Natural Hazards

Exploratory seismic site response surveys in a complex geologic area: a case study from Mt. Etna volcano (Southern Italy)

--Manuscript Draft--

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Abstract:	A preliminary study targeting to evaluate the local seismic response was performed in the eastern flank of Mt. Etna (Southern Italy) using ambient noise measurements. The obtained spectral ratios were subdivided through cluster analysis into different classes of fundamental frequency permitting to draw an iso-frequency contour map. The analysis set into evidence the extreme heterogeneity of lava sequences which makes difficult to identify a single seismic bedrock formation. Another important outcome, concerning the local seismic effects in terms of frequency and azimuth, is the important role played by the fracture fields associated with the main structural systems of the area. The existence of two zones with strong directional effects striking WNW-ESE and NW-SE, nearly orthogonal to the orientation of the main fracture fields, corroborate such hypothesis.
Response to Reviewers:	Dear Editor, please find enclosed a revised version of the paper # NHAZ-S-15-02265: “Exploratory seismic site response surveys in a complex geologic area: a case study from Mt. Etna volcano (Southern Italy)” by F. Panzera, G. Lombardo, E. Longo, H. Langer, S. Branca, R. Azzaro, V. Cicala, F. Trimarchi. We revised the paper following the very useful comments and remarks from both the reviewers.

	According to their suggestions, we modified the manuscript, highlighting in green the main changes. To help the reviewers work, we prepared a cover letter that we attach in this submission. Sincerely, Francesco Panzera.

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Catania, 08.07.2016

Prof. Sebastiano D’Amico
Guest Editor
Natural Hazard

Dear Editor,

please find enclosed a revised version of the paper # **NHAZ-S-15-02265**: “**Exploratory seismic site response surveys in a complex geologic area: a case study from Mt. Etna volcano (Southern Italy)**” by F. Panzera, G. Lombardo, E. Longo, H. Langer, S. Branca, R. Azzaro, V. Cicala, F. Trimarchi. We revised the paper following the very useful comments and remarks from both the reviewers.

According to their suggestions, we modified the manuscript, highlighting in green the main changes. To help the reviewer work, in the following text we address their comments and our answers.

Please note that according to the reviewer #1 suggestion we modified the original title: “Exploratory seismic site response surveys in a complex geologic area: the study case of Mt. Etna Volcano” into: " Exploratory seismic site response surveys in a complex geologic area: a case study from Mt. Etna volcano (Southern Italy)".

Sincerely,

Francesco Panzera.

Reviewer # 1

- The English write-up requires major revision.

We carefully checked all the English write-up of the manuscript, improving it and modifying in particular the words and the sentences pointed out by the reviewer.

- A huge numbers of sites have been covered with 135 numbers of locations to record ambient noise, however time series of 30 seconds is too short to talk about a site. So here I have serious question mark on database. At least minimum of 2 hours data could have been recorded for the analysis. The span of database used in this study obviously reduces creditability of the beautiful work coined upon.

Line no. 128: How come sampling rate could be 128 Hz? Please correct it. I assume that it may be read as 128 samples per second. If it so, please clarify why 128 sps has been assigned when the entire work is carried out within the frequency band of 0.5-20Hz. Add a few lines clarifying the same in the manuscript.

Following reviewer suggestions we better specified the acquisition criteria (see highlighted text at lines 157-160). However, we think that probably a misunderstanding occurred. In the text we refer to time series of 30 minutes length that were afterwards subdivided into time windows of 30 s. As concerns the sampling rate, 128 Hz is the minimum value that can be settled in the Tromino.

- The most desired value for the Konno-Ohmachi factor, generally used as 20, but the study uses the value as 40. Please explain the reason to be added in the manuscript.

We have now specified the smoothing criteria used in the Konno-Ohmachi window (lines 162-165).

- Line no. 90 : The word "latter" should be replaced with "succession".

Line no. 95 : "is" should be replaced by "are" and "unconformities" should be replaced by " non-conformities".

Line no. 249 : " with respect the main fault" should be replaced by " with respect to the main fault" Line no. 222 : "Nearest neighbor algorithm" should be replaced by " Nearest neighborhood algorithm"

The words mentioned by the reviewer were originally in the section 2.”Tectonic and geologic setting”. This section is now indicated as “Seismotectonic and geologic setting”. It was deeply and carefully revised taking also into account the reviewer’s comments. As regards lines 249 (now 283) and 222 (now 248-249), modifications were performed according to the reviewer suggestions.

Reviewer # 2

Abstract

Page 1, line 12: delete "surveys".

Page 1, line 13: add "(southern Italy)" after Mt. Etna.

Page 1, line 15: which kind of contour map? Iso-frequency? Specify.

Page 1, line 16: use "seismic bedrock" instead of "bedrock" alone.

Page 1, lines 16-17: the sentence "and the important role played by the main fault systems on the local seismic effects" is quite vague and should be reworded, specifying the role played by the faults.

Following the reviewer comments, we revised and modified the abstract accordingly.

1. Introduction

Page 1, line 24: substitute "occurring in the area" with "occurring in a given area".

Page 1, line 27: substitute "among the most significant issue" with "a crucial issue".

Page 1, line 34: add "(Southern Italy)" after Mt. Etna.

Page 2, line 35: "outcrops of sediments and lava closely alternating in a horizontal and vertical volume" is bad written. I would say that "lava and sediments exhibit complex stratigraphic relationships with strong lateral and vertical variations".

Page 2, line 36: what do you exactly mean with "fault fabric"? This is a very specific word in structural geology. I would rather use a simpler term suitable for geophysical studies of faults, like "fault zone structure" or "fault zone architecture".

Page 2, line 37: do you mean vertical velocity inversions? If so, specify.

Page2, line 38: "even if site investigations data are not at all times available" is incorrect.

Page 2, line 46: change "wave fields" with "wavefields".

Page 2, line 52: change "features which" with "features, which".

Page 2, line 55: in order to strengthen and broaden the interest of this work, this part of the Introduction should better describe the impact of site effects (natural hazard) on the densely urbanized setting of this part of Italy (risk). You should provide as well a brief summary of the main characteristics of the buildings in terms of overall quality, estimated resonance, and vulnerability. This information, indeed, should be presented as an example that is not only typical of this part of southern Italy, but of many other volcanic settings worldwide.

All the recommendations of the reviewer were accepted and included in the manuscript (see highlighted words at pages 1 and 2 of the new manuscript). Moreover, the impact of site effects on a densely urbanized area was now mentioned together with a brief description of building characteristics in the study area and their vulnerability (see lines 50-71).

2. Tectonic and geologic setting

From a general point of view, I think that the description of the geological background should be more concise and better focused on the really necessary elements (seismicity, active faults, fracture arrangement, top-basement morphology). There is plenty of information on stratigraphic details and chronology of deposits that makes the overall reading quite demanding.

Page 2, line 61: much information described in this part is missing in Fig. 1. For example, I cannot see the Malta escarpment, nor the front of the Sicilian thrust belt. Fig. 1 must be thoroughly edited. In particular, the inset on the top-left should include a larger area showing the outline of the Sicilian thrust belt front and the Malta escarpment. See also my other general comments to the figures at the end.

Page 2, lines 66-67: "Geodetic surveys indicate a relative movement toward E-ESE", it must be specified the stable reference.

Page 3, line 69: change "featuring the most striking evidence of active tectonics and geomorphic evidence" with "featuring the most striking geomorphic evidence of active tectonics".

Page 3, line 73: "structures" is too generic. Maybe better "fault scarps".

Page 3, line 77: change "offsets up to" with "offsets of up to".

Page 3, line 78: change "strongest earthquakes" into "very strong earthquakes" and indicate the maximum magnitude/intensity.

Page 3, lines 81-82: is the correct reference Azzaro et al., 2013a or Azzaro et al., 2013b?

Page 3, line 84: Bonforte et al., 2011 is missing in the references list.

Page 3, line 88: change "As concern" with "As regards".

Page 3, lines 88-94: these details on lava and tephra texture are unnecessary for the aim of this paper.

Page 3, lines 98-99: in my opinion, this is rather a matter of resolution of geological mapping, not a consequence of geological complexity…

Page 3, line 99: I don't understand "in agreement".

Page 3, line 102: I would expect to see the Gela-Catania Foredeep basin in Fig. 1.

Page 4, line 103: if you men "ky ago" you can use the term "ka" (i.e.: 330 ka), which is preferred in the geological community. If you use "ky" alone, the right English term is "kyr".

Page 4, line 111: indicate Valle del Bove in Fig. 1.

Page 4, lines 115-117: change "This volcano history gave rise to a strong thick volcanic succession extremely heterogeneous, that along the eastern volcano flank is characterized by an high variation of the thickness that ranges from 0 up to 900 m" with "This volcano history created an extremely heterogeneous volcanic succession, which along the eastern flank of Mt. Etna exhibits large thickness variations, from 0 up to 900 m".

Page 4, line 121: change "an high later" with "a high lateral".

We appreciated the reviewer comments and his useful suggestions to improve the overall quality of the text. Accordingly, we wrote again the "Tectonic and geologic setting" that now is named "Seismotectonic and geologic setting", focusing in particular on the description of the faults and fractures features . Details missing in Figure 1 were included. Moreover, a check was made in order to include all the villages and/or the names of the geologic structure termed in the text.

3. Methodology

From a general point of view, a clear statement with the main target of your investigation is lacking. You should state at the beginning of this section the issues you are addressing and the tools you need to solve these problems. Then, you should better describe the planning of your geophysical survey, with particular focus on the spatial distribution of noise measurements with respect to the main faults and other geological features.

Page 4, line 126: you should justify why you used the Tromino, also considering the extremely variable thickness of the volcanic succession (up to 900 m) above the sedimentary basement. In any case, a brief description of the advantages and limitations (particularly, in the lower frequency band) of using such a cheap and portable instrumentation (instead of a typical 24-bit data logger with at least 0.2 Hz eigenfrequency) is needed.

Page 4, line 131: Konno and Ohmachi (1998) is missing in the references list.

Page 4, lines 131-132: explain why you set the parameter b to 40.

Page 4, line 135: use "k-means" instead of "kmeans".

Page 5, line 157: change "until the points not change the cluster any longer" with "until the points don't change the cluster anymore".

Page 5, line 160: change "In present" with "In the present".

Page 5, line 162: change "requires" with "require".

Page 6, line 169: change "In present" with "In the present".

Page 6, line 170: "partition" has not been defined before.

Page 7, lines 198-199: use "bin size 10°" instead of "class width 10°".

The section Methodology was modified, describing at its beginning the approach adopted and the spatial distribution of recording sites. It was also specified that we intentionally choose to have a regular spacing in order to see if the data collected highlight an important contribution of either the lithology or the tectonic structures (or both) in the evaluation of local seismic response features (lines

142-149). We also justified the use of Tromino (see lines 152-157). The sentence at page 5, line 157 (now page 6, line 191) was modified. All other suggestions and corrections were accomplished.

4. Results and discussion

My general comment to this important part of your manuscript is that a through description of the relationships between local structural setting and directional site effects is very weak. The geological background (Section 2) is full of unnecessary information, whereas more focus on the faults and fractures is needed.

As far as I understood, your results partly rule out the role of the main faults on directional site effects in the study area, particularly those to the north (part of Zone I and Zone II). No data is presented regarding the so called "minor faults and fractures" (Page 8, line 257), which seem to be the main cause of the strongly polarized signal in the wide Zone III. Since no description is given of the geometric and structural arrangement of the minor faults, my opinion is that this explanation is not satisfying. To address this issue, at least a couple of structural surveys on specific fractured rock outcrops should be performed and compared with local HVNRs. Alternatively, you should provide published data on the geometry and architecture of those minor faults. In particular, a careful distinction between minor fractures related to the damage zone development of the km-scale faults and the "background" fracture field related to the regional stress (or to other secondary mechanisms like thermal effects) must be done: those two fracture systems may have different spatial density and average orientation, moreover they may reach different structural levels in the upper crust.

Finally, a discussion on the possible broad implications of your results must be implemented and expanded. For example, what about villages crossed by faults? And what about those sites far from the main faults but located on a fractured area?

Page 7, line 205: change "consist" in "consists".

Page 7, lines 215-216: "The cluster (d), whose spectral ratios can be partially ascribed to classes III and IV, was accordingly subdivided", this sentence is unclear.

Page 7, line 220: what is the average spacing of measurement points? This has consequences on the optimal grid size of the contour map you discuss in the followings.

Page 7, line 221: "was endeavoured" is incorrect. In general, try to avoid whenever possible the passive form because it is misleading for the reader.

Page 7, line 223: did you use a Delaunay triangulation?

Page 7, line 227: delete "mostly".

Page 7, lines 227-229: replace "Their occurrence can be explained as being linked to the Chiancone area which is a volcaniclastic conglomerate deposit, that appears poorly stratified and often hardened" with "Their occurrence can be explained as being due to the outcropping volcanoclastic conglomerate deposits of the Chiancone area, which are poorly stratified and often hardened".

Page, 7, line 230: Branca et al., 2011a or 2011b?

Page 8, lines 231-232: It seems to me that a clear match between the elongated areas of "broadband behaviour - $1<f0<5$ Hz resonance" and faults is visible only for the area enclosing the TFS fault system.

Page 8, line 237: change "geometric expression" in "geomorphic expression".

Page 8, line 239: "fault fabric", see my comment on Page 2, line 36.

Page 8, line 243: replace "More detail" with "More in detail".

Page 8, line 255: Pischiutta et al., (2013) is missing in the references list.

We have now improved the discussion concerning the results obtained, adding more descriptions about the main faults (see the section concerning the "Seismotectonic and geologic setting") and describing the results of published data regarding minor faults and fracture fields (see lines 287-293). We have also more clearly discriminated about results (in terms of observed amplification effects) that can be ascribed to lithologic features (lines 252-260) and results linked to directional effects that can be ascribed to faults and cracks related to the development of the damage zone (261-263). The description of the structural arrangement of minor faults is now reported by quoting published data concerning the geometry of minor faults (lines 290-292). Also the role played by the main fault systems in the polarization effects is mentioned by quoting the studies in the etnean areas dealing with this aspect (lines 277-280). These clarifications (see also lines 292-294; 300-303; 311-315) should, in our opinion, help the reader in understanding our interpretation of the observed effects.

Comments to the figures and captions

Figure 1. The inset map must be enlarged and it has to show all of the following elements: the Maltese Escarpment, the front of the Sicilian thrust-belt, a shaded relief image of the study area (avoid contours), the Gela-Catania foredeep basin. Also, insert coordinates both in the inset map and in the main figure.

Figure 2. The label "h" in the bottom left panel is missing.

Figure 4. Add the coordinates to the basemap and insert the labels for the main faults. Possibly, also add some place name that is cited in the text (Giarre, Acireale, Trecastagni and so on). Moreover,I suggest to use a light blue for the area with $1 < f0 < 5$ Hz in order to make the fault traces more clearly visible.

Figure 5. In its present format, it is quite hard to understand the geological meaning of this figure. In order to quickly improve the readability, add above each panel a topographic profile by simply interpolating the absolute elevation of each station. Then, you must clearly indicate the intersection between each section and the main faults in the study area (put labels of the main faults, of course). This will help the reader to follow your discussion on the relationships between structural setting and site effects.

Figure 6. Add the coordinates to the basemap and insert the labels for the main faults. If possible, also add some place name (Giarre, Acireale, Trecastagni and so on).

Comments to the references.

Bonforte et al., (2011) is cited in the text but missing in the references list.

Konno and Ohmachi (1998) is cited in the text but is missing in the references list.

Pischiutta et al., (2013) is cited in the text but is missing in the references list.

We fulfilled all the useful suggestions pointed out by the reviewer.

Exploratory seismic site response surveys in a complex geologic area: a case study from Mt. Etna volcano (Southern Italy)

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Abstract

A preliminary study targeting to evaluate the local seismic response was performed in the eastern flank of Mt. Etna (Southern Italy) using ambient noise measurements. The obtained spectral ratios were subdivided through cluster analysis into different classes of fundamental frequency permitting to draw an iso-frequency contour map. The analysis set into evidence the extreme heterogeneity of lava sequences which makes difficult to identify a single seismic bedrock formation. Another important outcome, concerning the local seismic effects in terms of frequency and azimuth, is the important role played by the fracture fields associated with the main structural systems of the area. The existence of two zones with strong directional effects striking WNW-ESE and NW–SE, nearly orthogonal to the orientation of the main fracture fields, corroborate such hypothesis.

1. Introduction

To microzone an area for earthquake ground motion purposes is one of the fundamental aspects of seismic risk assessment. Seismic input acting on buildings is related to surface ground motion features that depend on location and magnitude of the earthquakes, seismic attenuation and local site effects. These parameters are tightly linked to the characteristics of the investigated area in terms of the presence of soft soils, hill slopes and structural discontinuities (faults and fractures). Then, site effects should be considered a crucial issue in researches aiming to assess the earthquake ground motion. Generally, a study for seismic site classification is based on data coming from boreholes, geologic surveys and geophysical prospecting. Most of the international seismic codes make use of the average shear wave velocity of the upper 30 m ($V_{S,30}$) to discriminate soil categories (e.g. Eurocode8, 2003). Some doubts however arise whether $V_{S,30}$ is a suitable parameter for estimating the actual soil amplification especially in complex geologic zones such as volcanic areas. As shown in recent studies, on Mt. Etna we deal with the presence of frequent and marked lateral heterogeneities, due to lavas and sediments that exhibit complex stratigraphic relationships with strong lateral and vertical variations (Panzera et al., 2011a). The picture is further complicated by fractures and tectonic discontinuities linked to the architecture of the fault zone (Panzera et al., 2014 and 2016) and the occurrence of significant vertical velocity inversions (Panzera et al., 2015). In spite of these complications, information on seismic site response can be achieved by using microtremor measurements. In particular, a quick estimate of the site effects role in the seismic motion observed at the surface can be provided by the horizontal to vertical noise spectral ratio technique (HVNR). This method, introduced by Nogoshi and Igarashi (1971), was reformulated by Nakamura (1989) and became in recent years widely used. Many authors (e.g., Mucciarelli, 1998; Rodriguez and Midorikawa, 2002; Maresca et al., 2003) have questioned the existence of simple direct correlation between HVNR amplitude values and site amplification, since the ambient noise appears actually made of an unpredictable brew of different wavefields, rather than Rayleigh waves alone. Nonetheless, as demonstrated by Lermo and Chavez-Garcia (1993), it provides a reliable estimate of the fundamental frequency of soil deposits.

In the Etna area, the role of site effects in amplifying seismic ground motion has been recognised for Catania, the principal city (ca. 500,000 inhabitants) of Eastern Sicily that is exposed to relevant seismic risk due to regional earthquakes (Azzaro et al., 1999; Azzaro et al., 2008). Here, several studies focused on investigating the role of the stratigraphy or morphology in inducing resonance phenomena at the urban scale, were performed (Langer et al., 1999; Romanelli and Vaccari, 1999; Panzera et al., 2011a, 2015). The main goal of this work is extending to the whole eastern flank of the volcano a first identification of sites potentially prone to ground motion amplification following a seismic input. This area is particularly interesting since it is characterized by high spatial variability of the geologic features, which are also largely hidden by urbanization. Moreover, from the seismotectonic point of view it is the most active zone of Etna with faults capable of generating shallow earthquakes that produce destructive effects at local scale (Azzaro, 2004; Azzaro et al., 2013b; Panzera et al., 2011b). In the study area both masonry (MA) and reinforced concrete (RC) buildings are widely common. The MA buildings typology was predominant until 1950 whereas the RC buildings reached the maximum development in the seventies and eighties and represent the most widespread architectural typologies. It must be noticed that the seismic code provisions were enforced only as late as the 1980s and this fact, similarly to the main towns in eastern Sicily and southern Italy, has to be taken into account in typecasting the dynamical properties of buildings and the evaluation of their vulnerability. Finally, the densely urbanized setting of the volcano's eastern flank – hosting 27 municipalities over an area of ca. 500

km^2 – as well as the vulnerability of its residential building stock, expose towns and villages in the area to a relevant level of seismic risk, even just considering the economic losses determined by direct repair costs (D'Amico et al., 2016).

2. Seismotectonic and geologic setting

Mt. Etna is a 3300 m high basaltic stratovolcano located along the eastern coast of Sicily (Fig. 1b), at the boundary between African and European plates (Polonia et al., 2016). The volcanic edifice shows a diameter of about 40 km and lies at the front of the Sicilian thrust belt and at the footwall of the northern sector of the Malta escarpment delimiting the margin of the Ionian Sea (Finetti et al., 2005; Lentini et al., 2006). Its tectonic setting and present geodynamics result from the interaction of regional tectonics and local-scale volcano-related processes, such as flank instability and dyke-induced rifting (Azzaro et al., 2013a; Gross et al., 2016).

The eastern and south-eastern flanks of the volcano are the most tectonically active, being affected by a 20 km long system of extensional faults (Timpe, TFS in Fig. 1a) characterized by individual escarpments up to 200 m high, that offset late Pleistocene to historical age lava flows with normal-oblique kinematics (Azzaro et al., 2013a). The unstable, E-ESE seaward sliding sector (Bonforte et al., 2011) is delimited to the North by the Pernicana fault system (PFS in Fig. 1a), a 20 km long left-lateral strike-slip structure featuring the most striking evidence of active tectonics (Neri et al., 2004), with slip-rate higher than 2 cm/yr in the last 200 years (Azzaro et al., 2012 and reference therein). The southern boundary of the sliding flank (SFS in Fig. 1a) is composed of the NW-SE trending Tremestieri (TMF) and the Trecastagni (TCF) faults, whose dextral-oblique displacement is also accommodated by buried tectonic features revealed through geochemical surveys (Bonforte et al., 2013) and remote sensing data (Neri et al., 2009; Bonforte et al., 2011). The intense tectonic activity of these faults in the eastern sector of Etna, the most urbanized of the volcano, is demonstrated by the recurrence of very strong historical earthquakes determining a high level of seismic hazard (Azzaro et al., 2016). In this area macroseismic intensities, up to degrees VIII - IX on the European Macroseismic Scale (EMS, see Grünthal, 1998), as well as intense creep phenomena (Azzaro et al., 2012), are expected. In particular, the occurrence of extensive coseismic and aseismic surface faulting (Azzaro, 2004) produces permanent effects along strike such as fractures, scarplets and local subsidences affecting both the superficial layers and the hanging wall bedrock. These ground breakages determine not only damage to man-made features located astride dislocation lines (Azzaro et al., 2010), but they may also influence the site response following a seismic input (Panzera et al., 2014).

As regards the lithologic sequence, this region is formed by a complex volcanic succession (for details see Branca et al., 2011a) consisting of overlapping lava flows, whose structure ranges from massive to scoriaceous lavas, and subordinately tephra products. Tephra are mainly formed by unwelded fall pyroclastic deposits, rarely lithified, made up of scoriaceous lapilli and ash from fine to coarse, and by lithified pyroclastic flow deposits. Subsurface data evidenced that within the volcanic succession there are also limited epiclastic deposits and numerous debris and alluvial deposits interlayered along the lower flanks (Branca, 2003; Branca and Ferrara, 2001). In the investigated area (Fig. 1) the volcanic successions formed during the geological evolution of the past 220 ka through an almost continuous effusive activity of the Timpe phase (Supersynthem of Branca et al., 2011b). Since about 110 ka the central type effusive and explosive activity followed, producing the growth of the composite stratovolcano edifice (Valle del Bove and Stratovolcano phases of Branca et al., 2011b; see Fig. 1). In particular, the Timpe phase consists of a lava flows succession locally interlayered with thick debris and alluvial deposits cropping out along the Acireale and Moscarello fault-scarps. The volcanic products erupted during the last 60 ka formed the main portion of the investigated area. They are represented by the lava and pyroclastic successions of the Ellittico volcano (60-15 ka) and by the volcanics erupted during the last 15 ka related to the Mongibello volcano (Branca et al., 2011a, b). In particular, the intense effusive and explosive activity of Mongibello volcano produced a thick lava succession with interlayer pyroclastic deposits that cover about the 88% of the Etna's surface (Branca et al. 2011a). In addition to this typology of volcanic rocks, a thick Holocene volcanoclastic succession related to the formation of the Valle del Bove depression crops out immediately eastward of the valley down to the coast (Fig. 1). This succession is formed by a debris avalanche deposit and by a wide fan-shape detritic–alluvial deposit named "Chiancone" (Branca et al., 2011a, b).

The complex geological evolution of Etna volcano created an extremely heterogeneous volcanic succession, that along the lower eastern flank of Etna exhibits large thickness ranging from 0 up to 900 m (see for details Branca and Ferrara, 2013). In particular, the variation of the volcanic pile thickness is highly conditioned by the morphologic setting of the basement underlying Etna. In particular, the eastern flank is characterized by the presence of a deep depression filled by a thick volcanic and volcanoclastic successions characterized by a high lateral and vertical variation of the lithologies (Branca and Ferrara, 2013). This basement depression is delimited both to the north and southward by an E–W elongated morphostructural high of the basement (Vena and Aci Trezza ridge of Branca and Ferrara, 2013), where the volcanic pile is less than 200 m thick. Conversely, along the central portion of the lower eastern flank the volcanic and volcanoclastic successions reached thickness ranging from 600 m up to 900 m. Finally, in this sector of Etna the sedimentary basement crops out only in restricted portions of the morphostructural highs, where the Early-Middle

Pleistocene marly-clays are exposed up to an elevation of 770 m along the Vena Ridge (Branca and Ferrara, 2013).

3. Methodology

3.1. HVNR and cluster analysis

To investigate about the local seismic response several strategy could be adopted. A straightforward and not time consuming approach consists in performing a large number of ambient vibration measurements that highlight areas having homogeneous site response features. To this end, in the lower eastern flank of Etna volcano a grid (spaced 1.0 x 1.0 km) was planned, locating the recording sites at the nodes of it. Since the present study aims at an exploratory site response estimate, we intentionally did not focus the spatial distribution of recording sites with respect to location of the main faults and/or features of the outcropping lithotypes but we rather preferred a quite regular spacing of measurement points. The ambient noise was recorded in 135 sites (Fig. 1) using Tromino™, a compact 3-component velocimeter. This kind of seismometer was preferred to other commercial data logger for its compact configuration that permits a fast installation and then the acquisition of a great amount of data in short time. Using a short period instrument, despite the thickness of the volcanic succession reaches values up to 900 m, could imply the presence of low frequency effects (< 0.5 Hz). On the other hand, the reduced reliability of Tromino™ response, at relatively low frequencies, appears not of primary interest for engineering purposes. Studies concerning the dynamic properties of the buildings in eastern Sicily (Panzera et al. 2013 and 2016) pointed out indeed that their fundamental periods are lower than 1.0 s (> 1.0 Hz). Time series 30 minutes long were recorded with a sampling rate of 128 Hz (equivalent to 128 samples per second). Following the SESAME (2004) guidelines, the recorded signal was afterwards divided in time windows of 30 s not overlapping. For each windows a 5% cosine taper was applied and the Fourier spectra were calculated in the frequency range 0.5 - 20.0 Hz. The spectra of each window were smoothed using a Konno-Ohmachi window (Konno and Ohmachi, 1998). In this step it is crucial to set the parameter *b* properly. A small value of *b* will lead to a strong smoothing, whereas a large value of *b* will lead to a low smoothing of the Fourier spectra. Generally, for site response analysis the *b* value is fixed equal to 40 (SESAME, 2004). Finally the resulting HVNR was computed estimating the logarithmic average of the spectral ratio obtained for each time window, selecting only the most stationary part of the signal and excluding transients associated to very close sources.

The obtained HVNRs were subdivided into groups showing a similar shape using a *k-means* cluster analysis (Fig. 2). Such approach has been used in several studies (e.g. Rodriguez and Midorikawa, 2002; Cara et al., 2008) aiming to summarize the information coming from the HVNR in order to identify homogeneous areas in terms of site response and local geology. In particular, Cara et al. (2008) clustered sites by considering only the similarities in the HVNR function, whereas Rodriguez and Midorikawa (2002) tested the reliability of the cluster results through the comparison with earthquake spectral ratios. The clustering technique includes different algorithms and methods for grouping objects in a set of categories with relatively homogeneous characteristics. In the present study, the cluster analysis was computed taking into account only the HVNR amplitudes in the 0.5–10.0 Hz frequency range. Higher frequency values (> 10 Hz) were not included, being not interesting from the engineering point of view. The analysis was performed taking into account the 135 HVNRs (i = 1…135) whose amplitude was computed at 82 frequency values (M) in the range 0.5-10.0 Hz, expressing them by a vector y_{iM}. The degree of similarity between the HVNRs observed at two sites (e.g. i and j) was calculated using the Euclidean distance:

$$d_{ij} = \sqrt{\sum_{M=1}^{82} \left(y_{iM} - y_{jM}\right)^2} \quad (1)$$

Finally, the use of *k-means* clustering approach (MacQueen, 1967) led to the definition of the clusters. This technique consists in ranking into N_C clusters, chosen by the user, the N_K measurement points and evaluating the quality of the clustering by computing the sum of the squared error (SSE):

$$SSE = \sum_{i=1}^{N_K} \sum_{j=1}^{M} \left(y_{ij} - y_{C_{kj}}\right)^2 \quad (2)$$

where y_{Ck} is the centroid of the vectors y_i in the cluster, calculated through:

$$y_{C_{kj}} = \frac{1}{N_K} \sum_{i=1}^{N_K} y_i \quad (3)$$

The *k-means* algorithm directly attempts to minimize the *SSE*, assessing each measurement point to its nearest cluster and repeating the computation until the results do not change anymore.

The detection of the optimal number of clusters in a dataset is a general problem (Burnham and Anderson, 2002) that can be solved through several methods. In the present paper the identification of the best solution from a group of acceptable models was achieved through the Akaike Information Criterion (AIC, Akaike, 1974). This procedure does not require particular assumptions on the experimental data and is suitable for solving the model decision problem in many applications (Burnham and Anderson, 2002). To find the optimal number of clusters, the analysis was run for increasing values of NC (ranging from 1 to 20) and selecting the NC value for which the AIC is minimized. Assuming that the model error is normally distributed, the AIC formula is:

$$\mathrm{AIC} = N_K ln\left(\frac{RSS}{N_K}\right) + 2k + \frac{2k(k+1)}{(N-k-1)} \quad (4)$$

where N_K is the total number of HVNR, *ln* indicates the natural logarithm, *RSS* is the residual sums of squares and k indicates the number of free parameters as N_C-1. In the present study *RSS* is defined as the sum of the *SSE* of all the clusters.

3.2 Investigations on directional effects

The experimental spectral ratios were also calculated after rotating the horizontal components of motion by steps of 10 degrees starting from 0° (north) to 180° (south), using the same criteria (windows length, taper, smoothing) adopted for HVNR. This analysis was performed in order to investigate about the possible presence of directional effects. Examples of the results obtained are plotted in Figure 3 using contour plots of amplitude, as a function of frequency (x-axis) and direction of motion (y-axis). We also performed a direct estimate of the polarization angle by using the covariance matrix method (Jurkevics, 1988) to overcome the bias linked to the denominator behavior that could occur in the HVNR technique. This technique is based on the evaluation of eigenvectors (u_1; u_2; u_3) and eigenvalues (λ_1; λ_2; λ_3) of the covariance matrix obtained by three-component seismograms. Parameters describing the characteristics of the particle motion (rectilinearity L; azimuth A; incidence angle I) are extracted using the attributes from the principal axes. In particular, the degree of rectilinearity is defined as:

$$L = 1 - \left(\frac{\lambda_2 + \lambda_3}{2\lambda_1}\right) \quad (5)$$

and it is equal to unity for pure body waves and zero for spherical waves. The azimuth of a wave can be estimated by:

$$A = \tan^{-1}\left(\frac{u_{21}(sign\mathrm{u}_{11})}{u_{31}(sign\mathrm{u}_{11})}\right) \quad (6)$$

where u_{j1} j=1, 2, 3 are the three direction cosines of the eigenvector u_1 and the *sign* function is introduced to resolve the ambiguity of taking the positive vertical component of u_1. The apparent incidence angle of rectilinear motion may be obtained from the corresponding direction cosine of u_1:

$$I = \cos^{-1}|u_{11}| \quad (7)$$

Signals at each site were band-pass filtered using the entire recordings and a moving window of 1 s with 20% overlap, therefore obtaining the strike of maximum polarization for each moving time window. To summarize the general trend of the polarization azimuth at each site, rose diagrams were depicted (Fig. 3). Each diagram displays a circular histogram in which instantaneous polarization azimuth measurements are plotted as sectors of circles with a common origin (bin size 10°).

4. Results and discussion

The HVNRs obtained from measurements performed in the eastern flank of Etna volcano were subdivided into 7 clusters (see results in Fig. 2) according to the minimum value reached by the AIC (see panel (h) in Fig. 2).

The cluster (a) consists of 39 measurements characterized by flat HVNR (amplitude lower than 2 units) in the frequency range 0.5-10.0 Hz. The HVNRs in the clusters (b) and (c) are altogether 43, and show dominant peaks at about 1.5 and 3.0 Hz, respectively. The cluster (d) is composed by 13 spectral ratios with dominant frequency at about 5.0 Hz. High frequencies HVNR peaks (> 5.0 Hz) are observed in 15 sites that were included in the clusters (e) and (f). Finally, the cluster (g) is characterized by 9 spectral ratio curves broadly trending towards an increase in amplitude. The above described clusters were further merged in four classes taking into account the shape similarities (see green shadowed areas in Fig. 2). In particular, the identified classes are: I) flat HVNR, cluster (a), II) broadband behavior, cluster (g), III) spectral ratios with fundamental frequency in the range 1.0-5.0 Hz, clusters (b) and (c), and IV) high frequency peaks (> 5.0 Hz), cluster (e) and (f). The cluster (d), having a bimodal shape with spectral ratios that can be partially ascribed to both classes III and IV, was removed and the related HVNRs were accordingly subdivided. Finally, the HVNRs included in each group were checked to verify the reliability of the obtained classification. The check confirmed the consistency of the adopted cluster analysis showing that almost 90% of HVNRs belong to each assigned group, and the remaining 10% was manually re-allocated. The large number of measurements available, with a quite homogeneous spacing, allowed us to draw a macro-zones contour map of the studied area, discriminating sites having different "fundamental frequency classes" (Fig. 4). It was attained through the Nearest Neighborhood algorithm subdividing the study area into cells, using the Voronoi diagram method, and defining for each point its influence area through a Delaunay triangulation. Inspection of the map (Fig. 4) points out that it is very difficult to interpret the results in term of the outcropping lithologies. A rather good matching is observed only for the Chiancone area (to the south of the town of Giarre, see location in Fig.1) where flat spectral ratios were usually observed. This finding is consistent with the nature of the volcanoclastic conglomerate deposit, which is poorly stratified and often hardened. The overall thickness of this unit inferred by borehole data and geophysic investigations, is about 300 m (Branca et al., 2011a). It is also worth noting that the map shows wide areas, delimitating both the fundamental frequencies in the ranges $1.0 \leq F_0 < 5.0$ Hz and some broadband spots (see blue and red areas in Fig. 4). Although in these zones lava formations outcrop extensively, the presence of such amplification effects clearly points out the presence of several local discontinuities that delineate alternating soft and stiff layers. Moreover, inspection of Figure 4 sets also into evidence that these areas stretch out in a direction consistent with that of the main faults. This behavior is clearly evident in the southern part of the study area (Zafferana, Acireale, Trecastagni) and around the TFS, whereas it is only partially evident to the north of the PFS. The above considerations are confirmed by 2-D diagrams (Fig. 5) obtained by combining all the ambient noise measurements performed along each transects (see different colour measurement sites located in Fig. 1). The profiles highlight that it is quite hard to identify a continuous bedrock formation whereas heterogeneities producing resonance effects are detected. It is also evident that transects (a) and (b) in Figure 5 show in their SW part - where the TFS has a major geomorphic expression - that amplification site effects are particularly marked. In the (c) and (d) transects such effects spread all over the 2-D diagrams. This could be related to the existence of a more diffused fractured area linked to the fault zone.

Most of the investigated sites show a significant amplitude increment of rotated HVNRs in the frequency range 1.0-5.0 Hz (see examples in Fig. 3). These results highlight a preferential and site-dependent direction of the horizontal ground motion amplification. The investigated area is indeed extremely heterogeneous from the lithologic and structural point of view. More in detail, the existence of different fault systems (the WNW-ESE striking PFS and the NW–SE striking TFS and SFS) can induce a preferential polarization direction of seismic waves as observed and described in other studies investigating the wavefield polarization along faults at Etna (Rigano et al., 2008; Di Giulio et al., 2009; Pischiutta et al., 2013; Panzera et al., 2014; Imposa et al., 2015; Panzera et al., 2016;). To confirm the HVNR results and support our hypothesis that the directional effects are linked to a heterogeneous medium characterized by oriented fractures, a polarization analysis was performed. It is interesting to observe that azimuth polar plots clearly show a pronounced polarization in the frequency band 1.0-5.0 Hz, with maxima trending almost perpendicularly with respect to the faults (Fig. 6). In particular, three different zones are identified. The first, to the North, encloses PFS (see inset in Fig. 1a), in which rose diagrams show a prevalent NE-SW direction. The second zone is characterized by scattered or low polarization and the third one including TFS and TCF, represents the largest area with almost E-W trending polarization. It should be stressed that this area includes the sector investigated in the frame of a project funded by the Sicilian Civil Protection (Azzaro et al., 2010) aimed at mapping fractures and cracks that may induce or enhance damage to buildings during earthquakes. The study identified 26 fracture zones between Acireale, Santa Venerina e Milo that were mostly oriented N-S in the area of Acireale, and

NNW-SSE in the areas of Santa Venerina and Milo. Taking into account the results of this structural survey and the afore mentioned studies concerning features of the seismic site response along fault zones in the Etna area, the observed wavefield polarization could be interpreted as linked to the presence of these secondary cracks and fractures. The prevalence of a specific polarization azimuth, especially in the zones I and III (Fig. 6) is therefore determined by the strong anisotropic effects linked to the oriented fractures existing in the damage fault area (e.g. Pischiutta et al., 2014). In such conditions, different attenuation properties of the body waves take place, and in particular P waves, appear more attenuated perpendicularly to the fractures while S waves result amplified in the same direction (see for instance Carcione et al., 2012; 2013). Such findings emphasize the importance of delineating the fault damage zones in the city planning and, as observed in the Etnean area where faults crosses villages, put into practice a specific strategy in order to takes into account these effects in the seismic code provisions.

Concluding remarks

A preliminary and quick seismic site response surveys, using ambient vibration measurements was performed in the complex geologic setting such as the eastern flank of Mt. Etna. The obtained results can briefly be summarized as follow:

- The cluster analysis, based on the *k-means* technique, turned out to be a quite reliable procedure to subdivide HVNRs into four homogeneous classes of fundamental frequency.

- The results point out that lava flows, usually considered as stiff rock, are characterized by the presence of extensive areas where significant amplification effects take place. This behavior can be ascribed to the presence of alternating stiff and soft layers that very often characterize the lava successions. The complexity and heterogeneity characterizing the investigated area therefore imply that HVNR findings cannot be easily interpreted in term of the outcropping lithologies.

- Spectral ratios results point also out the outstanding heterogeneity of lava sequences making difficult to identify a single seismic bedrock formation.

- The contour map obtained by interpolating the frequency classes assigned to each measurement, highlights the important role played by the fractures fields linked to the main fault systems.

- The analysis of directional seismic site effects and results from polarization diagrams of the horizontal components of motion allowed us to identify two main areas with strong directional effects striking NW–SE and WNW-ESE that appear almost perpendicular to the trend of PFS and TFS, respectively.

The used methodologies represent in our opinion the preliminary steps for a quick, practical and inexpensive procedure to identify relevant macro-areas for future detailed studies aiming at reducing seismic risk in a very exposed region.

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Figure Captions

Figure – 1. Geological map of the investigated area (modified from Branca et al., 2011). In the Stratovolcano phase, successions of the Ellittico volcano consist of: a) pyroclastic deposits; b) debris-alluvial deposits; successions of the Mongibello volcano consist of: a) pyroclastic deposits; b) Milo debris deposit; c) Chiancone alluvial deposit. The inset map a) shows the main structural features of Mt. Etna eastern flank (modified from Barreca et al., 2013); from North to South: PFS (Pernicana Fault System), TFS (Timpe Fault System), SFS (Southern Fault System), TMF (Tremestieri-Mascalucia Fault), and TCF (Trecastagni Fault). The inset b) illustrates the tectonic framework of the study area with major structural domains (modified from Lavecchia et al., 2007).

Figure – 2. HVNR clusters resulting for the Etnean area (a), (b), (c), (d), (e), (f) and (g). Grey lines refer to each HVNR forming the cluster; black lines show the average HVNR for each cluster; red dashed lines correspond to $\pm\sigma$ standard deviations; dashed line indicate the significance value of spectral peaks; green area delimitate the frequency range of the observed HVNR peaks. (h) Akaike Information Criterion parameter vs. the number of clusters for the studied area.

Figure – 3. Examples of contours of the spectral ratios geometric mean, as a function of HVNR amplitudes (colour scale), frequency (x-axis) and direction of motion (y-axis), with corresponding polarization rose diagrams. (a) Shows the results obtained at sites with strong directional effects, (b) displays examples of results obtained at sites with no evidence of directional effects.

Figure – 4. Contour map bounding sites having different spectral ratio features.

Figure – 5. 2-D diagrams obtained by combining all the ambient noise records performed along the transects a, b, c and d (see fig. 1) as a function of distance (x axis), frequency (y axis) and HVNR contour plot amplitudes.

Figure – 6. Rose diagrams of the polarization azimuth in the frequency range 1.0-5.0 Hz for each measurement site. The different colored areas gather together rose diagrams showing similar features and/or prevailing azimuths.

Figure 1

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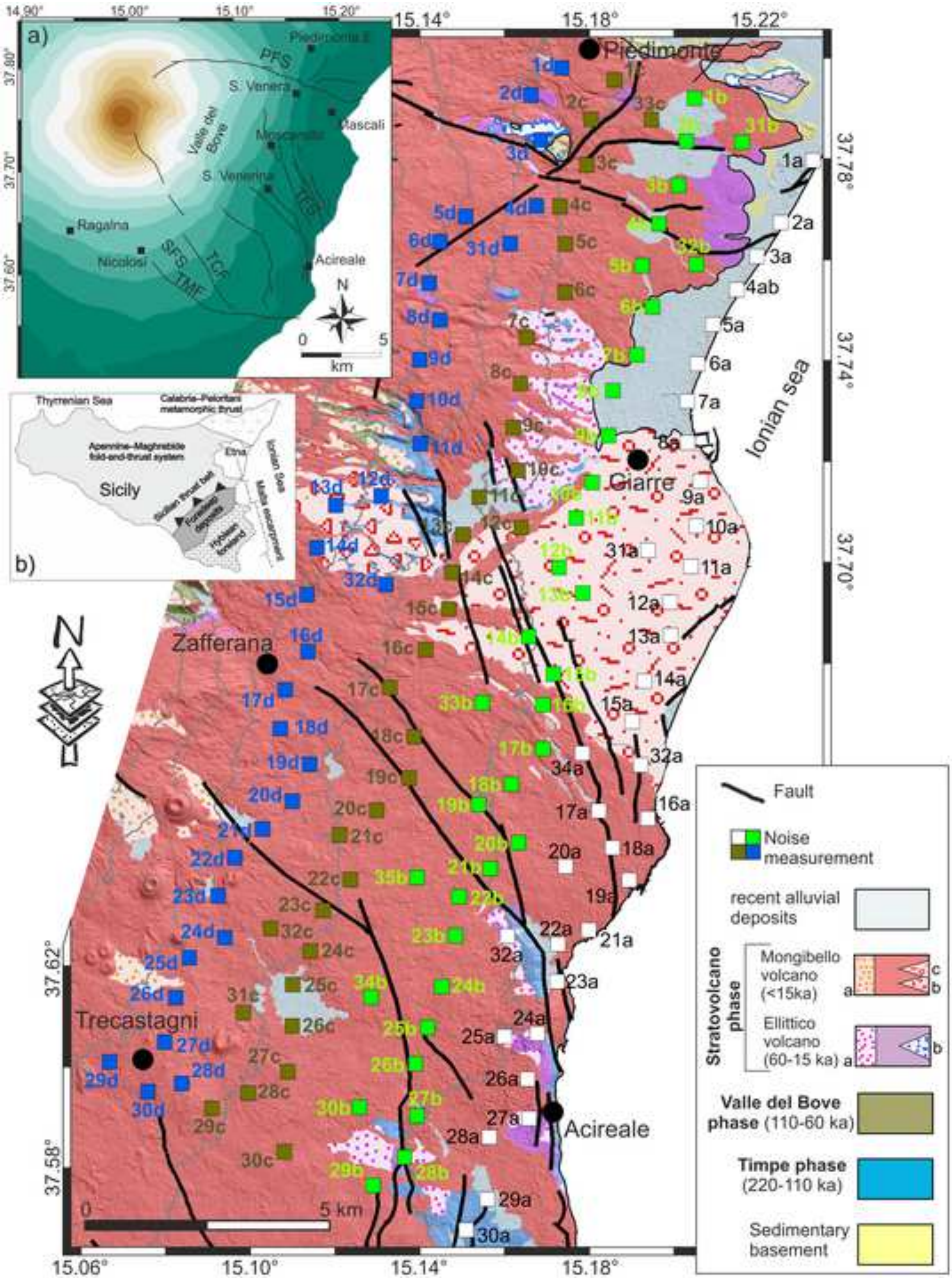
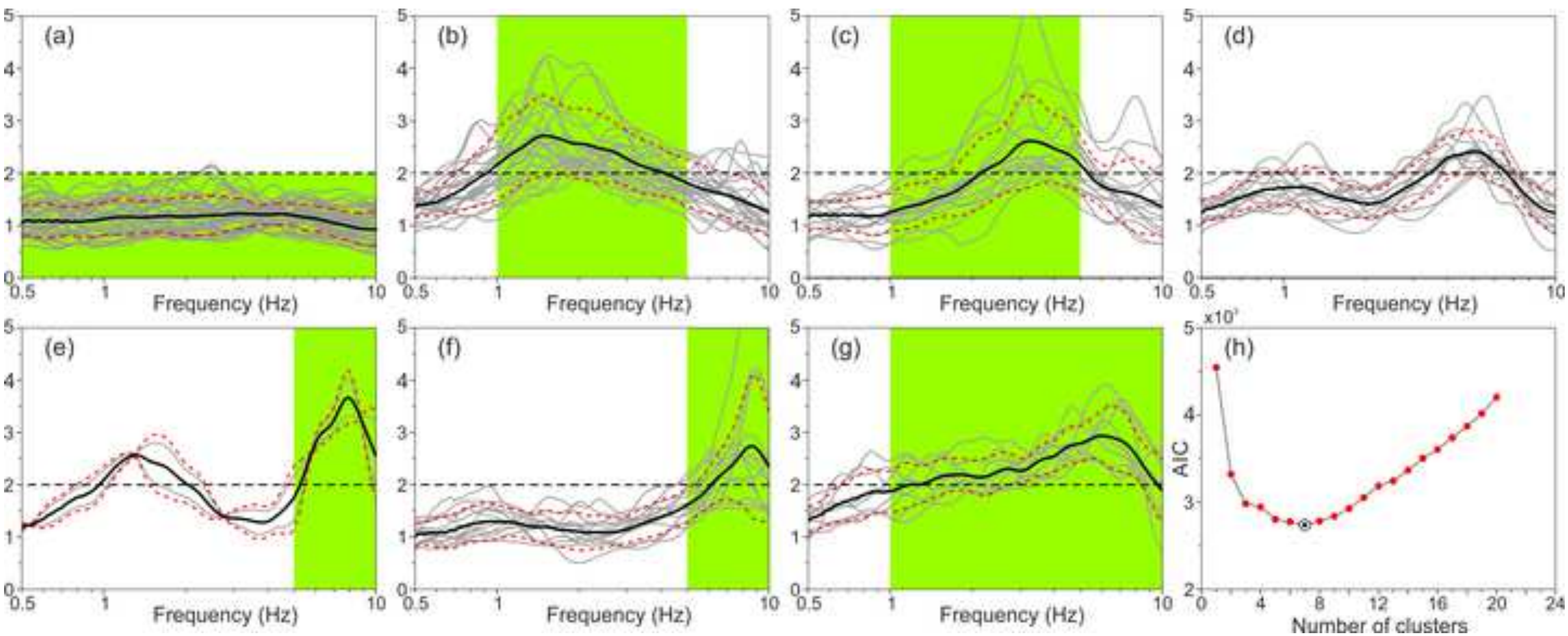


Figure 2



(a)
(b)
(c)
(d)
(e)
(f)
(g)
(h)
Frequency (Hz)
Frequency (Hz)
Frequency (Hz)
Frequency (Hz)
Frequency (Hz)
Frequency (Hz)
Frequency (Hz)
AIC
Number of clusters

Figure 3

Click here to download Figure Figure 3.tif

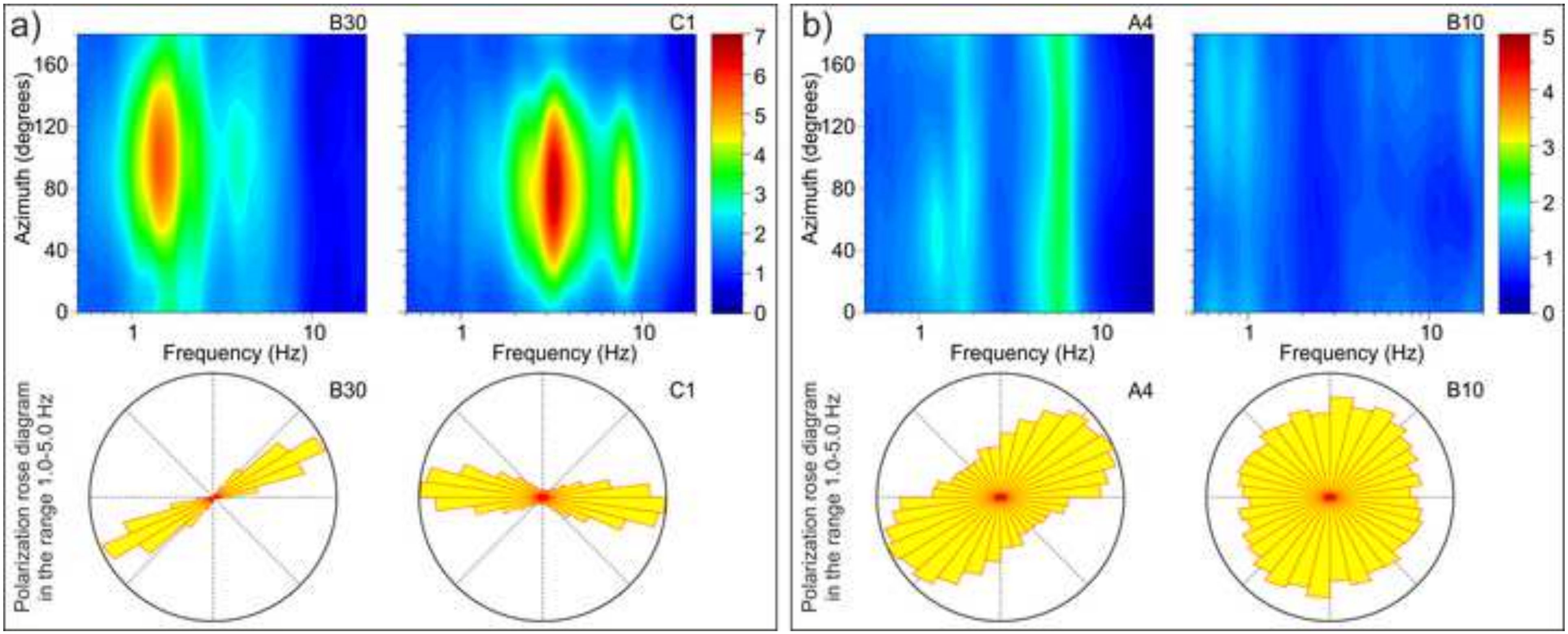


Figure 4

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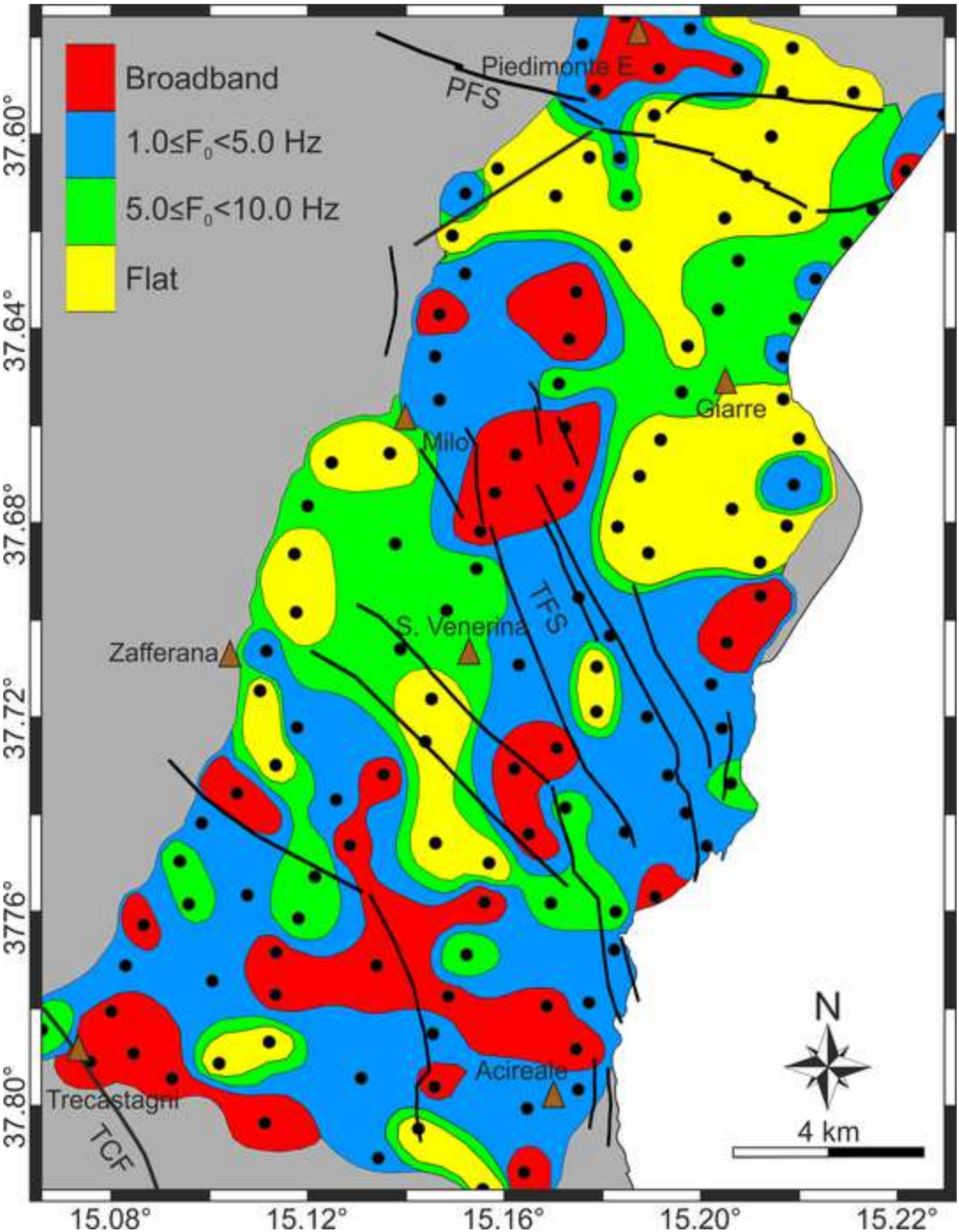

Figure 5

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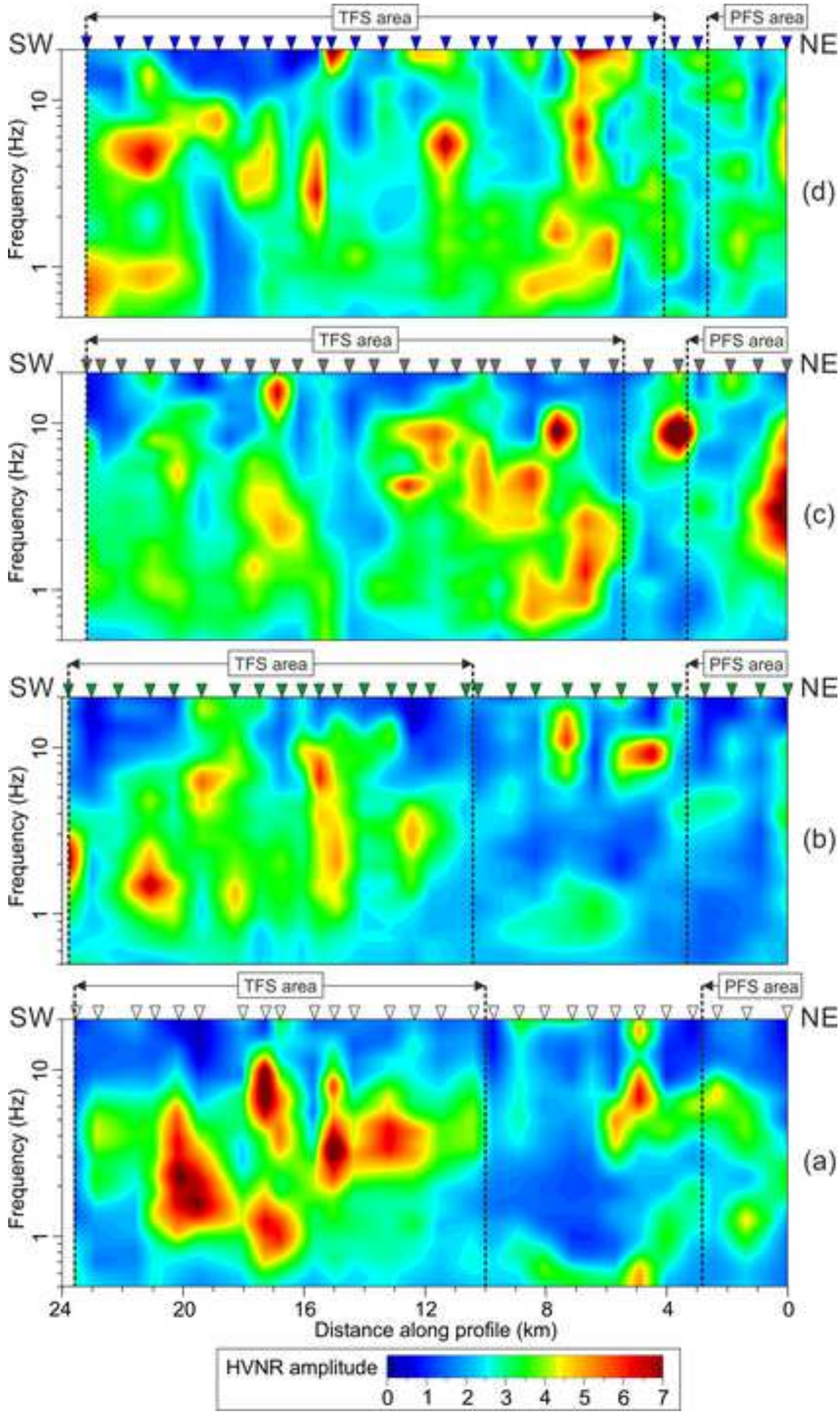

Figure 6

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