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Heat flow in Triton: Implications for heat sources powering recent geologic activity

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ABSTRACT

Triton's surface shows clear evidences of resurfacing processes such as volcanism, tectonic structures and a very low presence of impact basins, which indicates that Triton's interior could remain active currently. It is generally assumed in icy satellites that the depth of faulting associated with large faults corresponds to the brittle-ductile transition (BDT), and the properties of large faults penetrating to the BDT depth can be used to obtain information on the mechanical behavior of the lithosphere, and potentially can contribute to constrain the thermal state of a planetary body. Here we present a detailed study of *Raz Fossae,* suggesting that this structure is not only limited to the graben originally described in previous works. Our study shows that north of the classical *Raz Fossae* there is another trough set with similar structural characteristics that can be interpreted as part of the same system of faults. We have calculated surface heat flows for Triton from the depth of the BDT under both structures: *Raz Fossae* and the new northern trough set from a detailed analysis of the troughs widths, taking into account the possible composition of the ice shell (H_2O and $NH_3{\cdot}2H_2O$). Our results show surface heat flows values much higher than those estimated in previous studies by modeling radiogenic production and tidal dissipation for fixed orbital eccentricities. Furthermore, our results suggest regional differences in the pattern of heat loss throughout Triton's lithosphere.

1. Introduction

Even though only 40% of Triton's surface has been observed (Smith et al., 1989; Croft et al., 1995), the Voyager 2 spacecraft found one of the most astonishing surfaces of the Solar System. Voyager 2 images showed a geologically young surface, apparently active until recent times, with clear evidence of resurfacing processes such as cryovolcanism, tectonic structures and very low presence of impact basins. In this regard, Stern and McKinnon (2000) calculated that leading hemisphere plains may be of order 50 Myr, and the age of the young volcanic plains on Triton may be about 40 Myr, and Schenk and Zahnle (2007) concluded that the low presence of impact craters indicates that Triton's surface is very young (<100 Myr) even possibly as a young as a few million years.

All these surface characteristics are consistent with the turbulent history of this satellite. Based on its retrograde and inclined circular orbit, it is widely accepted that Triton had to be formed in the Kuiper belt in a heliocentric orbit and have been subsequently captured by Neptune into a highly elliptical one, that afterward evolved to its current near zero eccentricity orbit (McCord, 1966; Goldreich et al., 1989; Agnor and Hamilton, 2006; McKinnon and Kirk, 2006; Nogueira et al., 2011). The circularization of Triton's orbit should have dissipated a large amount of energy due to tides raised by Neptune within Triton's interior (Goldreich et al., 1989; Benner and McKinnon, 1994; McKinnon and Leith, 1995; Correia, 2009; Nogueira et al., 2011). Because of this heat, Triton's interior melted and differentiated and some of this heat would have remained until recent times, allowing the presence of an internal ocean beneath its surface (Goldreich et al., 1989; McKinnon, 1984; Benner and McKinnon, 1994; McKinnon and Leith, 1995; McKinnon and Kirk, 2006) and its recent geological activity.

In this regard, Gaeman et al. (2012) estimated Triton's surface heat flow of 2–4 mW m^{-2} by modeling radiogenic production and tidal dissipation for fixed orbital eccentricities, values very similar to those of ~3 mWm^{-2} obtained by Brown et al. (1991) and Hussmann et al. (2006) due only to radiogenic heating assuming a chondritic composition for Triton's rocky fraction. Gaeman et al. (2012) also concluded that radiogenic heating would not have been sufficient to maintain an internal ocean at present day. However, their tidal heating calculation is based on very low eccentricity values, which produce negligible tidal dissipation

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rates. Thus, another heat source would be needed to justify the geological activity observed on Triton, which could indeed be the tidal heating due to orbit circularization (e.g., Benner and McKinnon, 1994; McKinnon and Leith, 1995); if Triton had been (relatively) recently captured by Neptune, or even obliquity tidal heating (Chen et al., 2014; Nimmo and Spencer, 2015).

On the other hand, Ruiz (2003) calculated surface heat flows for Triton from the depth of the BDT beneath *Raz Fossae* (Fig. 1), two prominent en echelon troughs near Triton's equator, and obtained values of 35–86 mW m^{-2} for a H_2O ice-dominated lithosphere and between 5 and 11 mWm^{-2} for a $NH_3{\cdot}2H_2O$ ice-rich lithosphere. Because of the young age of the surface, these heat flows would be relevant for recent (or even present-day) times; thus, Triton would be currently able to sustain an internal ocean at a depth of 20 or 30 km if the entire ice shell is thermally conductive (Ruiz, 2003). Moreover, these high heat flows are clearly higher than those potentially produced by radiogenic heating, requiring an extra heat input.

In this work, we have performed a detailed study of *Raz Fossae*. In this regard, we have found another structure north of *Leviathan Patera* whose characteristics indicates that *Raz Fossae* could extend further the limits of the structure originally described by Croft et al. (1995). This study has allowed us to perform a more detailed estimation of the BDT depth beneath *Raz Fossae*, from a detailed analysis of trough width, including the results for the new identified structure. Based on our refined BDT depths and their variation, we calculate more reliable heat flow estimations than those published by Ruiz (2003), whose values were based on a generic width of 15 km considered to be representative for *Raz Fossae* (Croft et al., 1995). The new identified structure noted in this work permits also to extend the heat flows analysis to larger areas on Triton's surface. Finally, we compare our estimates with the previous results, and discuss their implications for heat flow local variations and for the nature of the heat sources powering the recent geological activity of Triton.

2. Set of troughs studied

Raz Fossae, located near Triton's equator, south west of the undulating high plains unit (see Croft et al., 1995) which conforms the so-called *Cipango Planum*, has been described as a pair of en echelon troughs with plain floors. It presents sharp scarps in its southwestern half and less well-defined ones in its northeastern half. *Raz Fossae* have been usually interpreted as a graben system (Croft et al., 1995).

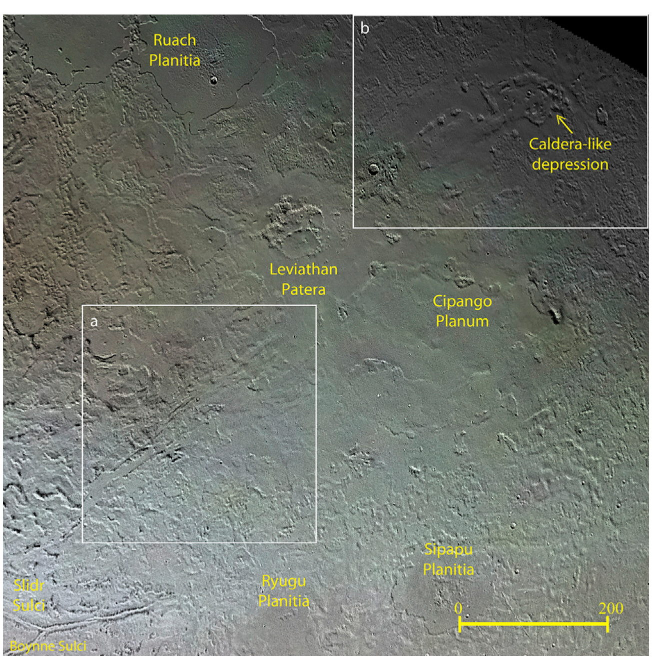

Fig. 1. Voyager 2 spacecraft mosaic image of *Raz Fossae* centered over Leviathan Patera and Cipango Planum. On the lower left corner, it can be observed the “Y” junction of Slidr and Boynne Sulci. In the upper right corner, it can be seen a “caldera-like depression” that limits the North trough set towards the north. White boxes indicate the two studied structures. Scale is in km.

We have analyzed mosaic images taken by Voyager 2 spacecraft to study and characterize in detail this Tritonian structure. Using USGS Integrated Software for Imagers and Spectrometers (ISIS) (https://isis.astrogeology.usgs.gov/), we first performed a data clean-up to correct and remove image artifacts or data drop-outs. Secondly, we proceed with the geometric processing of the image to transform it from spacecraft camera orientation to a common map coordinate system; using an orthonormal projection which places the observation point perpendicular to the image. Our analysis has allowed us to observe that north of Leviathan Patera and Cipango Planum (Fig. 1) there is a terrain area with smooth appearance limited by two parallel scarps and whose lighting characteristics are similar to those of *Raz Fossae*: west scarp has a high illumination (bright), east scarp has a low illumination (dark), which means that the part of terrain between both scarps is depressed. Therefore, this structure consists of a wide smooth floor trough limited by scarps, the same structural characteristics that defines *Raz Fossae*, which has been interpreted as a graben (Croft et al., 1995). Hereafter we will refer to them as North trough set, and will refer to the group of structures classically known as *Raz Fossae* as Raz Fossae Segment.

Later, we performed measurements of both length and width for both structures using ArcGIS® software (Fig. 2). Graben length was estimated along the structure, parallel to the troughs. In order to estimate the width, we have selected several zones, distributed throughout the troughs, where the boundaries of the trough were as sharp and clear as possible and do not exhibit significant evidence of modification or degradation. Both structures have been partially covered (the North trough set mainly) by *Leviathan Patera* and *Cipango Planum* materials, and the east escarpment of the North trough set is much degraded, we only have been able to select several zones in both structures. These zones were designated starting from north to south for each structure. Each zone has been designated with a letter (N or R) depending on the structure to which they belong and a number (1, 2, 3, 4) from north to south within each structure. Once selected, we proceeded to define the upper edge of the graben escarpments of both structures to perform accurate widths measurements. Last, we plotted several transects perpendicular to the structure troughs with a of separation between them of 0.7 km (Fig. 2b).

Raz Fossae Segment (Fig. 1) consists of several left-stepped en echelon troughs with plain floors, being the main trough of this structure about 260 km long, centered on 8°N, 21.5°E striking N51°E. The width of the main trough of this segment varies from 8.9 km to 11.9 km, with an average width of 10.3 ± 0.8 km. The southern limit is located about 161 km north of the “Y” junction of *Boynne Sulci* and *Slidr Sulci* ridges (Fig. 1), while the northern part of this segment is partially covered by *Leviathan Patera* and *Cipango Planum* materials being completely indistinguishable towards the north (Fig. 1). This structure has been usually interpreted as a graben system (Croft et al., 1995).

The North trough set (Fig. 1) is mostly covered by *Leviathan Patera* and *Cipango Planum* materials. It main trough consists in a wide smooth floor trough limited by soft scarps. Only a small part of the trough can be observed before it ends towards the North in a quasi-circular depression, interpreted as a caldera-like depression (see McKinnon and Kirk, 2006). The clearly visible part of this structure is centered on 22°N, 40°E, about 75 km long, striking N54°E. It presents an average width of 14.9 ± 2.0 km, widening apparently towards the NE, with minimum and maximum widths of 11.7 km and 19.7 km respectively in this segment. Fig. 3 shows a tectonic sketch map of both structures.

This North trough set presents the same structural characteristics of the previously defined Raz Fossae Segment: 1) Same strike (only 3° difference), 2) Trough with smooth floors limited by fault scarps. This troughs' set is located NNW with respect to Raz Fossae Segment. Both sets of troughs are not aligned, showing an en echelon left-stepped