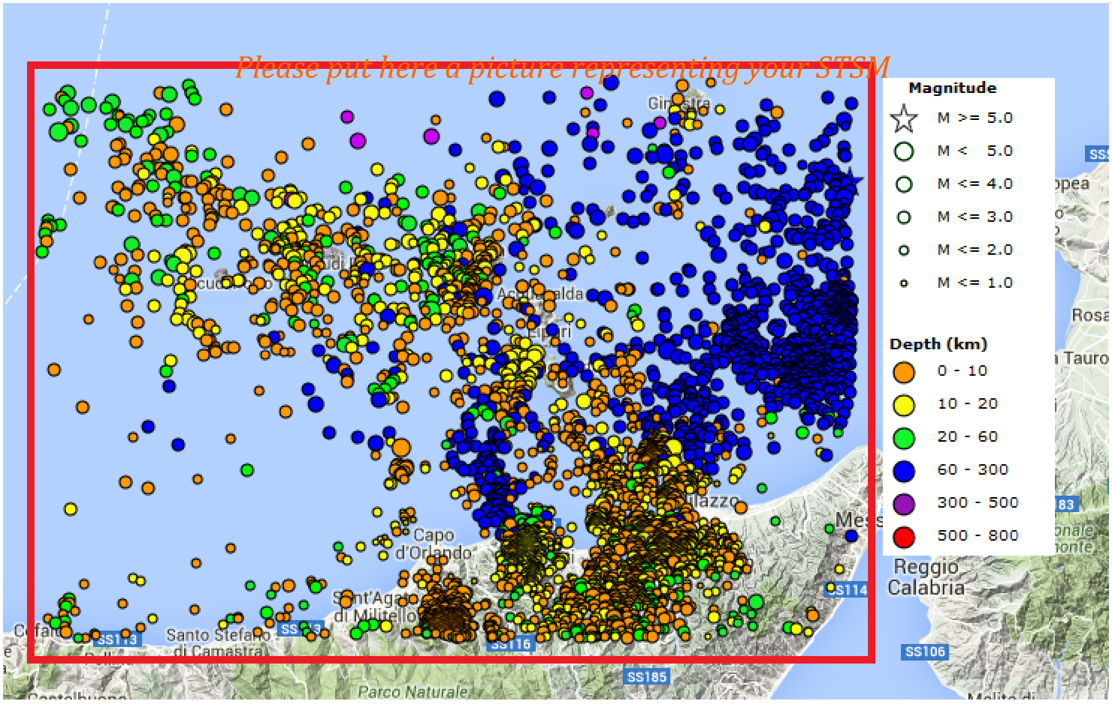
COST Action ES1301
"Impact of Fluid circulation in old oceanic Lithosphere on the seismicity of transfOrm-type plate boundaries: neW solutions for early seismic monitoring of major European Seismogenic zones (FLOWS)"

Report ES1301-240815-067144-67144

New scientific and technological solutions for seismo-volcanic monitoring of an active normal fault: the Panarea-Stromboli tectonic link



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1. Purpose of the STSM

The main goal of the STSM aimed to investigate relationship between seismicity and fluid emission in the Panarea-Stromboli area (Southern Italy). We investigated the seismicity through moment tensor computation using broadband waveform inversion. Furthermore few geophysical measurements were taken in the area in order to identify possible polarization effects due to the present of a fault line connecting the islands of Panarea and Stroboli. The chosen test site is located at the Aeolian islands where the management of natural risks (seismic and volcanic) required a special attention in the period 2002-2005 when a low-energy submarine explosion occurred at shallow depths off the coasts of Panarea island (Caracausi et al., 2005). The degassing activity induced by the explosion developed along fissures that opened at the seafloor trending N40°E, the same regional normal fault linking the islands of Panarea and Stromboli. The degassing crisis at Panarea was followed by a huge landslide and a tsunami wave originated at the nearby island of Stromboli (12 miles towards NE). A few weeks later a large eruption started from the flank of Stromboli. The sudden unrest of submarine volcanic activity that occurred off the island of Panarea (November 2002) opened a crater of 20 by 10 meters wide and 7 meters deep. That event dramatically changed the geochemical features and the degassing rate of the submarine hydrothermal vents of the area and pushed the scientists to develop new methods to monitor the sea-floor venting activity. During the unrest period, the huge degassing activity increased the CO_2 flow rate by some orders of magnitude, however very little investigations have been carried out on the local seismicity The monitoring of the volcanic activity and seismic activities was carried out by periodical observations of the vented fluids the former and by a local seismic network installed on the island of Stromboli, the latter. A further step over was achieved by the deployment of a sea-floor observatory connected to surface buoy a couple of miles off the coasts of Panarea. The observatory was able to perform real and near-real time measurements of selected parameters (temperature, pressure, acoustics) and allowed to establish for the first time a structural link between the two islands and their volcanic activities (Heinicke et al., 2009). Recently, due to a reactivation of the volcanic activity at the island of Stromboli, new investigations need to be developed on the Panarea-Stromboli fault line. A new observatory is under test in the area and the preliminary data have shown changes in fluid emission (particularly in CO_2). In the same period moderate earthquakes have occurred in the area.

2. Description of the work carried out during the STSM

2.1. Analysis of seismicity and moment tensor solutions

During the STSM a lot of seismological data were analyzed. The area investigated in the present study is indicated by a square in the main plate of Figure 1 figure, the smaller frame at the lower right (redrawn from Neri et al., 2009a) shows the Calabro-Peloritan Arc region in southern Italy. This smaller frame indicates that while the central portion of the Arc corresponds approximately to the southeast-ward retreating subduction hinge, the northern and southwestern edges of it lie in continental collision zones which developed after local detachment of the subduction system. The northwestward trending arrows in the bottom of the same frame indicate the Nubia–Europe convergence direction (Nocquet and Calais, 2004). The main frame shows the principal fault systems: hatched, normal faulting; half arrow, strike-slip component;

dashed, presumed strike-slip but different interpretations in the literature (Fabbri et al., 1980; Finetti and Del Ben, 1986, 2005; Monaco and Tortorici, 2000). The dotted curve in the southern Tyrrhenian Sea marks the high velocity anomaly found by seismic tomography at 150km depth (Neri et al., 2009a) indicating the only part of the subduction system where the slab is still continuous (i.e. detachment has not still occurred).

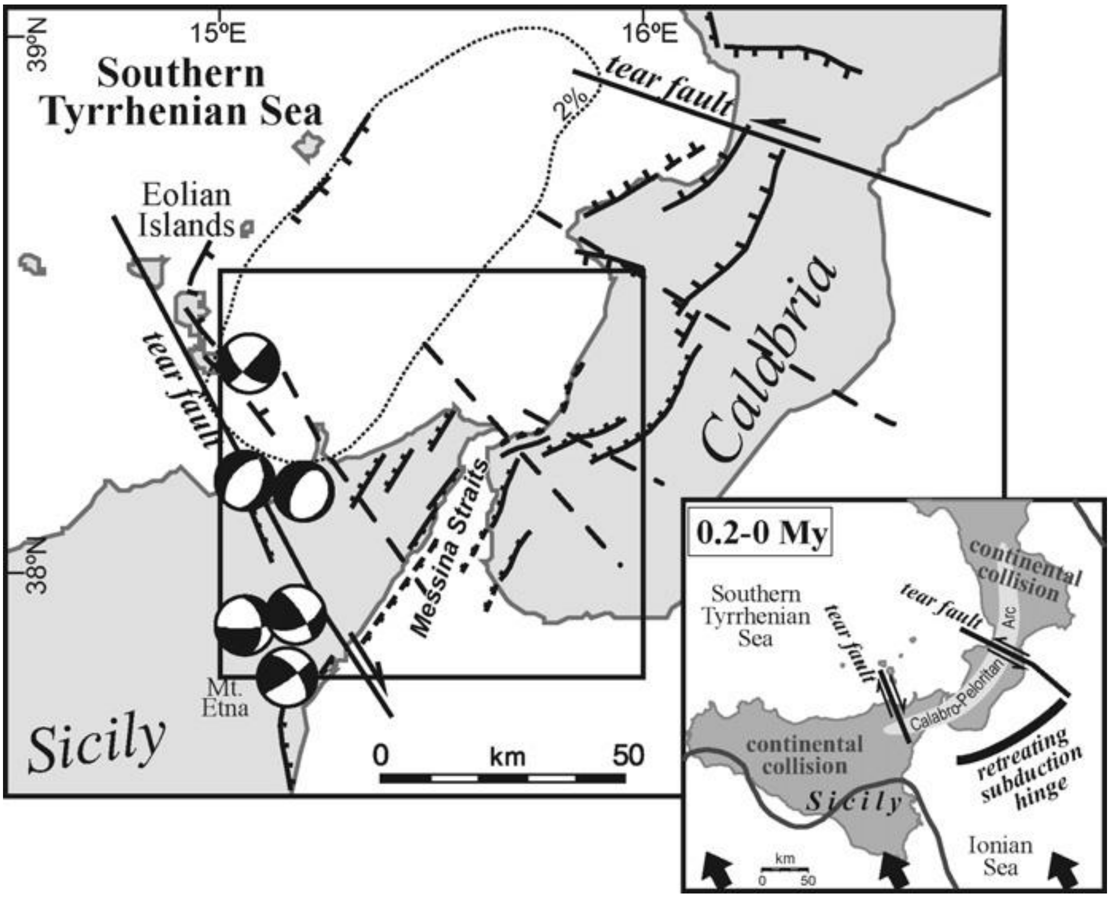

Figure 1: Main seismotectonic features of the study area.

The area is located in the Calabro-Peloritan Arc (Fig. 1), a tectonic structure uplifting at a rate of 0.5–1.2 mm/yr in the last 1–0.7My (Monaco and Tortorici, 2000). The deformation in the area is mainly accommodated by normal faults (Monaco and Tortorici, 2000; Catalano and De Guidi, 2003; Catalano et al., 2003). The dynamics of this area is controlled by two main tectonic factors: the Nubia–Europe plate convergence locally oriented NNW-SSE (Calais et al., 2003; Nocquet and Calais, 2004; Serpelloni et al., 2007) and the southeast-ward rollback of the Ionian lithospheric slab which subducts beneath the Tyrrhenian lithosphere (Malinverno and Ryan, 1986; Faccenna et al., 1996). The Nubia–Europe convergence velocity in this region has been estimated to be about 0.5 cm/yr (Goes et al., 2004; Nocquet and Calais, 2004; D'Agostino et al., 2008a), and the rollback of the Ionian slab and subduction trench retreat is supposed to be even slower, perhaps a few mm/yr (Devoti et al., 2008; D'Agostino et al., 2008b). Several authors (Spakman and Wortel, 2004 and references therein) argued that this very low outward migration velocity of the Calabro-Peloritan Arc and its fast uplift could suggest a shallow detachment of the subduction slab. A recent seismo-tomographic investigation (Neri et al., 2009a) focused on the present state of subduction in this region. They suggested that the deep portion of the subducting lithospheric slab has already detached from the shallow body near the edges of the Arc (e.g. beneath northern Calabria and northeastern Sicily) while the slab is still continuous beneath the central part of the Arc, along a 100km long NE-trending segment of the subduction system in southern Calabria (Fig.1). In addition to filling an information gap indicated by the previous investigators concerning the present state of subduction in this area (see e.g. Spakman and Wortel, 2004) the results of Neri et al. (2009a) may help the interpretation of the shallow seismicity in the Arc region through proper contextualization of the seismotectonic process occurring at crustal depths above the subducting lithosphere. Seismogenic stress inversion on a regional scale allowed Neri et al. (2005) to detect a clear change from an extensional domain in southern Calabria and northeastern Sicily to a compressional one in the rest of Sicily. Evidence for this tectonic change was seen in other geological and geophysical investigations (see e.g. Billi et al., 2006, 2007). The transition was approximately located across a belt running from the Eolian Islands SSE to the Ionian coast of Sicily near Mt. Etna (Fig. 1). The transition from the eastern extensional domain to the western compressional area may be explained in terms of joint action of two main factors, plate convergence and rollback of the subducting lithosphere (Neri et al., 2005; Billi et al., 2006, 2007). This view matches the findings of the most recent geodetic and seismological investigations (D'Agostino et al., 2008b; Neri et al., 2009a)which support the existence of a residual rollback of the subduction slab in southern Calabria and continental collision following slab detachment in western-central Sicily.

The Calabro-Peloritan region is one of the areas with high seismic hazard (http://zonesismiche.mi.ingv.it; "Mappa di pericolosità sismica del territorio nazionale"). Based on the historical earthquake records the area has suffered intensity X or higher several times in the past centuries [for example in 1638, 1659, 1783, 1870, 1905, 1908, see Boschi *et al.* (2000) and CPTI Working Group (2004)]. In the last thirty years, crustal seismicity has been recorded in a low-to-moderate activity with just a few events having magnitude above 5 ["Catalogo della Sismicità Italiana" (CSI Working Group, 2001), "Bollettino Sismico Italiano" at http://bollettinosismico.rm.ingv.it/, ISIDE at http://iside.rm.ingv.it, and the catalogue of the regional seismic network of the University of Calabria]. The study area is also characterized by an intermediate and deep seismicity clustered and aligned along a narrow (less than 200 km) and steep (about 70°) Wadati-Benioff zone striking NE-SW and dipping towards the NW down to 500 km of depth (Piromallo and Morelli, 2003; Neri *et al.*, 2009). In the last thirty years, about a dozen, sub-crustal earthquakes with magnitude greater than 5 occurred in the study area.

In particular, in this study we use seismic data collected and recorded by Italian National Seismic Network managed by the *Istituto Nazionale di Geofisica e Vulcanologia* (INGV). The investigated are for the setting of the seismological area is presented in Figure 2. The data set is comprised of more than 4,500 regional earthquakes of local magnitude (ML) ranging from 1.0 to 4.3, recorded between January 2005 and August 2015 (the geographical boundaries are between 38.00 and 38.8 for latitude and 14 to 15.5. for longitude).

Figure 2: study area

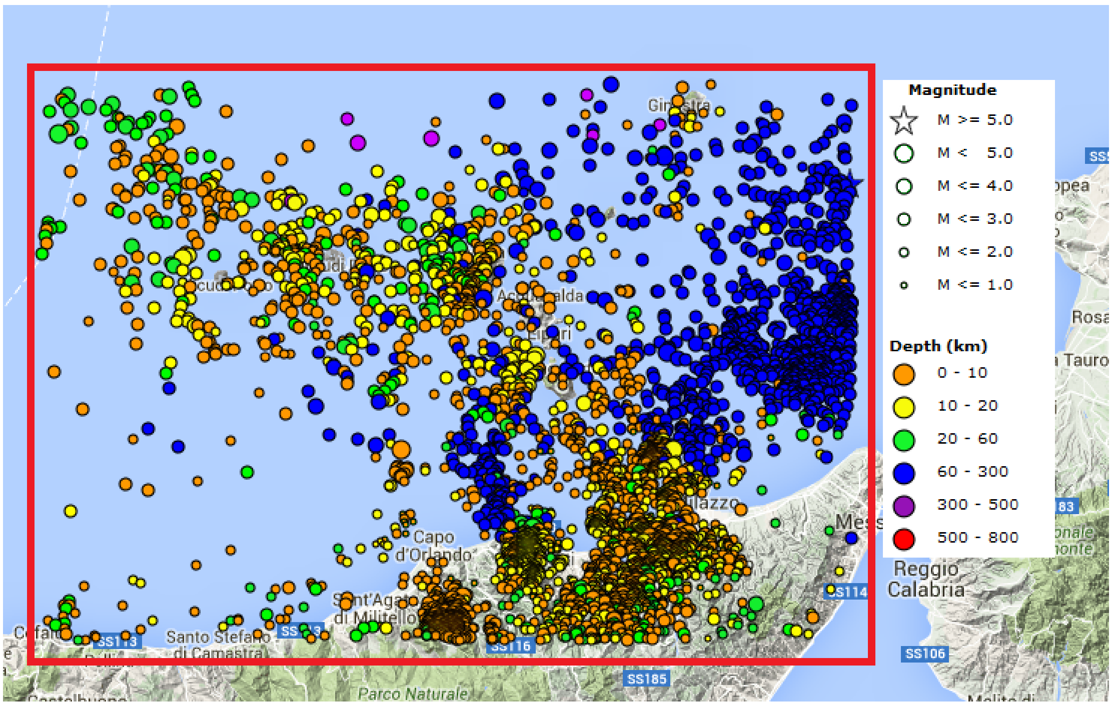

Figure 3.

As shown in Figure 3 the area is characterized by very shallow seismicity confined within the first 20km. However several deep events (more than 300km) can be found and their mechanism is linked with the subduction zone present in the area.

In order to characterize the seismotectonic setting of the area we focused our attention on few seismic events with focal depths less than 25km and local magnitudes larger than 3. The dataset has been restricted to the earthquakes recorded at a minimum of 4

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three-component seismic stations. This selection brings the dataset to about 60 events. Each waveform has been examined to eliminate recordings with spurious transients or low signal-to-noise ratios and corrected for instrument responses to yield to ground velocity. Finally the picking of P-arrivals were reviewed and the horizontal recordings rotated to radial and transverse components.

The main parameters of the analyzed earthquakes are listed in Table 1 as well as with the moment tensor solution obtained for each event The moment tensor solution computation was performed by using the CAP method originally proposed by Zhao and Helmberger (1994) and later modified by Zhu and Helmberger (1996). The method allows time shifts between synthetics and observed data in order to reduce dependence of the solution on the assumed velocity model and on earthquake locations. The source depths and focal mechanisms are determined using a grid search technique. For any fixed depth, the procedure attempts to find the best fit by aligning automatically the data with the synthetics. In the CAP method each waveform is broken into the body and surface wave segments that are weighted separately (see for details Tan et al., 2006). The Green's functions were computed using a 1-D velocity model with the frequency-wave number method described by Zhu and Rivera (2002) and stored in a separate library in order to reduce the computational time. The use of the appropriate regional velocity model is important not only to match the waveforms, but also to define the moment magnitude of the earthquake because the theoretical amplitudes at high frequencies depend very strongly on the velocity model. To compute the Green's functions we used a specific velocity model developed for the area (Barberi et al. 2004). Green's functions have been computed for a distance range from 1 to 200 km with a spacing of 1 km and a focal depth range from 1 to 50 km. To take into proper account the lithospheric heterogeneities, we used the most detailed 3-D velocity models available for the study region (Barberi *et al.*, 2004; Neri *et al.*, 2011) to derive a specific 1-D velocity model for each target area. To compute such 1-D model, we define sets of synthetic events and stations located at sea-level on regular two-dimensional grids covering the respective target area. For each pair of synthetic event-stations, we computed the theoretical travel times using the 3-D velocity models cited above and we used these data to build the relative plot of travel times versus epicentral distances. The data envelope may be fitted by a few piecewice continuous linear segments. Following the theory of travel-times in layered media (see e.g., Lay and Wallace, 1995), we estimated both velocity and thickness of the layers needed to build the 1-D velocity model. With this approach, we may reconstruct a 1-D velocity model "equivalent" to the 3-D one for a specific set of synthetic ray-paths. The chosen configuration of events and stations allows us to sample the investigated region with a high density of seismic paths also showing a very robust ray crossing and therefore the "equivalent" 1-D velocity model may be considered a good approximation of the local 3-D structure.

In the CAP method each waveform is cut into *Pnl* (defined as the first arrival from seismic source in the crust corresponding to waves reflected and multireflected from the top of the sharpest discontinuity) and surface wave segments that are weighted differently in the misfit calculation since body and surface waves are sensitive to different parts of crustal structure and have different amplitude decay with distance. The surface waves, although large in amplitudes, are easily influenced by shallow crustal heterogeneities while the Pnl waves are controlled by the averaged crustal velocity structure and therefore are more stable (Zhu and Helmberger, 1996). For this reason we weighted the Pnl segments 2–3 times more than the surface wave segments. Use of only surface waves permits a good estimate of the solution but requires a good azimuthal coverage around the source which makes the application less effective in case where only a few stations are available. In our analysis we used ground velocity instead of ground displacement in the CAP inversion as the magnitudes of the majority of the events are smaller than four and we needed to avoid the influence of long-period noise embedded in ground displacements. Synthetics and observed ground velocity were filtered in the same frequency bands chosen accordingly to the magnitude of each event. In this study we used, for earthquake around magnitude four, a frequency band from 0.02 Hz to 0.1 Hz for the surface waves and from 0.05 Hz to 0.3 Hz for the Pnl. These frequency bands were chosen to maximize signal-to-noise ratios of data and to avoid short-wavelength structural heterogeneities. However, to determine the moment tensor solution of smaller earthquakes, it is necessary to use higher frequencies. Fig. 4 reports an example of waveform fit obtained by applying the CAP method. We can see that the synthetic matches well the observed both in shape and amplitude. The use of many stations increases the reliability of the focal mechanism because a large number of waveforms are inverted simultaneously.

In general, Table 1 shows that normal faulting is the main style of seismic deformation in the study area. The polar plot of P- and T-axes shows a roughly NW-SE preferential orientation of the extension axes. In addition, we may note from the map that the regime of faulting significantly changes from north to south: normal faulting prevails clearly in the north while it appears mixed to strike-slip in the south.
The present application of the CAP method fills a remarkable lack of knowledge existing on the seismogenic mechanisms in the study area and provides a tool for further studies in the whole region. However, the network geometry used for focal mechanism studies is limited by the lack of OBSs in the wide offshore sectors of the study region and this is a major factor reducing the quality of these solutions. Thus, it is extremely important to plan a proper OBS campaign in order to better investigate the local seismicity and its pattern which will help to better highlight the connection among several physical parameters such as seismicity and fluid circulation in fault zone areas.

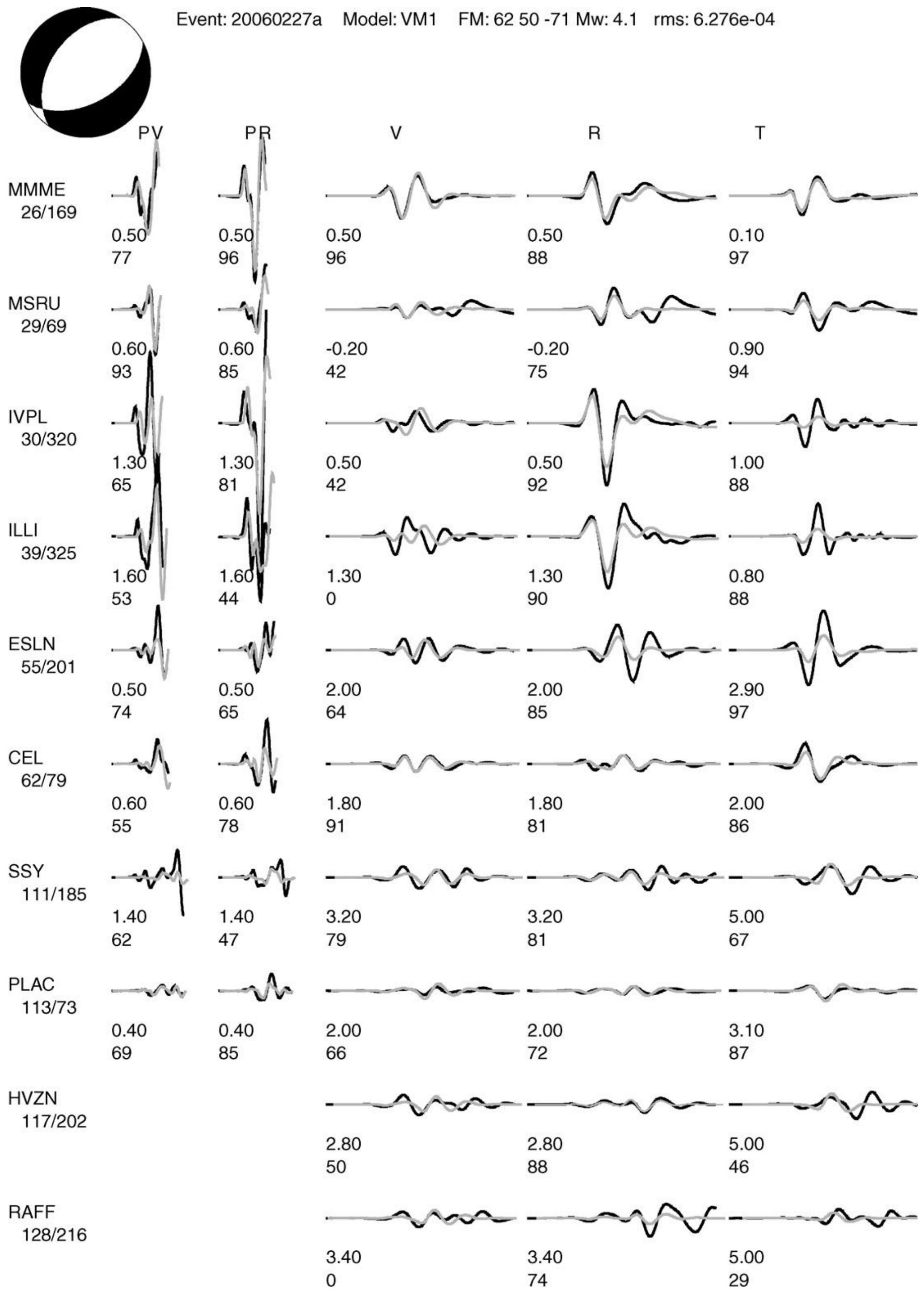

Figure 4: Example of waveform fit for the event ID 20060227a (see also Table 1). Data are indicated by black lines, synthetics are represented by gray lines. The left two columns show the waveform fits for the Pnl waves, while the next three ones show the waveform fit for the surface waves: vertical (V), radial (R), and tangential (T) component, respectively. The numbers below each trace segment are the time shift (in seconds) and the cross-correlation coefficient, respectively. The name of the station is reported on the left side of each trace fit; the numbers just below it represent the distance from the station and the azimuth.

2.2. Installation of portable seismic stations and polarization analysis

The area is an interesting natural laboratory and during the STSM we installed seismoters in different locations between the islands of Panarea and Stromboli. Using the seismic data collected during the STSM we aim to compute the polarization of the seismic signal with the final goal of gain evidences for the presence of the inferred fault in the area as well as to characterize the potential site effects at the investigated site.

Ambient noise measurements were taken at 4 different points over the study area (Figure 5) covering a wide range of geomorphological states. Ambient noise was recorded using a three-component seismometer (TrominoTM, www.tromino.eu). The Tromino is a compact, lightweight and self-contained instrument, and its ease of use makes it ideal for performing a large number of measurements in rugged terrain that are accessible only on foot (in this particular case we made use of a boat to reach all the small rocks). Time-series were recorded at a sampling rate of 500 Hz and, following the guidelines suggested by the SESAME project (Bard 2005) these were divided into non-overlapping time windows of 20 s each. The Fourier spectrum of each window was computed and smoothed, and after 'cleaning' the traces from spurious noise event windows, the resulting H/V, in the frequency range 0.5–64.0 Hz, was derived using the geometric mean of the spectral ratio obtained for each time window.

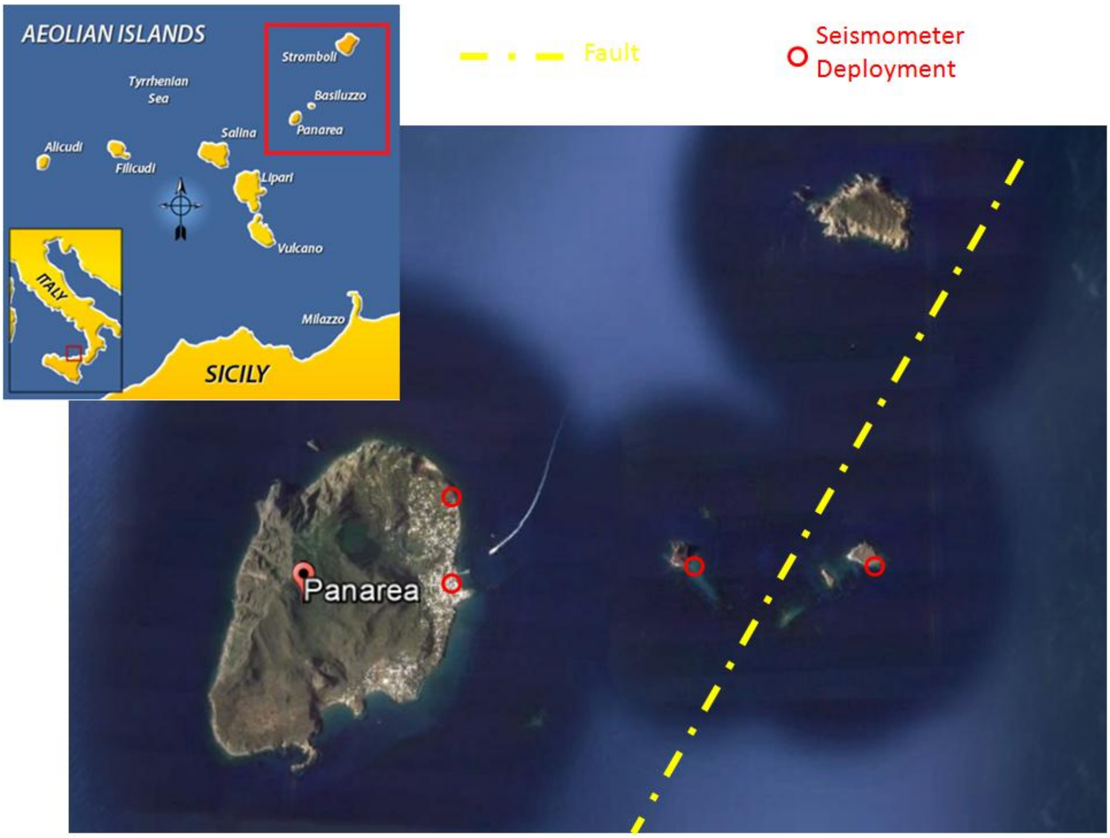

Figure 5: Location of measurement sites

The use of the H/V method was first proposed by Nogoshi &Igarashi (1971) for the estimate of seismic site response. Nakamura (1989) eventually made this method widely popular as a costeffective and reliable means of predicting the resonance frequency of a site, particularly when low shear-wave velocity layers present a sharp impedance contrast with the bedrock. The presence of a resonance peak in the H/V ratio has been interpreted both in terms of SH-wave resonance in soft surface layers, or in terms of the ellipticity of particle motion when the ambient noise wave train is made up predominantly of surface waves (Bonnefoy-Claudet et al. 2006). In practice, the wavefield is expected to be a combination of both types, and the H/V curve contains information about the shear wave velocity profile in shallow sediments.
In order to infer the presence of the fault we also perform polarization analysis using the data collected during the campaign. Polarization analysis was carried out using the method of Burj´anek *et al.* (2010) which is based on the complex covariance matrix method of particle motion polarization analysis, and generalized to the time-frequency domain by adopting a continuous wavelet transform (CWT). The particle motion is characterised at a given time and frequency by an ellipse in 3-D space. The WAVEPOL package outputs the analysis of an ambient noise time-series in visual representations of combined angular and frequency dependence. Histograms of strike of the ellipse major axis are represented as circles on a polar plot, in which the frequency increases along the radius, and colour is used to denote amplitude in each histogram. The ellipticity of the particle motion is defined as the ratio of the semi-minor axis to the semi-major axis of the ellipse, and is therefore equal to 1 for circular particle motion and equal to zero for purely linear motion, and is thus a good indicator of polarization effects. It is represented as a 3-D histogram of ellipticity versus frequency.

Figure 6 shows the H/V curves obtained in the present study. It is possible to notice that no clear picks can be observed in the lower portion of the spectra while more clearer peaks are evident around 10 Hz and above. These have been interpreted with very shallow local geological structures or, as in the case of Dattilo rock, linked with the natural vibration of the it. However the latter case needs to be better investigated also through numerical modelling.

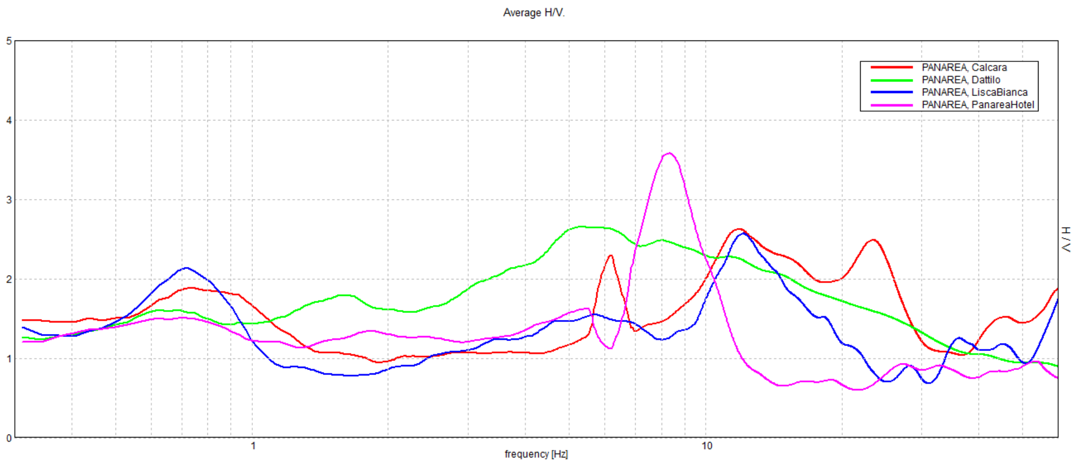

Fig. 6: H/V curves, measured during the surveys.

The polarization analysis shows strong characteristics in direct correspondence with these H/V peak frequencies. The polar plot shows directivity of particle motion approximately, while the ellipticity diagram shows a corresponding sharp drop to zero at the same frequencies, indicating a high degree of linearity in the particle motion. This could be related to the presence of the fault in the study area (Fig. 5) however further investigations are needed

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4. Future collaboration with the host institution

The two Institutions involved in this STMS intend to submit a common research proposal. In particular, the authors are considering the calls explicitly disegned and directed to facilitate Italian-Maltese scientific collaborations. On this framework we are going to propose a project that deals with innovation technologies in order to investigate the sea floor using several geochemical and geophysical parameters collected purposely during the project. Independently from this, we hope to have many future occasions to perform integrated studies and improve the ongoing collaborations.

5. Foreseen publications/articles resulting from the STSM

We would like to publish our results at national and international conferences, as well as on international journal. At the moment, the next occasions for publishing part of the data are the next ESC and EGU conferences.

COST - European Cooperation in Science and Technology is an intergovernmental framework aimed at facilitating the collaboration and networking of scientists and researchers at European level. It was established in 1971 by 19 member countries and currently includes 35 member countries across Europe, and Israel as a cooperating state.

COST funds pan-European, bottom-up networks of scientists and researchers across all science and technology fields. These networks, called 'COST Actions', promote international coordination of nationally-funded research.

By fostering the networking of researchers at an international level, COST enables break-through scientific developments leading to new concepts and products, thereby contributing to strengthening Europe's research and innovation capacities.

COST's mission focuses in particular on:

- *Building capacity by connecting high quality scientific communities throughout Europe and worldwide;*
- *Providing networking opportunities for early career investigators;*
- *Increasing the impact of research on policy makers, regulatory bodies and national decision makers as well as the private sector.*

Through its inclusiveness, COST supports the integration of research communities, leverages national research investments and addresses issues of global relevance.

Every year thousands of European scientists benefit from being involved in COST Actions, allowing the pooling of national research funding to achieve common goals.

As a precursor of advanced multidisciplinary research, COST anticipates and complements the activities of EU Framework Programmes, constituting a "bridge" towards the scientific communities of emerging countries. In particular, COST Actions are also open to participation by non-European scientists coming from neighbour countries (for example Albania, Algeria, Armenia, Azerbaijan, Belarus, Egypt, Georgia, Jordan, Lebanon, Libya, Moldova, Montenegro, Morocco, the Palestinian Authority, Russia, Syria, Tunisia and Ukraine) and from a number of international partner countries.

COST's budget for networking activities has traditionally been provided by successive EU RTD Framework Programmes. COST is currently executed by the European Science Foundation (ESF) through the COST Office on a mandate by the European Commission, and the framework is governed by a Committee of Senior Officials (CSO) representing all its 35 member countries.

More information about COST is available at www.cost.eu.