Geothermal potential of Mount Etna region, eastern Sicily

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ABSTRACT

Mt. Etna is a composite basaltic stratovolcano covering a surface of 1200 km^2 in eastern Sicily; with a maximum diameter of about 45 km. Structurally, Mt. Etna is located between the Gela-Catania foredeep and the frontal wedge of the allochthonous Apenninic-Maghrebian thrust-system. This chain-system tectonically overlies a deep seated thrust-system, originated since late-Miocene, by deformation of the old Hyblean Foreland margin (African continental plate Foreland). Recent stratigraphic data of the new geological map of Mt. Etna indicate a complex succession forming the volcano edifice, composed mainly by lava successions consisting of an alternation of massive, scoriaceous and autoclastic lavas characterized by high permeability with several typologies of interlayered volcaniclastic deposits. The whole sequence of volcanic products rests on a sedimentary basement mainly formed by clays and marly clays belonging both to the different tectonic units of the Apenninic-Maghrebian chain and the Quaternary foredeep succession. This structural setting of Mt. Etna region together with the high permeability of volcanic products favours the development of various hydro-structures extended from the top of the volcano to its periphery according to three main sectors located in the north, west and east flanks. For these reasons, the volcano edifice is one of the largest aquifer system and the main water resource in Sicily. Geothermal manifestations at Mt. Etna and in its surrounding area are well known and earlier attempts to exploit geothermal energy date back to 1930's. The most prominent geothermal manifestations in the Mt. Etna area, is the so-called Salinelle of Paternò mud volcanoes system (located in the lower south-western flank of Etna), which fluid emissions can reach temperature up to 48 °C. Between the water springs, only one is considered as a hypothermal emission (Santa Venera spring), though some water wells have revealed water with temperature of about 35 °C. Other indications of geothermal manifestation at Mt. Etna are indirectly suggested from hydro-geochemical surveys. Gas-water-rock interaction is particularly effective where deep faults cut the volcanic edifice down to the magma reservoirs and allow for an easier escape of magmatic volatiles to the surface. Examples can be found in the south-western and eastern flanks of Mt. Etna, where groundwater displays a significantly higher salinity as a result of higher contents of most of the elements leached from host rocks and higher values of dissolved CO_2. Changes in the chemical and physico-chemical characteristics of Mt. Etna's groundwaters are related, either directly or indirectly, to input of magmatic fluids (mostly water vapour and CO_2) to the aquifers due to the volcanic activity. Increased interaction between hot magmatic fluids and groundwater could also induce or intensify hydrothermalism at least in some parts of Etna's aquifers. Elements like Cr, Zn and Cu can be tracers of such conditions. Recent studies showed that hiper-saline waters discharged by the Salinelle of Paternò are fed by a hydrothermal system whose temperature was estimated at 100-150 °C.

1. INTRODUCTION

Earlier attempts to exploit geothermal energy on Mt Etna date back to the '30s (Fig. 1), when a water vapour condenser was installed in fumaroles located at the base of the summit cone, providing hot water to the Osservatorio Etneo (2940 m). Thirty years later, Facca (1964) carried out a more extensive field survey in the summit area of the volcano concluding that the retrieved heat flux data excluded any potential exploitable geothermal reservoirs. Later in 1985, Minett and Scott pointed out that the overall heat flux from Mt. Etna region was significantly and strongly controlled by the regional structural framework of the volcano. Following hydro-geochemical studies focused on the detection of indirect markers of hydrothermal conditions within the water table of the volcano. Aim of this study is to make a review of the existing data, with the attempt to draw likely future directions for a potential geothermal exploitation of the Mt. Etna reservoir also in consideration of the recent technological advancements in this field.



Figure 1: Etna, July 1932. Water vapour condenser made by Prof. Gaetano Ponte installed at the fumarole called Vulcarolo, at the base of the summit cone at an altitude of 2960 m. The image is taken from Fondo Fotografico Gaetano Ponte-Archivio Fotografico Toscano of Prato.

2. GEOLOGICAL AND STRUCTURAL SETTING OF ETNA REGION

The recent geological and structural investigation carried out on Mt. Etna volcano for the development of the new geological map at 1:50.000 scale (Branca et al 2011a) allowed to evidence the complex geodynamic setting of this region. In particular, Etna volcano is located between the Gela-Catania Foredeep and the frontal nappes of the Appenninic-Maghrebian Orogen (Fig. 2) that derived from the Neogene convergence between Africa and Europe plates (Lentini 1982; Ben Avraham and Grasso 1990). The orogenic domain consists of three distinct superposed chains, forming a complex duplex structure in northeastern Sicily (Lentini et al 2006). The geodynamic setting of the chain is connected to the activation of a NW-SE trending fault system, named South-Tyrrhenian System, since the Middle Miocene that is linked to the opening of the Tyrrhenian Basin (Lentini et al 2006). This complex shear zone is formed by main NW-oriented dextral strike-slip faults coupled by the associated NE-oriented normal faults, which together have caused the SE migration of the orogenic belt onto the Ionian Basin (Fig. 2).

Volcanism of Mt. Etna is divided into four phases according to Branca et al (2011b). The oldest phase, named Basal Tholeiitic, corresponds to a long period of discontinuous and scattered eruptive activity, begun about 500 ka ago within the Gela-Catania Foredeep basin through fissure-type submarine eruptions. This phase ended about 300 ka ago with fissure-type eruptions in a sub-aerial environment, forming a wide lava plateau developed on the old alluvial plain of the paleo-Simeto River. Between 220 and 121 ka ago, the Timpe phase volcanism was concentrated mainly along the Ionian coast building a primitive shield volcano. In this time span, scattered effusive eruptions also took place in a wide area corresponding to the present lower SW and SE flanks of Etna. Furthermore, eruptive activity shifted westward at the end of this phase, for the first time, toward the central region of the volcano that corresponds to the present day Val Calanna area. During the third phase, named Valle del Bove Centers, the stabilization of the magma source in the Valle del Bove area and the beginning of the central-type volcanism occurred with the formation of several small polygenic volcanic centers. In particular, the early edifices recognised are represented by Tarderia and Rocche volcanoes, whose activity ended between 106 ka and 102 ka ago. Thereafter, volcanism was mainly concentrated on the southwestern side of the Valle del Bove, with the formation of Trifoglietto volcano and other minor eruptive centers. Finally, the Stratovolcano phase combines the products of the Ellittico and those of Mongibello volcanoes. Ellittico volcanic activity started about 60 ka ago and ended 15 ka ago with four caldera-forming plinian eruptions. During the post-15 ka, persistent basaltic volcanic activity formed the Mongibello volcano through summit and flank eruptions whose products today cover about 85% of Etna's surface.

The volcanic pile along Etna slopes is formed by a complex lava flow succession with the presence of interlayered explosive products and reworked deposits (Branca et al 2011a) that are mainly located within the paleovalleys due to the interaction between volcanic processes and fluvial events (Branca and Ferrara 2001). In particular, the reconstruction of Mt. Etna edifice geometry performed by Branca and Ferrara (2013) evidenced that the maximum thickness of the volcanic pile is about 2400 m in the summit region, with an almost regular decrease towards the periphery. An exception is the lower eastern flank of the volcano that is characterized by a thickness up to 900 m. On the whole, the total Etna volume erupted during the past 330 ka is about 532 km^3, corresponding to an average rate of volcanic output of about 0.0016 km^3/a (Branca and Ferrara 2013). That study outlines that the growth rate of Etna volcano was characterized by a drastic increase during the different eruptive phases of volcanism in the past 220 ka, evidencing that 82% of the volcanic products were erupted in the past 110 ka. The gradual stabilization of the plumbing system of Etna during this time span enhanced the efficiency of magma ascent through the crust with a consequent increase in erupted products reaching an average eruptive rate of 0.0048 km^3/a during the past 60 ka (Branca and Ferrara 2013). From a structural point of view, Mt. Etna volcano is characterised by a complex structural setting that is related to the regional tectonics on which the volcano edifice is superimposed. Two main regional fault systems are recognizable on the lower eastern flank of Etna. The Timpe normal faults system, NNW-SSE trending, (Monaco et al. 1997; Azzaro 1999) that is considered the northern segment of the Malta Escarpment, a major lithospheric fault system separating the

continental crust of the Pelagian Block from the oceainc crust of the Ionian Basin (Scandone et al 1981; Finetti et al 2005; Ben-Avraham and Grasso 1991; Hirn et al. 1991). The NE-SW oriented Piedimonte and Ripe della Naca faults interpreted as the southernmost prolongation of the Messina-Fiumefreddo fault system (Ghisetti 1979; Monaco et al 1997; Lentini et al 2006).

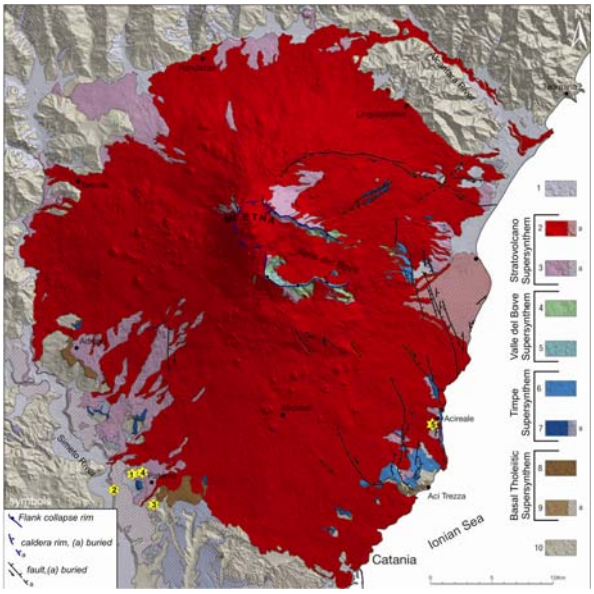

Fig 2: Schematic Geological map of Mt. Etna (modified from Branca et al 2011a): 1) Present and recent covers; 2) Il Piano Synthem a) sedimentary deposits; 3) Concazze Synthem a) sedimentary deposits; 4) Zappini Synthem; 5) Croce Menza Synthem; 6) S. Alfio Synthem; 7) Acireale Synthem a) sedimentary deposits; 8) Adrano Synthem; 9) Aci Trezza Synthem, a) sedimentary deposits; 10) Sedimentary and metamorphic basement. The arrow indicates the direction of strike movement in the fault symbol. Yellow stars indicate the main geothermal features: 1) Salinelle Paternò Stadium; 2) Salinelle Simeto River; 3) Salinelle Vallone Salato; 4) Acqua Grassa; 5) Santa Venera spring.

In addition to the regional tectonic a wide portion of the eastern flank of Mt. Etna edifice is involved in a large-scale instability phenomenon that caused an eastward sliding of this sector of the volcano (Borgia et al 1992; Lo Giudice and Rasà 1992; McGuire et al 1996; Montalto et al 1996; Rust et al 2005; Bonforte et al 2011). The large-scale flank instability is associated with a distinct set of faults radiating from the summit area down to the Ionian coast (Rust et al 2005 and reference therein). In particular, the Pernicana fault system, about E-W oriented, is a transtensive structure with left strike-slip that extends from Piano Provenzana in the upper NE flank down to the Ionian coast and represents the northern boundary of this unstable flank. The Tremestieri-Trecastagni fault is a normal fault system, about NW-SE oriented, formed by two main faults with right lateral component and the Ragalna fault is a dextral transtensive structure, about N-S oriented, with left strike-slip and dip-slip components. These fault systems correspond to the southeast and southwest boundaries, respectively, of the sliding sector.

Finally, the basement of Mt. Etna region is mainly made up of clays belonging to the Apenninic-Maghrebian chain units that crop out along the NW periphery of the volcano; conversely, the Quaternary foredeep sediments crop out along the NE and SE flanks from the coast up to 770 m and 320 m elevation, respectively (Branca et al 2011a). Along the eastern flank the only evidence of the Apenninic-Maghrebian chain sediments is a very restricted outcrop of Upper Cretaceous varicoloured clay at about 250 m of elevation, close to Nunziata village (Branca et al 2011a). The asymmetric topography of Etna basement is revealed by the different altitudes reached by the Quaternary sediments within the volcanic edifice as a consequence of an inhomogeneous long-term uplift rate affecting the region (Di Stefano and Branca 2002).

3. GEOTHERMAL MANIFESTATIONS AT MT. ETNA

3.1 Salinelle of Paternò

Salinelle is the name of an area dominated by three mud volcanoes areas located on the lower southwest flank of Mt. Etna, few kilometers apart of Paternò town and on the border, or just outside, of Etna's volcanic cover.

The first mud-volcanoes area is that of Paternò Stadium (PS) is located just NW of Paternò; fluid emissions occur on an alkalic lavas outcrop near the Paternò neck. The second, named Simeto River (SR), is located west of Paternò near the homonymous river and fluids are released through an undated lava flow that belongs to the Mongibello cycle and is partially covered by recent alluvial deposits. Finally, the third mud volcanoes area, Vallone Salato (VS), is located in a small valley located southeast of Paternò and fluids are emitted through marly clays belonging to the foredeep sedimentary deposits (Fig. 3). Overall, the chemical composition of the emitted fluids from the Salinelle complex results of gas and hypersaline waters that often pond in pools whose diameter ranges from a few centimeters to a few meters. The percentages of mud and water in the fluid mixture are highly variable. In some cases mud is the only fluid erupted with gas building up cones to a few meters high and with a base diameter up to about ten meters. Emitted waters have rather uniform and constant chemical composition, and physical-chemical characteristics; pH is ~6, the electrical conductivity is ~88 mS/cm, and the chemical abundance of major

species in solution (on equivalent basis) is Na»Ca>Mg>K and Cl^-»HCO_3^->$SO_4^=$ (Chiodini et al 1996; D'Alessandro et al 1996; Aiuppa et al 2004).



Figure 3: View of the main vents at salinella of Vallone Salato. Note the black oil layer within the crater.

Most of the pools and mud vents are ephemeral and show strong temporal variations in gas flow. Water outlet temperature is normally between 10 and 20 °C, increasing occasionally up to 40-50 °C. Such anomalous temperature values are always accompanied by increases in gas efflux. During the summer, intense evaporation produces large salt crusts around the emission vents.

Many paroxysms occurred in the degassing activity of Salinelle in the past. Silvestri (1866, 1878) reports of strong eruptive activities in early 1866 and late 1878, including fountains of muddy water up to 3 m high and water temperature of ~46 °C, and related those anomalous activities to local seismic events occurred some days/weeks before. More recently, over the last 13 years, similar anomalous behaviours in the degassing activity of Salinelle have also been observed, lasting from weeks to months. Commonly, increases in gas flux were accompanied by increases in the temperature of the issuing water, as observed in particular at PS (Fig. 4). Such anomalous episodes have proceeded periods of enhanced eruptive activity of Mt. Etna. This suggests a tight link between the Salinelle activity and the release of high enthalpy fluids from the deep magmatic system of Mt. Etna, during periods of magma recharge in the deepest portions of the feeder system of the volcano.

3.2 Acqua Grassa

This is a low-temperature water spring (T ~18 °C) located on the NE corner of the area where the Salinelle of PS are located (Fig. 1). The chemical composition of the water at Acqua Grassa is characterised by a Na–Mg–Ca–HCO_3^- composition, with a relatively low salinity of ~2 g/l. The spring is also characterized by bubbling gas, whose flux is rather constant in time and whose composition is mainly dominated by CO_2 with minor contribution of CH_4 (Chiodini et al 1996; Grassa et al 2006). This composition suggests a two-step process, with gases first being strongly dissolved into groundwater and then being exsolved from it when issuing at the surface (Chiodini et al 1996). Such interaction makes this site not of primary interest in terms of geothermal application.

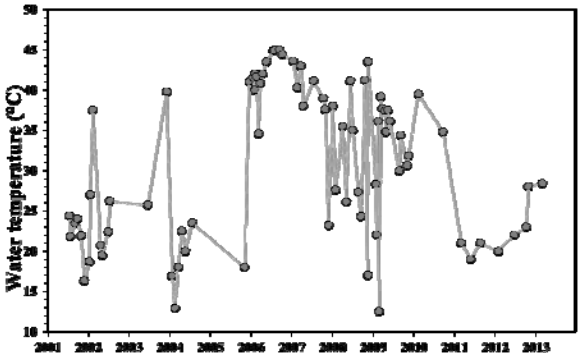

Figure 4: Temporal pattern of the maximum water temperature measured in the mud pools at the Salinella Paternò Stadium from 2001 to 2013.

3.3 S. Santa Venera spring

Santa Venera spring represents the only historically known thermal spring in the Mt. Etna area. It was exploited since very ancient times as a SPA, and this use persists still today. It's the only case of hypothermal spring in Sicily, though it is characterized by the highest outlet temperature among the Etnean water springs (~22 °C). The first modern reports on this spring date to the 19th century (e.g., De Gaetani 1839, 1843; Silvestri 1872), while the first complete chemical characterization of its water has been issued by Nasini et al (1925). More recently, a more comprehensive picture on the geochemical features of the Santa Venera spring has been published by Carapezza et al (1977, 1987), Dongarrà and Hauser (1982, 1987), Grassa et al (2006).

3.4. Vulcarolo fumarole

An earlier attempt to exploit geothermal energy has been made on Etna in 1930 (Fig. 1) when a water vapour condenser was installed in fumaroles located at the base of the summit cone that provided hot water to the Observatory Etneo located at an altitude of 2940 m. This fumarole has been existed until 1984, when it was covered by lava flows erupted by the South-East Crater (SEC) of Mt. Etna. The Vulcarolo was located at the southern foot of the SEC. According to Ponte (1927), a volume of 300 l day^{-1} was condensed, which converts to a theoretical heat flux of the order of 1600 W m^{-2}. In a previous study in the same area, Aubert and Baubron (1988) showed the existence of an active but hidden convective system, only detected by Self-Potential measurements (SP) and soil gas analysis. More recently, an estimate of the heat flux was performed by Aubert (1999), giving a value of about 210 W m^{-3}.

4. GEOTHERMAL EVIDENCE FROM GEOCHEMISTRY OF FLUIDS

Information on the presence of geothermal conditions within a water body can be indirectly obtained using some hydro-chemical markers. In active volcanic areas interaction between groundwater, the rock hosting the aquifers and high-enthalpy magmatic fluids is obviously considerable, even during periods of relative volcanic quietness. Gas-water-rock interaction is particularly marked where deep faults cut the volcanic edifice down to the magma reservoirs allowing an easier escape of magmatic volatiles to the surface. In the Mt. Etna region, evidence of this interplay is mostly in the groundwater of the south-western and eastern flanks of the volcano. Here, groundwater displays a high salinity as a result of higher contents of most of the elements leached from host rocks and higher values of dissolved magmatic CO_2. This water-chemical feature has allowed to statistically distinguishing these areas from the others of Mt Etna. Gas-water-rock interaction is generally enhanced when magma moves from the deep to the shallow portion of the magma feeding system of the volcano. During its up-rise, magma gradually releases a considerable amount of high-enthalpy fluids (mostly water) and incondensable gases, among which CO_2 is the most abundant. Depending on the local geological and tectonic setting, increased interaction between hot magmatic fluids and groundwater can also induce or intensify hydrothermal conditions in the aquifers of Mt. Etna. This implies that potential stable geothermal systems may exist in the Mt. Etna area, but, as reported by Brusca et al. (2001), they should be deeper than "cold" aquifers and would not normally interact with them. Overall, indication of hydrothermal conditions in the groundwater of Mt. Etna is not direct. Water temperature measurements in Etna groundwaters showed that most of waters are cold, with temperature values lower than 18 °C, although some of them have temperature up to 35 °C, thus suggesting at least a partial mixing with geothermal fluids. More generally, indication of hydrothermalism can be retrieved mostly by the presence in solution of some trace elements, such as Cr, Zn and Cu (Giammanco et al., 1998b, 2007).

So far, the only geochemical estimate of the equilibrium temperature in a geothermal aquifer on Mt. Etna was carried out by Chiodini et al. (1996) at the Salinelle mud volcanoes. According to these authors, the chemical composition of the Salinelle gases is controlled by multi-step separation of a CO_2-rich gas phase from boiling hydrothermal aquifers at temperature ranging from 100 to 150°C. According to Giammanco et al. (1998b, and literature therein cited), the high concentration of CH_4 in gas samples from site SVS results from CO_2 depletion in the residual gas phase after interaction between deep CO_2-rich gases and shallow CO_2-unsaturated groundwater. Since CH_4 has a solubility coefficient in water much lower than that of CO_2 (18 and 759 ml/l, respectively; Capasso and Inguaggiato, 1998), methane enrichment suggests interaction between deep gas and CO_2-unsaturated groundwater. Carbon and deuterium isotopes of CH_4 instead (Aiuppa et al., 2004; Grassa et al., 2004) might indicate a thermogenic origin of methane from relatively shallow hydrocarbon reservoirs, likely due to the higher-than-normal geothermal gradient affecting the sedimentary basement of the volcano (Parello et al., 1995; Giammanco et al., 1998a; Aiuppa et al., 2004).

6. CONCLUSIONS

Assessing the overall geothermal potential of Mt. Etna is not easy, since no direct and reliable measurement of the local heat flux exists and because no clear evidence of a widespread geothermal field can be found. However, several sites display characteristics that suggest the existence of geothermal reservoirs at depth within the volcanic pile or just underneath it. In view of the large number of sites with geothermal features, and considering the results obtained from indirect measurements of geothermal markers in local groundwater and hypersaline fluids emitted at the surface, Mt. Etna is certainly a very interesting site for exploitation of geothermal energy. New technologies today allow for a more efficient exploitation of such a source of energy, but more studies are needed in order to complete the mapping of sites with emission of high-enthalpy fluids and to define the real potential of the geothermal reservoirs within the volcano. The coupling of energy flows and the estimated dwellings energy demand of the area, gives an estimation of the potential coverage of the local energy demand in buildings (heating and air-conditioning) through: district heating and heat pumps. Assessment of geothermal energy flows at Mt. Etna can be done both by more focused geochemical studies and by directly accessing the thermal areas with rotary steerable systems.

REFERENCES

Aiuppa, A., Allard, P., D'Alessandro, W., Giammanco, S., Parello, F. and Valenza, M.: Magmatic gas leakage at Mount Etna (Sicily, Italy): relationships with the volcano-tectonic structures, the hydrological pattern and the eruptive activity, in: Mt. Etna: Volcano Laboratory, Bonaccorso, A., Calvari, S., Coltelli, M., Del Negro, C., Falsaperla, S. (Eds.), 129-145, *American Geophysical Union*, Washington, DC, (2004)

Aubert, M.: Practical evaluation of steady heat discharge from dormant active volcanoes: case study of Vulcarolo fissure (Mount Etna, Italy), *J. Volcanol. Geotherm. Res.*, **92**, (1999), 413-429

Aubert, M. and Baubron, J.C.: Identification of a hidden thermal fissure in a volcanic terrain using a combination of hydrothermal convection indicators and soil-atmosphere analysis, *J. Volcanol. Geotherm. Res.*, **35**, (1988), 217-225

Azzaro R.: Earthquake surface faulting at Mount Etna volcano (Sicily) and implications for active tectonics, *J. Geodyn.*, **28**, (1999), 193-213.

Ben Avraham, Z. and Grasso, M.: Collisional zone segmentation in Sicily and surrounding areas in the central Mediterranean, *Ann. Tectonicae,* **4**, (1990), 131-139.

Bonforte, A., Guglielmino, F., Coltelli, M., Ferretti, A. and Puglisi, G.: Structural assessment of Mount Etna volcano from Permanent Scatterers analysis, *Geochem. Geophys. Geosyst.*, **12 (2)**, (2011), doi: 10.1029/2010GC003213.

Borgia, A., Ferrari, L. and Pasquarè, G.: Importance of gravitational spreading in the tectonic and volcanic evolution of Mount Etna, *Nature*, **357**, (1992), 231-235.

Branca, S. and Ferrara, V.: An example of river pattern evolution produced during the lateral growth of a central polygenic volcano: the case of the Alcantara river system, Mt Etna (Italy), *Catena*, **45**, (2001), 85-102.

Branca, S., Coltelli, M., Groppelli, G. and Lentini, F.: Geological map of Etna volcano, 1:50,000 scale, *Ital. J. Geosci.*, **130 (3)**, (2011a), 265-291, doi: 10.3301/IJG.2011.15

Branca, S., Coltelli, M. and Groppelli, G.: Geological evolution of a complex basaltic stratovolcano: Mount Etna, Italy, *Ital. J. Geosci.*, **130 (3)**, (2011b), 306-317, doi: 10.3301/IJG.2011.13

Branca, S. and Ferrara, V.: The morphostructural setting of Mount Etna sedimentary basement (Italy): implications for the geometry and volume of the volcano edifice and its flank instability, *Tectonophysics*, **586**, (2013), 46-64, doi: 10.1016/j.tecto.2012.11.011

Brusca, L., Aiuppa, A., D'Alessandro, W., Parello, F., Allard, P. and Michel, A.: Geochemical mapping of magmatic gas-water-rock interactions in the aquifer of Mount Etna volcano, *J. Volcanol. Geotherm. Res.*, **108**, (2001), 199-218.

Capasso, G. and Inguaggiato, S.: A simple method for the determination of dissolved gases in natural waters. An application to thermal waters from Vulcano Island, *Appl. Geochem.*, **13**, (1998), 631-642.

Carapezza, M., Cusimano, G., Liguori, V., Alaimo, R., Dongarrà, G. and Hauser, S.: Nota introduttiva allo studio delle sorgenti termali dell'isola di Sicilia, *Boll. Soc. Geol. It.*, **96,** (1977), 813-836.

Carapezza, M., Cusimano, G., Liguori, V., Alaimo, R., Dongarrà, G. and Hauser, S.: Nota introduttiva allo studio delle sorgenti termali dell'isola di Sicilia, in: Risorse Termali della Sicilia, *Univ. di Palermo*, Palermo, (1987), 7-46.

Chiodini, G., D'Alessandro, W. and Parello, F.: Geochemistry of gases and waters discharged by the mud volcanoes at Paternò, Mt. Etna (Italy), *Bull. Volcanol.*, **58**, (1996), 51-58.

D'Alessandro, W., Parello, F., Valenza, M.: Gas manifestations of Mount Etna area: historical notices and new geochemical data (1990-1993), *Acta Vulcanol*., **8 (1)**, (1996), 23-29.

De Gaetani, G.: Sopra l'acqua solforosa del pozzo di S. Venera, *Atti Acc. Gioenia Sc. Nat. in Catania*, Catania, **1**, **14**, (1839).

De Gaetani, G.: Intorno alle acque solforose del Pozzo di S. Venera. Nuove Osservazioni, *Atti Acc. Gioenia Sc. Nat. in Catania*, Catania, **1, 20**, (1843).

Di Stefano, A. and Branca, S.: Long-term uplift rate of the Etna volcano basement (Southern Italy) from biochronological data of the Pleistocene sediments, *Terra Nova*, **14 (1)**, (2002), 61-68.

Dongarrà, G., Hauser, S.: Isotopic composition of dissolved sulphate and hydrogen sulphide from some thermal springs of Sicily, *Geothermics*, **11 (3),** (1982), 193–200.

Dongarrà, G. and Hauser, S.: Isotopic composition of dissolved sulphate and hydrogen sulphide from some thermal springs of Sicily, in: Risorse Termali della Sicilia, *Univ. di Palermo*, Palermo, (1987), 93-103.

Facca, G.: Studi geotermici sull'Etna, *Rivista Mineraria Siciliana*, **85-87**, (1964), 66-75.

Finetti, I.R., Lentini, F., Carbone, S., Del Ben, A., Di Stefano, A., Forlin, E., Guarnieri, P., Pipan, M. and Prizzon, A.: Geological Outline of Sicily and Lithospheric tectono-dynamics of its Tyrrhenian margin from new CROP seismic data, in: CROP, Deep Seismic Exploration of the Mediterranean region, Finetti, I.R. (Ed.), *Elsevier*, (2005), 319-376.

Ghisetti, F.: Relazione tra strutture e fasi trascorrenti e distensive lungo i sistemi Messina-Fiumefreddo, Tindari-Letojanni e Alia-Malvagna (Sicilia nord-orientale): uno studio microtettonico. *Geol. Rom.*, **18**, (1979), 23-58.

Giammanco, S., Inguaggiato, S. and Valenza, M.: Soil and fumarole gases of Mount Etna: Geochemistry and relations with volcanic activity. *J. Volcanol. Geotherm. Res*., **81**, (1998a), 297-310.

Giammanco, S., Ottaviani, M., Valenza, M., Veschetti, E., Principio, E., Giammanco, G. and Pignato, S.: Major and trace elements geochemistry in the ground waters of a volcanic area: Mount Etna (Sicily), *Wat. Res.*, **32,** (1998b), 19-30.

Giammanco, S., Ottaviani, M. and Veschetti, E.: Temporal variability of major and trace elements concentrations in the ground waters of Mt. Etna (Italy): evidence of transient input of magmatic fluids highlighted by means of Cluster Analysis, *Pure Appl. Geophys*., **164**, (2007), 2523–2547.

Grassa, F., Capasso, G., Faber, E., Inguaggiato, S. and Valenza, M.: Molecular and isotopic composition of free hydrocarbon gases from Sicily, Italy, *Geophys. Res. Lett.*, **31**, (2004), L06607, doi:10.1029/2003GL019362.

Grassa, F., Capasso, G., Favara, R. and Inguaggiato, S.: Chemical and isotopic composition of waters and dissolved gases in some thermal springs of Sicily and adjacent volcanic islands, Italy, *Pure Appl. Geophys*., **163**, (2006), 781–807.

Hirn, A., Nercessian, A., Sapin, M., Ferrucci, F. and Wittlinger, G.: Seismic heterogeneity of Mt Etna: structure and activity, *Geophys. J. Int*., **105**, (1991), 139-153.

Lentini, F.: The geology of Mt. Etna basement, *Mem. Soc. Geol. It.*, **23**, (1982), 7-25.

Lentini, F., Carbone, S. and Guarnieri, P.: Collisional and postcollisional tectonics of the Apenninic-Maghrebian orogen (southern Italy), in: Postcollisional tectonics and magmatism in the Mediterranean region and Asia - GSA Special Paper 409, Dilek, Y., Pavlides, S. (Eds.), *G.S.A.*, (2006).

Lo Giudice, E. and Rasà, R.: Very shallow earthquakes and brittle deformation in active volcanic areas: the Etnean region as an example, *Tectonophys.*, **202**, (1992), 257-268.

McGuire, W.J., Moss, J.L., Saunders, S.J. and Stewart, I.S.: Dyke-induced rifting and edifice instability at Mount Etna, in: Etna: 15 Years On, Gravestock, P.J. and McGuire, W.J. (Eds.), *ODA/Cheltenham & Gloucester College of Higher Education*, (1996).

Minett, S. T. and Scott, S. C.: Theoretical considerations of heat flux on Mount Etna, Sicily, *J. Volcanol. Geotherm. Res*., **25**, (1985), 53-67.

Monaco, C., Tapponnier, P., Tortorici, L. and Gillot, P.Y.: Late Quaternary slip rates on the Acireale-Piedimonte normal faults and tectonic origin of Mt. Etna (Sicily), *Earth Planet. Sci. Lett*., **147**, (1997), 125-139.

Montalto, A., Vinciguerra, S., Menza, S. and Patanè, G.: Recent seismicity of Mount Etna: implication for flank instability, in: Volcano instability on the Earth and other planets, McGuire, W.J., Jones, A.P. and Neuberg, J. (Eds.), *Geol. Soc. London*, London, (1996).

Nasini, E., Porlezza, C. and Donati, A.: Indagini chimiche e chimico-fisiche eseguite sull'acqua idrocarbonato-sulfureo-borica-salino-bromo-iodo-litinica di S. Venera (Acireale), *Ann. Di Chim. Appl*., **15 (11)**, (1925), 183-212.

Parello, F., D'Alessandro, W., Bonfanti, P. and Dongarrà, G.: Subsurface gases in selected sites of the Mt.Etna area (Sicily), *Acta Vulcanol*., **7 (1)**, (1995), 35-42.

Ponte, G.: Il vulcarolo sull'Etna e la utilizzatzione del suo vapore aequeo, *Boll. Acc. Gioenia Sc. Nat*., **57 (1–2)**, (1927), 14–17.

Rust, D. and Neri, M.: The boundaries of large scale collapse on the flanks of Mount Etna, Sicily, in: Volcano instability on the Earth and other planets. McGuire, W.J., Jones, A.P., and Neuberg, J. (Eds.), *Geol. Soc. London*, London, (1996).

Rust, D., Behncke, B., Neri, M. and Ciocanel, A.: Nested zones of instability in the Mount Etna volcanic edifice, Sicily, *J. Volcanol. Geotherm. Res*., **155**, (2005), 137–153.

Scandone, P., Patacca, E., Rodoicic, R., Ryan, W.B.F., Cita, B., Rawason, M., Cherazan, H., Miller, E., McKenzie, J. and Rossi, S.: Mesozoic and Cenozoic rocks from Malta Escarpment (Central Mediterranean), *A.A.P.G. Bull.*, **65**, (1981), 1299-1319.

Silvestri, O.: Le salse e la eruzione di fango di Paternò (Sicilia) – Osservazioni e ricerche, *Stabilimento Tipografico C. Galatola*, Catania, (1866).

Silvestri, O.: Sopra due sorgenti di acqua natural salino-sulfurea idrocarbonata detta di Santa Venera alla base orientale dell'Etna, *Atti Acc. Gioenia Sc. Nat. In Catania*, **3, 8,** Catania, (1872).

Silvestri, O.: Importante eruzione di fango comparsa a Paternò nelle adiacenze dell'Etna ai primi di dicembre 1878, *Boll. Vulcanol. It.*, **5**, (1878), 131-132.