PRELIMINARY MICROTREMOR SURVEY RESULTS IN SALINELLE MUD VOLCANOES: PATERNÒ, ITALY

F. Panzera[1], **S. Sicali**[2], **G. Lombardo**[1], **S. Imposa**[1]

[1] Dip. di Scienze Biologiche, Geologiche e Ambientali – Sez. di Scienze della Terra, Università di Catania, Italy

[2] Istituto Nazionale di Geofisica e Vulcanologia – Osservatorio Etneo, Catania, Italy

Introduction. The gas emissions observed at Etna, are linked to the persistent emission of a huge volcanic plume, in the summit craters during both quiescent and eruptive magma degassing, and others gas manifestations such as mud volcanoes and soil degassing which occur in peripheral sectors of the volcano (Allard *et al.*, 1991; Caracausi *et al.*, 2003; Aiuppa *et al.*, 2007). The *Salinelle* of Paternò are mud volcanoes located in the lower southern western flank of Mt. Etna, that it is one of the largest basaltic active volcano in Europe (Fig. 1a). The *Salinelle* are characterized by emissions of muddy and frequently salty water which sometime create specific pseudo-volcanic structures known as mud volcanoes. Their formation is due to the presence, in the subsoil, of over-pressured gases that escape upward through permeable rocks and structural and/or lithologic discontinuities, carrying to the surface a mixture of water, mud, hydrocarbon fluids and lithoid fragments that is emitted as a flowing liquid (Aiuppa *et al.*, 2004).

The water emitted at mud volcanoes frequently contains salty solutions that precipitate forming deposits. For this reason, in certain areas of Italy they are named *Salinelle*. Such phenomena have been observed and studied in different parts of the world and in different

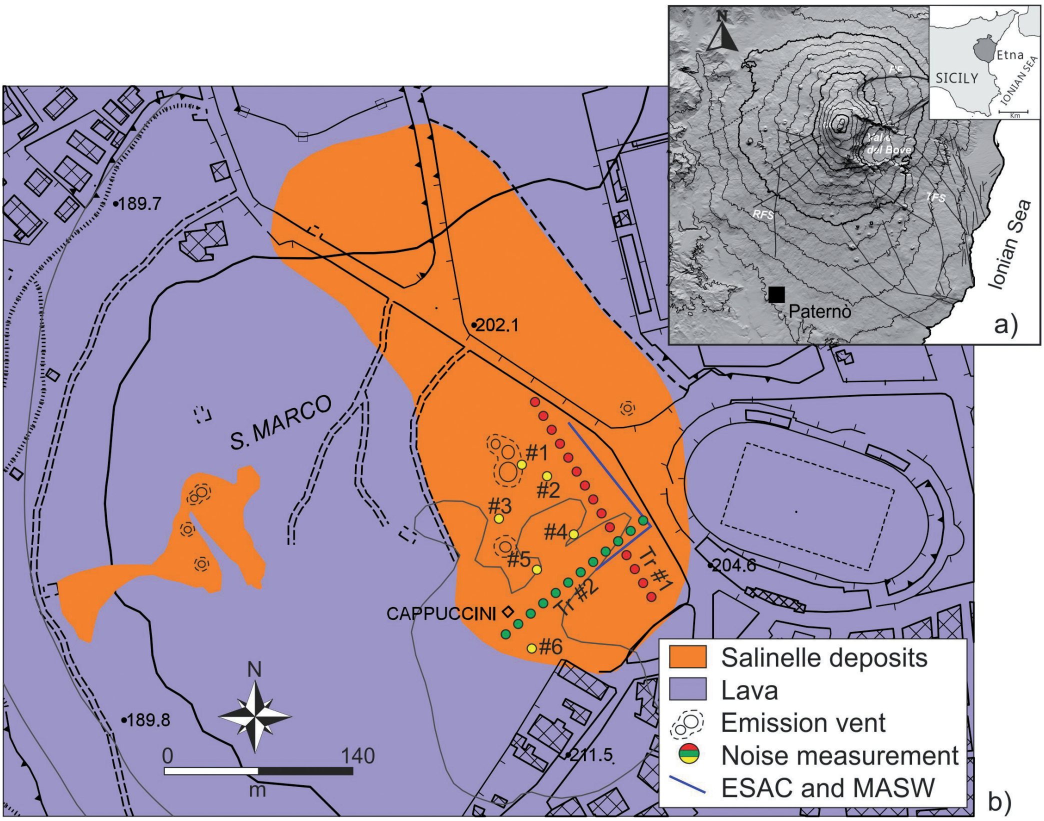

Fig. 1 – a) Simplified geological map of Mt. Etna showing the main structural features (RFS = Ragalna fault system, TFS = Timpe fault system, PF = Pernicana fault). b) Simplified geo-lithologic map of the *Salinelle* area.

areas of Italy (Dimitrov, 2002; Carveni *et al*., 2012; Adrian *et al*., 2015). In Sicily, in addition to Paternò (Catania), mud volcanoes can be observed in the areas of Agrigento and Caltanissetta, where they are also known with the name *Macalube* (Carveni *et al*., 2001; Etiope *et al*., 2002; Cangemi and Madonia, 2014). The results of some studies conducted on mud volcanoes represent the basis for the geothermal energy utilization, which presence is inferred by the composition of the gas ascending from depth (Mburu, 2014).

The present study through microtremor survey aims to provide useful information to increase the knowledge on the geo-thermal activity concerning the *Salinelle* of Paternò (Catania, Italy), whose activity is also well recognizable at a macroscopic level. Different studies throughout the world were performed to monitor the activity of mud volcanoes in terms of gas outflow (Albarello *et al*., 2012) and to study the presence of spectral anomalies in the passive seismic wavefield over different hydrocarbon reservoirs by using passive seismic surveys (Dangel *et al*., 2003; Holzner *et al*., 2005).

The *Salinelle* mud volcanoes features. Etna volcano edifice overlies the sedimentary basement made of flysch and clayey deposits that belong to the limestone of the Maghrebian-Appenninic chain (Lentini, 1982). The whole volcanic sequence can be considered as a highly porous medium, with a permeability coefficient that varies as a function of both the lithology and the volcano-tectonic structures. In particular, the volcanic sequence is characterized by alternating porous and fractured highly permeable lava layers and scarcely permeable pyroclastics. Then, the limit between lava and clay represents the base of the main aquifers of Etna. An exception is represented by the aquifer feeding the *Salinelle* mud volcanoes (Aiuppa *et al*., 2007). In this area the emitted waters are characterized by an abundant free gaseous phase and show typical features of waters linked to hydrocarbon reservoirs. Geothermometric estimates carried out on both the liquid and the gaseous phases emitted at the *Salinelle*, gave temperatures, at depth, that range 100-150°C (Chiodini *et al*., 1996). The fluids emitted generally consist of hydrocarbons (mainly CH_4) and hypersaline water (Giammanco *et al*., 1998; Amici *et al*., 2013). The mud and water mixtures are highly variable, and in some cases mud is the only fluid erupted with gas that builds cones up to a few meters high having a base diameter that can reach ten meters (Amici *et al*., 2013). These findings seem to suggest the presence of hydrocarbon reservoirs trapped in the shallow sedimentary rocks and characterized by the presence of thermal water enriched and heated by gas coming from magma of the Etna conduits.

The *Salinelle*, therefore, represent a very interesting geological-natural area, located at the NW boundary of Paternò, covering around 30,000 m^2 (Savasta, 1905). The main activities take place in two sites of Paternò area: *Salinelle del Fiume* and *Salinelle dei Cappuccini*. We focused our investigations in the latter site, in an area located close to the public football stadium (Fig. 1b), which is characterized by the most active vents. For practical reasons, we will refer to the general name *Salinelle* to indicate the study area. How thermal water reaches the surface is not fully clear, but some authors believe that at the *Salinelle* the mud rises through an old lava conduit (Carveni *et al*., 2001). To support this hypothesis there are data concerning a mechanical drilling performed during 1958 for hydrocarbons research (Carveni *et al*., 2001). A thick vacuolar lava rich in pyrite up to 400 m was found, in contrast with the average thin thickness of the surrounding lava in the area.

The temperature of the muddy waters varies from 10 and 20°C (Giammanco *et al*., 2007), but during some paroxysmal phases (1866, 1879 and 1954) the temperatures reach values between 46 and 49°C (Etiope *et al*., 2002). In the latter case, columns of muddy water as high as 1.5 m (Cumin, 1954) were observed. Silvestri (1867, 1879) reports of intense eruptive events occurred in early 1866 and late 1878. This phenomena included fountains of muddy water up to 3 m high and water temperature increases up to 46°C, that the author associated with local seismic events that occurred some days/weeks prior to the gas eruptions. In addition, previous studies revealed a strong correlation between specific earthquakes in eastern Sicily, the paroxysmal phases of *Salinelle* and significant variation of the concentration of the main gases emitted.

In particular, anomalous changes in the emission of Helium, typical geochemical precursor of earthquakes, and methane have been observed during the earthquake of Carlentini of December 13, 1990 (D'Alessandro *et al.*, 1993). However, some authors assert that the overall heat flux from Etna region has shown to be significantly and strongly controlled by the regional structural framework (Minett and Scott, 1985).

Method. A quick estimate of the surface geology effects on seismic motion is provided by the horizontal to vertical noise spectral ratio technique (HVNR). This technique firstly introduced by Nogoshi and Igarashi (1971), was put into practice by Nakamura (1989) and became in recent years widely used since it provides a reliable estimate of the fundamental frequency of soft soil deposits. The good agreement observed between results obtained using earthquake records and ambient noise has pointed out that microtremors are a valid tool to investigate ground motion polarization properties (Rigano *et al.*, 2008; Di Giulio *et al.*, 2009; Panzera *et al.*, 2013; Panzera *et al.*, 2014).

Ambient noise recordings were performed randomly in the area where the main activity of Salinelle is located (yellow points in Fig. 1b) and along two profile Tr#1 and Tr#2 (red and green points in Fig. 1b). A total number of thirty-two recording sites were usedto investigate the main features of the area. Time series of 30 minutes length were recorded through a long period velocimeter, using a sampling rate of 256 Hz and processed through the HVNR technique. According to common assumptions (Bard, 1998; Parolai *et al.*, 2001), the shortest window length of the signal has to be selected in a way that at least 10 cycles of the lowest frequency analyzed are included. Then, time windows of 100 s were considered and the most stationary part of the signal was selected excluding transients associated to very close sources. In this way the Fourier spectra were calculated in the frequency range 0.05-20.0 Hz and smoothed using a proportional 20% triangular window. Finally the resulting HVNR were computed estimating the logarithmic average of the spectral ratio obtained for each time window, selecting only the most stationary and excluding transients associated to very close sources. 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) in order to investigate about the possible presence of directional effects. Examples of the results obtained are plotted in figure 2 using contour plots of amplitude, as a function of frequency (x-axis) and direction of motion (y-axis).

However, in presence of lateral and vertical heterogeneities or velocity inversion, the HVNR can be "non-informative" due to the occurrence of amplification on the vertical component of motion (Panzera *et al.*, 2015). Thus in this study we also computed a direct estimate of the polarization angle, for noise data by using the method proposed by Jurkevics (1988). This technique is very efficient in overcoming the bias linked to the denominator behavior that could occur in the HVNR's technique. Polarization analysis makes full use of the three component vector field to characterize the particle motion and it is based on the evaluation of eigenvectors and eigenvalues of the covariance matrix obtained by three-component seismograms. Signals at each site were band-pass filtered using the whole recordings and considering a moving window of 10 s with 20% overlap, therefore obtaining the strike of maximum polarization for each moving time windows.

The dynamic site properties and, in particular, the shear wave velocity of Salinelle deposits were investigated through non-invasive techniques such as the Multichannel Analysis of Surface Waves (MASW: Park *et al.*, 1999) and Extended Spatial AutoCorrelation (ESAC: Okada, 2003). The combined use of different techniques allowed us to compare and check the obtained results going also all over the limitations of each methodology.

A "L" array configuration was used for the ESAC measurements, recording 20 minutes of noise (blue lines in Fig. 1b). The array was settled using a 26-channel seismograph and 4.5 Hz geophones. The length was 60 m in NE direction and 70 m in NW direction. Time windows of 20 s were considered to calculate dispersion curves of the fundamental mode and the average of the dispersion curves was computed, excluding those not showing a clear dispersion or in which

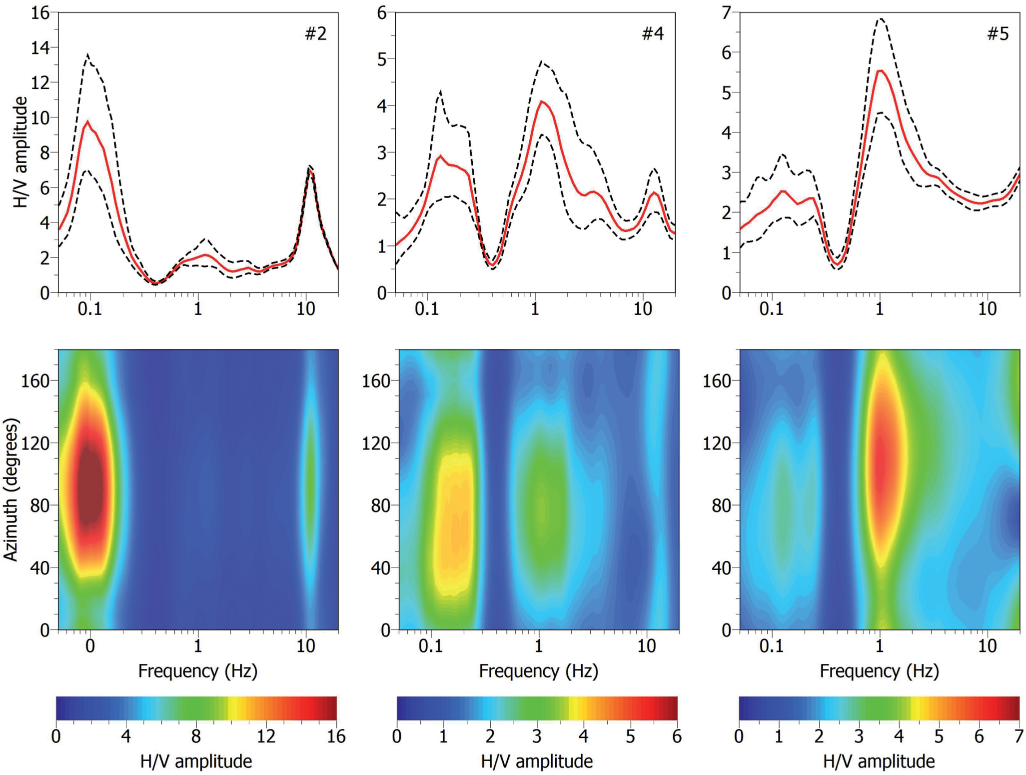

Fig. 2 – Examples of HVNR and directional resonance diagrams observed in the *Salinelle* area.

higher modes were dominant. The MASW tests were performed using the two branches of the array separately. Tests were made using a hammer source of 8 kg, with a fixed offset distance of 10 m, recording five shots to reduce the possible interference with other sources in the vicinity, with a registration length of 3 s and sample rate of 512 Hz.

In present study, the Rayleigh wave dispersion curves, obtained from the experimental setup, were inverted using the DINVER software (www.geopsy.org) which provide a set of dispersion curve models compatible with the observed dispersion curve. Inversion of the experimental dispersion curve needs a rough definition of the free parameters. This can be obtained using information coming either from a preliminary geological survey or from borehole data. If, as in our case, this information is not available, the values of parameters can be directly deduced from the fundamental mode of the Rayleigh wave dispersion curves (Albarello and Gargani, 2010). To invert the dispersion curve, a set of 1 to 8 uniform layers with homogeneous properties was considered, taking into account five parameters: shear waves velocity (V_S), thickness, compressional waves velocity (V_P), Poisson's ratio and density (ϱ).

Results and discussions. Present study was focused on the part of the *Salinelle* area in which main activity is concentrated, as shown by the mud flow deposits. A dense microtremor measurement survey was carried out, selecting the recording sites in order to obtain detailed information on subsoil structure. For this reason, many of the measurements were performed on a linear deployment.

The HVNR results set into evidence three different frequency ranges that appear interesting to get information on the subsoil structure. A low frequency peak at about 0.1 Hz was identified both on the Tr#1 and Tr#2, but with different amplitude (black arrows in Fig. 3a). Although, along the Tr#1 these peaks cannot be judged as particularly significant, we are incline to consider reliable such amplitude increase. In particular, we believe that these peaks could be interpreted as related to the presence of a discontinuity located at depth, linked to the clay overlaying the limestone. According to Aiuppa *et al*. (2004) this discontinuity could be the natural location of a hydrocarbon reservoir from which the mud rises through an old lava conduit (Carveni *et al*., 2001). Another signature of the presence of this reservoir can be extracted by inspecting the HVNRs, that show a strong HVNR de-amplification at about 0.4 Hz (grey arrows in Fig. 3a). Summarizing, low-frequency surficial waves (particularly Rayleigh waves), propagate through the subsoil with strength which varies in time. Then, as suggested by Lambert *et al*. (2007), when Rayleigh waves interact with the reservoir the resulting radiation pattern consists essentially in P-waves, along the vertical direction, and S-waves in the horizontal one. The observed low frequency peak and the de-amplification in the HVNRs could be interpreted as linked to the body waves generated at depth by the reservoir. At frequency values greater than 1.0 Hz the HVNRs show peaks variable both in frequency and in amplitude which could be related to the presence of the volcanic sequence characterized by blocks, free to oscillate and fractures filled by mud. The frequency peaks at values higher than 6.0-7.0 Hz could be interpreted as related to the *Salinelle* deposits whereas, at frequencies higher than 10.0 Hz the effects linked to noise generated by the gas emission can be observed (Fig. 3a).

We also investigated the existence of directional effects in the site response by rotating the horizontal components of the spectral ratios obtained at each measurement site (see examples in Fig. 2). Clear directional effects, with an angle of about 50°-80° N, in the frequency range 0.1-0.2 Hz, were detected. Conversely, different resonant frequencies and directions, that could be ascribed to the vibration of smaller blocks, can be observed at frequencies greater than 1.0 Hz. Furthermore, the rose diagrams of the noise polarization strikes, in the frequency range 0.1-0.5 Hz, are plotted (example in Fig. 3b). Rose diagrams are circular histograms in which instantaneous polarization azimuth measurements are plotted as sectors of circles with a common origin (class width 10°). In literature exists several studies (Panzera *et al.,* 2014 and references therein) discussing the role played by oriented fractures on seismic wavefield. In particular, in this kind of anisotropic medium the faster shear-waves became parallel to possible dikes, fissures and tensional cracks. On the contrary, the amplification of ground motion takes place orthogonally with the azimuth of the main fracture field (Panzera *et al.,* 2014 and references therein). As consequence the ENE-WSW polarization orientations observed in most of the sites could explained with the presence of a fracture field NNW-SSE oriented.

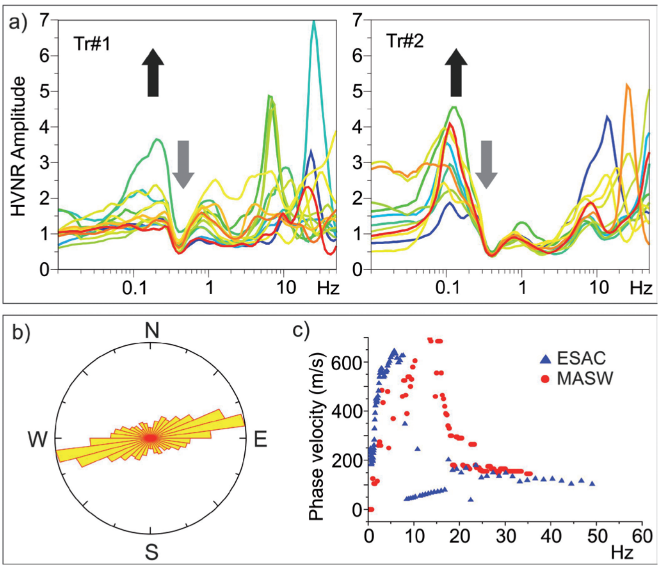

Fig. 3 – a) HVNR computed at each site along the Tr#1 and Tr#2 profiles. Black and grey arrows point out the low frequency peak and the spectral ratio de-amplification, respectively. b) Equal-area polar diagrams of the polarization azimuth obtained by filtering the noise in the frequency band 0.1-0.5 Hz. c) Dispersion curves obtained by ESAC and MASW tests.

Inspection of the dispersion curves acquired through ESAC and MASW prospections (Fig. 3c), shows that only slight differences in the quality of the obtained phase velocity – frequency plots, are present. The comparison of the two methodology clearly shows the prevailing of the contribution of high frequencies (>15.0 Hz) components in the definition of the MASW dispersion curves whereas, the phase velocity - frequency curves obtained through the ESAC approach, appear better defined at lower frequency (>5.0 Hz). Sediments outcropping at *Salinelle* according to the results of the dispersion curve inversion have a shear wave velocity in the range 100-200 m/s and a thickness of about 8-10 m.

Concluding remarks. The results obtained in the *Salinelle* area can be summarized as follow:

- the HVNRs put into evidence the presence of a hydrocarbon reservoir highlighted by the presence of a low frequency peak around 0.1 Hz followed by a de-amplification;
- the low frequency peak is strongly directional, with strike oriented ENE-WSW, suggesting the existence of a NNW-SSE oriented fracture system;
- the high variability in frequency and direction above 1.0 Hz could be linked to the vibration of small blocks or fractures. At frequencies higher than 10.0 Hz, evidences of a thin *Salinelle* deposit and noise generated by the gas emission is present;
- ESAC and MASW prospections allowed us to determine the possible thickness and shear wave velocity of the *Salinelle* deposits.

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