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Fracture density analysis at Stromboli Volcano, Italy: implications to flank stability

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Fracture density analysis at Stromboli Volcano, Italy: implications to flank stability

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Abstract. Stromboli volcano has experienced four sector collapses over the past 13,000 years, resulting in the formation of the Sciara del Fuoco (SDF); a horseshoe-shaped flank collapse scarp where episodes of instability are continuously observed and recorded. A NE / SW striking rift zone across the SDF and the western sector of the island is inferred to be a potential weakness zone for further instability episodes. This study reports new data of fracture density using remote sensing imagery, across within and outside the rift zone, to identify areas of damage that could reduce the edifice strength and promote fracturing. Pleiades satellite data of 0.5 m resolution was processed to highlight 23635 distinct linear features, determine fracture density across the island, and identify key areas of macro-scale weakness on the volcano. These data suggest that the SW sector of the island, including the summit area and the slopes of SDF, have an average fracture density between 1.18 – 2.73 x $10^{-5}\mathrm{m}^{-2}$ in contrast to the rest of the volcano that has an average fracture density of 4.56 x $10^{-6}\mathrm{m}^{-2}$. Analysis was also conducted on the orientation of fracture strikes across the volcanic edifice by analysing fracture data specifically associated with areas of intrusions and fissures: the NW / SE rift zone and the SDF. Preliminary results show that the average fracture strike ranged from between 030 – 047 NE/SW and thus broadly parallel to the inferred rift axis.

1. Introduction

Stromboli is the north easternmost island of the Aeolian archipelago in the Tyrrhenian Sea. The eruptive activity of this volcano is a consequence of tectonic activity between the Eurasian and African plates resulting in the subduction of the Ionian plate [1–3]. The volcano formed from a series of sheet and dike intrusions from a shallow magma chamber located 2-3 km below sea level and is characterised by a regular and short-duration explosive activity from active craters at the summit of the volcano, named Strombolian activity. From structural investigations conducted on the volcano a preferential NE – SW axis has been found to the various intrusions emplaced along the edifice (figure 1), suggesting that the island has been affected by extensional activity in this orientation [4,5]. Over the last 13 ka the island has experienced multiple phases of eruptive activity and subsequent sector collapses. This has resulted in the formation of multiple steep depressions (flank collapse scarps) around the island such as the well-known Sciara del Fuoco (SDF) on the NW side of the volcano. Field investigation carried out by Tibaldi *et al.*,[4] presents 109 sheet intrusions mapped around the Stromboli edifice, striking mostly NE and becoming more abundant toward the rift axis. They concluded that the presence of the rift zone controlled the NE/SW emplacement of sheets across the volcano. Using high resolution satellite data, this investigation aims to systematically investigate this hypothesis by quantifying the extent to which the rift zone and areas of intrusive events have influenced the location, direction and density of fractures across the volcano.

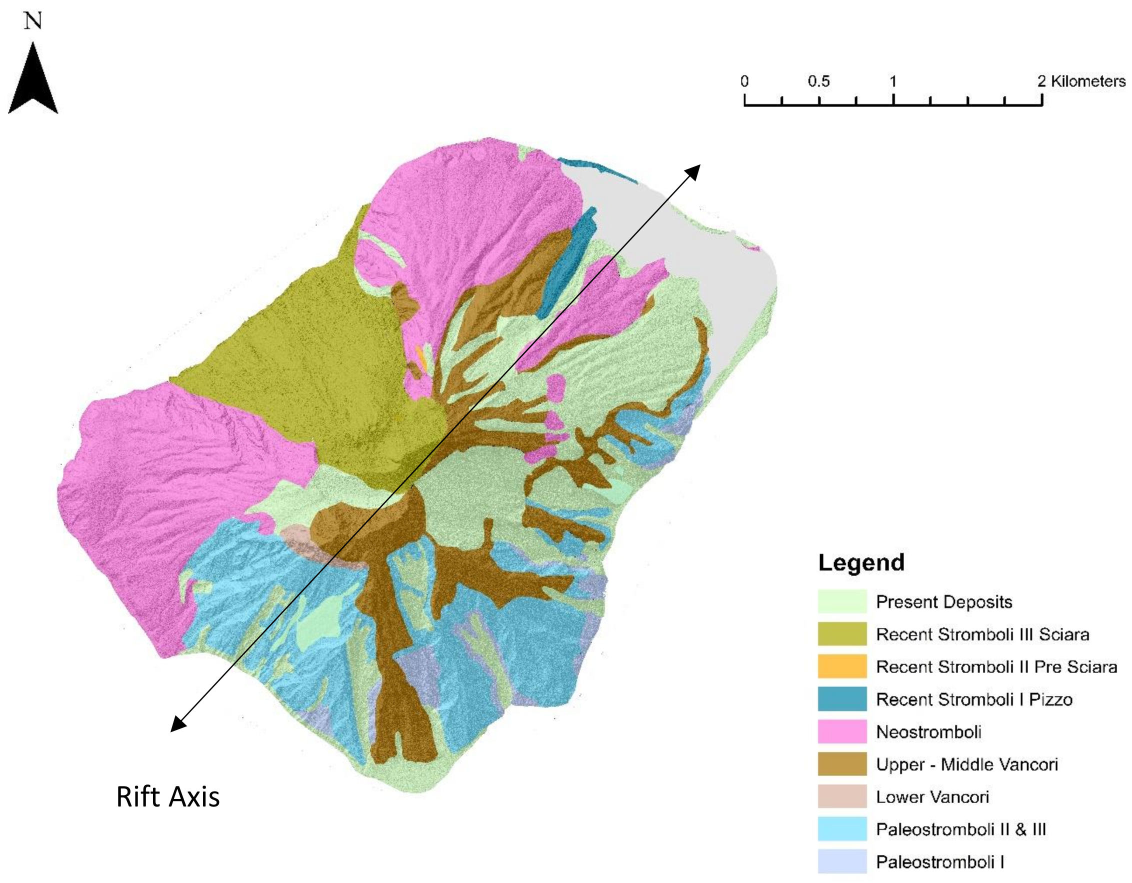

Figure 1. Geological map of Stromboli showing the main geological units and the NE / SW trending rift axis on the island.

2. Method

A 0.5 m resolution digital elevation model (DEM) was generated from Pleiades satellite images to assess the distribution of fracture networks across the island (figure 2). Structural features associated with episodes of intrusions and tectonic lineaments were recorded and classified using both aerial and field photographs as well as previous structural surveys [6,7] . Fracture maps of the island were subsequently processed using the fracture mapping MatLab toolbox FracPaQ [8]. This toolbox was used to quantify the fracture density and preferential orientations from the DEM allowing these to be linked to the rift processes that have taken place during the life span of the volcano. The code employs the Mauldon [9] method to determine the length of fracture segments, their strike and density within a selected area. FracPaQ was used to create a comparative study of fracture segments from extrusive locations and overlay these onto the structural features in and around the SDF and NE / SW rift zone.

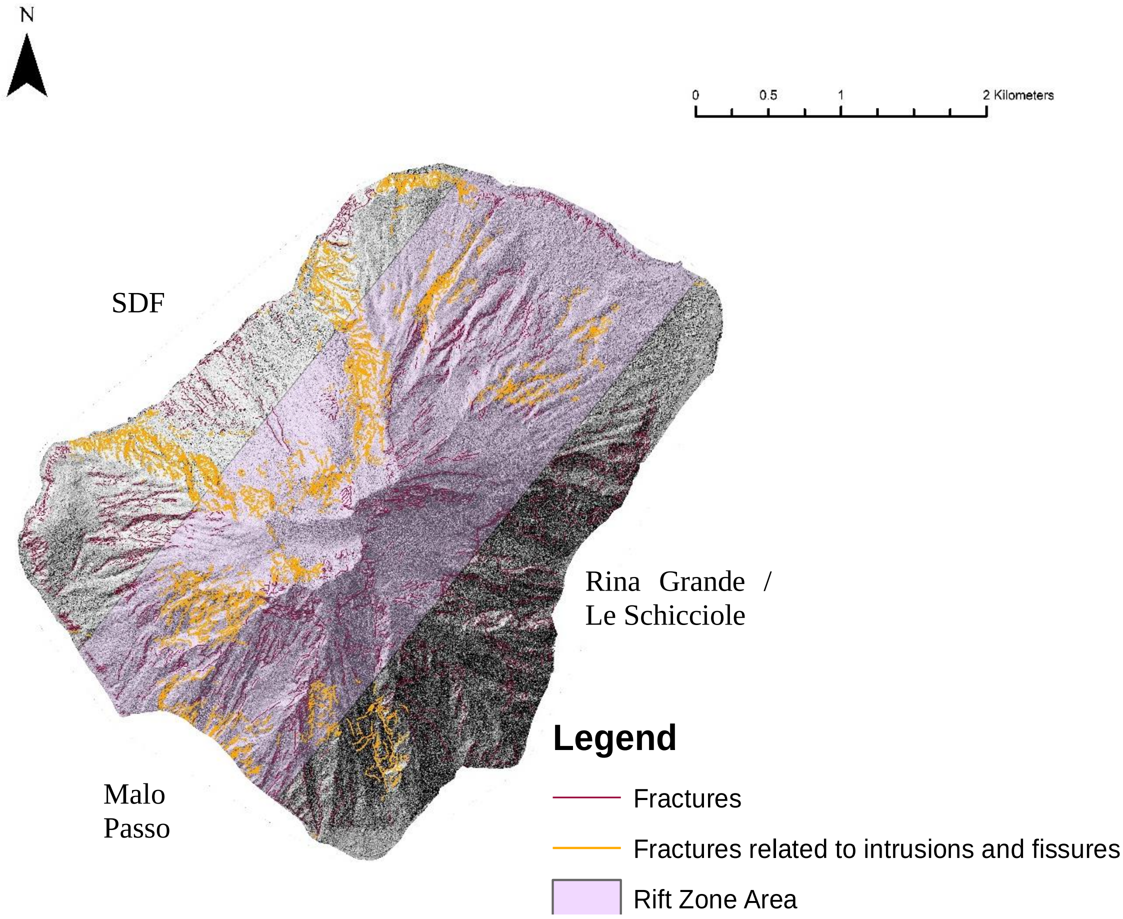

Figure 2. Fracture map of Stromboli using 0.5 m resolution Pleiades satellite images. Fractures have been separated between occurred near areas of intrusions and fissures (orange) using Tibaldi *et al*., (4) structural map that highlights areas of sheet intrusions and fissures surrounding the edifice. Fractures that are not related to eruptive events are primarily located near collapse scars such as the Rina Grande / Le Schicciole and Malo Passo. These fractures have an average length and strike of 21 m and 049.

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3. Results

3.1. Fracture analysis

A total of 23635 linear segments were processed through FracpaQ. Fracture density data generated using FracPaQ show that nearly 50 % of the total fracture density calculated across the island was concentrated around areas of intrusions and fissures (figure 3) with the remaining 50 % distributed along the coastline of the island and around the upper echelons of the edifice (Malo Passo & Rina Grande/Le Schicciole) where previous collapses have taken place. Fracture density was separately calculated along the rift zone (figure.4a) and for the SDF (figure. 4b). Higher concentrations of fracture density around intrusions and fissures (1.5×10^{-3} to 3×10^{-3} m^{-2}) were located around the summit and slopes of the SDF, the rocks of the upper to middle Vancori collapse, and on the north western side of island along the Vallonazzo fissure. Similarly, fracture density concentrations within the rift zone (5×10^{-4} $m^{-2} - 9 \times 10^{-4}$ m^{-2}) were also concentrated around the upper to middle Vancori caldera collapse, the top of the SDF, and along extrusive fissures on the northern slopes of the volcano. The highest fracture density values around the SDF (3×10^{-3} m^{-2}), were measured around the western side of the scarp along the boundary between the Sciara and Neostromboli units as well as at the active caldera at the top of the slope. The average fracture strike direction for the whole of the island was 041 (NE/SW). The mean strike of segments from areas studied in figures 3 & 4 ranged from 036-047 (NE/SW). The fractures are broadly parallel to the strike of the NE /SW rift zone.

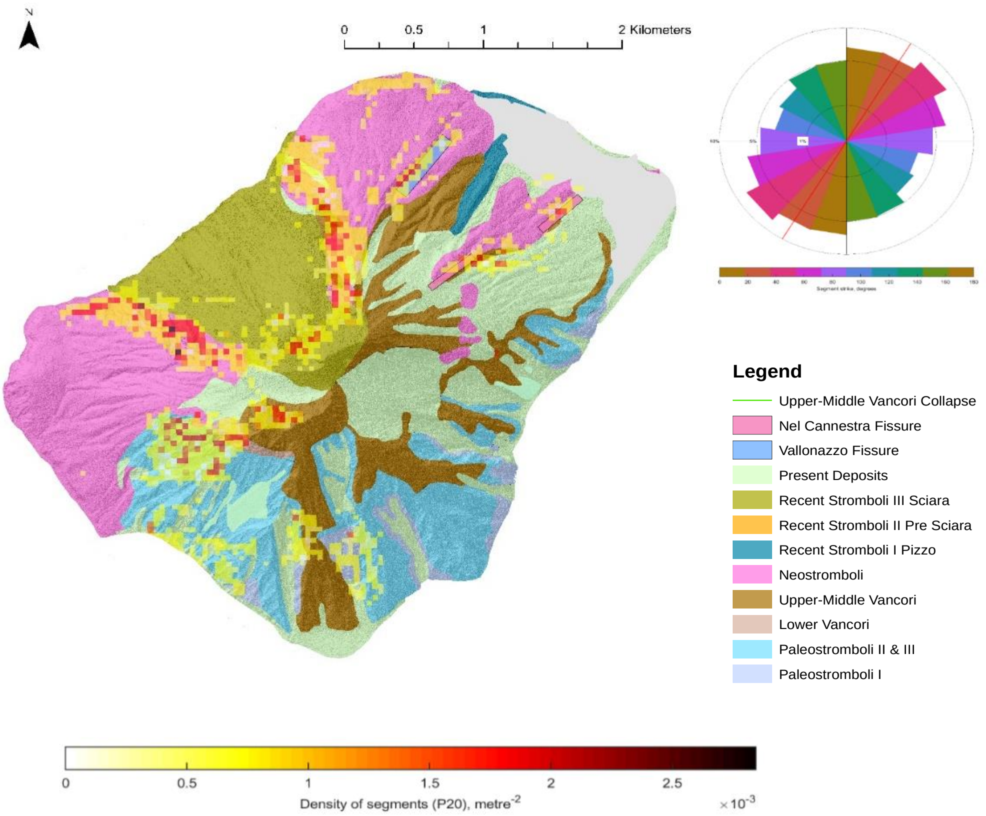

Figure 3. (Right) Fracture density map of intrusions and fissures on Stromboli. (Left) Rose diagram showing the distribution of strike angles from intrusions and fissures.

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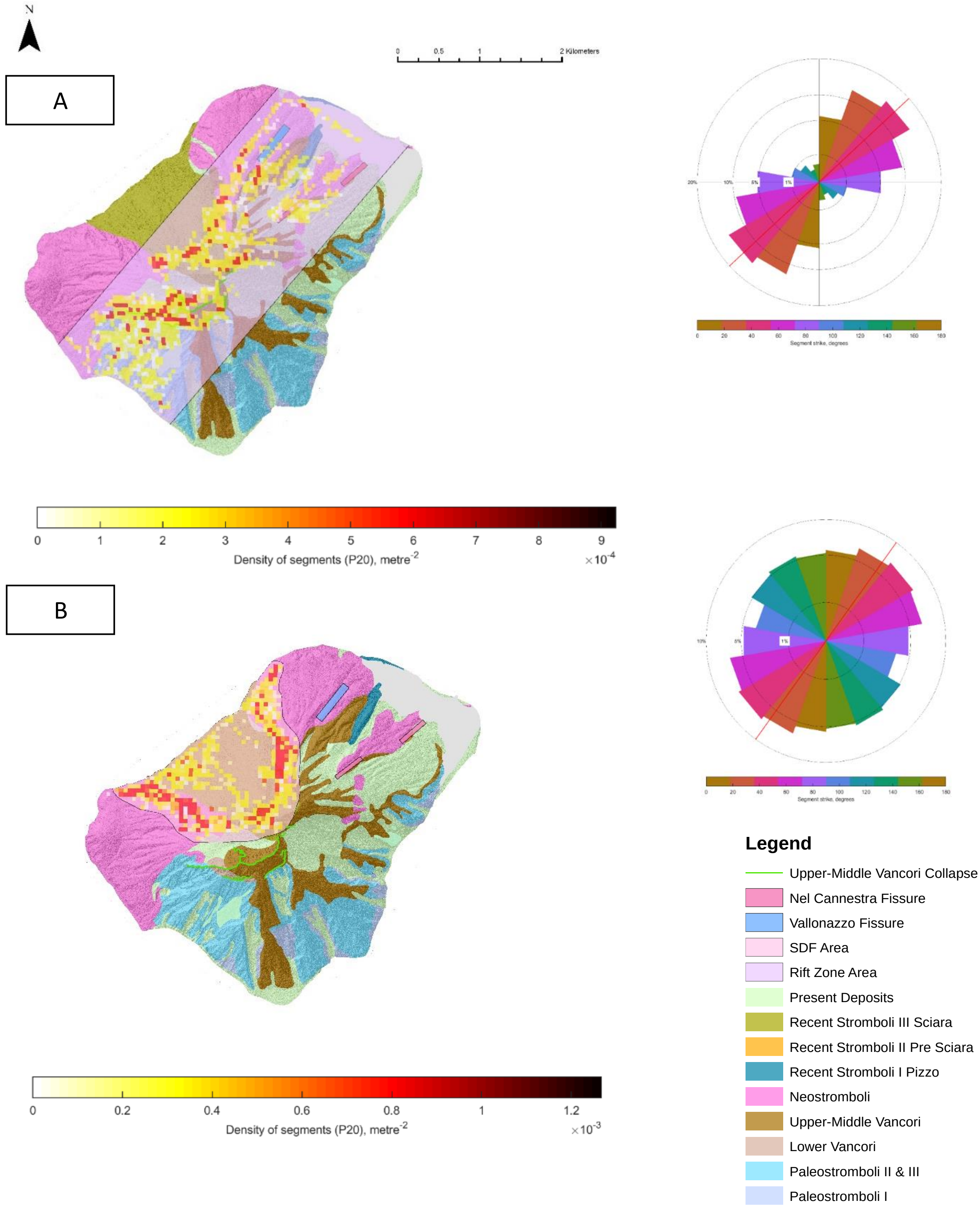

Figure 4. (A) Fracture density of the NE / SW rift zone across Stromboli. (B) Fracture density of the SDF.

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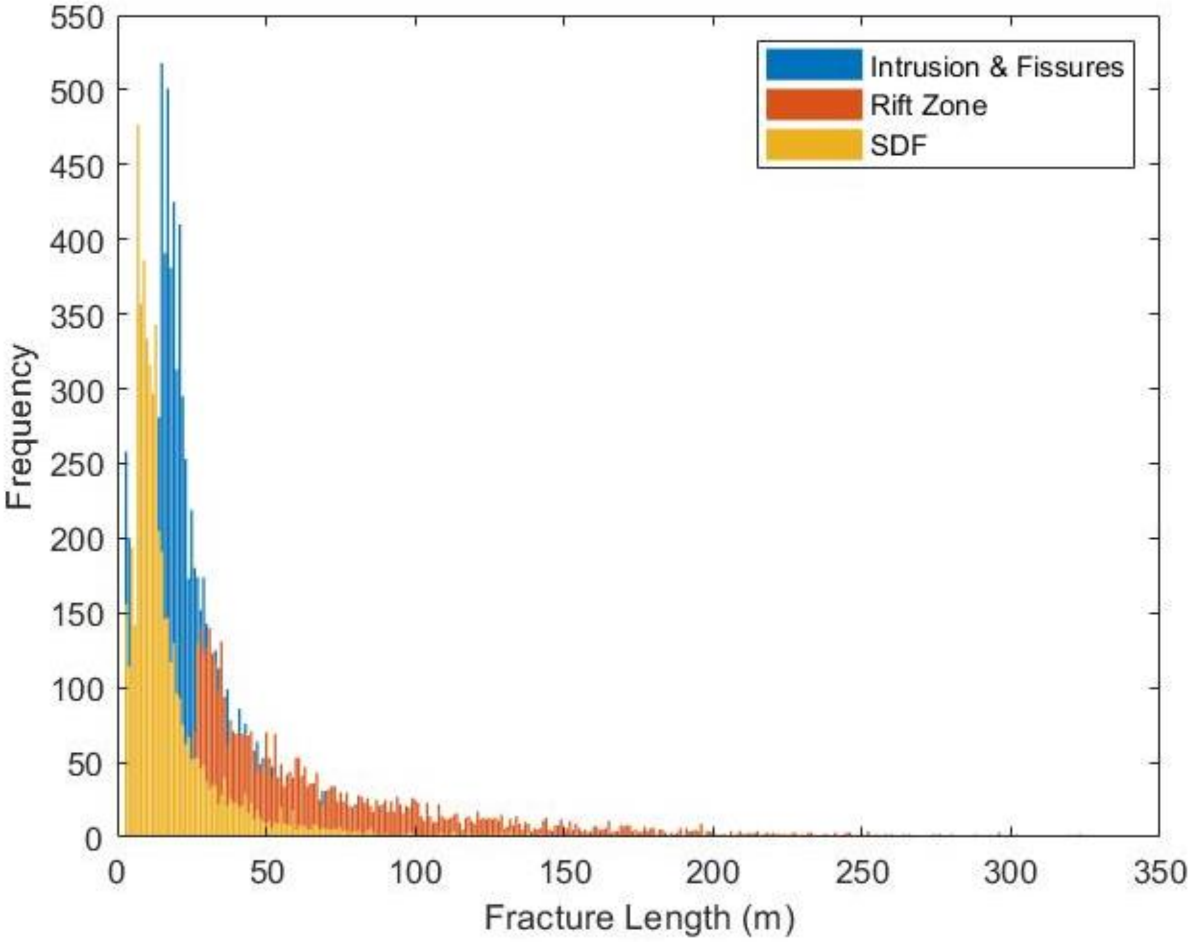

Figure 5. Stacked histogram of fracture lengths from areas of Intrusions and fissures around the island (blue), the rift zone (orange) and the SDF (yellow) as calculated from FracpaQ.

In total 9503 fractures were related to areas of extrusive activity with an average fracture length of 32 m. In contrast to the rift zone where 5547 fracture segments were recorded with the average length of fractures being 65 m. Similarly, 5551 fracture segments were recorded around the SDF with an average segment length of 20 m. In the 3 areas of specific interest in this investigation, Intrusions and fissures, the rift zone and the SDF, the frequency in fracture segment lengths from 0 – 50 m was 1504, 2592 and 369.

4. Discussion and conclusion

A fracture density analysis has been performed on the island of Stromboli using remote sensing (Pleiades 0.5m resolution satellite data) to assess the nature and localisation of fracturing processes related to regional tectonics and the continuous eruptive activity. Data was processed via the FraqPaQ model that applied a quantitative approach to the images and derived both a degree of localisation (density) and orientation of numerous widespread fracture networks across the volcano. These volcanic processes have likely resulted in fracture segments around areas of known extrusive activity and collapse and to tectonic lineaments. A preferential orientation for structural instability is inferred to be linked to a potential weakness zone, the NE/SW trending rift zone, resulting from the NW / SE direction of regional extensional around Stromboli, that has enhanced the NE trending intrusions emplacement [4]. Fracture density around the SDF, Vallonazzo Fissure and Upper-Middle Vancori caldera collapse was 3 to 5 times greater than areas that were not a clear morphological result of volcanic activity such as around Malo Passo and coast of the northern sector where fracture density is typically less than $1 \times 10^{-3}\ \mathrm{m}^2$. Fracture density assessment around the SDF is a useful method to determine the main points of weakness where sheet intrusions, previously mapped by Tibaldi *et al.,* [4], have influenced the stability of the slope subsequently leading to flank collapse events.

Orientation analysis also reveals that the average strike calculated from the areas studied in this investigation was close to parallel with the inferred NE/SW rift axis indicating a common trend in the direction of fractures from around the edifice [4–6,10,11]. Further evidence of a developing rift axis across the volcano can be observed by assessing the frequency of strike direction in the rift zone (figure 4a). Most fractures within the rift margin were close to parallel to the rift axis with < 1 % of total fractures not aligned to the rift. The main trend of fracturing is likely to be the product of volcano-tectonic forces such as high pressure and thermal erosion from the influx of magma acting upon pre-existing linear features or morphological features within host rocks that do not align with the stress field. When assessing fracture strike directions in the SDF and around areas of caldera collapse near intrusive emplacements, we see evidence for volcano-tectonic interactions influencing a preferential trend in the strike and propagation of fractures from their intrusive source. Fracture strikes around the SDF ranged from 0 - 359 which can be evidence for how dykes exploit and occupy pre-existing weaknesses to initiate flank collapses thus mould the slope into a horseshoe toe [12–14].

The range of fracture segment lengths from 0 - 579 m along the rift margin can be considered an expression of the dynamic nature of volcano-tectonic processes occurring along the rift zone. The frequency of larger fracture segments (over 50 m) was higher along the rift zone in comparison to areas subject to intrusions and fissures and the SDF where there was a higher frequency of fractures of less than 20 m. Higher fracture lengths within the rift zone can be interpreted as evidence for development of faulting at the regional scale along a rift axis, involving larger crustal volumes, as proposed by several authors [15–17] . Whereas the higher frequency of smaller fractures, such as those found in the vicinity of the SDF, may be credited to stress rotation in response to flank instability and subsidence associated with volcanic rifting acting at local scale [18-19].

The data gathered through satellite analysis supports evidence of a rift zone cutting through the edifice and the formation of volcano-tectonic features across Stromboli. Additional rock physics studies will be conducted to assess the internal mechanical characteristics of lavas on Stromboli at the block scale. Friction angles, P-wave velocity, and electrical resistivity measurements will be taken to integrate field scale seismic tomographies and to determine any pre-existing microstructure feature that could control the deformation and faulting and influence the development of slip surfaces.

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