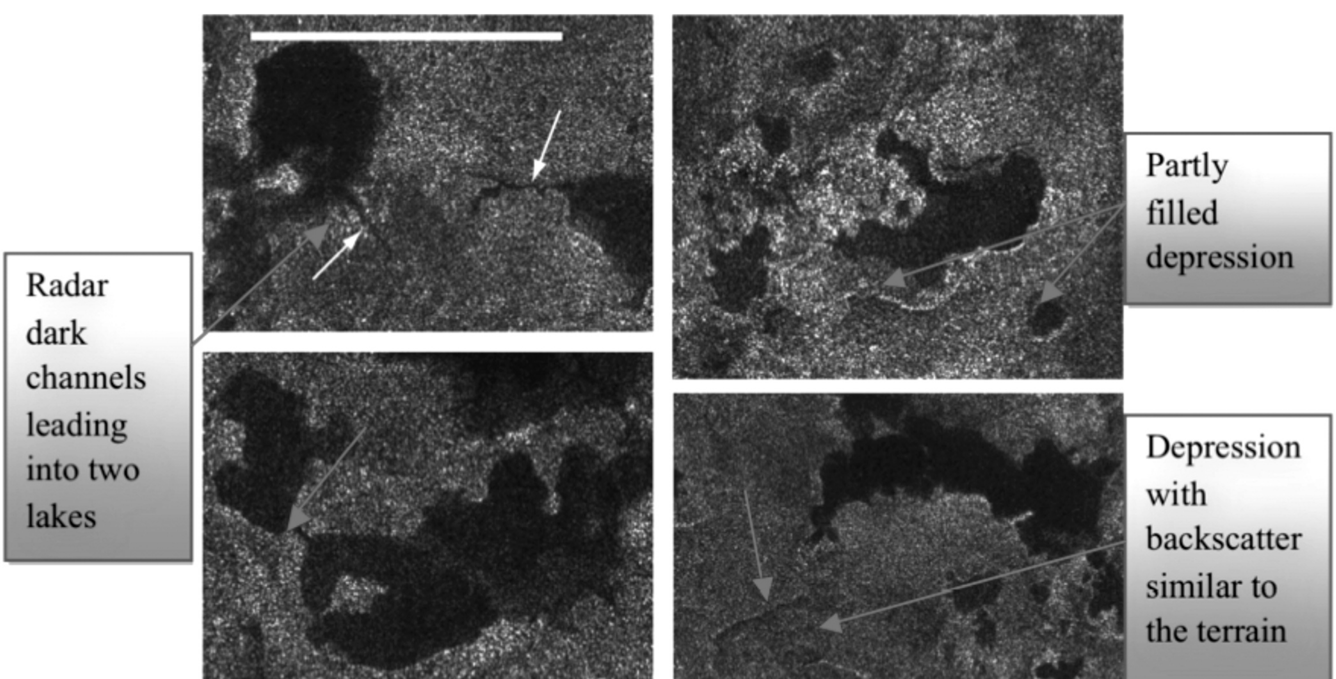


Fig. 6. Lakes on Titan's surface as recorded during the Cassini's T16 flyby on July 22, 2006 (Stofan *et al.*, 2007a).

the visible ground "powder'' in the image is possibly precipitation from the hydrocarbon haze above (TOMASKO *et al.*, 2005).

One of the moon's exceptional characteristics is the existence of large liquid bodies described as lakes of surface liquids (Fig. 6) (STOFAN *et al.*, 2007). These features resemble terrestrial lakes consitute a unique characteristic displayed by the icy moons. Based on data provided by the Cassini/Radar, the presence of hydrocarbon lakes on Titan's surface is now well established (Fig. 6) (LOPES *et al.*, 2007a).

Candidates of cryovolcanic areas on Titan

Our study involves two major areas on Titan that are the most significant, as well as, interesting cryovolcanic candidates. These areas are Tui Regio and Hotei Regio (Fig. 7) lying within the bright region of Xanadu (100°N, 15°S). Tui Regio is centered at 130°W, 20°S and presents relatively high 5 μm reflectivity. Its size is 1,500 km long and 150 km wide. This bright area has been identified as a surface feature and not as the image capture of fog, due to the area's spectral behavior at 2.7 mm (MCCORD *et al.*, 2006). Tui Regio is a massive flow-like terrain, which resembles flow field volcanic areas on Earth. Another area whose spectrum matches that of Tui Regio is Xanadu's Hotei Regio. Hotei Regio is centered at 78°W, 26°S and comprises a 700 km wide field that is probably volcanic in origin. VIMS images confirm the interpretation that the area is a low basin surrounded by higher terrains with possible calderas, fault structures and extensive cryovolcanic flows (SODERBLOM *et al.*, 2009).

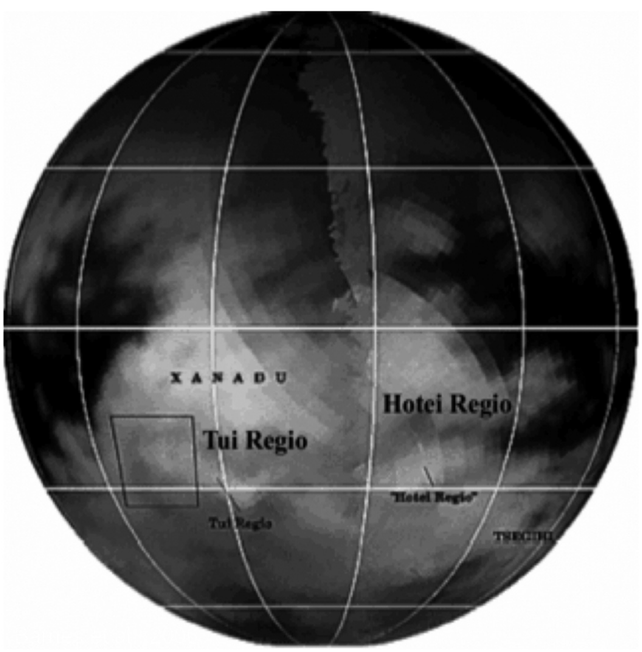
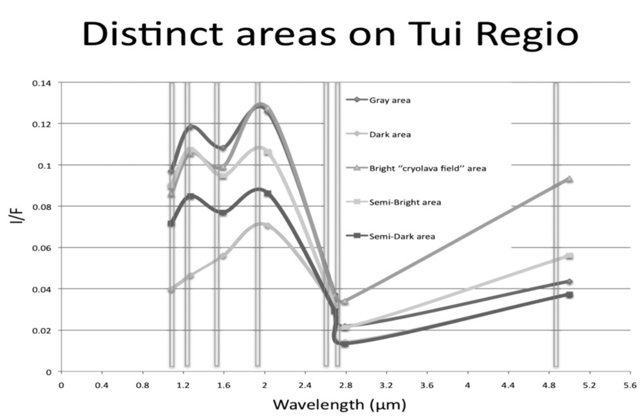


Fig. 7. The location of Tui Regio and Hotei Regio on Titan's globe (BARNES *et al.*, 2006).



Plot 1. Spectral plot of five distinct areas at the seven atmospheric spectral windows.

Method and Data analysis

Both Tui Regio and Hotei Regio are suggested to be geologically young due to the fact that both present anomalously bright and spectrally distinct areas that have not changed from seasonal precipitation (BARNES *et al.*, 2006).

In order to investigate geologically the regions of interest, it is essential to study their chemical composition that lead to the aforementioned brightness as well as their morphology in order to derive the geological factors that led to their formation.

We have processed spectral images acquired from VIMS, for both areas in the seven narrow spectral windows centered at 0.93, 1.08, 1.27, 1.59, 2.03, 2.8 and 5 μm for which absorption by atmospheric methane is minimal.

The main goal is to identify the composition as well as the alterations of the components that compose the possible cryovolcanic structures. We have used the principal components (PCs) of the Principal Component Analysis (PCA) method. The PCA method involves a mathematical procedure that transforms a number of possibly correlated variables into a smaller number of uncorrelated ones called principal components (JOLLIFFE, 2002). The PCA is well adapted to our study, as our primary concern is to determine the minimum number of factors that will account for the maximum variance of the data we use in this particular multivariate analysis. The main goal of PCA is to reduce the dimensionality of a data set consisting of a large number of interrelated variables, while retaining as much as possible of the variation present in the data set. This is achieved by transforming, the principal components (PCs) into a new set of variables, which are uncorrelated, and which are ordered so that the first few retain most of the variation present in all of the original variables (JOLLIFFE, 2002).

PCA images for both Tui Regio and Hotei Regio allowed us to isolate areas with distinct and diverse false coloring, which imply areas of distinct and diverse spectral and chemical composition (Fig, 9; 11). Such chemical diversity suggests that endogenic and/or exogenic geodynamic processes have formed these regions.

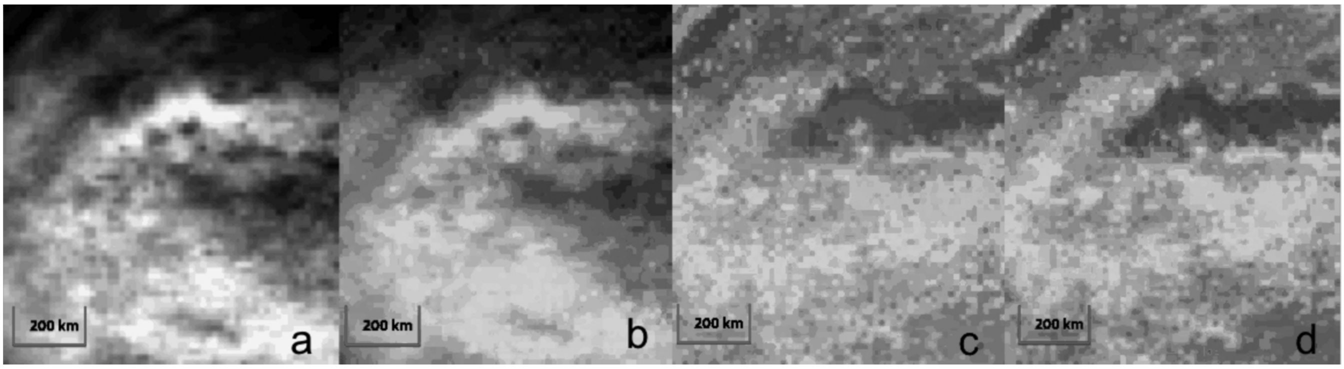


Fig. 8. Reprojection of Tui Regio: (a) Gray scale 2.03 μm, (b) RGB false colors R: 5 μm, G: 2 μm, B: 1.08 μm, (c) PCA R: 1st , G: 2nd , B: 3rd components, (d) PCA R: 3rd , G: 2nd , B: 1st components.

RESULTS

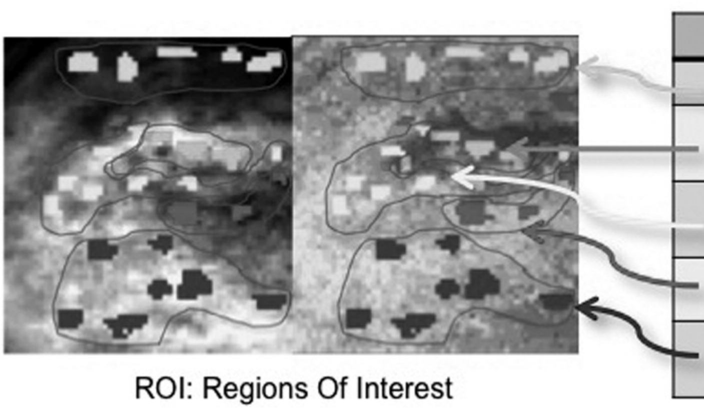
Tui Regio

We have isolated five distinct areas (Fig. 9) within Tui Regio. The Principal Component Analysis projections (Fig. 8c, d) showed areas of different colors and brightness suggesting diversity in surface composition. The PCA method is compatible to gray scale (a) and RGB (b) projections of Tui Regio. The visually brighter areas represent the highest I/F values and the darker areas the lowest, where I stands for the intensity of reflected light measured by the instrument and F the plane-parallel flux of sunlight incident on the satellite normalized for Titan (Thekaekara, 1973; Barnes *et al.,* 2007; Brown *et al.,* 2004).

The plot (Plot 1) of "Bright cryolava field" terrain is different from the other plots, presenting higher I/F values. This suggests that, additionally, this area is extremely brighter than the rest of the region. The wavelengths at which this area presents obvious alterations are the 2 μm, 2.8 μm and 5 μm.

Hotei Regio

We have also isolated five distinct areas within Hotei Regio's probable volcanic field (Fig. 11). The PCA projections (Fig. 10c, d) are presented in false colors areas of different spec-



Gray scale	PCA	ROI Color
Dark area	Green area	Cyan
Bright "cryolava field" area	"Lava field" (Dark pink)	Green
Semi-Bright area	"Lava field edges" (light pink)	Yellow
Semi-Dark area	Bright Blue area	Red
Gray area	"Deposits" (pink-yellow mixture)	Blue

Fig. 9. Isolated areas with the use of visual colour alterations, which suggest areas of spectral difference.

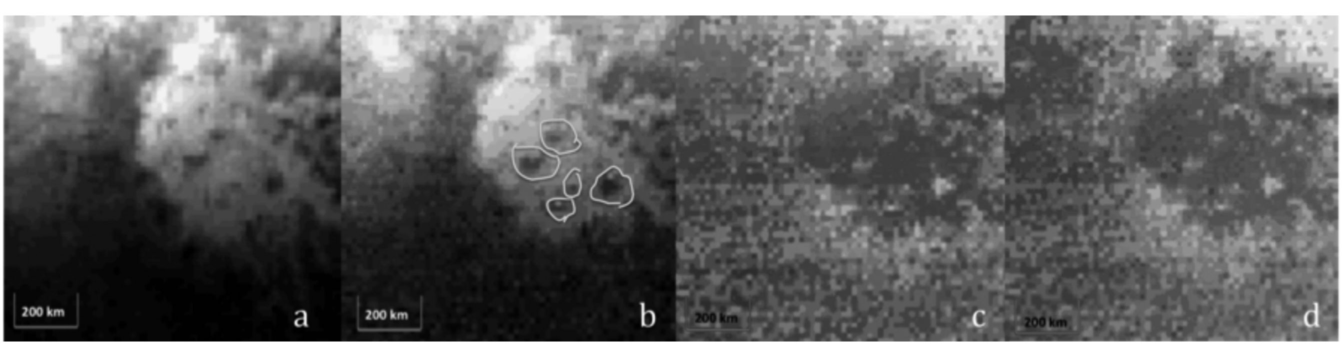
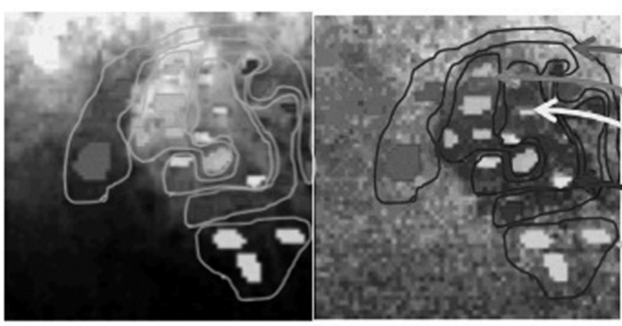


Fig. 10. Reprojection of Hotei Regio: (a) Gray scale 2.03 μm, (b) RGB false colors R: 5 μm, G: 2 μm, B: 1.08 μm, (c) PCA R: 1st , G: 2nd , B: 3rd components, (d) PCA R: 3rd , G: 2nd , B: 1st components.



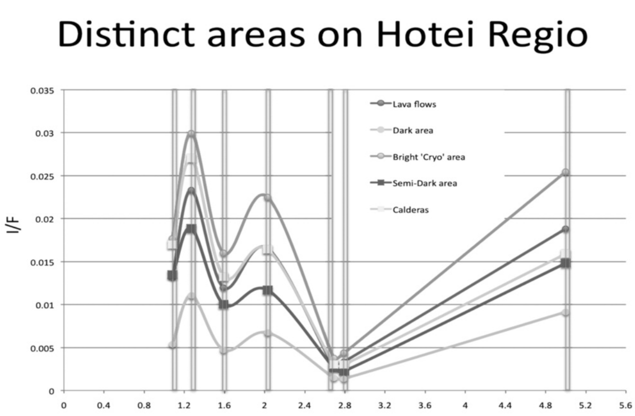
Gray scale	PCA	ROI Color
Semi-Dark area	Bright blue	Red
Bright "Cryo" Area	Dark Red	Green
"Dark spots"	"Yellow-Green spots"	Yellow
"Lava flows"	"Lava flows"	Blue
Dark Area	Light Green Area	Cyan

ROI: Regions Of Interest

Fig. 11. Isolated areas with the use of visual color alterations, which suggest areas of spectral difference.

tra and brightness, suggesting alterations in surface composition. Thus, the area suggested to be cryovolcanic is distinguished from the surroundings. The only compatible figures with the surrounding area are the caldera-like structures (pointed by green lines, [b]), which probably reveal the primal surficial material, before resurfacing (i.e the surrounding area). The PCA images are compatible to gray scale (a) and RGB (b) projections of Hotei Regio.

Hotei Regio's spectral graph (Plot 2) indicates that the "Bright Cryovolcanic area" presents the highest I/F values and remains brighter than the other areas at all wavelengths. In addition, the "Dark area" remains darker with low values of I/F at all wavelengths. Surprisingly, the spectra from caldera-like structures present medium I/F values, lying almost in the average between the brighter ("volcanic area") and the darker ("primal surface") at most wavelengths. This is compatible with terrestrial caldera structures that consist partially of primary surficial components on which the volcano is being built, as well as new material coming from the interior.



Plot 2. Spectral plot of five distinct areas at the seven atmospheric spectral windows.

DISCUSSION

Whilst it offers a particularly interesting opportunity for research, the existence of past or current cryovolcanic activity on Titan's surface, especially in areas with high reflectance, as observed by Cassini's VIMS instrument, is currently a highly controversial subject. This study has focused on evidence derived from Tui Regio and Hotei Regio, in order to analyze and interpret the data gathered from the VIMS instrument. The spectrographic analysis of VIMS data shows that the visually bright flow-like figure, seen in Tui Regio, has the highest I/F value from its surroundings, especially in the 2.03 μm, 2.8 μm and 5 μm spectral windows (Plot 1), suggests compositional variability in the material between the dark and the bright spots. Furthermore, the dark area presents the lowest I/F values at all wavelengths of the seven spectral windows. This suggests that the flow field has possibly been deposited over the initial (dark) material after single or multiple diachronic eruptions. If Tui Regio is a massive cryolava flow field, then it resembles the terrestrial Carrizozo flow field in New Mexico. Hotei Regio's field displays a low basin with flow-like features lying in the basin interior and at the margins. The flow field has higher I/F values at all wavelengths than the semi-dark and dark areas that either surround the field or lie within it (Plot 2). The dark areas present significantly lower I/F values. Even though the caldera-like structures are seeing as dark as the surrounding areas at VIMS images, they demonstrate medium I/F values suggesting altered chemical composition. The medium I/F values compared with the other areas, suggest that the calderas consist of the initial substrate (dark) material and the cryomagmatic (bright) new material. Such a combination could result in the formation of rough surfaces with high textural variability. The VIMS analysis for the caldera-like structure of Hotei Regio reinforces the theory that assumes the volcanic origin of the area's pattern. In addition, the area resembles the terrestrial volcanic terrain, Harrat Khaybar as well Enceladus' volcanic-tectonic zone of weakness, Tiger Stripes.

Further investigation and comparison of similar features from the three bodies, Titan-Enceladus-Earth, could provide information regarding their formation and future development. Titan, as described in detail hereabove, is perhaps one of the most intriguing objects in our Solar system. The combination of Titan's nitrogen atmosphere and the geologically complex and dynamic surface possesses the satellite as an

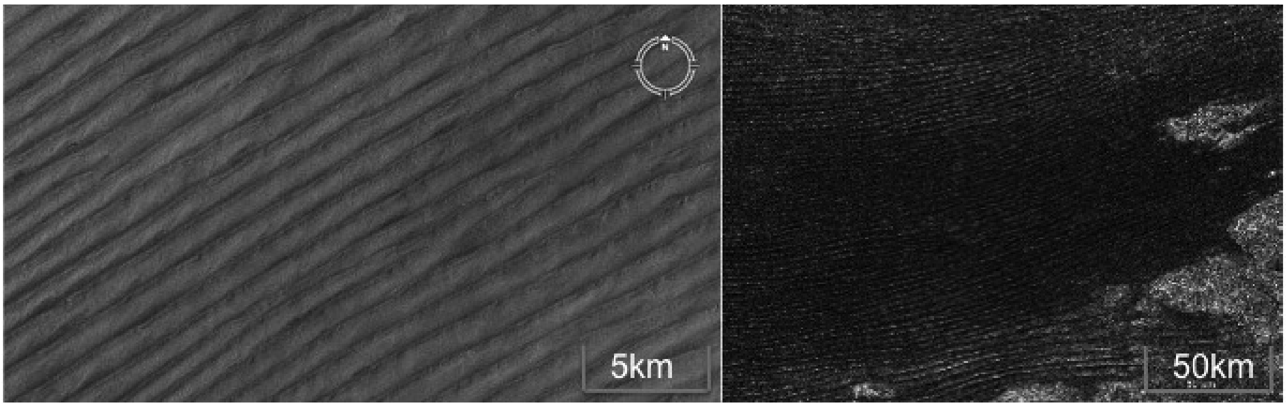


Fig. 12. (left) Longitudinal Sand dunes in Saudi Arabia (NASA). (right) Longitudinal equatorial dunes on Titan (Radebaugh *et al.,* 2009).

Earth-like body (Coustenis & Taylor, 2008). In addition, many atmospheric aspects such as the climate and the meteorology, as Titan displays a 'methanological' weather cycle of clouds, rainfall and evaporation that parallels the 'hydrological' cycle of the Earth, as well as, its complex morphology, make Titan an extremely important astrobiological place. Specifically, cryovolcanism has important astrobiological implications, as it provides a mechanism to expose Titan's organics to liquid water, transforming hydrocarbons and nitriles into more evolved and oxidized prebiotic species (Neish *et al*., 2006). Also it has been suggested that life could exist in the lakes of liquid methane on Titan (McKay & Smith, 2005). The existence of liquid bodies identified as lakes exposed on the surface (Stofan *et al*., 2007), the equatorial dunes (Fig. 4c), dendritic flows, potential tectonics and volcanism, enhance Titan's resemblance to our own planet. Prior to this discovery, such combination of surface features and dense nitrogen atmosphere had only been identified on Earth.

All the aforementioned aspects, which mainly are the nitrogenic atmosphere, the liquid lakes, as well as the Earth-like geological structures, suggest that Titan resembles Earth more than any other body in the Solar System; despite the huge differences in temperature and other environmental conditions. Thus, an holistic understanding of Titan's system will help us better understand Earth's evolution starting with its primordial phase since early Earth probably looked much like Titan looks today (Owen, 2005). In general, the activity of cryovolcanism might operate in analogy to terrestrial hydrovolcanic eruptions (Solomonidou *et al*., 2010). Fig. 13 shows the supervolcano of Lake Toba in North Sumatra, Indonesia, which is 100 km long and 30 km wide, in comparison with the possible supervolcanic structure called Ganesa Macula (50°N, 87°W) (Lopes *et al.,* 2007b). The Volcanic Explosivity Index (VEI) for Lake Toba, which provides a relative measure of the explosiveness of volcanic eruptions (scale 0-8), was set to be 8 values and the total amount of erupted material volume of 2,800 km^3. Taking into consideration the amount of the erupted material, the size of the volcanic structure and the hazards that could affect the satellite, we can assume that supervolcanoes could be hosted in Titan's geological history. The candidate cryovolcanic figures Ganesa Macula, Tui Regio and Hotei Regio could resemble the supervolcanic structures seen on Earth.

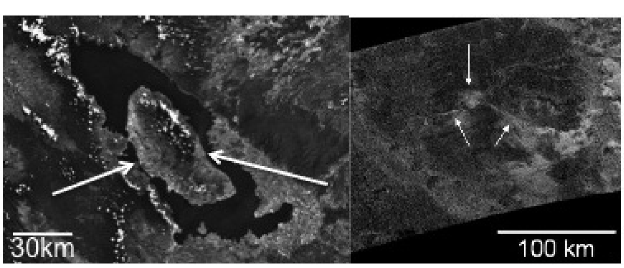


Fig. 13. (left) Supervolcano on Earth. Lake Toba (USGS). (right) Possible supervolcano on Titan. For both figures, the central part of calderas is indicated by the white arrows (Lopes *et al.,* 2007b).

In this study, we focus on the volcanological structures like the ones seen in Tui Regio and Hotei Regio that resemble terrestrial volcanic terrains and characteristics. Tui Regio is a massive (1,500 km) flow field-like figure that could possibly have formed after accumulation of cryolava flows erupted at different times, following the area's topography. On Earth, a massive edifice resembling Tui Regio, emerges in the Tularosa Basin in south-central New Mexico, USA. Carrizozo flow field (Fig. 14) is 75 km long and covers 328 km^2. The volume of eruptive material was 4.3 km^3 (Bleacher *et al*., 2008). The field was probably formed from periodic deposition of eruptive material spewing from a source located 27 m

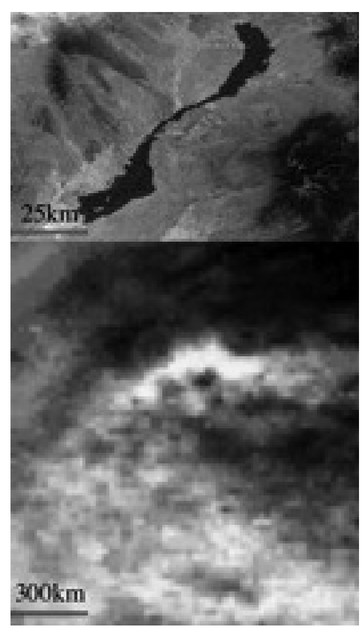


Fig. 14. (up) Carrizozo flow field, New Mexico, USA (USGS). (down) One of the largest candidate cryovolcanic flows on Titan, Tui Regio.

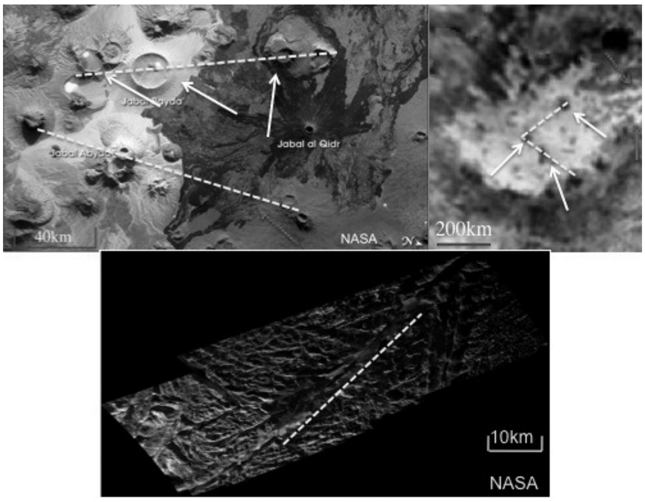


Fig. 15. (up left) Harrat Khaybar volcanic terrains, North of Medina, Saudi Arabia (NASA). (up right) Possible cryovolcanic terrain on Titan, Hotei Regio (Soderblom *et al.,* 2009). (down) Baghdad Sulcus, volcanic fracture on the south pole of Enceladus, Tiger Stripes (NASA). Pockets of heat have been appeared along the fracture. The white arrows indicate structures of tuffs, domes and calderas for Harrat Khaybar and possible dome and caldera formations for Hotei Regio. Additionally, the red arrows indicate lava flows and possible cryovolcanic flows within the volcanic terrain. The yellow dashed lines indicate areas that are possibly tectonic zones of weakness from which internal material may pass through.

high named Little Black Peak. The peak consists of three nested cinder cones and a solidified lava pond. The Titanian analogue (Fig. 14) is the possible cryovolcanic flow, Tui Regio; one of the largest seen on Titan. It presents similar shape as Carrizozo flow field (Fig. 14).

As indicated above, Hotei Regio is probably a massive cryovolcanic terrain that consists of caldera-like figures and depositional areas filled with lava flows. One terrestrial terrain that resembles Hotei Regio is the Harrat Khaybar volcanic field (Fig. 15), which is located at North of Medina in Saudi Arabia. The western half of the Arabian Peninsula contains extensive lava fields known as haraat (Pint, 2006). One such field is the 14,000 km^2 volcanic field that was formed by eruptions along a 100 km N-S vent system over the past 5 million years. The area contains a wide range of volcanic rock types, spectacular landforms and several generations of dark fluid basalt lava flows (Pint, 2006). Jabal Abyad, in the center of the image, was formed from more viscous, silica-rich lava classified as a rhyolite. While the 322 m high Jabal al Qidr exhibits stratovolcano, Jabal Abyad is a lava dome. To the west (image top center) is the impressive Jabal Bayda. This symmetric structure is a tuff cone, formed by eruption of lava in the presence of water. The combination produces wet, sticky pyroclastic deposits that can build a steep cone structure, particularly if the deposits consolidate quickly (Pint, 2006). In Fig. 15, we present a comparison between Earth's, Titan's and Enceladus' possible volcanic terrains and tectonic zones of weakness that consist the passage for internal material to deposit on the surfaces.

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