Gruppo di Lavoro CSTI; 2005: *Catalogo Strumentale dei Terremoti Italiani dal 1981 al 1996* (Versione 1.1), <http://gaspy.df.unibo.it/paolo/gndt/Versione1_1/Leggimi.htm>

Lavecchia G., Brozzetti F., Barchi M., Menichetti M. and Keller J. V.; 1994: S*eismotectonic zoning in east-central Italy deduced from an analysis of the Neogene to present deformations and related stress fields*. GSA Bulletin, **106**, 9, 1107-1120.

Lomax A., Virieux J., Volant P. and Berge-Thierry C.; 2000: *Probabilistic earthquake location in 3D and layered models: introduction of a Metropolis-Gibbs method and comparison with linear locations*. In Advances in Seismic Event Location (pp. 101-134). Kluwer, Amsterdam: eds Thurber C.H & Rabinowitz NonLinLoc software, version 6.00, <http://alomax.free.fr/nlloc>

Monachesi G., Castelli V. and Vasapollo N.; 1991: *Historical earthquakes in central Italy: Case history in the Marche area*. Tectonophysics, **193**, 95-107.

Riguzzi F., Tertulliani A. and Gasparini C.; 1989: S*tudy of Seismic Sequence of Porto San Giorgio (Marche) - 3 July 1987*. Il nuovo cimento, **12**, 4, 453-466.

Rovida A., Locati M., Camassi R., Lolli B., Gasperini P. (eds); 2016: C*PTI15, the 2015 version of the Parametric Catalogue of Italian Earthquakes*. Istituto Nazionale di Geofisica e Vulcanologia. doi: http://doi.org/10.6092/INGV.IT-CPTI15.

Scognamiglio L., Tinti E. and Michelini A.; 2009: Real-Time Determination of Seismic Moment Tensor for the Italian Region. Bulletin of the Seismological Society of America, 9, 4, 2223–2242, doi: 10.1785/0120080104.

EVIDENCE OF ROMAN EARTHQUAKE SURFACE FAULTING AT SANTA VENERA AL POZZO (CATANIA, SOUTHERN ITALY): A PROBABLE SEISMIC EVENT IN 251 AD?

C. Bottari[1], P. Capizzi[2], D. Cavallaro[3], S. Giammanco[3], R. Martorana[2], S. Scudero[4], F. Sortino[5], P. Bonfanti[3]

[1] *Istituto Nazionale di Geofisica e Vulcanologia, Roma 2*

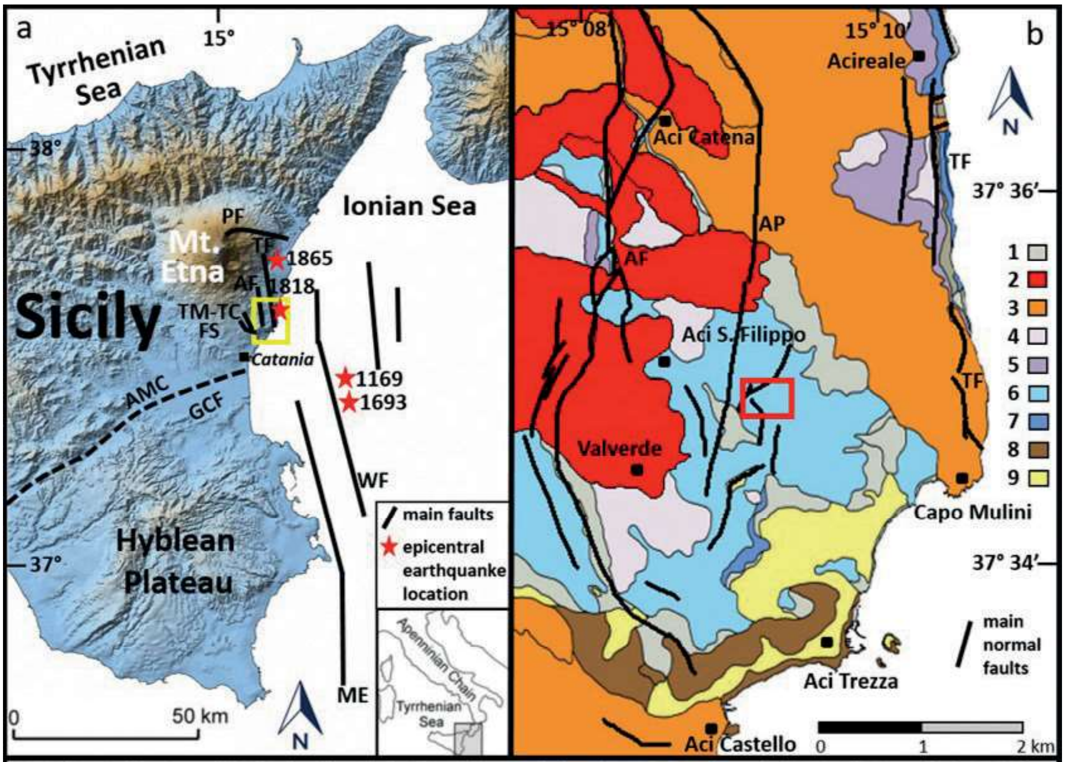
[2] *Università di Palermo, Dipartimento di scienze della Terra e del Mare*

[3] *Istituto Nazionale di Geofisica e Vulcanologia, OE*

[4] *Istituto Nazionale di Geofisica e Vulcanologia, ONT*

[5] *Istituto Nazionale di Geofisica e Vulcanologia, Roma1*

Introduction. The record of historical seismicity of Catania and its neighbourhood during the first millennium AD is largely incomplete due to the scarcity of sources reporting information on earthquake damage. Although numerous historical sources provide plentiful description of past Etnean eruptions affecting the Catania area, only a vague picture of the local seismicity is available for ancient times. This study provides new insights on seismic history of Catania, which was struck by large earthquakes during its recent history (i.e. 1542, 1693, and 1818 earthquakes). During the first millennium, the only documented earthquake occurred in 251 AD, a year before of the big Etna eruption of 252 AD (Guidoboni *et al.*, 2014). This earthquake left well-visible traces in the archaeological site of Santa Venera al Pozzo (Catania), which was continuously inhabited since 3000 BC, due to the presence of sulphur warm water springs. The buildings uncovered by archaeologists are a podium of a Roman temple; a thermal bath provided with five different pools at least; a Roman rural Villa; and a church of Byzantine age. The site is located on the eastern flank of Mt. Etna volcano, where seismic activity has often caused significant damage, even though localized, especially when associated with remarkable flank eruptions. Evidence of Roman age faulting has been observed in the archaeological site, which is clearly affected by a set of sharp fractures generating an overall ~ 4 m wide fracture zone. The main fracture extends for about 40 m with a ~N-S direction, offsetting the foundations of a podium, some pools and minor walls. It shows an extensional displacement of up to 5-8 cm and a right-lateral component with an offset of up to 4 cm. Fracture zones related to normal faults are quite common in the lower eastern flank of Mt. Etna (Azzaro *et al.*, 2012). Some of these structures are also characterized by anomalous diffuse CO_2 emissions from the soil (Giammanco and Bonfanti, 2009). The archaeological site is placed in proximity of one of



AMC: front of the Apenninic-Maghrebian Chain, GCF: Gela-Catania foredeep, PF: Pernicana fault, AF: Aci Catena fault, AP: Aci Platani fault, TF: Timpe fault, TM-TC FS: Tremestieri-Trecastagni fault system, WF: western fault, ME: Malta Escarpment.
1: talus/recent alluvial deposits; 2: Torre del Filosofo formation (122 BC—present); 3: Pietracannone formation (15 ka—122 BC); 4: Osservatorio Etneo member (15 ka); 5: Piano Provenzana formation (~ 40 ka); 6: Valverde formation (~ 120 ka); 7: Timpa formation (155–130 ka); 8: Aci Castello formation (~ 500 ka); 9: Argille grigio-azzurre formation (lower-middle Pleistocene).

Fig. 1 - **a** Main faults with epicentral location of some of the most important earthquakes of Eastern Sicily (from Monaco and Tortorici, 2007); the yellow box corresponds to Fig. 1b; **b** Cut out of the geological map of Etna Volcano (Branca *et al.*, 2011b); the red box indicates the study area.

these tectonic lineaments (Fig. 1), belonging to the NNW oriented normal fault system called the "Timpe" system. The finding of this earthquake damage and its time constraints represents the starting point for archaeoseismological research in the Etnean area.

Geological framework. Geological, seismological and geophysical evidence indicate that the lower eastern flank of Mt. Etna is affected by a slow but continuous fault-controlled seawards extension, with prevailing ESE-WNW direction, interpreted as due to flank instability. This sector is basically confined within two ~E-W oriented boundaries (Fig. 1). Geodetic measurements over the last decades suggest a short-term deformation rate of some cm/yr, reaching even faster peaks in some restricted places or periods, sometimes in association with eruptive episodes (Alparone *et al.*, 2013). This unstable area is dismembered into different blocks characterized by homogenous kinematics and bordered by tectonic lineaments where abrupt changes in the ground velocity field have been marked (Bonforte *et al.*, 2011). The most important of these lineaments is arranged to form a system of several parallel fault segments, mostly dipping eastward, reaching lengths up to 5-8 km and forming tens of meters fault scarps (called Timpe system). The archaeological site of Santa Venera al Pozzo lies just to the north of one of above mentioned fault segment (Fig. 1), which offsets, with a N-S direction, some volcanic products of an ancient phase of Mt. Etna, dated at ~120 ky (Branca *et al.*, 2011a).

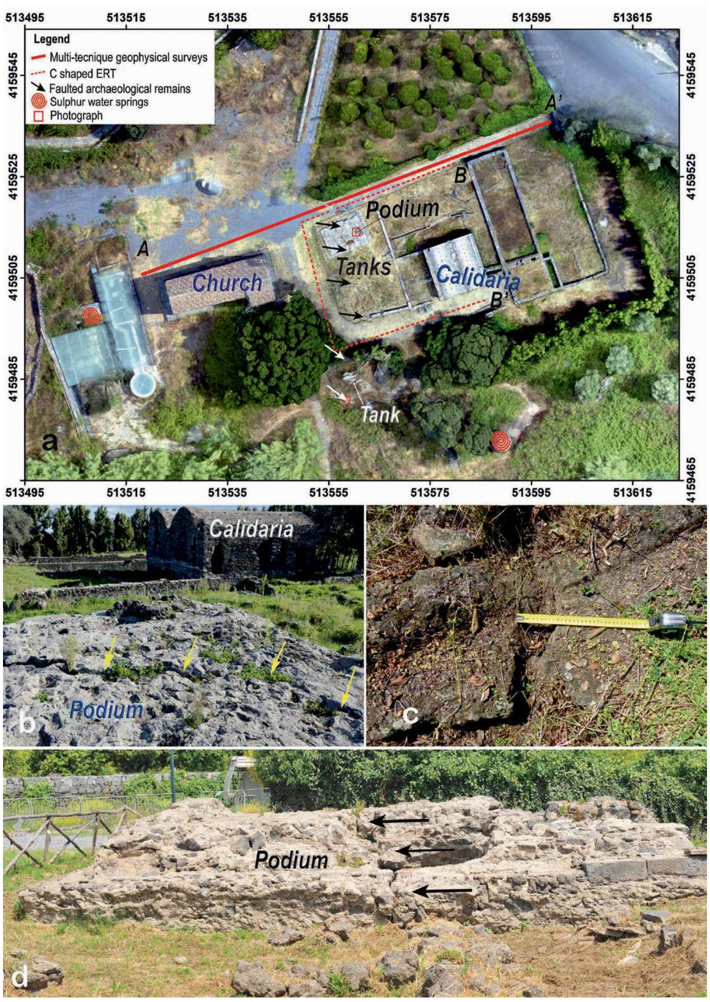


Fig. 2 - **a** Digital Surface Model (DSM) of the archaeological area. The red line A-A' shows the location of the geophysical surveys; arrows indicate the surface faulting observed at the site; **b** zoom in on the faulted podium, **c** zoom in on the faulted floor of the tank; **d** southern view of the faulted podium.

The fault segments located in the lower eastern flank of Mt. Etna, have been responsible, both in historical and recent times, for earthquakes with magnitude up to 4.5 (Azzaro *et al.*, 2004; De Guidi *et al.*, 2012). Because of the shallow foci depth (<2–3 km), earthquakes have often caused significant damage, even though localized, especially when associated with remarkable flank eruptions. Some examples are the Santa Venerina earthquake connected with the 2002 eruption, the 1865 earthquake that occurred at the end of a large flank eruption, and the seismic activity associated with the 252 AD eruption (Guidoboni *et al.*, 2014).

Field data. *Geophysical investigation.* A multi-techniques geophysical survey was carried out at Santa Venera al Pozzo, in order to investigate a deeper portion of the subsoil and to verify the presence of a fault zone. The survey consisted of seismic refraction tomography (SRT), electrical resistivity tomography (ERT), ground-penetrating radar (GPR), and a magnetic survey in addition to remote sensing applications using unmanned aerial vehicles (UAVs), which provided new data for ultra-high resolution mapping.

As suggested by the surficial evidence of displaced archaeological structures, the inferred fault should be oriented N-S. For this reason, we mainly performed the geophysical investigations along a 90 m long profile, directed almost perpendicular to the presumed fault (Fig. 2).

The SRT reveals a reliable P-wave velocity model down to a depth of ~ 20 m. Seismic velocities ranged from about 400 m/s to about 2900 m/s (Fig. 3a). A portion characterized by

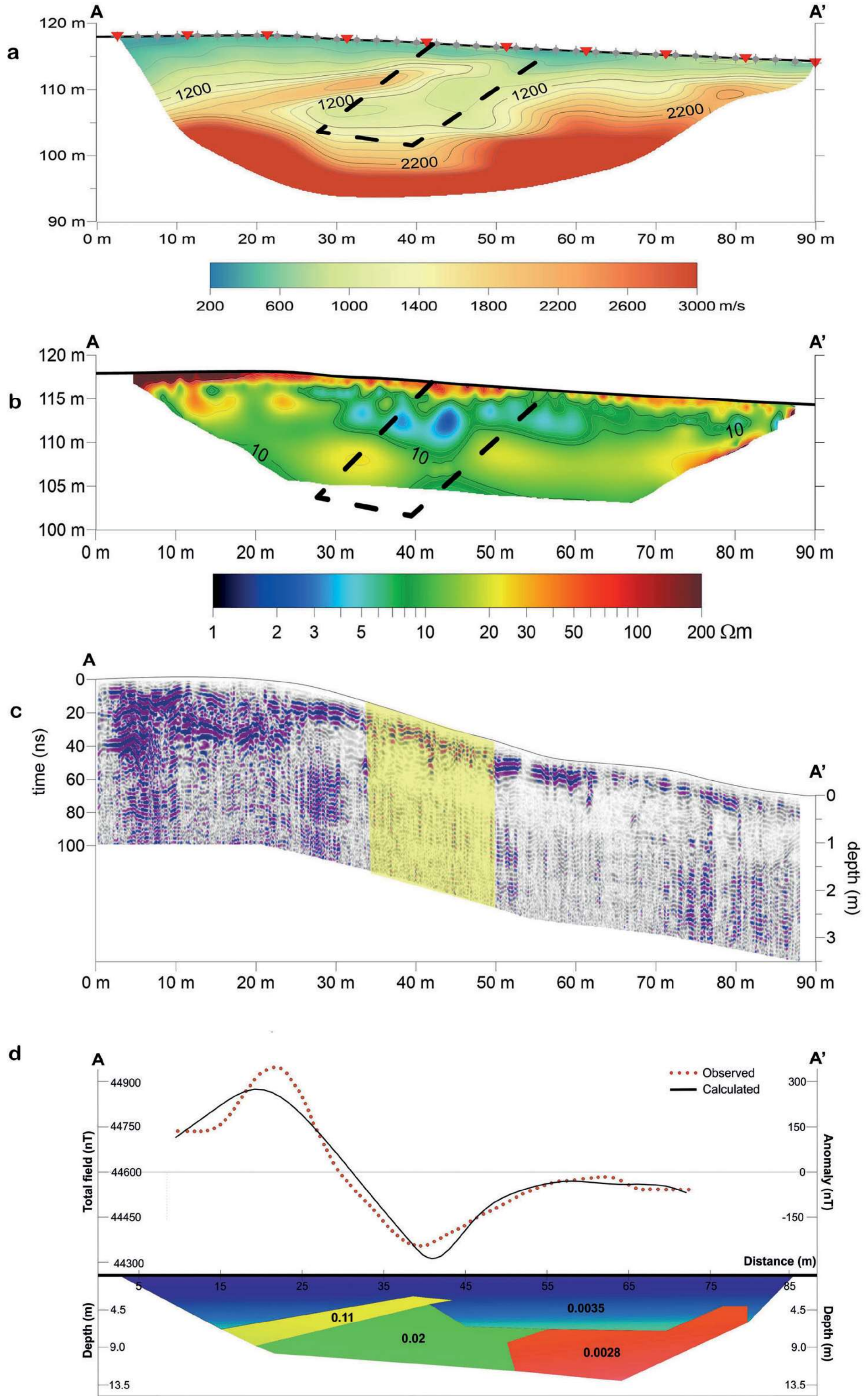


Fig. 3 - **a** SRT; **b** 2D ERT; **c** GPR profile; **d** Magnetic sampling line along the AA' profile shows the comparison between observed and calculated data and the related magnetic susceptibility model.

low P-velocity is recognizable from 30 to 50 m depth along the profile, which was interpreted as fractured material confined within two more compact blocks (dashed black line).

Two ERT profiles were also performed, the first one is a 2D ERT profile acquired along the road that runs from west to east, whereas the second one is a quasi-3D ERT profile.

The 2D ERT profile shows a generalized low resistivity of the terrain ($10^1 < \varrho < 10^2$ Ωm). This would find correspondence with the stratigraphy of the area characterized by a marine silty-clayey deposit below a thin layer of weathered volcaniclastic rocks, as revealed by some geognostic boreholes (Ferrara, 2010). At about 5 m depth, the portion between 30 and 50 m, is characterized by the lowest resistivity values (black-dashed line in Fig.3b, which encloses a zone with $\varrho < 5$ Ωm, blue circle) and it can be interpreted as a layer of water-saturated material.

The GPR profile shows some truncations and offsets of the reflections, interpreted as fractures along a fault plane. A change in the electromagnetic facies is recognizable between the progressive distances of 35 and 50 m (the yellow area in Fig. 3c). This was interpreted as a physical separation between the western and eastern zones, characterized both by high reflectivity and by high absorption of the electromagnetic signal. Furthermore, the electromagnetic facies in the westernmost part of the radargram can be correlated with the shallow zone having higher velocity in the SRT (Fig. 3c), where the anomalies found are likely associated with buried structures.

The magnetic survey revealed two main bipolar anomalies: a smaller one, about 10 m wide, with amplitude of about 60 nT, and a larger one (40–45 m wide) with amplitude of about 570 nT (Fig. 3 d). The first one is probably due to a buried pipe, while the second one is ascribable to a geological source.

Geochemical investigation. Soil CO_2 effluxes were measured using the accumulation chamber method, which consists of measuring the rate of increase of CO_2 concentration inside a cylindrical chamber open at its bottom and placed on the ground surface (Parkinson, 1981). The change in concentration during the initial measurement is proportional to the efflux of CO_2 (Tonani and Miele, 1991).

Anomalous diffuse CO_2 emissions at Mt. Etna are caused by deep magma degassing through tectonic lines at lithospheric and shallow levels. The spatial distribution of CO_2 effluxes revealed three main areas of anomalies at the site. The first one, located to north, displays anomalies aligned with an existing fault line belonging to the Timpe system. The second area, located to south, seems correlated to a buried ~NE-SW oriented fault. Finally, the third area, located in the central part, shows anomalies of lower intensity than the previous, and are scattered over a larger surface, around the emission points of slightly thermalized sulphurous waters. In this case, soil gas anomalies may represent degassing of deep CO_2 exsolved from a thermal aquifer along its underground path.

Continuous monitoring of bubbling gases emitted in a thermal well have been performed in order to better identify the components of hydrothermal system and to assess variations in chemical composition in the short period. Cromatography Monitoring Station (CMS) offers a high frequency of automatic gas analysis (our gap was 30') allowing to identify two anomalous degassing. At the end of January, the chemical composition changed drastically with detectable concentration of H_2S and ethane associated with very high concentration of CH_4 (70%) without sensible variations of CO_2. The correlation among CH_4 and H_2S and ethane suggest that the hydrothermal end member (methane dominant) has a mix with a superficially component more rich in CO_2.

Finally, we measured the temperature of the thermal waters every 15' by using a Tinytag datalogger. The data showed regular daily fluctuations and a seasonal trend. Instead, the hydrothermal fraction is mainly composed of low-enthalpy gases (CH_4) that do not affect significantly the water temperature; therefore, any future ascent of hot fluids would be immediately emphasized.

Conclusions. The integration of geophysical and geological data allowed the recognition and characterization of coseismic faulting affecting the archaeological site of Santa Venera al

Pozzo. In addition to the identification of a tectonic discontinuity, whose surface expression is the fracture zone offsetting the thermal bath of the site. Unfortunately, the investigation has not allowed imaging a clear fault plane at depth, but rather it highlighted a broad anomalous zone interpretable as a fault zone. This is ascribable to the shallow depth of geophysical investigation, to the lithology of outcropping rocks and to the circulation of fluids in the subsoil. The geochemical surveys suggest that the fault affecting the archaeological site could be still active and that the local hydrothermal system could record changes in the heat/gas flux coming from the magmatic system of Mt. Etna.

Geoarchaeological evidence suggests the occurrence of an earthquake that produced a displacement of man-made structures and destructive effects on the ancient Roman remains, possibly in the middle-end of the third-century AD. Time constraints are inferred through the dating of the different buildings phases and on archaeological findings. This event was conceivably a local earthquake with a severe impact on archaeological structures. Unfortunately, the extension of the fracture zone at the surface does not provide reliable information on earthquake magnitude. The lack of well-documented historical accounts of seismic activity does not help with the recognition of coseismic deformation elsewhere. Consequently, this event could be either associated to the volcano-tectonic earthquake of 251 AD preceding the 252 AD eruption (see Guidoboni *et al.*, 2014), or alternatively to a local pure tectonic earthquake not mentioned in the Italian seismic catalogue.

References

Alparone S., Bonaccorso A., Bonforte A., and Currenti G.; 2013: *Long-term stress–strain analysis of volcano flank instability: the eastern sector of Etna from 1980 to 2012*. J. Geophys. Res. Sol. Earth. **118**, 5098–5108.

Azzaro R., Branca S., Gwinner K., and Coltelli M.; 2012: *The volcano-tectonic map of Etna volcano 1:100.000 scale: morphometric analysis from high resolution DEM integrated with geologic active faulting and seismotectonic data*. Ital. J. Geosci. **131**,153-170.

Azzaro R.; 2004: *Seismicity and active tectonics in the Etna region: constraints for a seismotectonic model*. In: Bonaccorso A, Calvari S, Coltelli M, Del Negro C, Falsaperla S (eds) Mt. Etna: volcano laboratory, vol 143. American Geophysical Union, Geophysical Monograph, Washington, pp. 205–220.

Bonforte A., Guglielmino F., Coltelli M., Ferretti A., and Puglisi G.; 2011: *Structural assessment of Mount Etna volcano from permanent scatterers analysis*. Geochem. Geophys. Geosyst. **12**, Q0200.

Branca S., Coltelli M., and Groppelli G.; 2011a: *Geological evolution of a complex basaltic stratovolcano: Mount Etna, Italy*. Ital. J. Geosci. **130**(3), 306–317.

Branca S., Coltelli M., Groppelli G., and Lentini F.; 2011b: *Geological map of Etna volcano, 1:50,000 scale*. Ital. J. Geosci. **130**(3), 265–291.

De Guidi G., Scudero S., and Gresta S.; 2012: *New insights into the local crust structure of Mt. Etna volcano from seismological and morphotectonic data*. J. Volcanol. Geotherm. Res. **223**, 83–92.

Ferrara V.; 2010: *Le acque termominerali di S. Venera al Pozzo Studi e indagini idrogeologiche*. Mem. Rend. Ac. Sci. Lett. Zelant. Dafn., Serie V, vol IX.

Giammanco S., and Bonfanti P.; 2009: *Cluster analysis of soil CO_2 data from Mt. Etna (Italy) reveals volcanic influences on temporal and spatial patterns of degassing*. Bull. Volcanol. **71**, 201-218.

Guidoboni E., Ciuccarelli C., Mariotti D., Comastri A., Bianchi M.G.; 2014: *L'Etna nella storia. Catalogo delle eruzioni dall'antichità fino al XVII secolo*. INGV, Rome.

Monaco C., and Tortorici L.; 2007: *Active faulting and related tsunami in eastern Sicily and south-western Calabria*. B.G.T.A. **48**(2), 163–184

Parkinson K.J.; 1981: *An improved method for measuring soil respiration in the field*. J. App. Ecol. **18**, 221-228.

Tonani F., and Miele G.; 1991: *Methods for measuring flow of carbon dioxide through soils in the volcanic setting*. Istituto di Analisi Globale e Applicazioni C.N.R., Firenze, Italy.