CANDIDATE REGIONS ON TITAN AS PROMISING LANDING SITES FOR FUTURE IN SITU MISSIONS

Solomonidou Anezina [1,2], Coustenis Athena[1], Jaumann Ralf[3], Stephan Katrin[3], Sohl Frank[3], Hussmann Hauke[3], Hirtzig Mathieu[4,1], Bampasidis Georgios[1,5], Bratsolis Emmanuel[5], Moussas Xenophon[5], Kyriakopoulos Konstantinos[2].

(1) LESIA - Observatoire de Paris, CNRS, UPMC Univ. Paris 06, Univ. Paris-Diderot –Meudon, France, (Athena.Coustenis@obspm.fr)
(2) National and Kapodistrian University of Athens, Department of Geology and Geoenvironment, Athens, Greece,
(asolomonidou@geol.uoa.gr)
(3) DLR, Institute of Planetary Research, Berlin, Germany,
(Ralf.Jaumann@dlr.de)
(4) Fondation La Main à la Pâte, Montrouge, France,
(mathieu.hirtzig@fondation-lamap.org)
(5) National and Kapodistrian University of Athens, Department of Physics, Athens, Greece,
(xmoussas@phys.uoa.gr)

ABSTRACT

The highly successful and still on-going Cassini-Huygens mission to the Saturnian system points to the need for a return mission, with both remote and *in situ* instrumentation. The surface of Saturn's moon Titan, hosts a complex environment in which many processes occur shaping its landscape. Several of its geological features resemble terrestrial ones, albeit constructed from different material and reflecting the interior-surface-atmosphere exchanges. The resulting observed morphotectonic features and cryovolcanic candidate regions could benefit from further extensive exploration by a return mission that would focus on these aspects with adapted state-of-the-art instrumentation affording higher spectral and spatial resolution and *in situ* capabilities. We suggest that some features on Titan are more promising candidate locations for future landing and we present the case for Tui Regio, Hotei Regio and Sotra Patera as to why they could provide a wealth of new scientific results.

1. INTRODUCTION

Data retrieved from the Visual and Infrared Mapping Spectrometer (VIMS) [1], the Synthetic Aperture Radar (SAR) and RADAR [2] and the Imaging Science Subsystem (ISS) [3] aboard Cassini and the instruments on board the Huygens probe supplied information regarding Titan's atmosphere, surface composition and morphology. This detailed approach on Titan's geological environment has classified it as extremely interesting due to its complex surface composition. A combination with unique geological features [4, 12, 20] make Titan a prime candidate for geological, internal and surface *in situ* investigation. Multiple flybys (91 to this date) of the NASA/ESA Cassini-Huygens spacecraft, which is still in commission, brought into light surficial expressions that were not expected to be observed on an icy surface. Many of them have counterparts in Earth geology, but the materials in play are different. The diversity of surface formational mechanisms include potential cryovolcanism on a number of areas such as Tui Regio (20°S, 130°W), Hotei Regio (26°S, 78°W) and Sotra Patera (15°S, 42°W) [4]. In this work, we actually focus on these areas from VIMS and RADAR data. The two cameras of Cassini/VIMS have observed the surface of the candidate areas at visible and infrared wavelengths, giving insights about their composition. Furthermore, the Cassini/RADAR with SAR acquires topographic pictures using microwaves, penetrating Titan's hazy thick atmosphere. Combined investigations specifically of Hotei Regio and Sotra Patera suggest that both instruments are in agreement with results pointing to a variety of geological processes having occurred in the past [4, 5] or recently [6], possibly indicating cryovolcanism. Indeed, data correlation and analysis from VIMS and RADAR provided us with images and mosaics combining both spectral and morphological information [4]. However, the problem of atmospheric haze scattering and particle absorption is still present, making surficial imaging ambiguous unless a complete and accurate modelling of the atmospheric contribution is performed. In our processing VIMS and RADAR data, we take into account the atmospheric effect and photometric corrections, as well as filtering with a view to produce constraints on the surficial chemical composition and morphology. The evidence of such interesting areas like Tui Regio, Hotei Regio and Sotra Patera as it will be shown hereafter, enhances the significance of a future mission to Titan with *in situ* capabilities [7,8].

2. GEOLOGY OF AREAS OF INTEREST

In general, Titan's surface appears to host diverse types of both smooth and rough areas of various relief types, which - among other - include volcanic-like features and impact craters that are intermittently filled by atmospheric precipitations which have been reported [9, 10]. In addition, Titan exhibits topographic features such as mountains, ridges, faults, and aeolian and fluvial features such as dunes and lakes. Chronologically, the surficial geological features are young and unique for a celestial satellite [11].

The geological terrains of Tui Regio, Hotei Regio, and Sotra Patera are the main focus of this study and they are proposed as interesting candidates for future landing sites. The wealth of data acquired from VIMS and RADAR on board Cassini spacecraft and their analysis with specific software provide the evidence as to why [4, 5, 21, 24]. These candidate regions consist of diverse geomorphology, possible surface albedo changes with time and a correlation with the interior's high zones of tidal potential. Not only have the data revealed the uniqueness of all three areas by means of morphological aspects such as caldera-like features, a deep crater, high mountains and lobate flows, but also depicted the variability in composite component. Moreover, Tui, Hotei and Sotra are the only ones among the cryovolcanic candidate regions as in [4] that appear anomalously bright at 5μm and have been observed adequately by VIMS for a temporal variation study. The candidate regions for *in situ* investigations should combine atmospheric, surficial, near sub-surficial and deep internal investigations [12]. If the cryovolcanic origin of Tui, Hotei and Sotra is identified, they will stand as case study areas for all the aforementioned investigations.

a) **Tui Regio**

Tui Regio (20°S-130°W) is one of the areas which was observed as anomalously bright at 5μm wavelength and therefore constitutes a component of the most reliable evidence yet obtained concerning the activity of cryovolcanism on Titan's surface (Fig. 1). Tui Regio consists of a flow-like figure 150 km-wide and extends for 1,500 km in an East-West direction [13]. Theories suggest that it may be geologically young and that the resembling lava flows could be deposits of cryovolcanic activity. The analysis of Cassini ISS and mainly VIMS data suggest that the area is a massive flow field since at least three long lobate spectrally distinct tendrils [13] have been observed and have possibly being effused from a main point like a caldera-like structure, fracture or fissure. The observed geological surficial expressions such as calderas, ejecta deposits, alluvial terrains, flows, the low basin and more, depict the imprints of dynamic activities. The area has been characterized by [14] as a spectrally distinct unit in composition, especially because of its anomalous brightness at 5 μm, which has been confirmed by using updated VIMS maps from [15]. Reference [16] proposed that Tui Regio could be an active centre of cryovolcanism. Reference [13] suggested that a flow-like feature in the western part of Tui Regio could represent past cryovolcanic activity based on its morphology, relative age and chemical composition.

b) **Hotei Regio**

Hotei Regio is a 700 km-wide area that is probably volcanic in origin [4, 5] (Fig. 1). The Cassini SAR images confirm the interpretation that the area is a low basin surrounded by higher terrains with possible calderas, fault features and extensive cryovolcanic flows. Reference [5] have studied the area and indicated significant geological features that resemble terrestrial volcanic features. These are viscous flow-like figures, a 1 km mountainous terrain (ridge-like) that surrounds the basin as well as dendritic channels, caldera-like features, dark blue patches (in RGB coloring) and possibly alluvial deposits. Processing of RADAR images showed that Hotei Regio is a low basin depression, (as expected to be observed in a volcanic terrain) one km deep. It is filled with terrestrial volcanic-like flows that are 100 to 200 km thick. The peripheral area lying at higher altitudes has rough as well as smooth texture. This means the surrounded formations are probably alluvial deposits [5]. The ring-fault-like structures seen within the basin present possibly a caldera-like feature. Hotei Regio is the first Titan area that has been reported to exhibit changes in brightness with time from July 2004 until March 2006 [6]. Reference [6] described evidence for photometric variability on Hotei Regio by analyzing VIMS data, which could be linked to cryovolcanism and ammonia deposits.

Alternatively, Tui and Hotei Regio have been suggested to be sites of large low latitude paleolakes based on estimations of Titan's topography [17]. In addition, reference [19] suggested the presence of dry lakebeds at Titan's north pole with spectral characteristics similar to Tui and Hotei Regio, suggesting a common evaporitic origin. Recent studies [18] also suggested that the areas are the result of exogenic deposits, either fluvial or lacustrine.

c) **Sotra Patera** (formerly known as Sotra Facula)

Sotra Patera, a 235 km in diameter area, has recently been identified as an additional potential cryovolcanic feature [4] and is currently under investigation by means of endogenic processes that might have shaped it (Fig. 1). Reference [4] have found that there are two peaks more than 1-km high and one deep volcanic crater (1-km deep) and finger-like lobate flows.

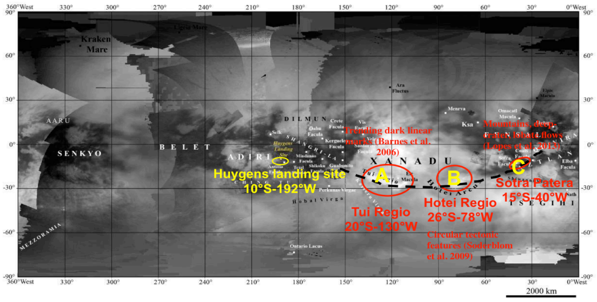

Fig. 1. Map of Titan's indicating three promising landing sites: Tui Regio (A), Hotei Regio (B), Sotra Patera (C) [21].

3. IMAGE PROCESSING

In order to understand Titan's geology and evolution, it is critical to investigate and identify the chemical composition of the areas of interest. The VIMS instrument acquired many spectral images from several flybys in the interest of chemical composition analysis. Even though many images captured parts of the surface, the fact that Titan possesses an extended, hazy and dense atmosphere suggests a major constraint on data accuracy. As mentioned earlier for our study case, observations from VIMS in 352 wavelengths have indicated three anomalously bright areas, Tui Regio, Hotei Regio and Sotra Patera. All three areas are imaged in narrow spectral windows centered at 0.93, 1.08, 1.27, 1.59, 2.03, 2.8 and 5 μm, through Titan's thick atmosphere. Despite the weak atmospheric methane absorption within theses windows, the surficial imaging is still ambiguous due to haze scattering and particle absorption. Our goal is to obtain relatively clear surface images without the interference of the atmospheric contribution. Atmospheric scattering and absorption need to be clearly evaluated before we can extract the surface properties.

We are sequentially using two methods in order to acquire the optimal result from the data set [21]. First, the Principal Component Analysis (PCA), which is a statistical method, de-correlates the features visible on many similar images into a new set of images that show the main features only, sorted by frequency of appearance. We have tested this method on the previously studied Sinlap crater [22], delimitating compositional heterogeneous areas compatible with the published conclusions. Secondly, the radiative transfer method is a 1-D multi-stream radiative transfer (RT from now on) code based on the open-source solver SHDOMPP [23]. We have used as inputs most of the Huygens Atmospheric Structure Instrument (HASI) and the Descent Imager/Spectral Radiometer (DISR) measurements, as well as new methane absorption coefficients, which are important to evaluate the atmospheric contribution and to allow us to better constrain the real surface alterations, by comparing the spectra of these regions [21]. Figure 2 presents the surface albedo ratios from RT as selected with PCA (Regions of Interest –RoI) of the brightest (red) and the darkest (green) RoIs.

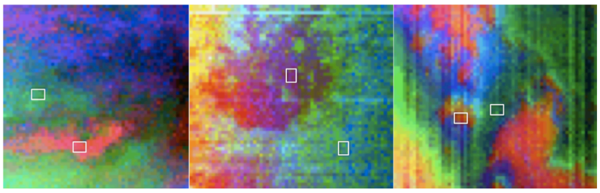

Fig. 2. PCA on VIMS data (the red spot marks the brightest RoI and the green the darkest) using specific Principal Components (PCs) for each data cube [21].

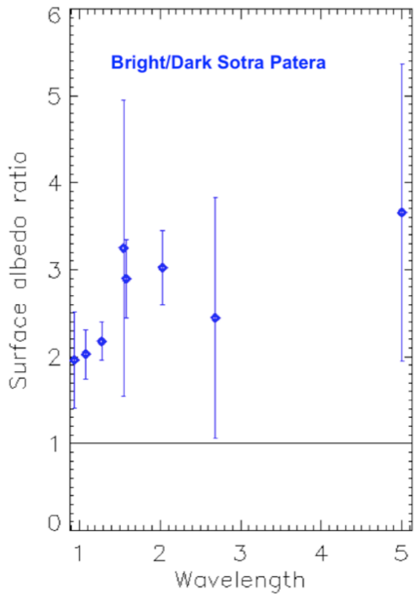

Fig. 3. Retrieval of surface albedo ratios with radiative transfer between the brightest and the darkest Sotra Patera RoIs with respect to the Huygens landing site albedo -HLS (black horizontal line) [21].

Furthermore, we study the temporal surface variations of the three regions at all wavelengths (Fig. 4). In order to validate our results we applied the same method for the same periods of time on two dark dunes fields as test cases and did not find any changes in surface albedo.

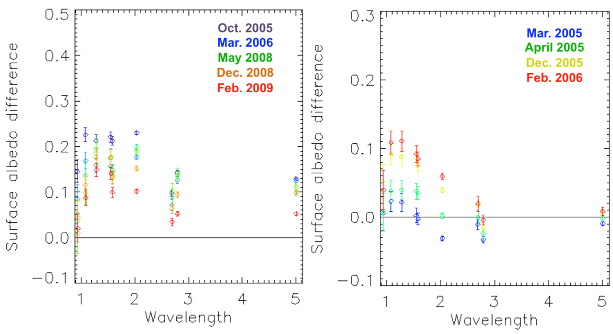

Fig. 4. Temporal variation of the average surface albedo of Tui Regio (2005-2009) (left) and the Sotra Patera area (2005-2006) (right) [24]. The surface

albedo differences (with respect to HLS) with time from radiative transfer application on VIMS data from 2005 (purple points) to 2009 (red points) showing that within 3.5 years Tui Regio has decreased in brightness while from 2005 (blue points) to 2006 (red points) Sotra Patera has increased in brightness. The dark line always corresponds to HLS surface albedo [24].

4. RESULTS

We have isolated 2 regions (RoIs) in Tui Regio, Hotei Regio and Sotra Patera with PCA that have different spectral response as shown by the radiative transfer simulation [21]. The dynamical range in surface albedo within the three areas indicates that the bright RoIs are always brighter than the dark ones by significant amounts. For Tui Regio and Hotei Regio the largest differences in surface albedo are in the longer wavelengths while for Sotra Patera the offsets are rather homogenously distributed throughout the spectrum with the largest ones at 5μm. We then study the temporal surface variations of the three regions.

Our findings indicate a significant darkening for Tui Regio from 2005-2009 (at all wavelengths). For Sotra Patera a brightening is observed from 2005-2006 (Fig. 4) [24]. On the contrary, the dunes fields' test cases did not change with time. Hotei Regio has been previously suggested to present brightness variations over a two-year period (2004-2005) [6]. However, we find that to-date available observations of that region present issues (e.g. geometry) prevent an accurate application of our RT model to infer surface information with the desired accuracy. The surface albedo variations together with the presence of volcanic-like morphological features suggests that the cryovolcanic candidate features are connected to the satellite's deep interior, which could have important implications for the satellite's astrobiological potential. This idea has been recently augmented by the construction of new interior structure models of Titan and corresponding calculations of the spatial pattern of maximum tidal stresses at the satellite's surface [25]. Tui Regio, and Sotra Patera are found to be situated in most prominent tidally flexed zones (yellow) on Titan's, thereby enhancing the possibility of tide-induced weakening and the generation of cryovolcanically 'active' zones (Fig. 5).

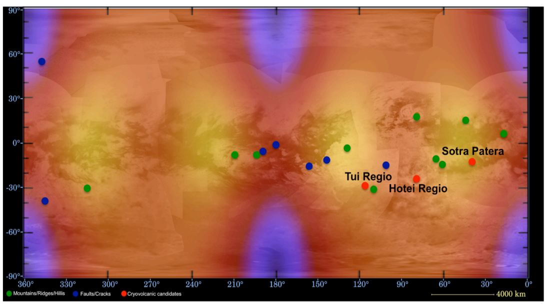

Fig. 5. Map showing the correlation between cryovolcanic candidate regions and the maximum tidal stress pattern (color-coded)[25].

5. LANDING SITES

The suggestion of Tui Regio, Hotei Regio and Sotra Patera as landing sites (Fig. 6) is based on their geomorphological variability as well as the expected compositional alterations of all areas. A crucial point of such selection is the determination of investigation and sampling after landing. A potential lander, like the Huygens probe should be capable to land on a solid surface and carry a fully instrumented robotic laboratory down to the surface. The lander's principal function is to sample and analyze grains attributed from regions of the surface within the areas of interest that lie at the margins of alternative structures (i.e. the area where two geological edifices/plains conjunct). Since all three areas have been suggested to be cryovolcanic in origin, the sampling process should be treated similarly as on terrestrial volcanic terrains. Tui Regio is possibly an accumulation of cryolava flows forming a massive flow. Ideal *in situ* and remote imaging of the Tui Regio area should comprise sampling from diverse regions by means of chemical composition and morphology. Such regions could be the main part of the flow, the marginal areas, and the surrounding terrain, which is considered as the primary material on which possible cryovolcanic material deposited. Since *in situ* imaging of multiple areas, which are considerably distant between them, is impossible, then the selection of a landing area is restricted to an area that presents spectral scientific interest. Such area could be the margin between the flow-like feature and the "old" spectrally dark terrain (Fig. 6 -left).

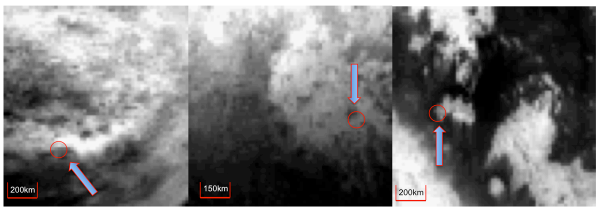

Fig. 6. Areas of potential landing on Tui Regio (left), Hotei Regio (middle) and Sotra Patera (right).

Hotei Regio presents a more complex geological terrain than Tui Regio in terms of morphology as seen from the current data. As mentioned before (Section 2), central Hotei Regio is a low basin consisting of caldera-like figure, flows, channels, and faults while mountains surround it. Data processing showed that the area suggested to be cryovolcanic is different from its surroundings in terms of surface albedo [21]. This is compatible with terrestrial caldera structures that consist partially of primal surficial components on which the volcano is being build as well as newly fresh material coming from the interior. Potential sampling and identification of the chemical composition of both the surrounding dark area and the material from the caldera-like feature could bring into light significant information regarding internal processing on Titan. Thus, the landing region proposed is the margin area lying between the largest caldera within Hotei Regio's terrain and the bright component that surrounds the caldera (Fig. 6 -middle).

For Sotra Patera, that consists of a topographically diverse terrain with a 1-km crater (Sotra Patera), two mountains (Doom and Erebor Monters) and a lobate flow region (Mohini Fluctus) [4] a potential landing site option should be carefully selected having in mind the safety of the landing (Fig. 6 -right). Thus, it seems that the lobate flow region is a safe and scientifically interesting option since the *in situ* identification of the material covering such feature will provide insights regarding the unknown material of the 5μm anomalously bright regions.

6. FUTURE EXPLORATION – SOME TITAN MISSION CONCEPTS

Undoubtedly, the Cassini-Huygens mission has provided us with valuable data that have expanded our knowledge. However, there are still aspects, especially regarding the surface that are not yet covered, along with several unanswered questions. The revelation of Titan's surface will be a key point to unveil the atmosphere and the interior but also a major contribution to icy moons' understanding. After having evaluated Cassini-Huygens mission's data, it is now clear how important it is to acquire direct sampling of the surface and have mobility in the near-surface environment. Thus, we should have the opportunity to map Titan on a global scale from orbit and visit other targets in the Saturn system. The geological objectives request landing site measurements of the *in situ* geological context, chemical composition by several types of spectroscopy, mineralogy provided by infrared data and petrological properties such as porosity, grain size, permeability and more [12]. This could be achieved with measurements from close range of scientifically interesting areas with a montgolfière which could explore close-up the surface and also perhaps crash onto the surface and get measurements [26]; and/or a lander that will descend in an equatorial or polar region and make measurements of solid ground or a liquid.

Therefore, a future mission focusing on this Earth-like world is important, with a dedicated orbiter and *in situ* elements. Such concepts have been proposed in the past, like Titan Explorer [28], TandEM [7], the Titan Saturn System Mission (TSSM) [26], the Titan Aerial Explorer (TAE) [30], the Aerial Vehicle for In-situ and Airborne Titan Reconnaissance (AVIATR) [29] and the Titan Mare Explorer (TiME) [32].

The TSSM mission was a merge of the Titan explorer [31] and the Titan and Enceladus Mission [7] concepts, which had been selected respectively by NASA and ESA for studies. TSSM was studied in 2008 [26]. It has to do an in-depth long-term exploration of Titan's atmospheric and surface environment and in situ measurements in one of Titan's lakes with the goals to explore Titan as an Earth-like System, examine Titan's organic inventory and explore also Enceladus and Saturn's magnetosphere. To achieve these goals, a dedicated orbiter would carry two in situ elements: the Titan montgolfière (hot air balloon) and the Titan Lake Lander, which would combine to provide data and analyses directly in the atmosphere, on the surface and sound the interior of Titan. The mission would launch in the 2023-2025 timeframe on a trajectory using Solar Electric Propulsion (SEP), as well as gravity assists, to arrive ~9 years later for a 4-year mission in the Saturn system. Soon after arrival at Saturn, the montgolfière would be delivered to Titan. The TSSM three elements would operate as follows:

a) The orbiter, using nuclear power, would perform 7 close-up Enceladus' flybys and then enter into orbit around Titan for 2 years of dedicated observations.

b) The hot air balloon would probe both Titan's atmosphere and surface from above the equator and a low altitude orbit of 10 km for at least six months using MMRTGs.

c) The Lake Lander would perform the first extraterrestrial oceanographic experiment by landing in one of the Titan's lakes, the Kraken Mare at approximately 75° N.

The TSSM concept was designed to carry the adapted instrumentation in order to study the atmosphere, the surface as well as the subsurface. The surface exploration payload included specific instruments on-board the orbiter, such as a high-resolution imager and spectrometer that is capable to acquire spectra at 1–6 μm and perform global mapping at 50 m/pixel in three colors, which would greatly improve the spectral data to an extremely high extend, considering that the current resolution from images acquired from Cassini/VIMS observations of Tui Regio, Hotei Regio and Sotra Patera range between 12-150 km/pixel. Another important part of the payload would be the Penetrating Radar and Altimeter instrument that could obtain global mapping of subsurface reflectors with 10 m altitude resolution in altimetry mode and more than 10 m depth resolution with roughly 1 km x 10 km spatial resolution. Furthermore, a montgolfière travelling over 10,000 km in linear distance could image and map Titan's diverse landscapes at close range. The TSSM montgolfière would contain instrumentation such as a Balloon Imaging Spectrometer, a Visual Imaging System and also a Titan Radar Sounder (>150 MHz) for more than a year. In addition to topography, the radars on both the orbiter and the montgolfière will provide information on the tectonics and stratigraphy of the crust with different and complementary resolution. TSSM is planned to have the ability to examine in detail the lakes and their surrounding environment through the probe entry, descent and landing of a lake lander, which could also include efficient electronic equipment focusing on the study of the liquid its self, like MEMS (Micro-Electro-Mechanical Systems) instrumentation. The proposal of MEMS as part of the science surface properties package on board of a future Lake Lander on Titan, reinforces such kind of research [27]. MEMS devices offer a low cost and reduced size of instrumentation in order to accomplish the 3D sounding of the liquid deposit and detect the presence of any biomarkers in a broader area. By dramatically reducing the production cost without decreasing the efficacy, these micro devices can execute scientific investigations in places and micro scales never imagined before.

This mission came second in the decision by the agencies and was abandoned, however it inspired several other proposed concepts for smaller size missions, like the following.

- Titan Aerial Explorer (TAE) was an M3 candidate for ESA's Cosmic Vision call [30]. TAE was a balloon, which was planned to fly in the lower atmosphere of Titan at an altitude of 8 km from 3 to 6 months on Titan's equatorial latitudes, with Direct to Earth transmission and no need for an orbiter.
- The Aerial Vehicle for In-Situ and Airborne Titan Reconnaissance (AVIATR) was an alternative idea to the Titan balloon. In Titan's low gravity and a dense atmosphere, a nuclear powered airplane could fly more easily than on Earth and could sample directly the atmosphere over large swaths of Titan's surface [29].
- The Titan Mare Explorer (TiME), a Discovery candidate, is a probe focusing on exploring Titan's lakes and especially the Ligeia mare. This lake lander could study the chemical composition and the geological characteristics of the hydrocarbon pools [32]. Adjacent to this idea, was the Titan Lake Probe which included a submarine [33].
- Another Discovery candidate was the Journey to Enceladus and Titan (JET), a simple orbiter with two instruments only and radio science that would explore the plumes of Enceladus and the atmosphere and surface of Titan [34].
- A seismic network proposed as part of the geophysical payload of such missions [28], resembling a geophone array widely used on the Earth, capable of detecting ground motions caused by natural or controlled sources.

Discussions on future missions to Titan, beyond the end of the *Cassini* mission in 2017, are already underway with proposals for aerial explorers, such as airplanes or balloons (as discussed here above), and dune and lake landers that will more thoroughly investigate this complex world.

7. SUMMARY

Titan's spectacular surficial terrain requires further and deeper investigation. The identification of ongoing processes on the surface will reveal the internal, sub-surficial and atmospheric processes as well, giving an holistic view on Titan's evolution. Tui Regio, Sotra Patera and Hotei Regio are some of Titan's cryovolcanic candidates [4] with the first two probably subject to changes in surface albedo with time. The indications of multivariable processes occurring in all three areas, identifies them as desirable candidate landing sites for a lander that could measure the chemical composition as well as detect the geological properties of each area. Future in situ explorations with landers and close-up *in situ* elements would be the way to go for such investigations.

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