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Technical note

Structural features of Panarea volcano in the frame of the Aeolian Arc (Italy): Implications for the 2002–2003 unrest

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ABSTRACT

Panarea, characterized by gas unrest in 2002–2003, is the volcanic island with the least constrained structure in the eastern-central Aeolian Arc (Italy). Based on structural measurements, we define here its deformation pattern relative to the Arc. The main deformations are subvertical extension fractures (63% of data), normal faults (25%) and dikes (12%). The mean orientation of the extension fractures and faults is ~N38°E, with a mean opening direction of N135° ± 8°, implying extension with a moderate component of dextral shear. These data, matched with those available for Stromboli volcano (pure opening) and Vulcano, Lipari and Salina volcanoes (predominant dextral motions) along the eastern-central Arc, suggest a progressive westward rotation of the extension direction and an increase in the dextral shear. The dextral shear turns into compression in the western arc. The recent unrest at Panarea, coeval to that of nearby Stromboli, may also be explained by the structural context, as both volcanoes lie along the portion of the Arc subject to extension.

1. Introduction

Defining the shallow structural configuration of a volcanic arc is fundamental for understanding the behavior of active and quiescent volcanoes at convergent settings. Volcanoes usually show a consistent along-arc structural setting, characterized by compression (NE Japan; Sato, 1994), strike-slip motions (Mexican belt; Tibaldi, 1992) or predominant extension (Taupo Volcanic Zone, New Zealand; Spinks et al., 2005). Significant structural variations are expected along longer arcs (Aleutians or Andes), where the direction of the arc changes with respect to that of plate motion.

The micro-Aeolian volcanic Arc, <200 km long, lies within the back-arc Tyrrhenian basin and is related to the NW-directed subduction of the Ionian slab below Calabria (Southern Italy; Fig. 1; Barberi et al., 1974; Gvirtzman and Nur, 1999; Chiarabba et al., 2008). It consists of a central portion (Vulcano, Lipari and Salina islands), N20°W aligned; an eastern arc (Stromboli and Panarea islands), NE-SW trending; and a western arc (Alicudi and Filicudi islands), WSW-ESE trending (Fig. 1a). Volcanism occurred between 1.3 Ma and 3040 years in the western arc, from 0.8 Ma to present in the eastern-central arc (De Astis et al., 2003, and references therein), with documented coeval unrests, such as in 2002–2003 (degassing at Panarea and effusive eruption at Stromboli). A lack of deep seismicity (>20 km) in the western arc suggests active subduction in the eastern sector only (De Astis et al., 2003, and references therein). While the western arc undergoes predominant compression (De Astis et al., 2003), the eastern arc undergoes predominant extension (De Astis et al., 2003; Neri et al., 2005; Billi et al., 2006).

The structural features of the eastern-central Aeolian Arc have been mostly investigated at Vulcano, Lipari, Salina (Mazzuoli et al., 1995; De Astis et al., 2003) and Stromboli (Tibaldi et al., 2003; Tibaldi, 2004). The Vulcano–Lipari–Salina alignment lies along a NNW-SSE trending dextral transtensive system (Tindari–Letojanni), controlling volcanic activity (Fig. 1b; Ventura et al., 1999) and surface expression of a tear in the slab (Gvirtzman and Nur, 1999; Billi et al., 2006). Stromboli is characterized by NE-SW trending extensional structures, controlling active volcanism and sector collapse (Tibaldi et al., 2003; Tibaldi, 2004).

The tiny NNE-elongated island of Panarea lies between Stromboli and Salina (Fig. 1a). Subaerial volcanism occurred between 200 and 8 ka (Gabbianelli et al., 1990; Calanchi et al., 1999; Lucchi et al., 2003). Most eruptive structures arising from this period cluster along the western coast, ~NNE-SSW trending, but NE-SW and NW-SE trending systems are present (Fig. 2; Lanzafame and Rossi, 1984; Calanchi et al., 1999). In 2002–2003, a submarine gas eruption, possibly related to the uprising of magmatic fluids, occurred ~2 km E of Panarea. A significant part of the associated fractures display the main strike of the NE-SW regional structures (Chiodini et al., 2006, and references therein; Esposito et al., 2006).

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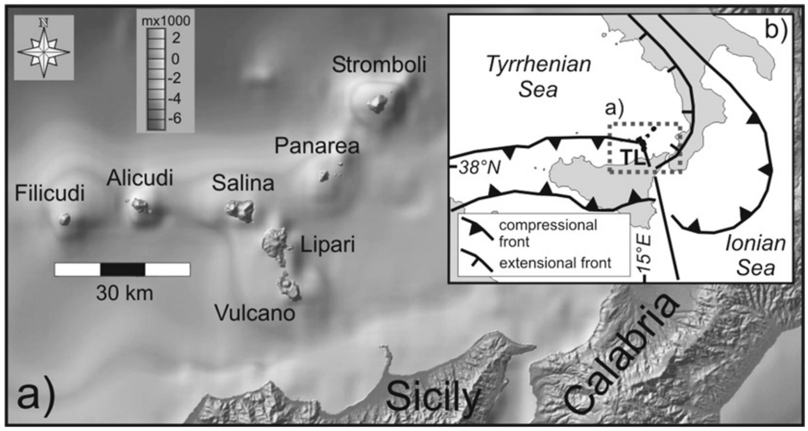

Fig. 1. The Aeolian Arc (a) and its tectonic setting (b).

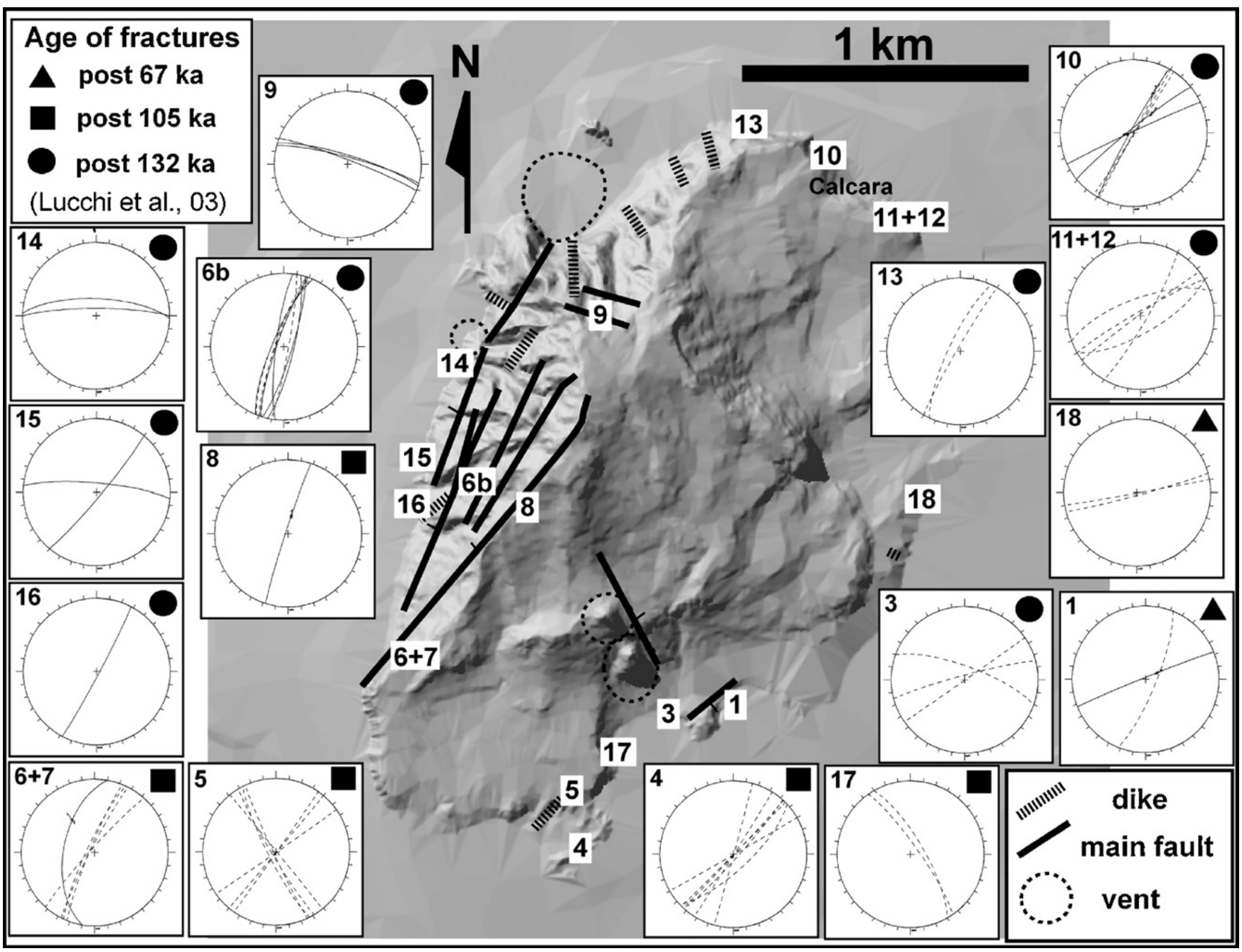

Fig. 2. Structural features of Panarea, on Schmidt's lower hemisphere nets; numbers, measurement sites; solid lines, faults; dashed circles, vents; symbols in upper right of plots, maximum age (Lucchi et al., 2003) of fractures.

Despite the many investigations at Panarea (Lanzafame and Rossi, 1984; De Astis et al., 2003, and references therein; Anzidei et al., 2005; Esposito et al., 2006), its onshore structural features are the least defined within the central-eastern Aeolian Arc, and a systematic structural approach is lacking. This work uses an original structural analysis at Panarea, to: (a) define its volcano-tectonic features and (b) place these in the tectonic context of the Arc, trying to explain its unrest in the regional frame.

2. Structural features of Panarea

To have a representative dataset, we considered previous descriptions of the deformations at Panarea (Lanzafame and Rossi, 1984; Calanchi et al., 1999, and references therein) and incorporated these into an original and systematic structural analysis.

The field analysis recognized 77 elements, consisting of extension fractures (63% of data), faults (25%) and dikes (12%). The limited

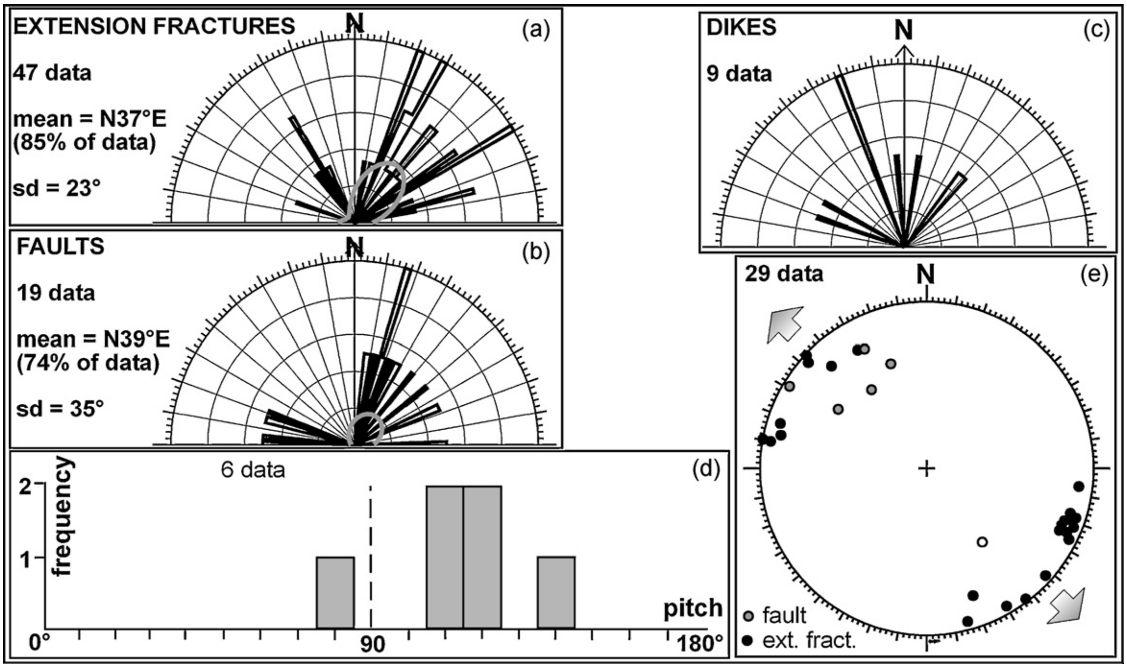

Fig. 3. Strike of extension fractures (a), faults (b) and dikes (c) at Panarea; (d) pitch distribution of the faults; (e) opening directions of extension fractures (black dots) and faults (gray dots).

amount of collected data results from the availability of accessible outcrops displaying deformation on the tiny island. The collected data have been weighted relative to each other (small, medium, and large structures), accordingly, with the following criteria. Extension fractures were weighted in consideration of their extent (from m to tens of m) and opening (from mm to cm). They were emplaced very close to the surface and are interpretable as tension fractures. Their subplanar geometry and subvertical attitude, their significant extent in the field, independent of lithology, permit inference of a tectonic origin, excluding any significant control of other processes (cooling, emplacement, and gravity). Faults were weighted in consideration of their inferred displacement (from a few tens of cm to a few tens of m). Dikes were weighted according to their thickness (usually in the order of a few m). A maximum age, based on the deposits on which the fractures are found, is inferred for each structure (Fig. 2; Lucchi et al., 2003); however, the minimum age could not be defined in most cases. It is anticipated that no variation in the significant deformation pattern with time is observable.

All the structural features are subvertical. The dikes do not show any preferred orientation, suggesting an overall radial pattern (Fig. 3c). Previous mapping (Calanchi et al., 1999, and references therein) suggests that this radial pattern is probably related to a magma-induced local stress field, associated with multiple vents in the NW and SE portions of the island. The extension (or tension) fractures have a mean N37°E strike, consistent with the mean N39°E orientation of the faults (Fig. 3a and b) and with that of the regional structures.

The faults have a predominant normal motion. Their precise kinematics could be determined only by observing the striations on the fault plane, estimating the pitch value (the angle that a slickenline makes with respect to the strike direction). The obtained pitches are usually consistent with values slightly >90°, suggesting a moderate component of dextral shear in addition to the predominant extension (Fig. 3d). Despite their limited number, all the faults with known pitch have a displacement of several meters at least and are therefore weighted as medium to large.

To reduce the impact of fault orientation in evaluating the extension directions, we determine the orientation of the minimum strain axes (Marrett and Allmendinger, 1990). Their stereographic technique permits the determination of the orientations of the maximum, minimum and intermediate strain axes. The extension direction is 45° from the slip vector along the plane that passes through the pole to the fault and the slip vector. These extension directions are consistent with a mean of N144° (Fig. 3e). The opening direction of the tension fractures was obtained for the 23 largest systems. Assuming that their strike is orthogonal to the least compressive stress $\sigma 3$, their mean opening direction is N127° (Fig. 3e). Therefore, the normal faults and tension fractures formed at Panarea in the last ~130 ka show a mean extension direction of N135° ± 8° (Fig. 3e).

The on-shore fumaroles are consistent with NE-SW fractures (measure sites 10, 11, 12; Fig. 2). These are in part similar in direction to those, NE-SW to E-W trending and NW-SE trending, recognized or inferred offshore, associated with the 2002–2003 unrest (Anzidei et al., 2005; Esposito et al., 2006). This suggests that the on-shore and offshore hydrothermal system is, at least in part, controlled by regional structures. Therefore, regional tectonics may provide the control on a significant part of the degassing episode.

3. Discussion

The collected structural data constitute the most complete dataset obtained so far at Panarea, which includes, in a systematic way, faults and fractures. It allows us to define the fracture pattern on the island, as well as its associated mean extension direction. This is N135°, similar to the mean extension direction (N123°) obtained with an earlier and smaller dataset (De Astis et al., 2003, and references therein).

Our structural data at Panarea are compared to those, already a significant amount, previously collected at the neighboring volcanic islands. At Stromboli, the NE-SW trending extension fractures and faults (except those related to sector collapses) of the last 100 ka show an overall ~NW-SE extension direction (Tibaldi et al., 2003; Tibaldi, 2004). Their detailed measurement gives a mean of N151° ± 7°. At Vulcano, Lipari, and Salina the NNW-SSE trending extension fractures and faults of the last 400 ka show an overall ~E-

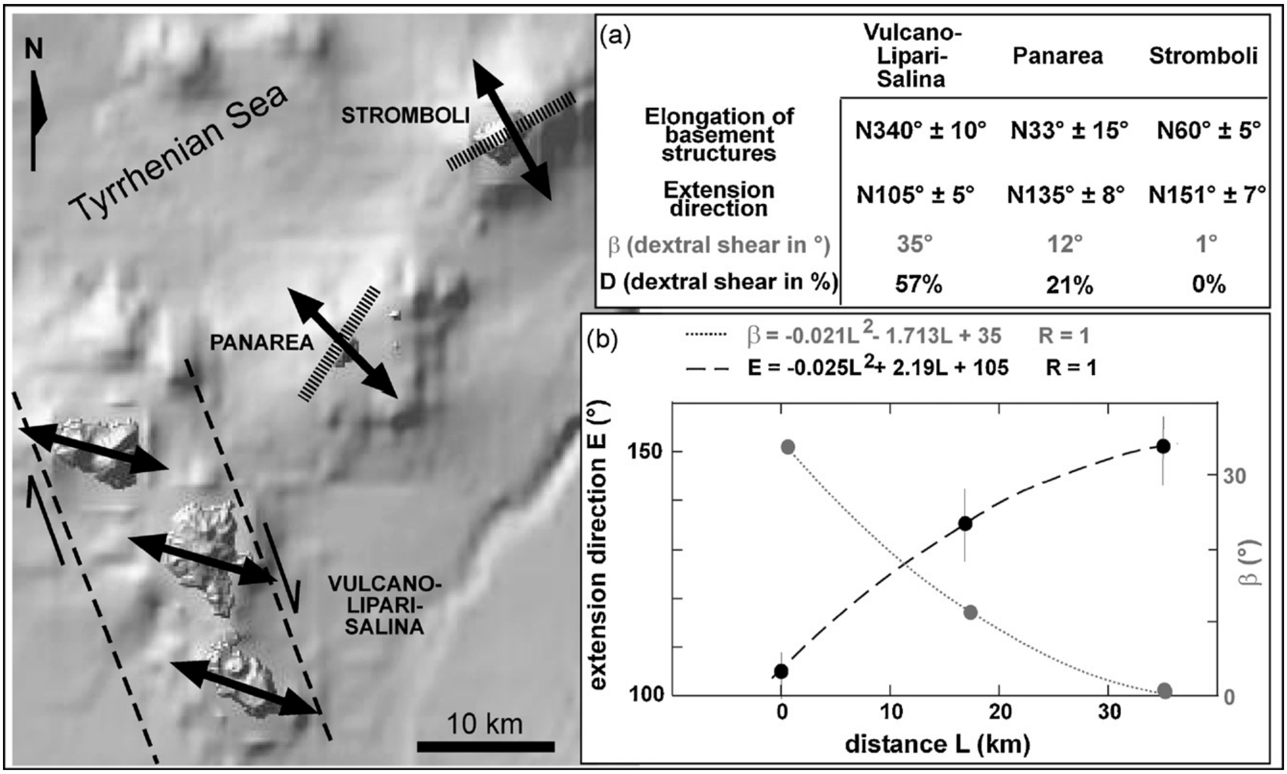

Fig. 4. Variation of the extension direction (black arrows) along the eastern-central Aeolian Arc, at Stromboli (Tibaldi, 2004 and references therein), Panarea (this study) and Vulcano–Lipari and Salina (De Astis et al., 2003 and references therein). Insets (a) and (b), respectively show the data and diagram of variation of the extension direction (in black) and amount of dextral shear (in gray) with distance along the Arc.

W extension direction (Mazzuoli et al., 1995; Ventura et al., 1999; De Astis et al., 2003). Their detailed measurement gives a mean of N105° ± 5°. In combination, the available data reveal a progressive eastward clockwise variation in extension direction, from N105° to N135° to N151° (Fig. 4a). The variation, shown in Fig. 4b, refers to the last ∼100 ka at least (maximum age of the deformations common to all the islands). This behavior is consistent with that constrained on the Calabria–Sicilia margin, suggesting a progressive rotation from an ∼E-W to a NW-SE direction (D'Agostino and Selvaggi, 2004; Goes et al., 2004; Pondrelli et al., 2004).

To obtain information on any horizontal shear, we relate these extension directions to the direction of the regional structures at each volcano, as produced by the tectonic stress. Detailed information on regional structures in the offshore domain is scarce (De Astis et al., 2003). One possibility is to consider as representative of the regional setting the mean direction of the fractures measured at the surface. However, the obtained value may be affected by the presence of scarps near unstable flanks (Tibaldi, 2004, and references therein) or, more generally, volcanic activity, and thus not represent the true tectonic setting. The elongation of a volcano usually results from the activity of a major structure at its base, parallel to the elongation direction, which enhances the rise and emission of magma along a preferred trend (e.g. Nakamura, 1977; Tibaldi, 1995). For these reasons, the direction of elongation of the base of the volcano is considered as representative of the regional structural setting.

To evaluate the direction of elongation of the base of the volcano, we considered previously published data from accurate bathymetric maps (Favalli et al., 2005). The elongation of the base of the Vulcano–Lipari–Salina group and Stromboli may be readily calculated as coinciding with the main axis of the ellipse encircling the submerged portion of the volcano (or group of volcanoes), in map view. The ellipses encircling the submerged portion of Stromboli and Vulcano–Lipari–Salina have a moderate eccentricity E (where E = length of minor axis/length of major axis of the ellipse), and their main axis (or elongation) can be evaluated with a small uncertainty. However, the ellipse encircling the base of Panarea shows a higher eccentricity (Favalli et al., 2005) and thus the direction of its major axis has a higher scatter, of ∼15°; (Fig. 4); still, this uncertainty is interpreted as reasonable to estimate the trend of the base of Panarea.

The base of Stromboli is oriented at N60°E ± 5°, perpendicular to the obtained extension direction and the volcano is therefore subject to orthogonal extension (Fig. 4a). The base of Panarea is oriented at N33°E ± 15°, slightly obliquely to its extension direction, with a moderate component of dextral shear (consistent with fault slip data). The base of the Vulcano–Lipari–Salina volcanoes is oriented at N340° ± 10°, highly oblique to the extension direction, with a predominant dextral shear. This progressive kinematic variation is expressed by β (difference between opening direction and direction of pure extension) and the related percentage of total strain $D = \sin \beta$. At Stromboli, $\beta = 1°$ gives $D = \sin 1° = 0$; at Panarea, $\beta = 12°$ gives $D = \sin 12° = 21\%$ of the total strain; at Lipari–Salina–Vulcano, $\beta = 35°$ gives $D = \sin 35° = 57\%$ of the total strain (Fig. 4b). The correlation of the quadratic best-fit curve in Fig. 4b suggests that the variations in the extension direction and the angle β along the arc are not linear. In the western Arc, compression predominates (Goes et al., 2004; Neri et al., 2005; Billi et al., 2006).

The 2002–2003 unrests at Panarea and Stromboli may find an explanation in such a structural context, as both occurred in the extended portion of the Arc, activating a quiescent (Panarea) and an active (Stromboli) volcano. Extension may facilitate the local rise of deep fluids in the eastern Arc. In the short-term, this rise of fluids might be enhanced by tectonic earthquakes, such as the September 2002 $M = 6.0$ earthquake that occurred ∼130 km to the W of Panarea (Capaccioni et al., 2007; Cigolini et al., 2007; Walter et al., 2009). Vulcano, subject to predominant dextral shear and known for its hydrothermal activity, did not show any significant response immediately after the earthquake. In fact, variations in the temperature and composition of the fumaroles here were observed only from November 2004 to December 2005, and are interpretable in the frame of the variations quite consistently observed every decade (Granieri et al., 2006).

One may speculate whether volcanoes situated in an extensional context are more likely to become the focused sites of rising fluids and lead to coeval volcanic activity. Hence the tectonic setting appears to be important for controlling volcanic activity in both the short- and the long-term. Therefore, for understanding the interaction of volcanic activity and tectonic events, the regional tectonic framework and state of stress needs to be taken into account. This may help to better understand why some volcanoes become activate after earthquakes while others are not, as exemplified by the events that took place in 2002 in the Aeolian Islands.

4. Conclusions

This study allows the following points to be made:

- the overall fracture pattern of Panarea has been evaluated through a systematic approach considering the main structural features (faults and extension fractures) of the island;
- the progressive variation in the extension direction, as well as of the kinematics, through the central-eastern portion of the Arc has been recognized;
- the structural context of the eastern portion of the Arc may help explain the unrests observed in 2002 at Panarea and Stromboli, as both volcanoes lie along the portion of the Arc subject to extension.

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