SITE EFFECTS ON FAULT ZONE: RESULTS FROM AMBIENT NOISE MEASUREMENTS

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Introduction. It is well known that fault zones are generally characterized by a highly fractured low-velocity belt (damage zone), hundreds of meter wide, bounded by higher-velocity area (host rock) that can broaden for some kilometres (Ben-Zion *et al,*. 2003; Ben-Zion and Sammis, 2003, 2009 and references therein). Such geometrical setting and impedance contrast is in principle proficient to produce local amplification of ground motion (Peng and Ben-Zion, 2006; Calderoni *et al.*, 2010; Cultrera *et al.*, 2003; Seeber *et al.*, 2000), as well as to support the development of fault zone trapped waves.

There is a large number of papers that describe propagation properties of fault-guided waves (e.g., Li *et al.*, 1994; Mizuno, Nishigami, 2006) in terms of ground motion amplification having a propensity to be maximum along the fault-parallel direction. These observations, both in theoretical and experimental approaches deal with almost pure strike slip faults such as the S. Andreas and the Anatolian faults (see Li *et al.*, 2000; Ben Zion *et al.*, 2003). Studies about local seismic response nearby fault zones have been performed in Italy and in California by Cultrera *et al.* (2003), Calderoni *et al.* (2010), Pischiutta *et al.* (2012) who observed evidences of ground motion amplification in the fault zone environments and strong directional effects with high angle to the fault strike. Similar studies, performed by Rigano *et al.* (2008) and Di Giulio *et al.* (2009) documented the presence of a systematic polarization of horizontal ground motion, near faults located on the eastern part of the Etnean area, that was never coincident with the strike of the tectonic structures. These directional effects were observed both during local and regional earthquakes, as well as using ambient noise measurements, therefore suggesting the use of microtremors for investigating ground motion polarization properties along and across the main tectonic structures of all the volcanic area. All the observations showed evidence of directional amplifications not parallel to the fault strike, as would have been expected for trapped waves.

In the present study, the results of new measurements are shown and discussed. The data were recorded in newly investigated tectonic structures of the volcano located both on the western flank of Mt. Etna (Ragalna fault system) and on the eastern flank of the volcano (Piedimonte fault) as well as in a non-volcanic area (Malta Island), located in the Hyblean foreland. Moreover, several measurements were performed in areas significantly distant from the studied tectonic structures (Piano dei Grilli and Malta area), in order to observe how directional effects can change at increasing distance from the fault lines.

Tectonic of the study area. South-eastern Sicily is located in a complex tectonic region being at the boundary between African and European plates (see inset map in Fig. 1a). Along this border, Mt. Etna, a basaltic volcano more than 3300 m high and with a diameter of about 40 km, resulting from the interaction of regional tectonics and local scale volcano-related processes (McGuire and Pullen, 1989), is sited. The island of Malta is placed in the Hyblean foreland, belonging to the African plate. Although the sedimentary platform on which the Maltese islands are situated was formed during the Triassic, there are no surface outcrops of this age. Most of the formations here outcropping were deposited during the Oligocene and Miocene when the whole area was part of the Malta - Ragusa platform and, as such, attached to the African margin (Pedley *et al.*, 1978).

The whole study area is delineated by the crossing of lithosphere structures that give rise to the origin of Mt. Etna and by the presence of the Malta Hyblean fault system that runs down the Sicilian coast towards the Ionian sea. A series of horst and graben structures, NW-SE and NNW-SSE oriented, that are linked to the Malta-Hyblean escarpment, characterize indeed the tectonic setting of this area.

On Malta, the geo-structural pattern is dominated by two intersecting fault systems which alternate in tectonic activity. An older ENE-WSW trending fault, the Victoria Lines Fault (or Great Fault), traverses the islands and is crossed by a younger NW-SE trending fault, the Maghlaq Fault

(Fig. 1b), parallel to the Malta trough which is the easternmost graben of the Pantelleria Rift system. The faults belonging to the older set, all vertical or sub vertical, are part of a horst and graben system of relatively small vertical displacement.

As concerns Mt. Etna, its eastern flank is the more tectonically active part. Here, several NNW and NNE-trending fault segments, arranged in a 30 km long system (Fig. 1a), control the present topography and show steep escarpments with very sharp morphology (Monaco *et al.*, 1997). This system represents the northernmost prolongation of the Malta Escarpment and forms a system of parallel step-faults having vertical offsets up to 200 m that down-throw towards the sea. Most of these faults are highly seismogenic and generate shallow earthquakes as well as coseismic cracks in the soil and creep phenomena (Azzaro, 1999). In the north eastern part of the area, the active Pernicana fault system (PFS) represent the most significant tectonic structure. It is a strike-slip fault roughly E-W oriented with a length of about 18 km from the NE rift to the coastline (Neri *et al.*, 2004; Azzaro *et al.*, 2001; Acocella and Neri, 2005). At the end of such structure, close to the coast line, the Calatabiano and Piedimonte faults (PF) can be considered, following Lentini *et al.* (2006), as the neotectonic structures of the basement outcropping in north-eastern Sicily (Fig. 1a). These structures displaces a large part of the north-eastern flank of Mt. Etna by a 15 km long set of extensional faults, striking broadly ENE-WSW, that are segmented into individual structures 3-5 km long and up to 120 m high, offsetting late Pleistocene to Holocene volcanics and represent important features that displace the units of the sedimentary basement in the coastal area. However, they seem to represent old structural elements inherited from the basement tectonics since no evidence of activity (earthquakes or creep) is known for these structures in historical times (Azzaro *et al.*, 2012).

The western flank of the volcano is affected by a moderate tectonic activity, the Ragalna fault system (RFS) being the main structure (Fig. 1a). Such system is formed by three distinct fault segments the Calcerana and the Ragalna faults trending NE-SW and the Masseria Cavaliere fault, N–S striking (Azzaro, 1999; Rust and Neri, 1996). This latter structure is a fresh east-facing escarpment up to 20 m high and 5 km long. Dextral, oblique-slip displacements are indicated by geomorphic markers and its tectonic activity, reported in the last two centuries, seems only due to fault creep (Azzaro *et al.*, 2012). Less evident compared to the previous one, the NE-SW striking Calcerana fault and the NE-SW trending structure, reported by some authors in the area between Ragalna and Biancavilla, that do not show strong field evidences. The relationship between these fault segments is unclear and there is lack of apparent continuity in the field.

Methodology. The evaluation of site response using the HVNR technique, as largely asserted by many authors (e.g., Bard, 1999; Cara *et al.*, 2003), gives reliable information about the fundamental frequency peak. In the present study ambient noise was recorded in several sites located along profiles crossing the RFS and the PF (in the Etnean area Fig. 1a) as well as in the Malta Island fault segments belonging to the Great Fault system (Fig. 1b). In each fault segment, at least two transects were carried out each formed by five-six measurement points. Investigations were also performed in the Piano dei grilli (PG area, western flank of Mt. Etna) and in the northern Malta area in order to record data in areas significantly far (hundred-thousand meters) from the investigated tectonic structures, to observe if directional effects do exist and how they modify when measurements are performed away from any surrounding fault lines.

Ambient noise records were performed using Tromino (www.tromino.it), a compact 3-component velocimeter with a reliable instrumental response in the frequency range 0.5-10 Hz. Time series, 30 minutes long, were recorded using a sampling rate of 128 Hz. The signals were processed evaluating the horizontal-to-vertical noise spectral ratios (HVNSR), as functions of frequency and direction of motion, to investigate possible directional resonance frequencies. HVNSRs were calculated after rotating the NS and EW components of motion by steps of 10 degrees from 0° (north) to 180° (south) and the contours of such spectral ratios amplitude were plotted. According to the guidelines suggested by the European project Site EffectS assessment using AMbient Excitations (SESAME, 2004), time windows of 30 s were considered, selecting the most stationary part and not including transients associated to very close sources. Fourier spectra

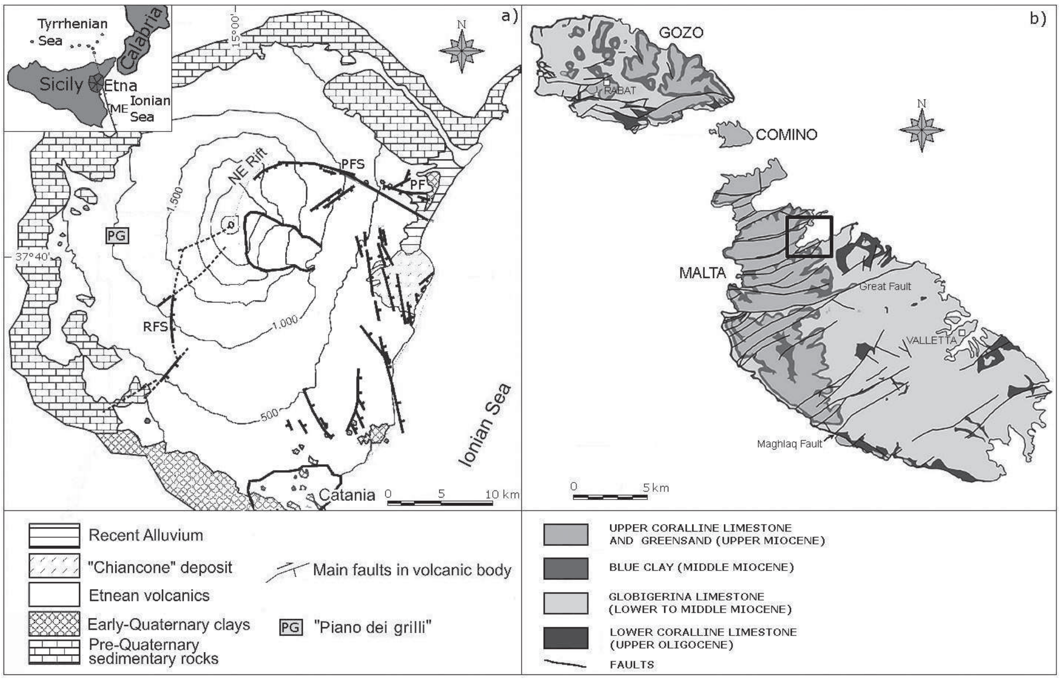

Fig. 1 - (a) Simplified geological map of Mt Etna showing the main structural features (modified from Neri *et al.*, 2007), RFS = Ragalna fault system, PFS = Pernicana fault system, PF = Piedimonte fault. In the inset map, the Malta Escarpment (ME) is shown. (b) Sketch geological map of the Maltese Islands (modified from Various Authors, 1993). The black square indicates the investigated area.

were calculated and smoothed using a triangular average on frequency intervals of ± 5% of the central frequency. This approach, firstly applied to earthquake data by Spudich *et al.* (1996) is powerful in enhancing, if any, the occurrence of site specific directional effects. A similar procedure was used for ambient noise signals by Del Gaudio *et al.* (2008) and Panzera *et al.* (2011; 2012) for the identification of site response directivity in presence of an unstable slope. Moreover this technique was adopted by Rigano *et al.* (2008), Di Giulio *et al.* (2009) and Pischiutta *et al.* (2012) to detect the features of seismic site response in fault zones.

In present study a direct estimate of the polarization angle, for noise data, was achieved by using the time-frequency (TF) polarization analysis by Burjánek *et al.* (2010, 2012). The results obtained through the polarization technique are quite robust since this approach is very efficient in overcoming the bias linked to the denominator behavior that could occur in the HVSNR's technique and at the same time, longer time-series are processed therefore reducing the problems that may be linked to signal-to-noise ratio. In the TF method, a continuous wavelet transform for signal time-frequency decomposition, is firstly used. Subsequently, the polarization analysis on the complex wavelet amplitude for each time-frequency pair, is applied. In particular, histograms of the polarization parameters are created over time for each frequency. Polar plots are then adopted for depicting the results which illustrate the combined angular and frequency dependence.

Results and Discussion. In Fig. 2, some examples of both directional resonances and polarization plots, obtained at selected ambient noise recording sites, about 50 m spaced from each other, located along the short profiles crossing the investigated structures are shown. Notably, at the sampling sites located in close proximity of the RFS (Figs. 2a and 2b), the H/V spectral ratios show a tendency to increase the amplitude, in the frequency range 1.0-6.0 Hz, at angles of about 80°-90° for Masseria Cavalieri and 60°-70° for Ragalna faults. In general, H/V spectral ratios show a broad band frequency effect with several adjacent peaks pointing out a preferential direction which is the

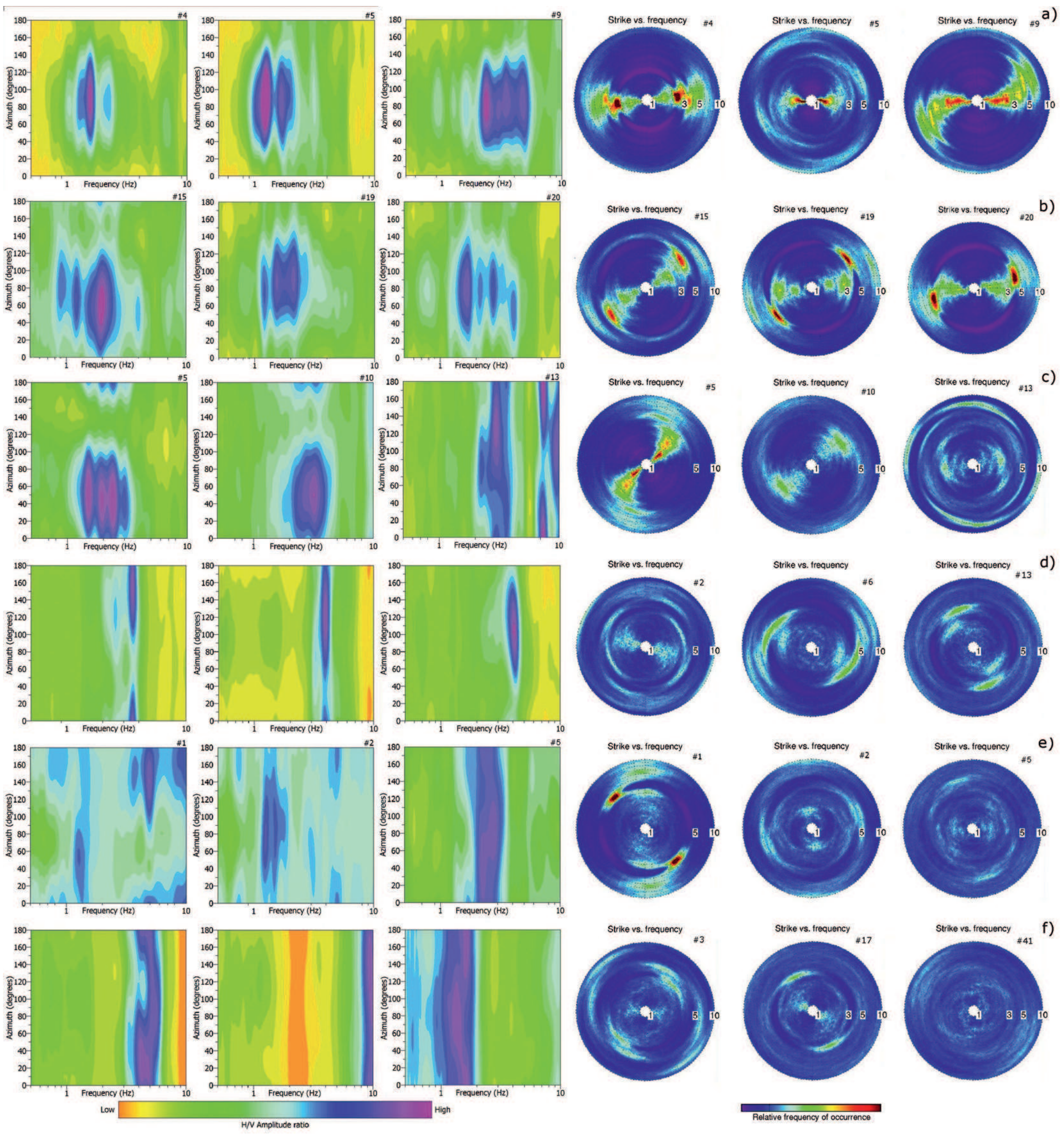

Fig. 2 - Examples of directional resonances and horizontal polarization azimuths obtained at selected ambient noise recording sites located on the Masseria Cavalieri (a), Ragalna fault (b), the PF (c), the Malta Great Fault system (d), the PG area (e) and in the northern Malta area (f).

typical behavior of directional resonances. The results coming out from the use of the covariance matrix method in the time-frequency domain allowed us to better quantify the horizontal polarization of the ground motion, giving a clear indication that ambient noise is affected by a significant horizontal polarization at the measurement sites along and across the investigated faults. It is indeed interesting to observe that the recorded ambient noise is polarized in a narrow frequency band (1.0-6.0 Hz), following a roughly east-west and northeast-southwest trend, for the Masseria Cavalieri and the Ragalna faults respectively. It is noteworthy to point out that the use of the TF polar diagrams sets into evidence that possible contributions of high-frequency noise, related to transients or to small scale geologic heterogeneities of a site, may occur at higher frequencies only (6.0-10.0 Hz).

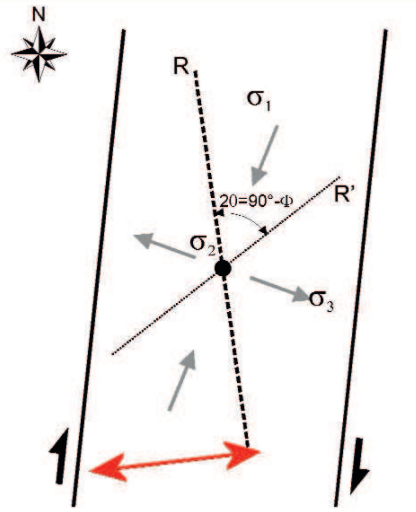

Fig. 3 - Example of the theoretical trend of the fracture field for the Masseria Cavalieri fault. Grey arrows indicate the trend of the local stress field (from Cocina *et al.*, 1997). The red arrow indicate the observed polarization direction.

Examples of the results obtained from measurements performed in the Piedimonte fault (PF) are reported in Fig. 2c. The directional resonance obtained by rotating the NS and EW components of motion seems to highlight this particular structural behavior. The results from measurements performed on footwall (#5 , #10 in Fig. 2c) highlight a strong directional effects in the frequency range of about 1.0-6.0 Hz with a NE- SW strike. In the hanging wall (#13 in Fig. 2c) the azimuths, the frequency bands and the amplitudes of the HVNRs vary at each measurement point in relation with the small scale geologic framework of each site. Polarization results confirm the frequency range and azimuths observed through the rotated spectral ratios. Indeed, in the footwall of major Piedimonte fault the recorded ambient noise is polarized in a narrow frequency band (1.0-6.0 Hz), similarly to the faults in the western area of the volcano, but with an angle of about 45° (Fig. 2c). In the hanging wall a rather scattered distribution of polarizations is observed.

As already mentioned, ambient noise records were performed in some fault segments belonging to the Great Fault system of the Malta area, in order to investigate about site effect features of tectonic structures located in a non volcanic area. Results obtained (Fig. 2d) set into evidence the existence of directional effects similar to those found in the investigated Etnean structures, although a slightly more complicated pattern, probably linked to the influence of the complex lithology existing at both the sides of the fault, is observed. However, polarization plots obtained from records near the fault show a prevailing direction not parallel to the structure strike.

Finally, tests were performed to check if the observed directional effects keep the same orientation in areas significantly distant from fault lines. For this reason, ambient noise was recorded in the PG area, located in the western flank of Mt. Etna, as well as in an area in the northern Malta island. The results (Figs. 2e and 2f) point out that directions coming from both rotated spectral ratios and polarization diagrams tend to become randomly distributed and/or uniformly scattered.

Present results could, in our opinion, be explained in the frame of the brittle rheology of the hosting rock, taking also into account the features of the local stress tensor as proposed by Pischiutta *et al.* (2012). We have to remember that four types of fractures can develop in fault zone: a) extensional fracture (T); b) synthetic cleavage (R); c) antithetic cleavage (R'); d) pressure solution surfaces (P). Their orientation depends on the direction of the resulting stress localized around the fault. The R and R' fractures, in particular, create an angle of about $\phi/2$ and 90-$\phi/2$ to the general shear-zone direction, respectively, and they intersect in an acute angle of $2\theta = 90-\phi$, where ϕ is the angle of internal friction (Riedel, 1929; Tchalenko, 1968). Moreover, according to Pischiutta *et al.* (2012), the mean polarization azimuth results to be perpendicular to the expected synthetic cleavages. Trying to explain our observations in the frame of fracture field of the considered fault, we took into account, from the available literature (e.g., Cocina *et al.*, 1997), the regional stress orientation of investigated areas. Examining the angular relation between the polarization azimuth of amplified motion and the possible R direction, resulting from the described regional stress orientation, assuming ϕ=30°, as an average value for various rock types, we observe a nearly orthogonal relation (see example in Fig. 3).

Concluding remarks. The outcomes of present research allow us to draw the following considerations:

The directional site effects and the polarization angles found through noise measurements for all the investigated structures are never parallel to the fault strike, making a simple explanation in terms of fault-trapped waves not convincing.

To try to find a possible explanation for this recurrent ground motion property, a comparison with results from studies about stress directions and fracture orientation in the presence of faults was carried out. Present findings suggest as an interpretative hint the existence of a nearly orthogonal relation between the fracture field and the azimuth of observed seismic site effects, in the investigated faults.

An exception is observed in the results concerning the Malta fault, which does not show such an orthogonal relation. This behavior could be a consequence of the complex lithology existing at both the sides of the fault.

The directional resonance and the TF polarization analysis set into evidence that fault effects appear concentrated in the frequency range 1.0-6.0 Hz. The stability of this frequency interval, observed both in the western and in the eastern flanks of the volcano, encourage us to affirm that it is a possible marker for observing site effects in fault zones, at least in the Etnean area.

Directions coming from both rotated spectral ratios and polarization diagrams tend to become randomly distributed and/or uniformly scattered when noise measurements are performed in areas without fault evidences.

Finally, it seems important to point out that present results give further support to findings from previous studies (e.g., Rigano *et al.*, 2008; Di Giulio *et al.*, 2009; Pischiutta *et al.*, 2012) concerning site effects in fault zone and promote the use of ambient noise recordings as a fast technique for preliminary investigations about angular relations between fractures field and directions of amplified ground motion.

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EVALUATION OF THE OCCURRENCE OF LIQUEFACTION PHENOMENA IN THE EMBANKMENTS OF THE PO RIVER

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Introduction. The paper regards the evaluation of the occurrence of liquefaction phenomena in the right embankments of the Po river between Boretto and Ro municipalities.

The study has been considered the results obtained by the previous studies, performed in the same area, related to the standard seismic hazard (Albarello, 2009; Marcellini *et al.*, 2010), to the characterization of the deposits through geologic and geomorphologic analyses (Martelli *et al.*, 2011), through geotechnical in-situ and laboratory tests (Costanzo *et al.*, 2011) and local seismic response (RSL) (Pergalani and Compagnoni, 2011; Fioravante and Giretti, 2011).