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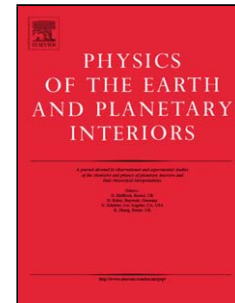
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Evolution of volcanism around the eastern sector of Mt. Etna, inland and offshore, in the structural framework of eastern Sicily.

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Abstract: The authors highlight a new perspective to understanding the volcanism in the Mt. Etna eastern sector, inland and offshore, based on original studies of the sea floor off the Ionian coast of Etna by means of various direct surveying methods (underwater explorations) and indirect ones (bathymetric reconstructions using echosounders). They also propose a new interpretation of geophysical, geochemical and structural surveys carried out over the last two decades. Results show that eastern etnean sector's volcanism extends as far as the Ionian Sea, to a maximum distance from the coast of probably about 20 Km. In our opinion, the absence of outcropping apparatuses in the lower eastern flank of Etna is due to these apparatuses being buried by a large detritic formation ("Chiancone") due to the dismantling of the Ancient Alkaline Centres (AAC) localised to the West. The authors consider the structures highlighted by the study of the Digital Elevation Model (DEM) of the Ionian sea floor and by the Multibeam analysis (Marani et al., 2004), to be of a volcanic nature. This hypothesis opens up a new field of study within the evolution of the eastern etnean edge's volcanism, inland and offshore, in the last 500Ky and would further confirm the eruptive axes migration from East to West.

Keywords: Mt. Etna, Volcano-Tectonic, Pillow Lava, Morphotectonic, Geophysics

1. Introduction

Eastern Sicily is affected by regional faults with a NE-SW and NNE-SSW trend along which basaltic magmas have migrated towards the surface (Rittmann, 1963; Ogniben, 1969; Rittmann and Sato, 1973; Barberi et al., 1973, 1974). Despite the volcanism developing mainly between the mid to late Tertiary and the Quaternary in the northern sector of the Hyblean Mount, the Catania Plain and the etnean area, the products of Mesozoic volcanism have been found in the south-eastern edge of Sicily, in bore holes or embedded in carbonate formations in the southern and northern sectors of the Hyblean Foreland respectively (Fig. 1). The Mesozoic and Tertiary vulcanites, above ground

and undersea were erupted from fractures associated with the two abovementioned structural trends but did not built volcanic edifices with central rising axes comparable to Mount Etna.

Along the NNW-SSE structural trend, which affects south eastern Sicily, inland and offshore, there are no reports of eruptive activity. To the north, in the etnean area, the NNW-SSE and NNE-SSW trends cross over showing a volcanism which began in around 500 Ky B.P.

The frequent eruptive activity generated the largest volcanic apparatus in Europe with an area of about 1200 Km² and a height of over 3000 metres asl. In particular the volcano Etna developed in the convergence zone between the African and Euro-Asiatic Plates and is intersected by extended regional faults which reflect quite complex geodynamics. These faults could have contributed to the feeding of the Etnean volcanism through an asthenospheric window (Gvirtzman Z., Nur A., 1999). First tholeiitic basalt upraised towards the surface between 500 Ky and 300 Ky B.P. In this time span there were eruptive manifestations along well-developed fracture lines which did not give rise to central volcanoes (Kieffer, 1985). Later, from 250 Ky B.P., ever bigger volcanoes with central rising magma formed, which migrated from ESE towards WNW until they reached the present Mongibello (Romano, 1982). The first apparatuses called Alkaline Ancient Centres (AAC) formed in the middle lower eastern side of Etna. To the east of these, inland and offshore, no other peripheral eruptive structures have been found, probably because they have been buried by younger products.

Geophysical and geochemical data and direct exploration of the sea floor east of the coast of Etna, allow us to hypothesise that the volcanism continuously affected the eastern side of the volcano and the adjacent sea floor as far as 20 Km from the coast.

2. Tectonic setting and Dynamics of eastern Sicily inland and offshore

The structural setting of eastern Sicily and its volcanism are strictly linked to the Central Mediterranean geodynamics. In the 1970s various different models were proposed to explain the evolution of this area, based on stratigraphical, geophysical and drilling studies (Biju-Duval etc. 1977). Finetti (1982), while taking these studies into account, recognised the existence of four phases of distension correlated to an equal number of volcanic activity phases between the middle Triassic and the Quaternary. In the mid to late Miocene the northern edge of the African continent collided with the southern edge of the European Plate causing folds, reverse faults and thrusting forming the Appennino-Maghrebide chain (Lentini, 1982). Over time many different NNE-SSW, NE-SW, NNW-SSE and NW-SE oriented strike-slip fault systems developed, determined by a main stress in a N-S direction. As the collision proceeded, the subduction of the Ionian lithosphere under

the Calabrian Arc created a slab, which triggered intermediate and deep earthquakes (Depth \leq 600Km) localised in the lower Tyrrhenian and near Southern Calabria (Panza & Pontevivo, 2004). According to recent studies (Monaco et al., 1997; Monaco & Tortorici, 2000), the eastern sector of Sicily is affected by the Siculo-Calabrian Rift Zone (SCRZ), that develops both on land and offshore in the Ionian and Tyrrhenian basins. This hypothesis may explain the disastrous earthquakes which affected the Tyrrhenian side of Calabria, the Messina Strait and the Ionian coast of Sicily (Fig. 2) (Barbano et al., 1980; Postpischl, 1985; Westaway, 1993) and eastern Sicily's volcanism inland and offshore. The SCRZ might have been generated by a WNW-ESE trending regional extension which had been active since middle Pleistocene (Tapponier, 1977; Monaco et al. 1997). This extension was the consequence of a detachment and foundering of the Ionian slab (De Jonge et al. 1994), which caused a regional rebound and uplift of the overthrust plate (Westway, 1993). One very important central Mediterranean morphotectonic element is the Hyblean-Maltese Escarpment (Fig.1). The literature disagrees on its dating: between the late Palaeozoic and the early Triassic (Stampfli et al., 1991; 2001) or from early Cretaceous (Dercourt et al., 1993) to early Jurassic (Finetti, 1985; Catalano et al. 2000). The Hyblean-Maltese Escarpment is a steep slope connecting eastern Sicily's shelf with the deep Ionian basin. Some seismic profiles using P refraction carried out in the Ionian Sea to the east of the Escarpment show that the crust ranges from 12 Km to 16 Km in thickness and presents a velocity structure similar to that of an oceanic crust (De Voogd et al., 1992). The northern edge of the Hyblean-Maltese Escarpment is mainly affected by NNW-SSE extensional fault systems (Cernobori et al., 1996; Hirn et al., 1997; Bianca et al., 1999; Nicolich et al. 2000) where several high intensity earthquakes have been localised (Boschi et al., 1995a,b). Significant seismic activity has been recorded in recent instrumental catalogues of the 'Istituto Nazionale Geofisica e Vulcanologia'. On Mt. Etna the NNW-SSE structures cross NNE-SSW and NE-SW oriented regional faults; these latter cut across the Hyblean Foreland (Figg.1 and 2). Lastly, north of Mt. Etna, discontinuities develop along the NNW-SSE and NNE-SSW trends; the latter is the main seismotectonic alignment of the Strait of Messina and of Southern Calabria (Fig. 2) (Catalano et al. 2008).

3. Evolution of scientific thought on etnean volcanism

The volcanism in the etnean area seems to be associated with the fourth and final distension phase of the central Mediterranean which occurred between the Neogene and the Quaternary (Finetti, 1982), during which various magmatic intrusions and volcanic eruptions affected the northern edge of the Hyblean Foreland, the Catania Plain, the Ionian Sea and the Canal of Sicily (Fig.1) (Tanguy, 1980).

106 The presence of an extensive basic volcano with a central rising axis like Etna, in an area with a
 107 complex tectonic and geodynamic framework, has caused wide debate among researchers over the
 108 last 50 years.

109 According to Rittmann (1973), Cristofolini et al. (1979), Lo Giudice et al. (1982), the volcanism is
 110 associated with the intersection of crustal discontinuities, trending NE-SW, NNW-SSE, and WNW-
 111 ESE. Frazzetta and Villari (1981), hypothesise instead that this volcanism is determined by a shear
 112 along a regional E-W trending left lateral wrench fault zone. Lo Giudice & Rasà (1986), Lanzafame
 113 & Bousquet (1997), prefer the hypothesis that the rise of the magmas should be associated to a
 114 right-lateral strike slip fault system, oriented NNW-SSE. According to McGuire & Pullen (1989),
 115 McGuire et al. (1990), Lo Giudice & Rasà (1992), Borgia et al. (1992), Bousquet et Lanzafame
 116 (2001), Tibaldi and Groppelli (2002), the etnean volcanic eruptions are linked by an eastward
 117 gravitational spreading of the crust. Tanguy et al. (1997), Clocchiatti et al. (1998), hypothesise that
 118 the magma rise may be associated to the presence of a hot spot in the earth's mantle. Hirn et al.
 119 (1997), Gvirtzman and Nur (1999) Doglioni et al. (2001), propose that there is a rather complex
 120 geodynamic model to explain the volcanism in eastern Sicily: the eruptive phenomena are
 121 associated to the vertical movement of asthenospheric matter in the SW edge of the rollbacked Ionian
 122 slab subducting under the Tyrrhenian lithosphere. Monaco et al. (2005) and Catalano et al. (2008),
 123 consider the hypothesis of an active rifting process (Tapponier 1977; Ellis & King, 1991; Monaco et
 124 al., 1997) associated to a WNW – ESE extension near southern Calabria. The rift zone is found in
 125 the eastern sector of Etna. Finally, Patanè et al. (2006) suggest that the overall tectonic setup of the
 126 etnean area must be correlated to the interaction between the regional dynamism and a diapiric
 127 upwelling of the mantle. This phenomenon has determined the formation of a sub-crustal magma
 128 reservoir, the deformation and fracturing of the crust overlaying it and the tholeiitic magma
 129 emission along the southern border of the volcanic area between 500 Ky and 300 Ky B.P.

130 The process of fracturing moves from the SW towards the NE, following some regional tectonic
 131 lines oriented in the same direction and determines a similarly oriented horst. Between 200 Ky and
 132 80 Ky the eastern side of this horst fractured transversally NW-SE (Patanè et al. 2006); the first
 133 volcanic apparatuses were formed in this net of discontinuities with a central magma rise, indicated
 134 as Ancient Alkalic Centres (AAC). Later, the eruptive centres of Trifoglietto and Mongibello
 135 (Chester et al., 1985; Branca et al., 2004), shifted generally westward over time. Up until a few
 136 years ago, knowledge of both the geology and the morphology of the sea floor was rather poor so
 137 there was no evidence of volcanic activity east of the AAC, inland or offshore. Indeed, clues of a
 138 much more ancient volcanism could have been hidden by the Chiancone, a pyroclastic deposit on
 139 average about 500 metres thick, which formed between 14 Ky and 4 – 3 Ky B.P. (Guest et al. 1984;

Kieffer, 1985) following the demolition of the volcanic apparatuses which today are situated in the area occupied by the Valle del Bove (Fig.3); moreover, any eventual volcanic formations on the Ionian sea floor could have been hidden by deposits of various types of marine and/or earth sediments. In our opinion, the dataset obtained in these last few decades in various ways, suggest the existence of volcanic manifestations under the Chiancone, and the presence in the sea floor near the coast, of volcanic bodies either older than or contemporary with those of the AAC.

4. Analysis of the pre-existing geophysical and geochemical results

The analysis of the evolution of Etnean volcanism carried out by various researchers over the last forty years has revealed a phenomenon of major scientific importance: the eruptive axes of the central rising volcanic apparatus, aligned along the structural trend NE-SW (Patané et al. 2006) have migrated from the SE towards the NW and it is in this direction that some calderas have developed (Fig. 3). Moreover, Patané et al. (2006) highlight that the various eruptive apparatuses developed at the crossing point of the structural discontinuities oriented NE-SW and NW-SE. There are two such crossing points at the Chiancone and offshore, in the Ionian Sea, with the faults linked by two major crustal-scale features: the Hyblean-Maltese Escarpment and the Fiumefreddo-Messina line; so in these two areas, a volcanism has developed which is difficult to detect using classic geological methods, because the volcanics are buried by the Chiancone pyroclastics and, further to the east, hidden by the sea and/or by sediments.

Di Stefano et al. (1999) inverting P-wave arrival times from local and regional earthquakes, calculated a Vp model in the lower crust and uppermost mantle of Eastern Sicily. A velocity reduction weaker than 5% was found in the lower crust beneath the Chiancone and bordering areas (Fig.4A), which are affected by the Siculo-Calabrian Rift Zone (Monaco et al., 1997; Monaco & Tortorici, 2000). It is probable that in the past there was a migration towards the surface of magma and magmatic fluid in this crust along the numerous discontinuities which cut across the low eastern side of Etna. This hypothesis is supported by the strong emissions of magmatic-derived CO₂ recognized in the Chiancone area by Aiuppa et al. (2004) (Fig. 4B). Moreover, La Delfa et al. (2007) have shown that the rise of high temperature aqueous fluids derived from the magma to the crustal levels ever closer to the surface during the 2002-2003 eruption, in the Chiancone zone, has led to alteration in the rheology of the crust and in October 2002 triggered shallow earthquakes (Depth < 6 Km). The geo-electric data confirm the observations previously made. The results of an E-W Resistivity Cross Section, obtained through the interpretation of axial dipole geo-electric soundings (Loddo et al., 1989) (Fig.4C), show the existence of a lower level of resistivity which

varies between 2000 Ωm (sounding 26) and 5500 Ωm (sounding 5). This level corresponds to massive Flysch terrains embedded with quartzite and limestone (Loddo et al., 1989). These resistivity values are lower than those found in sounding 4, where a resistivity value of 40000 Ωm was found for the same sedimentary formation. In our opinion, the higher conductivity (surveys 5 and 26; Fig. 4C) could be ascribable to a decrease in resistivity, induced by volcanic phenomena and/or the presence of severely altered vulcanites. Above this bedrock lies a more conductive formation less than 1 Km thick, with a resistivity of 220 Ωm , which fills in a morphological low of the bedrock. We believe that this geological formation with a resistivity of 220 Ωm may correspond to the pyroclastic facies of the Chiancone, made up of levels with medium-fine granulometry, deriving from the dismantlement of the central volcanoes found to the west. On this facies lies a third level with a notably higher and laterally variable resistivity ($\rho = 6300 \Omega\text{m}$, $\rho = 1200 \Omega\text{m}$), with a thickness of less than 100 metres. It is mainly constituted of lava blocks with a diameter of 1-2 metres in a medium-fine granulometry matrix. In this third level there are sometimes thin flows of lava (Kieffer, 1985) and it corresponds to a late phase of the formation of the Chiancone. West of the Chiancone, underneath even the historical lava coverings, lies a layer with a resistivity of 500 Ωm which can be associated with lahar deposits (Romano, 1982).

Lastly, the strong magnetic anomalies measured in Ionian area near eastern Sicily, suggest the existence of crustal volumes rich in magnetic minerals inside the regional discontinuities. These are the anomalies shown on the maps of the southern areas close to the African coast, which come from a collection of magnetic surveys acquired by Gedge of Leeds (UK), as part of a study of the African Magnetic Mapping Project (sponsored by major World Oil Companies). Bernardelli et al. (2005) using these data, propose a map of the residual magnetic field reduced to the pole. This shows many different magnetic anomalies localised in the northern and southern sector of the Hyblean Foreland, in the Catania Plain to the North, in the Hyblean-Maltese Escarpment, and inland and offshore of the etnean area (Fig. 4D and Fig. 1).

As is known, magnetic anomalies become apparent through an increase in the concentration of magnetic minerals in the crust's rocks. Geological field surveys and drilling surveys in some of the above mentioned areas clearly show that vast basic volcanic bodies exist in outcrops or just below the surface (Fig. 1), which are rich in magnetites and titanites which determine intense local anomalies. In our opinion, the higher values for residual magnetic fields in correspondence to the Hyblean-Maltese Escarpment and to the Eastern side of Mt. Etna, offshore, are the effect of cold old magmatic bodies which have not been explored, hidden as they are by the sea or by sediments.

Del Negro & Napoli, (2002) in a detailed magnetic survey found a wide interval in the anomaly of magnetic values ($-800 \leq nT \leq 1200$) in the Ionian Sea off the eastern coast of Etna between Fondachello and Capo Mulini (Fig. 4E). There is a noteworthy magnetic anomaly of a limited extension NNE of Capo Mulini and offshore, corresponding to lava flows and submarine volcanic bodies. In agreement with Del Negro & Napoli (2002), La Delfa (1999) finds several dykes along the coast, North of Capo Mulini, which feed lava flows mostly submerged by the sea, due to the rise in sea level and/or of the eastward gravitational sliding of the coast South of Santa Caterina. Finally, Del Negro & Napoli (2002) by comparing the magnetic anomalies measured with those calculated, along seven profiles oriented NNE-SSW situated in the eastern etnean sector and offshore, describe seven geological models, in which they graph the thickness and relationships of superimposition and juxtaposition of the various outcropping formations in the explored area: the sedimentary substratum, the Chiancone and/or volcanoclastic deposit, the etnean lava, and the alluvium. The anomaly values ($nT \leq 400$) computed east of the etnean coast are substantially smaller than those measured by Bernardelli et al. (2005) ($nT > 3000$), and so Del Negro & Napoli (2002) retain that in this area generally Pleistocene clays outcrop, and that locally there are not very thick levels of volcanoclastic deposit (on average less than 100m) (Fig. 4E). According to Corsaro et al. (2002) instead, not far from the etnean coast in the Ionian Sea, there are the products of volcanism which can be associated with the rising of magmas previously trapped in the crust and linked to the dynamics of the Hyblean-Maltese Escarpment, whose northern extremity affects the eastern sector of Etna and the adjacent marine floor.

5. Morphological evidence and petrographical features of submarine volcanism

Our hypothesis of the presence of volcanic manifestations near the Ionian coast of Etna seems to be supported by subvolcanic bodies and volcanics erupted from fissures located in the Acitrezza – Acicastello area inland and offshore, slightly south of the Acireale Timpa (i.e. the name Timpa indicates a morphotectonic escarpment) and by the columnar lavas located in correspondence with the Timpa di Don Masi, Santa Caterina and Santa Maria la Scala (Fig. 5). According to Corsaro et al. (2002) the magma which formed these columnar structures was erupted from fractures oriented N-S between 225 Ky and 142 Ky B.P., generating a single or a coalescence of several edifices offshore and east of the present exposures. To the South, between the Timpa di Don Masi and Capo Mulini, along the coast, instead, various dykes oriented ENE and WNW outcrop (La Delfa, 1999) (Fig. 5A). Finally lava pillows, typical formations from submarine volcanism, have been dredged at depths of between 1300 and 800 metres, offshore of Acireale (Coltelli et al., 1997).

In a recent survey carried out offshore of Riposto, a location situated on the Chiancone, the authors have found new evidence supporting submarine volcanism. Using a cartographic type GPS linked to an echo sounder (Lowrance LMS-337C), the sea bottom in a rectangular area 1.5Km x 1.0Km was explored to a depth of 150m. The bathymetric profiles recorded and the relative geo-referential traces gave the necessary data to draw up a detailed bathymetrical chart in 3D (Fig. 5B). The three-dimensional bathymetrical chart shows two ridges, one with a NE-SW linear development, about 1500m long in the surveyed area (Fig. 5Ba), and the other of a conical shape with its top cut off (Fig. 5Bb). The two ridges are linked by a saddle-shaped hump (Fig. 5Bc) running NW-SE. These bulges are traditionally known as the “Shoal of Riposto” located two kilometres from the Ionian coast (Fig. 5C, white rectangle) near the western edge of an underwater structure in the shape of a WNW-ESE oriented amphitheatre which develops, in the area under study, between 500m and 2000m b.s.l. (Fig. 5Cd). This structure is shown up by the seafloor level contours determined from the chart of quoted points on sheet n°22 of the ‘Istituto Idrografico della Marina Italiana’ which are more frequents nearer the coast.

The proposed Digital Elevation Model (DEM), illuminated by a light source placed at N45E and with an inclination of 50° relative to the horizontal (Fig. 5C) reproduced the morphology of this underwater structure very well. Offshore Riposto and Santa Tecla, the DEM shows a morphological escarpment as deep as 200m b.s.l. to the North and 500m b.s.l. to the South (Fig. 5Ce). This escarpment represents the eastern underwater edge of the Chiancone, covered over inland to the North of Santa Maria La Scala by historical and protohistorical lavas (VV. AA., 1979; La Delfa et al. 2007). East of the coast, between Santa Caterina and Acicastello, another ridge trending roughly E-W develops to depths of 1500 b.s.l. (Fig. 5Cf). This trend is that of the dykes found near Capo Mulini (Fig. 5A) (La Delfa, 1999). Lastly, the Multibeam survey carried out by Marani et al. (2004) of the Seafloor Bathymetry of the Ionian Sea, within the Tyrrhenian Project Survey (Fig. 5D), shows a large underwater ring-shaped structure open towards the South-East. This structure with a diameter of about 20 Km (Fig 5Dg) descends to depths of 2800m b.s.l.; it is found at the crossing point of two morphotectonic escarpments trending NNW-SSE (Hyblean – Maltese Escarpment) and NNE-SSW, this latter associated with the Fiumefreddo – Messina Line. The amphitheatre morphology shown up by the DEM outcrops inside the ring structure found by Marani et al. (2004) (Fig. 5Dg).

One of the authors (RL) explored the summit area of one of the two bulges directly in several diving trips, to a depth of 85m b.s.l. During the diving trips, a SCUBA to ternary mixture (O, N, H) was used and a Remotely Operated Vehicle (ROV), for video documentation. The video images show that the sea level was for a long time at 80m below the present one. This level is characterised by

the presence of a deposit of rounded and flattened volcanic pebbles, located at the base of a palaeocliff on which there were evident notches, ascribable to the Wurmian glacial period (70-20 Ky B.P.) (Bonifay, 1973; Fanucci et al., 1974). The images show the presence of aggregates of ovoid masses, resembling lava pillows (Photos A and B) which were sampled. A macroscopic examination of these samples revealed a lot of surface alteration, numerous marine incrustations of an organic origin and a diffuse porosity probably determined by strong degassing in an underwater environment.

Analysis on thick sections highlight the presence of severely altered lavas (very probably due to exposures to environmental conditions for a long time) immersed in a very fine matrix similar to clay; therefore it has not been possible to carry out geochemical analyses. However it is known that the etnean volcanism, on the whole, shows a series of magmas which are quite continuous and homogeneous, to which can be ascribed tholeiitic, alkaline and all the intermediate petrographic types of terms. The columnar lavas outcropping between the Timpa di Don Masi and Santa Maria La Scala are sub alkaline basalts (Corsaro and Pompilio, 2004), whose composition can be compared to that of etnean products indicated as tholeiitic transitional (Atzori, 1966; Tanguy, 1967, 1978; Cristofolini, 1972; Corsaro & Cristofolini, 1997). These compositions constitute the most evolved terms in the area under study and outcrop on the north western edge of the underwater ridge oriented roughly E-W (Fig 5Cf). According to Corsaro et al. (2002) the fluid inclusions in mafic minerals of these sub- alkaline basalts, suggest a trapping pressure ranging from 0.35 to 0.45 GPa corresponding to crustal storage depths between 11 Km and 17 Km.

6. Discussion

The identification of eruptive manifestations and/or volcanic apparatuses older than or contemporary with the AAC in the eastern edge of Mt. Etna, inland and offshore, using traditional geological and geophysical methodologies is quite difficult due mainly to the complex volcano-tectonic evolution of these areas, and to the sea depth (as much as 3 000 m b.s.l. 20 Km from the coast).

Between S.M. La Scala and the Timpa di Don Masi, the lavas and the pyroclastic products of Trifoglietto and of Mongibello (VV. AA., 1979) have covered over most of the most older eruptive manifestations. These latter are formed by isolated outcrops of chaotic breccias with scoriaceous clasts and columnar lavas, which are the product of cooling magma injected into eruptive fissures and vents. According to Corsaro et al. (2002), these discontinuities, associated with eruptive apparatuses located seaward east of the present coastline probably developed between

225 Ky and 142 Ky B.P. To the south, inland between the Timpa di Don Masi and Capo Mulini
 some as yet undated dykes outcrop (on a marine terrace), which in some cases have fed the
 subaerial lavas mostly submerged by the sea, due to changes in sea level during last 200 Ky
 together with a seaward gravitational sliding. The seafloor just off Capo Mulini shows, moreover, a
 well evidenced ridge to at least 1500m b.s.l., which develop E-W following the average orientation
 of the dykes found on this marine terrace. The SW edge of this ridge includes Acicastello and
 Acitrezza's underwater tholeiitic volcanics, which are the most ancient in the etnean area
 (Cristofolini, 1972; Tanguy, 1980; Tanguy et al., 1997). Also in this area fissures injected with
 magma, breccias and lava pillows have been found, but there is no proof of ancient central rising
 eruptive apparatuses. Moreover, the underwater volcanic bodies outcropping in the Acicastello area
 show extensive fractures oriented ENE – WSW (Corsaro & Cristofolini, 2000) like the direction of
 dykes found north of Capo Mulini (Fig. 5A). North of S.M. La Scala, in the Chiancone area, there is
 only indirect proof of a current volcanism. In fact, in the western zone of the Chiancone, high
 concentrations of CO₂ in the soil and in the groundwater were recorded before the summit eruption
 of 1991-1993. The values of these concentrations together with the thermal anomalies measured
 were consistent with the rise of hot fluids released by ascending magma (Aiuppa et al., 2004). La
 Delfa et al. (2007) made similar considerations when studying the seismic swarm of 29 October
 2002 associated to the summit eruption of 2002-2003. According to these researchers, during the
 eruption, the fracturing mechanisms appear to be linked to the mutation of the mechanical crust
 properties below a depth of 6 Km, which goes from brittle to ductile as a consequence of rising high
 temperature aqueous fluids derived from the magma in the western sector of the Chiancone. Finally,
 this latter shows a sedimentary substratum formed by massive flysch terrains embedded with
 quartzite and limestone, whose resistivity varies from 40 000 Ω m to a few thousand Ω m from W to
 E (Loddo et al. 1989). The drastic reduction in resistivity revealed by the axial dipole geo-electric
 soundings in the Chiancone area, in our opinion, could be determined by the presence of extremely
 altered ancient volcanic rocks injected into the sedimentary terrains. The vast fracturing of this area
 due to the crossing of regional fault systems could have favoured magma rise in the past and hot
 magmatic fluid migration in the present. East of the Chiancone, seafloor takes on the morphology of
 a ring shaped structure open towards the SE which reaches a depth of 2800 b.s.l. It interrupts the
 quite irregular trend of the Hyblean – Maltese Escarpment and the Fiumefreddo-Messina Line one,
 and it lies where the two morphotectonic structures cross each other. Moreover, this type of
 morphology is unique all along the escarpment which bounds eastern Sicily and is located east of
 the etnean volcanic apparatus. The ring shaped structure circumscribes another smaller structure in
 the shape of an amphitheatre also open towards the SE, as is shown by contouring and by the DEM.

In our opinion the two morphologies belong to an ancient volcanic edifices, probably formed by the coalescence of more than one caldera. The geometry of these presumed calderas is analogous to the development of calderic rims outcropping on the eastern flank of Etna (Fig. 5Ch) (Patané et al., 2006), both constrained by the prevailing NW-SE structural trend.

The “Shoal of Riposto” (80 m depth), represents the highest point of the ring shaped structure, on its top there is evidence of beaches ascribable to marine terraces, formed during the last glaciation (Wurm: 70-20 Ky). By considering the general uplift of the eastern etnean area of about 2 mm/yr (Monaco et al., 1997), the above mentioned marine terraces, currently at a depth of 80 m, was at about 120 m below the present sea level, undergoing an uplifting of 40 m during the last 20 ky. Therefore the Shoal of Riposto, which is older than 20 Ky, was very probably formed in the last phases of a volcanism which involved that area. By considering the large extension of the remaining ring structure (20 km in diameter and up to -2.4 km deep), it is possible to hypothesise that it was formed over a longer time span.

According to Del Negro & Napoli (2002) the magnetic anomalies found in this area, which show values of between 400 nT and -800 nT, are mostly ascribable to sedimentary rocks (Pleistocenic clays) and to fine volcanoclastic deposits. The discrepancy between our interpretation and theirs may have various different reasons: 1) to generate models of magnetic anomalies which fit well with experimental data, they considered values for remanent magnetization (J_{NRM}) and susceptibility (χ) of rocks with genetic and petrographic characteristics held similar to those of the Ionian coast of Etna which were formed over the last 165 Ky. They considered this procedure necessary because there were no measurements of the magnetic properties of volcanics outcropping in this area; moreover 2) a single average value of J_{NRM} (6,77 A/m) and χ (0.03 SI) was considered for all types of lava; 3) volcanites of an age before 165 Ky B.P. were not considered; and, above all, 4) the state of alteration of volcanic rocks affects their magnetic characteristics in two ways: how the process of alteration occurs, and the environment in which the volcanites were deposited as they cooled. None of this was considered, although the alteration factor certainly affects magnetic properties. In particular hydrothermal alteration and weathering transform titanomagnetite into non magnetic (e.g. hematite) or a less magnetic mineral (e.g. titanomaghemite), reducing both the remanent magnetization and susceptibility (Watkins & Paster, 1971; Hildebrande et al., 1993). Thus the underwater lavas sampled off Riposto, cooled underwater and remained there for thousands of years. They have probably undergone hydrothermal alteration and the action of atmospheric agents during the Wurmian, and so display a systematic decrease in magnetization; however subaerial basalts do not (Prévot & Grommé, 1975). In our opinion, therefore, the discrepancy between our results and those of Del Negro & Napoli (2002) spring from the hypothesis made that the field of

magnetic anomalies in the Ionian Sea should only be associated to clays and a thin layer of the pyroclastic rocks. In reality instead there are underwater lavas which are very altered and, probably, have undergone a process of transformation into clay like minerals with a vast areal distribution. This is shown by the numerous outcrops in the sea along the coast between Acicastello and Santa Maria La Scala, the “lava pillows” dredged offshore of Acireale, and our samples.

The aeromagnetic data of this area (Bernardelli et al., 2005) are further proof that in the past there could have been volcanic activity. As is known, this type of geophysical survey carried out at a particular height over the topographic surface, naturally filter out geological noise coming from small shallow magnetic bodies and highlight deep large-scale structures. In fact the two ridges are situated at the northern extremity of the Hyblean-Maltese Escarpment, in an area in which the magnetic anomalies are particularly high and even exceed the value of 3000 nT. Such high intensities can only be explained if inside the crust itself there are extensive cold bodies rich in magnetotitanites, which would explain the submarine volcanism east of the etnean coast too. For this reason we maintain that the intense magnetic anomalies found at the northern edge of the Hyblean-Maltese Escarpment, near the etnean coast, are associated with magmatic bodies cooled inside the crust which fed underwater volcanism.

7. Conclusions

Fissure volcanism in eastern Sicily has generally migrated from south to north reaching as far as the etnean area (between Acicastello and Acitrezza) in the Pleistocene age with the first tholeiitic volcanics (Fig. 6) (Branca et al., 2008). The rise of magma towards the seafloor begun in about 500 Ky B.P. favoured by the fissures and normal faults which cut across the Hyblean – Maltese Escarpment (HME). Over the last 225-142 Ky B.P volcanism affected the area north of Acitrezza, erupting volcanic products varying from sub-alkaline to alkaline basalts, between the Timpa di Don Masi and Santa Maria La Scala (Fig. 6) (Corsaro et al., 2002). To the north, the intersection between the Hyblean-Maltese escarpment and the Fiumefreddo-Messina line could have determined the change of volcanic activity from fissures to magma uprising through a central axis, favouring the building of a volcano edifice. Unfortunately, no absolute dating of the volcanites sampled from the “Shoal of Riposto” is available, and therefore no certainty about their age can be proved. According to Corsaro et al. (2002) and Branca et al. (2008), between 142 Ky and 126 Ky, an alkaline volcanism developed in the low eastern side of Mt. Etna, between Santa Maria La Scala and Moscarello, immediately west of Riposto. Moreover, the existence of beaches situated at a depth of 80 m b.s.l. (east of Riposto) ascribable to the last glaciation (Wurm), shows that such

volcanisms should be older than 20 ky. Therefore, on the basis of the literature and new geophysical and morphological data interpretation, we can hypothesise that volcanism linked to the ring shaped structure has developed between the last 126 Ky and 20 Ky B.P. (Fig. 6). Nevertheless, in order to confirm the above mentioned time interval, we need to know the age of the volcanites, which can only be obtained when less altered lavas are sampled at greater depths. As the evolution of the Ionian etnean edge is still largely a matter of scientific debate, we have not yet excluded that, in our studied area, the magma uprising and the development of volcanic activity might be older than 126 Ky. Instead, there may certainly exist a spatial continuity between the actual centres of magma rising and the eastern peripheral areas of Etna, as shown by the strong concentrations of CO₂ and the variations in the reology of the crust found in the Chiancone area during the summit eruptive activity. We hold therefore that in this area volcanism has not yet totally ceased and that ancient volcanic bodies may be buried by the Chiancone itself. Lastly, the obtained results further confirm the model of the eruptive axes migration from East to West.

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Figure Captions

Fig.1. Tectonic setting of eastern Sicily and areas with volcanic manifestations: 1) Buried Triassic volcanics near Ragusa; 2) Lavas and dykes of the Cretaceous; 3) Vulcanics of the Upper Cretaceous – Pleistocene in the northern sector of the Hyblean Mountains; and in the Catania Plain 4); Quaternary volcanics of Etna 5), (from Rittmann, 1963, modified)

Fig. 2. Faults and epicentres (black dots) of highest energy earthquakes which have happened in the Siculo Calabra Rift Zone (SCRZ) between 1659 and 1990. The numbers (N) relative to the points are the same as the first column in the table shown in the Figure; Large arrows indicate the regional extension direction (Catalano et al., 2007, modified).

Fig. 3. Sketch map showing the succession of eruptive centres identified in the Etna area (modified after Chester et al., 1985): MP=Tardaria-Monte Po; CL=Calanna; SA=Sant' Alfio; T1=Trifoglietto 1; T2Z=Trifoglietto 2- Zoccolaro; VB=Vavalaci-Belvedere; SGP=Serra Giannicola Piccola; MG=Mongibello; ch= Chiancone. The arrow shows the temporal migration of the various different eruptive centres.

Fig. 4A. Variation of the velocity of the P waves in % at the depth of 22 Km: the rectangle shows the area studied, the zones in yellow and orange are associated to low-velocity layers (Di Stefano et al., 1999, modified).

Fig 4B. Trend of CO₂ concentration in the etnean area: the highest values are in the Chiancone area (ch) (Aiuppa et al., 2004, modified).

Fig 4C. Profile (F-F') of axial dipole geoelectric soundings along the Chiancone (ch), in E-W direction; the dots and numbers show the location of survey sights for the original paper.

The section shows the various lithotypes associated to the resistivity values obtained from the geoelectrical soundings 4, 5 and 26 (for detail see text) (Loddo et al. 1989, modified).

Fig 4D. Map of the residual magnetic field reduced to the pole of the central Mediterranean Sea. Strong magnetic anomalies are evident along the Hyblean-Maltese Escarpment (HME: area inside the white line), in the Hyblean Foreland (HP), in the Catania Plain(PC) in the Etna area (ET) and in the area under study (A), as well as in the Tyrrhenian area (AU) (Bernardelli et al., 2005, modified).

Fig 4E. Map of the field of magnetic anomalies reduced to pole. F-F' and G-G' are two lines of sampling of the magnetic survey in the Ionian Sea (Del Negro & Napoli, 2002, modified).

Fig. 4F. On top: graphs of the magnetic anomalies measured (blue line) compared with those calculated (Red line) along the sampling lines F-F' and G-G'. Below: geological models obtained from the calculated anomalies. The sedimentary substratum is in light blue, the Chiancone and/or volcanoclastic deposits are in yellow, (Del Negro & Napoli, 2002, modified).

Fig. 5. Morphological escarpment called the “Timpa” between Capo Mulini and the Timpa di Don Masi. The volcanic dykes outcropping on it are in orange A); “Shoal of Riposto” (for detail see text) Ba, b, c); Digital Elavation Model (DEM) of the sea bottom near the etnean coast: amphitheatre shaped morphology Cd), ridge between Acicastello and Santa Caterina orientated E-W Cf), Chiancone inland and offshore area Ce), pattern of the calderic rims outcropping Ch); ring structure open towards E-SE Dg) which contains the amphitheatre shaped morphology Cd).

Fig. 6. Sketch of the temporal and spatial evolution of volcanism along the eastern etnean coast, inland and offshore. The ages of the lavas marked (a) and (b) are taken from (a) Branca et al., 2008; (b) Gillot et al., 1994.

Photo A. Shell shaped structure with two valves with a diameter of about 80 cm. The morphology could be determined by the way lava flows in an underwater environment and by rapid cooling (depth 80 metres).

Photo B. Structures similar to pillows emerging from the sea bottom (diameter up to 1m) formed by terrigenous and chemico-organogenic deposits. The surface of the “pillows” show various incrustations caused by colonising marine animals (depth 80 metres).

