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# Brittle ice shell thickness of Enceladus from fracture distribution analysis

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ABSTRACT

We determine the depth of fracture penetration in multiple regions of Enceladus by performing self-similar clustering and length distribution analysis of fractures. The statistical characterization of fault-population attribute, such as length and clustering, provide a productive avenue for exploring deformation rate, stress transmission mode, rheology of the medium, and mechanical stratification of the ice satellite. Through this analysis, we estimate the depth of the mechanical discontinuity of Enceladus' ice shell that is the depth to which fractures penetrate the brittle ice layer above the ductile one.

In this work, we find that for the South Polar Terrain (SPT), the brittle ice shell interested by fracture penetration is about 30 km and corresponds to the total depth of the ice shell because the SPT has a very high thermal gradient and, hence, fractures likely reach the ocean-ice interface. In the other regions analyzed, the depth of fracture penetration increases from 31 to 70 km from the South Pole to northern regions up to 75°.



## 1. Introduction

Enceladus is the smallest Solar System body that presents intense geologic activity on its surface. It is a heavily deformed satellite with a visible geological history stretching from billion of years ago to the present. The geologically-youngest region of the satellite is the strongly fractured area surrounding the South Pole, called the South Pole Terrain (hereafter SPT). The numerous cracks in the SPT appear to be directly related to high-energy effusive activity of vapor plumes revealed in images taken by the NASA Cassini spacecraft (Hansen et al., 2006; Porco et al., 2006; Porco et al., 2014). The SPT equally-spaced, tension fractures are known as "tiger stripes" (Yin and Pappalardo, 2015; Yin et al., 2016) and are in correspondence with high rates of heat flow indicated by thermal measurements (Spencer et al., 2006). The geologically active SPT has been interpreted as evidence of a liquid water reservoir beneath the South Pole (Collins and Goodman, 2007), and most likely below the entire ice crust (Patthoff and Kattenhorn, 2011). Estimates of the SPT total ice shell thickness have been derived using gravity and physical libration data, with values between 15 and 40 km (Iess et al., 2014; McKinnon, 2015; Thomas et al., 2016). The determination of the total ice shell thickness of Enceladus has important implications for both its thermal history and astrobiological potential. However, the mechanical boundary between the ice layer and ocean is not discrete, rather, the brittle ice layer is underlained by ductile ice that deforms in accordance with satellite strain rates and thermal gradients (Roberts and Nimmo, 2008). Temperatures near the surface of Enceladus are sufficiently cold and overburden pressures are sufficiently small that tectonic stresses are likely to result in brittle deformation exhibiting evidence of extensional deformation and strike-slip faulting.

The analysis of faults and fault populations on the icy satellite can reveal insight into the evolution of its surface that cannot be gained from other techniques. Statistical characterization of fault-population attributes, such as length and clustering, provide a productive avenue for exploring deformation rate**s**, stress transmission mode**s**, rheology of the medium**,** and mechanical stratification (e.g. Benedicto et al., 2003; Soliva and Schultz, 2008; Gudmundsson et al., 2010; Schultz et al., 2010; Gudmundsson et al., 2013).

For instance, fractal analysis has been utilized in terrestrial studies to determine the thickness of the fractured (brittle) crust (e.g., Mazzarini and D' Orazio, 2003; Mazzarini, 2004; Soliva and Schultz, 2008; Mazzarini and Isola, 2010). Similarly, on Enceladus we can constrain the depth at which fractures penetrate the brittle ice layer exploring some of the main characteristics of fault populations such as length and clustering. We provide thickness estimates of Enceladus' brittle ice crust in multiple regions using

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a structural geology approach that employs fractures' self-similar clustering and length distribution analysis. This method provides constraints on the depth of fracture penetration (still an unanswered problem) (Rudolph and Manga, 2009), and demonstrates the prevalence of fractal populations of faults on Enceladus.

The paper is structured as follows: after mapping the distribution of fractures belonging to five different regions of Enceladus, we analyze their length distribution and self-similar clustering (Bonnet et al., 2001; Bour et al., 2002; Gudmundsson et al., 2013). We compare the SPT pattern-fracture results with literature (Gioia et al., 2007; Smith-Konter and Pappalardo, 2008; Rudolph and Manga, 2009; Olgin et al., 2011; Iess et al., 2014; Yin et al., 2015) to assess the reliability of our approach and, finally, we extended the analysis to all datasets providing the behavior of fracture penetration in the Enceladus ice shell up to 75°N latitude.

## 2. Case study

We analyzed patterns of fractures located in different regions of the icy satellite to which we applied the fractures' length distribution and self-similar clustering analysis, explained in the Method section. We used the Enceladus mosaic from images acquired by the Imaging Science Subsystem (ISS, onboard NASA Cassini spacecraft) that consists of a wide-angle camera and a narrow-angle camera (Porco et al., 2005). The narrow-angle camera provides high-resolution images of targets of interest, while the wide-angle camera allows a more extended spatial coverage at lower resolution. The global mosaic used as a base map is provided by USGS and contains 586 images in various filters (color, green, UV3, and infrared 3), selected for the control network (Becker et al., 2016). Images were selected according to coverage, quality and spatial resolution ranging between 50 and 500 m/px with phase angles less than 120°. Some existing gaps in the global coverage (between 90°N and 50°N in places) were filled with one image from NASA's Voyager 2 spacecraft, which visited Enceladus more than 25 years ago. All the images underwent a high-pass filter to remove low frequency albedo and enhance the surface fractures and structures. The map is projected as equidistant (simple cylindrical) with a scale of 110 m/px at the equator (Fig. 1). The mean radius of Enceladus used for projection of this map is 252 km (Becker et al., 2016).

We mapped fractures in five different regions improving the recently published geological map of Crow-Willard and Pappalardo (2015), following the same definition criteria of their structural interpretation. In particular, we have taken into account the fractures located in well-defined geological units. On these fractured terrains, we improved the mapping of the *wide troughs* and *narrow troughs* (Fig. 1). The *wide troughs* are defined by Crow-Willard and Pappalardo (2015) as relatively long (> 100 km long and > 2 km wide) curvilinear features in planar view, which often present branched tips and appear rounded smooth in cross section. The *narrow troughs*, commonly shorter than the *wide troughs*, present a width < 2 km and cross cut other geologic units and structures (Crow-Willard and Pappalardo, 2015). Troughs are the most widespread structural feature on the satellite's surface and, in this work, we focused particularly on the narrow ones, being larger in number and most likely related to recent/incipient brittle tensional deformation of the ice shell (Crow-Willard and Pappalardo, 2015). Along with the *narrow troughs*, we also mapped the features interpreted as tension fractures (Yin and Pappalardo, 2015) with steep walls, almost constant aperture and lateral tips often exposed, that are present in evenly-spaced straight parallel sets. In our analysis, we focused particularly on tension fractures to investigate an interconnected fracture network, which could even work as pathway for cryovolcanic fluids (Bonini and Mazzarini, 2010).

The five different datasets used in the analysis are the following (Fig. 1):

- Dataset 1 (ds1): region around the South Pole (up to 50°S latitude) with 253 fractures mapped (Fig. 1b);
- Dataset 2 (ds2): region extending mainly in the southern hemisphere**,** centered at longitude value of 175°W (55°S - 10°N latitude, 165°W – 185°W longitude) with 384 fractures mapped (Fig. 1c);
- Dataset 3 (ds3): region extending down from the equator**,** centered at longitude value of 10°W (25°S – 0° latitude, 350°W - 40°W longitude) with 481 fractures mapped (Fig. 1c);
- Dataset 4 (ds4): Regions extending around the equator, more precisely centered at longitude values of 283°W (15°S - 25°N latitude, 265°W – 306°W longitude) with 328 fractures mapped (Fig. 1c);
- Dataset 5 (ds5): northern region centered at longitude value of 330°W (35°N - 75°N latitude, 315°W - 345°W longitude) with 85 fractures mapped (Fig. 1c).

The mapping was carried out with ESRI ArcGis software, calculating the fractures' length as well as the barycenter of each fracture in latitude and longitude. To reduce the deformation due to the image projection, we used a sinusoidal projection with a local reference meridian for each equatorial dataset, while a polar stereographic projection was applied for the south polar dataset (see Appendix A).

For the ds1 (South Pole region), which is mainly characterized by isooriented wide troughs, we considered fractures inside the central South Polar unit (csp), following the geological map nomenclature of Crow-Willard and Pappalardo (2015). We mapped the narrow branched troughs that crosscut and interact with the TSF, but we did not consider the southern curvilinear ($cl_3$) ring surrounding the SPT (Crow-Willard and Pappalardo, 2015). This region mainly consists of a belt of ridges and troughs that are subparallel to the outer limit of the central SPT, with two Y-shaped branches that depart radially from the $cl_3$ towards the trailing hemisphere. Within these branches, ridges and troughs are present and they appear convex towards the north in planar view (Crow-Willard and Pappalardo, 2015). A slightly complex tectonic history is hypothesized for the $cl_3$ unit. In particular, strike slip deformation was detected in some areas, mainly in the sub-Saturnian and anti-Saturnian margins (see Yin and Pappalardo, 2015), while compression was identified in the section facing the trailing hemisphere, especially localized on the Y-shaped branches. These features are interpreted as contractional fold and thrust belts that transition into extensional structures to the north, where extensional bookshelf structures were identified in the $cl_3$ section facing the leading hemisphere (Yin and Pappalardo, 2015). The most likely origin for such a complex structural framework in $cl_3$ is the SPT spread and lateral escape towards the trailing hemisphere, due to the presence of a near South-Pole-centered transient thermal anomaly (Barr, 2008; Yin and Pappalardo, 2015). Although the presence of tension fractures radial to the SPT margin and crosscutting the larger structures was spotted by several authors (Porco et al., 2006; Gioia et al., 2007; Yin and Pappalardo, 2015; Yin et al., 2016), their number is negligible for a fractal clustering analysis. For these reasons, the $cl_3$ region was not considered in this study.

Ds2 and ds3 were chosen inside the Cratered Plains unit ($cp_1$). This geologic unit is most likely the oldest one on Enceladus (crater age retention ~4.2–4.6 Ga, Porco et al., 2006, Kirchoff and Schenk, 2009) and presents heavily cratered terrain, including subducted material and shallow craters with sizes ranging between the image resolution and ~35 km (Crow-Willard and Pappalardo, 2015). $Cp_1$ bears morphologically fresh *narrow-troughs* crosscutting larger craters (up to 30 km) and in some places merging pit chains that suggest an incipient extension. On the other hand, the presence of