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Evidence of tectonic control on active arc volcanism: The Panarea-Stromboli tectonic link inferred by submarine hydrothermal vents monitoring (Aeolian arc, Italy)

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[1] The combination of the latest geophysical instruments and geochemical methods applied to the arc volcanism (Aeolian Islands, Italy) has given new insights on the role of active tectonics on fluids migration. A continuous monitoring of the hydrothermal system off the island of Panarea has shown contemporaneous modifications of the vented fluids and the seismic activity of the nearby Stromboli volcano. The almost contemporary start of the last volcanic crisis at Panarea and Stromboli in 2002, besides the contemporary variation of the $^3He/^4He$ ratios at both the islands and the large number of submarine crater-shaped structures at Panarea, bears testimony to interconnections between the volcanic edifices. To confirm a tectonic drive of magmatic fluids over volcanic arcs implies that episodes of volcanic unrest can be triggered by the tectonic activity increasing the volcanic risk for the whole area, and this might be the case of the Stromboli-Panarea volcanic complex. **Citation:** Heinicke, J., F. Italiano, R. Maugeri, B. Merkel, T. Pohl, M. Schipek, and T. Braun (2009), Evidence of tectonic control on active arc volcanism: The Panarea-Stromboli tectonic link inferred by submarine hydrothermal vents monitoring (Aeolian arc, Italy), *Geophys. Res. Lett.*, *36*, L04301, doi:10.1029/2008GL036664.

1. Introduction

[2] Submarine hydrothermal systems occur in different tectonic settings (e.g., axial zone of the East Pacific Rise, Mid-Okinawa Trough Backarc basin, arc volcanism of the Aeolian Islands). Hydrothermal fluids are normally acid, hydrogen sulphide and metal-rich of high temperature water-rock interactions origin, in areas where magmatic masses had placed in recent times. The investigations carried out off Panarea Island revealed that the vented fluids, consisting of both CO_2-dominated gases and thermal waters (temperature in the range of $40 \div 135°C$) are an expression of recent volcanic activity [*Italiano and Nuccio*, 1991]. The submarine hydrothermal system is controlled by the NE-SW, NW-SE regional faulting systems (Figure 1), which activity is testified by deeper hydrothermal deposits right along the N40°E tectonic line joining Panarea and Stromboli [*Gamberi et al.*, 1997].

[3] The November 3rd, 2002 gas burst episode (Figure 1) occurred at the end of a prolonged seismotectonic paroxysmal period in southern Italy. From autumn 2002 on, a series of seismotectonic paroxysmal events hit the Tyrrhenian Sea and adjacent areas, as the M = 5.6 earthquake on 6/9/2002 with epicenter located between the Aeolian Arc and Ustica Island (*Azzaro et al.*, 2004), the onset of the Mount Etna eruption on 27/10/2002, the gas burst episode near Panarea Island on 3/11/2002, the onset of the Stromboli eruption phase on 28/12/2002 with subsequent lava flow episode and the paroxysmal explosion of April 5, 2003, the largest one since the September 11, 1930 eruption [*Cesca et al.*, 2007].

[4] The vicinity of the single events and their temporal coincidence may suggest a supra-regional correlation, that has to be carefully analyzed, without overstating or underrating the single phenomena. The wide-scale regional activity seems to be started by the 6/9/2002 earthquake which fault plane solution (FPS), determined by MedNet applying the Centroid Moment Tensor method and reported by *Azzaro et al.* [2004], indicates a NE-SW striking thrust fault which correlates well with FPS of the strongest aftershock ($M_L = 4.3$) and the spatial alignment of the entire aftershock sequence. Although we deal with wide-scale activities, it must be pointed out that the epicentre is located 100 km W of Panarea and hence well outside our study area.

[5] To better understand the ongoing volcano-geothermal activity, periodic samplings were carried out showing changes in the fluid geochemistry and the flow rate of the venting hydrothermal fluids [*Caracausi et al.*, 2005a; *Capaccioni et al.*, 2007]. However, the sampling intervals were too large to evaluate short time-scale temporal modifications. To overcome this problem, continuous monitoring was carried out at selected vents during 2006–2007, three years after the end of the volcanic crisis. Previous experiences, such as continuous recordings in the Aegean Sea [*Aliani et al.*, 2004], in NE Taiwan [*Chen et al.*, 2005]) and long-term monitoring (one year) at the TAG hydrothermal mound [*Sohn*, 2007], had chiefly focused on temperature and bottom pressure measurements. Apart from those parameters, our investigations also focused on the gas flow rate, detected by a new device able to monitor the acoustic emission produced from the gas bubbles of submarine vents.

[6] This paper accounts for the unexpected acoustic (namely gas flow) and thermal anomalies correlated to the seismic and volcanic activity of Stromboli volcano. The adjacency of the degassing phenomena observed at Panarea and the intensification of the Stromboli volcanic activity

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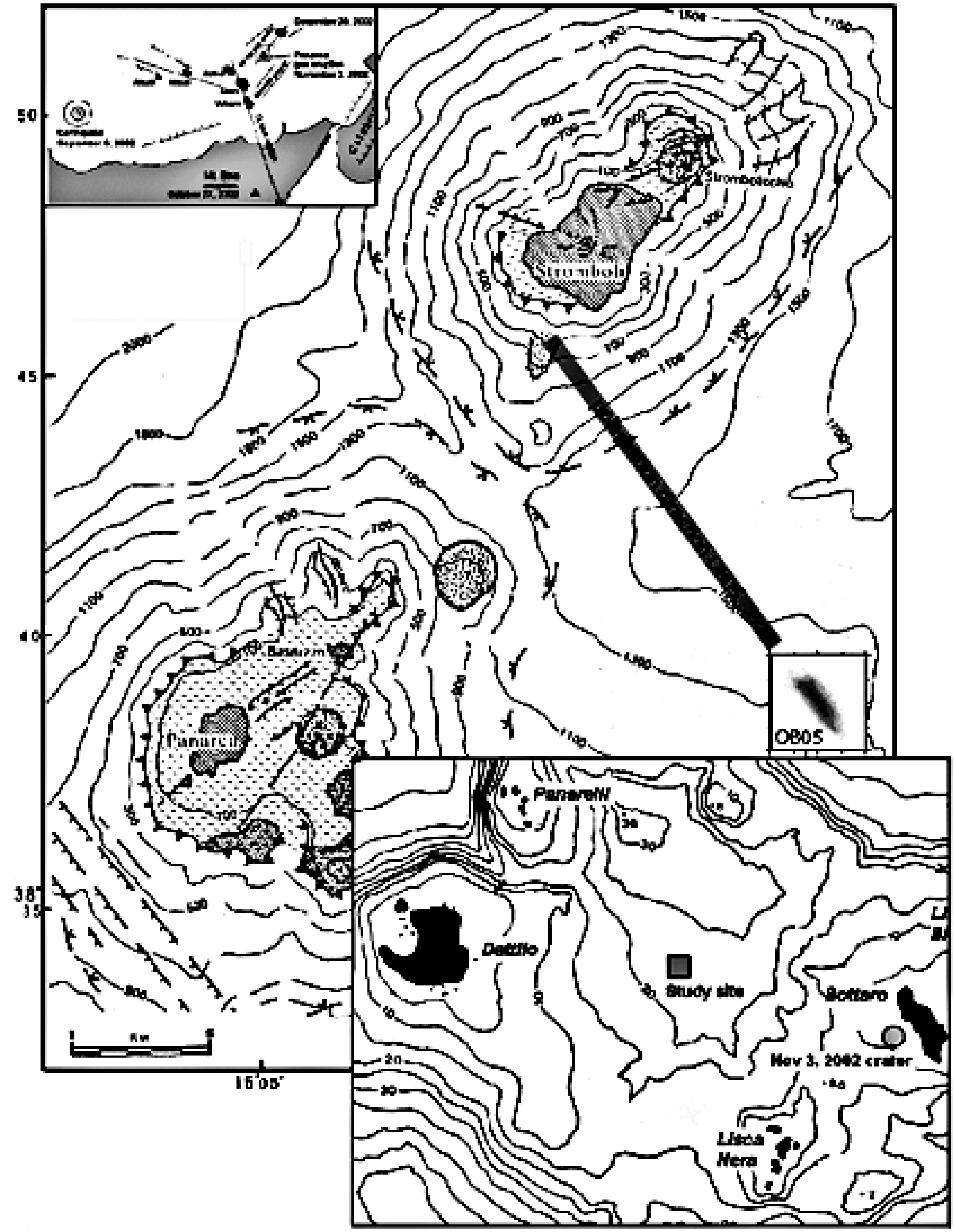

Figure 1. The volcanic edifices of Panarea and Stromboli elongated along the NE-SW trend. The submarine hydrothermal vents off Panarea island are regulated by the main tectonic structures of the Aeolian islands. The study site (38°38′14″N, 15°06′18″E) and the crater (38°38′14″N, 15°06′34″E) produced by the submarine blast of November 2, 2002, are shown by the grey marks (squared and circular, respectively). The small squared box shows the polarization plot of the tremor-like signals observed at the ocean bottom seismometer OB05 by *Dahm et al.* [2002].

suggests an interconnection between the volcanic islands, which we will attempt to address here.

2. Methods

[7] The outlet temperature and the degassing rate were continuously monitored at a study site (Figure 1) from September 2006 to April 2007. The geochemical data from the discontinuous-based monitoring were collected following literature methods [e.g., *Italiano and Nuccio*, 1991]. The $^3He/^4He$ ratios were measured by a VG 5400-TFT mass spectrometer (resolving power of 600 at the 5% peak height; error <1%). A new acoustic-based bubble counter probe (Acoustic Bubble Counting, ABCO) was applied to the bubbling gases and provided information on the degassing rate. The ABCO probe is sensitive to the sound emitted during the bubble formation [*Leighton*, 1994]. The acoustic noise at the vent covers a frequency spectrum from 0.5 to 3 kHz as a function of the bubble sizes. The sound intensity produced by the whole spectrum is recorded as an analogical signal and turned into digital pulses providing a signal whose intensity per time unit (counts sec^{-1}) is log proportional to the gas flux as shown by laboratory experiments. The temperature of a thermal water vent was measured by a Pt100-type probe.

3. Results and Discussion

[8] The results of the continuous gas flow rate and temperature are displayed in Figure 2 where is also reported the seismic activity of the nearby Stromboli volcano. The collected data show short-term variations induced by earth tides, waves (water level variations = pressure variations, ca. 0.1 bar) and local weather conditions (barometric pressure variations, ca. 0.01 bar) similar to the typical tide-dependent variations already recorded in other submarine environments [i.e., *Aliani et al.*, 2004; *Chen et al.*, 2005; *Sohn*, 2007]. The collected data lead us to the assumption that further parameters are responsible for the anomalies observed during the 8-month monitoring. Since the data were collected during the quiescent volcanic activity, we considered the geodynamic activity as a probable trigger factor, and used the seismicity recorded at the nearby Stromboli volcano as an independent parameter for the local geodynamic/stress activity indicator.

[9] Stromboli's volcanic activity is characterized by periodic eruptions occurring within relatively short intervals of less than one hour. The seismic stations deployed on the Stromboli volcano record signals which are either related to the visible Strombolian eruptions (explosion quakes), or to the so-called Very Long Period events (VLP). VLP events are assumed to be generated by volumetric gas expansion in the feeding system [*Chouet et al.*, 2003; *James et al.*, 2004; *Ripepe et al.*, 2004] and seem to be very sensitive to gas pressure fluctuations inside the conduit. Hence, the number of the VLP events is one of the activity parameters successfully used for the volcanic monitoring of Stromboli.

[10] Striking coincidences between the sudden gas flux variations at Panarea and an abrupt drop in the VLP-rate at Stromboli occurred throughout the monitoring period (Figure 2). A sharp drop in the gas flow rate (from 90 down to 20 relative units) and water temperature (from 33 to 31°C) was recorded on October 30, 2006 (see Figure 2b for details) and on December 22, coinciding with a drop in VLP events at Stromboli [see *Patanè et al.*, 2007]. The last Stromboli eruption began on February 27, 2007 and lasted up until April 3rd. The hydrothermal vents recorded a sharp increase in the flow rate on March 15, 2007 at 9.30 pm (arrow on Figure 2c) coinciding with the strongest paroxysmal explosion and a sharp drop in mid-April, a few days after the end of the eruptive activity. In spite of a distance of about 20 km between the volcanic islands, the simultaneous variation in both parameters suggests an interconnection between the gas feeding systems that seems to contemporaneously drive the volcanic activity of Stromboli and the hydrothermal activity at Panarea.

[11] Moreover, the recent temporary installation of ocean bottom seismometers (OBS) off the Aeolian Islands [*Dahm et al.*, 2002] has allowed us to record seismic signals that were not dominated by the local volcanic activity of Stromboli. Tremor-like noise bursts observed at one station (OB-05), which was the closest to Stromboli, resembled signals that have been observed at volcanoes during periods of activity, with main frequencies between 2–2.5 Hz and harmonic overtones. The tremor bursts showed a high degree of polarization in the NW direction, in respect to the OB-05 station, which was not exactly the direction of Stromboli (Figure 1). As it was the only station of the OBS-network to record such signals, it was not impossible to locate the seismic source, so that *Dahm et al.* [2002] concluded that the Rayleigh waves originated from a seismic source (either volcanic or hydrothermal) located off but still close to Stromboli, somewhere along the N40°E trend linking Stromboli to Panarea (Figure 1).

[12] A further, independent, indication comes from isotopic composition of helium and its temporal evolution recorded at both the islands. The $^3He/^4He$ ratios measured at Panarea (Figure 3) fall within a narrow range of 4.27 ± 0.1 Ra (Ra = atmospheric $^3He/^4He$ ratio = 1.39×10^{-6}). During the 2002–2003 crisis, samples collected at both the islands between January and May 2003 provided similar values in the range and 4.15 ± 0.12 Ra (Figure 3, right). The question is whether the measured values provide the typical helium signature for Panarea and Stromboli or whether they mark the volcanic fluids released by one of the islands. Helium isotope ratios measured in solid samples from the two volcanoes display different ranges: from 3.1 to 6.09 Ra at Panarea and from 2.51 to 4.78 Ra at Stromboli. The whole $^3He/^4He$ data set of Panarea area (Figure 3) has shown an almost constant signature for all the gases vented inland, from the sea bottom and from the vents off the islet of Basiluzzo (Ra = 4.26; F. Italiano, unpublished data, 2008) indicating a provenance from the same degassing source. Those data might derive from different local magmatic sources belonging to the volcanic series of Punta Torrione (6.09 Ra) [*Martelli et al.*, 2008] and La Fossa (3.1Ra) [*Martelli et al.*, 2008]. A cooling magma belonging to the Punta Torrione volcanic series, a magma volume intruded beneath the island or magmatic fluids from Stromboli Island, might be capable of releasing helium with the measured isotopic signature. On the other hand, the contemporary $^3He/^4He$ data collected at Panarea and Stromboli show an astonishing coincidence both in their absolute $^3He/^4He$ value and in their temporal variations (Figure 3, right), providing the information for a common genesis of the degassed volatiles over the whole study area. This makes a helium provenance from a cooling

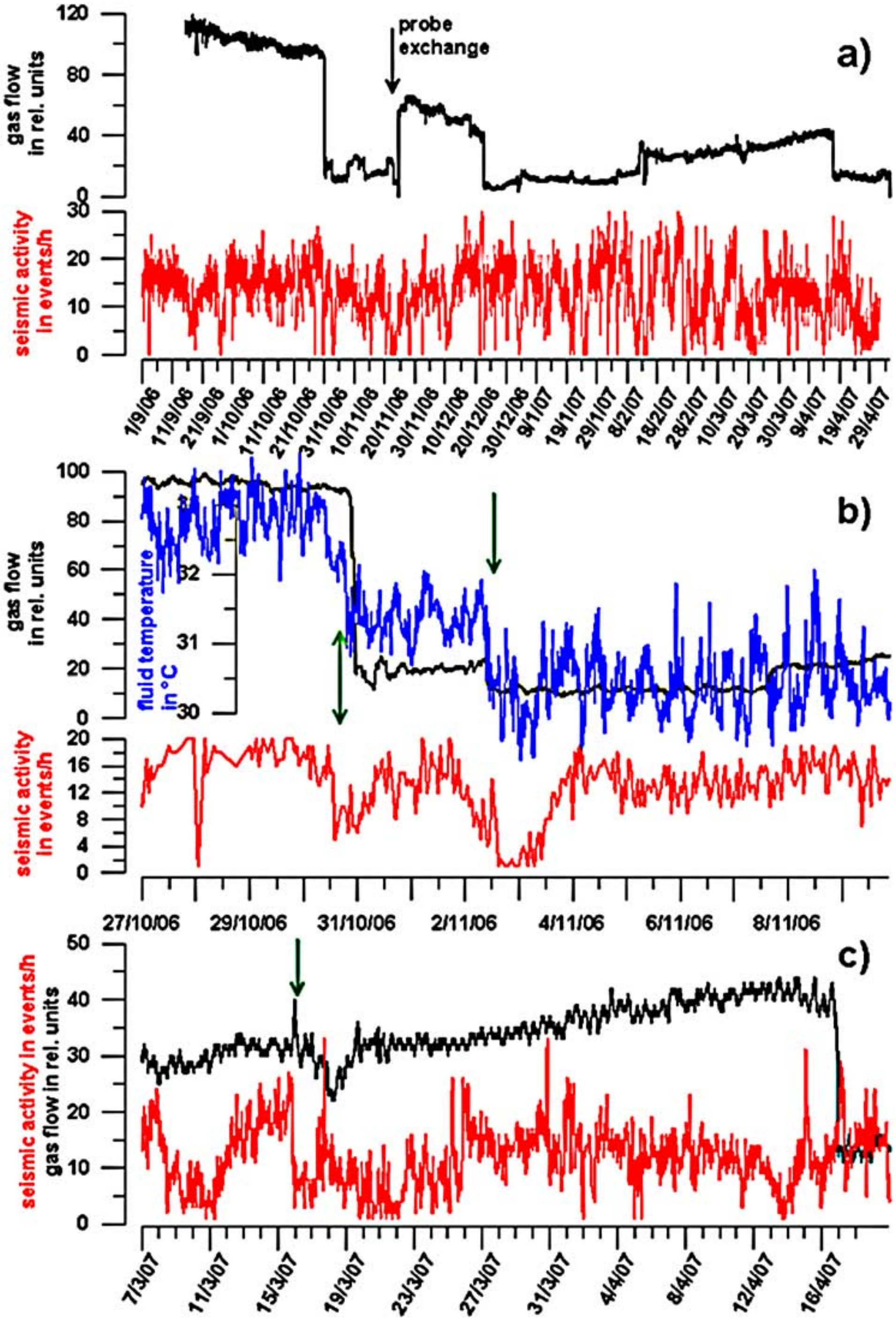

Figure 2. Data from the acoustic device (namely the gas flow rate) over the whole monitoring period plotted versus the seismic activity of the nearby Stromboli Island. A zoom in Figure 2b details an example of the recorded variation, in particular the contemporary variations of all parameters (green arrows). The arrow in Figure 2c shows the gas flow-rate increase recorded just before the paroxysmal explosion occurred at Stromboli on March 15, 2007. The spike-like anomaly lasted for 5 hours.

magma beneath the island of Panarea less likely and supports the hypothesis of a provenance from an interconnected Panarea-Stromboli volcanic system. We propose that magma batches from the same parent source feeding Stromboli volcano may intrude at shallow levels along the main fault joining the two volcanoes. The volcanic fluids can easily migrate along the fault and degas following high permeability pathways. All the volcanic structures (e.g., craters, calderas, dikes) commonly represent preferential degassing ways and following this model, any fault movement induces permeability changes that enhance the fluids' motion along the fault. Such a model implies a sort of ‘‘dependence’’ of the

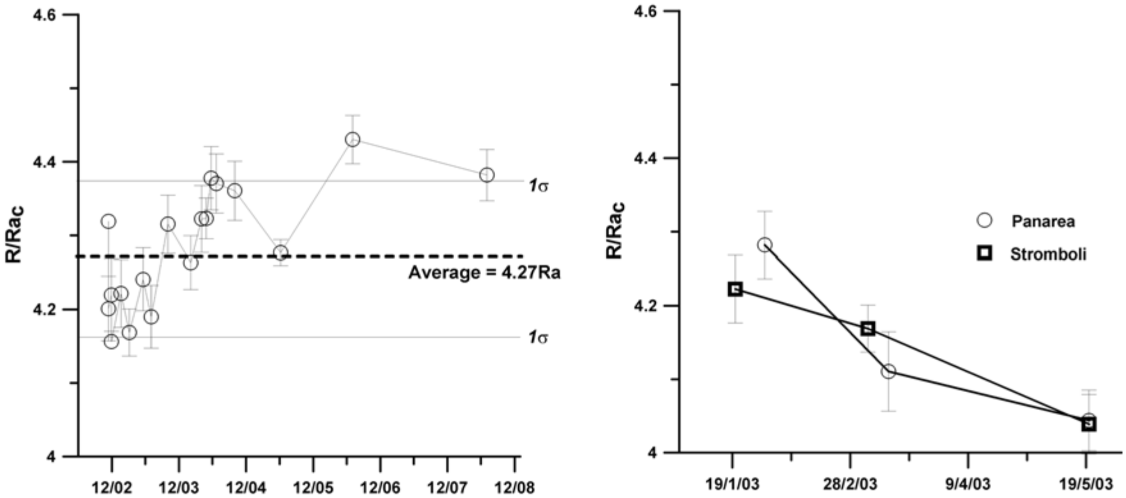

Figure 3. (left) The isotopic ratio of helium recorded at the submarine venting gases of Panarea during the 2002–2003 crisis and (right) a comparison of some of them with data from Stromboli (dissolved gases from Cusolito well). It is worth noting how the helium isotope ratio is the same in fluids from both the islands and exhibits synchronous changes.

volcanic activity of Panarea on Stromboli, possibly via the N40°E normal fault linking the two islands that is recognized as playing a significant role in the area.

4. Conclusions

[13] The combination of geochemical and geophysical methods applied to the submarine hydrothermal system off Panarea Island allowed us to gain a better insight of the role of tectonic structures in an arc volcanism context. The study case of the active volcanoes of the Aeolian arc (Italy) demonstrated that magmatic fluids may move even at long distances through tectonic lines and an extinct volcano might be kept as active by magmatic intrusions or hot fluids migration from another magma source. The reactivation of a NE-SW fault may suggest a triggering of the hydrothermal events near Panarea from November 3, 2002 on, and the subsequent Stromboli eruption phase. Permeability changes induced by, even small, fault movements may in fact have allowed magmatic fluids to migrate far from their area of generation in the Stromboli-Panarea volcanic system, where, in accordance with *Caliro et al.* [2004], *Caracausi et al.* [2005a, 2005b] and *Capaccioni et al.* [2007] a sudden, intense and short-lived feeding of magmatic fluids caused the episode of volcanic unrest at Panarea. The results obtained by the application of new devices for a continuous monitoring carried out between 2006 and 2007, coupled with the VLP seismicity recorded at the nearby Stromboli Island, and the helium isotopes recorded at both the islands, provide the indication that the modifications at the submarine venting fluids off Panarea are related to the seismic activity of Stromboli, thereby indicating that a common degassing source, probably made of magma intrusions along the N40°E fault, affects both volcanoes. The $^{3}He/^{4}He$ ratios measured at Panarea and Stromboli during the 2002–2003 volcanic crisis, had shown both superimposable values and temporal variations supporting the hypothesis that a common source supplies volcanic fluids able to interact with the geothermal system of Panarea through a deep tectonic connection. Hundreds of fossil craters located among the islets off Panarea bear testimony to the long-standing history of hydrothermal activity and gas eruptions [*Esposito et al.*, 2006]. One of those submarine eruptions was also observed in 1865 coinciding with intense Stromboli eruptions [*Mercalli*, 1883]. As a consequence, also taking into account the variations recorded coinciding with the last (February–April 2007) eruptive period on Stromboli Island, a fluid pressure-dependency of Panarea from a common reservoir is considered as the most reasonable explanation also capable of justifying all the observed phenomena. Such a conclusion must be taken into a account when assessing the volcanic risk for the area, since the existence of hundreds crater-shaped structures at Panarea demonstrates that episodes similar to and even stronger than the 2002 submarine blast have frequently occurred in the recent past as well [*Mercalli*, 1883]. Huge gas outbursts could occur again triggered by variations in permeability or in the reservoir pressure associated with Stromboli volcanic unrest. The proposed results outline a way of providing information for civil defence to depict possible evolutionary scenarios, considering volcanic unrest not simply as a "self-standing" activity but also as being deeply related to regional-scale tectonic settings.

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