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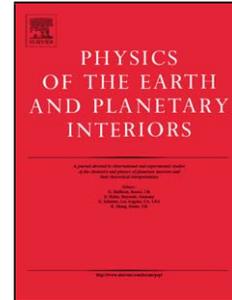
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1 **Evolution of volcanism around the eastern sector of Mt. Etna, inland**
2 **and offshore, in the structural framework of eastern Sicily.**

3

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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.

24

25

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

27

28 **1. Introduction**

29

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

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

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

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

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

58

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

60

61 The structural setting of eastern Sicily and its volcanism are strictly linked to the Central
62 Mediterranean geodynamics. In the 1970s various different models were proposed to explain the
63 evolution of this area, based on stratigraphical, geophysical and drilling studies (Biju-Duval etc.
64 1977). Finetti (1982), while taking these studies into account, recognised the existence of four
65 phases of distension correlated to an equal number of volcanic activity phases between the middle
66 Triassic and the Quaternary. In the mid to late Miocene the northern edge of the African continent
67 collided with the southern edge of the European Plate causing folds, reverse faults and thrusting
68 forming the Appennino-Maghrebide chain (Lentini, 1982). Over time many different NNE-SSW,
69 NE-SW, NNW-SSE and NW-SE oriented strike-slip fault systems developed, determined by a main
70 stress in a N-S direction. As the collision proceeded, the subduction of the Ionian lithosphere under

71 the Calabrian Arc created a slab, which triggered intermediate and deep earthquakes (Depth \leq
72 600Km) localised in the lower Tyrrhenian and near Southern Calabria (Panza & Pontevivo, 2004).
73 According to recent studies (Monaco et al., 1997; Monaco & Tortorici, 2000), the eastern sector of
74 Sicily is affected by the Siculo-Calabrian Rift Zone (SCRZ), that develops both on land and
75 offshore in the Ionian and Tyrrhenian basins. This hypothesis may explain the disastrous
76 earthquakes which affected the Tyrrhenian side of Calabria, the Messina Strait and the Ionian coast
77 of Sicily (Fig. 2) (Barbano et al., 1980; Postpischl, 1985; Westaway, 1993) and eastern Sicily's
78 volcanism inland and offshore. The SCRZ might have been generated by a WNW-ESE trending
79 regional extension which had been active since middle Pleistocene (Tapponier, 1977; Monaco et al.
80 1997). This extension was the consequence of a detachment and foundering of the Ionian slab (De
81 Jonge et al. 1994), which caused a regional rebound and uplift of the overthrust plate (Westway,
82 1993). One very important central Mediterranean morphotectonic element is the Hyblean-Maltese
83 Escarpment (Fig.1). The literature disagrees on its dating: between the late Palaeozoic and the early
84 Triassic (Stampfli et al., 1991; 2001) or from early Cretaceous (Dercourt et al., 1993) to early
85 Jurassic (Finetti, 1985; Catalano et al. 2000). The Hyblean-Maltese Escarpment is a steep slope
86 connecting eastern Sicily's shelf with the deep Ionian basin. Some seismic profiles using P
87 refraction carried out in the Ionian Sea to the east of the Escarpment show that the crust ranges from
88 12 Km to 16 Km in thickness and presents a velocity structure similar to that of an oceanic crust
89 (De Voogd et al., 1992). The northern edge of the Hyblean-Maltese Escarpment is mainly affected
90 by NNW-SSE extensional fault systems (Cernobori et al., 1996; Hirn et al., 1997; Bianca et al.,
91 1999; Nicolich et al. 2000) where several high intensity earthquakes have been localised (Boschi et
92 al., 1995a,b). Significant seismic activity has been recorded in recent instrumental catalogues of the
93 'Istituto Nazionale Geofisica e Vulcanologia'. On Mt. Etna the NNW-SSE structures cross NNE-
94 SSW and NE-SW oriented regional faults; these latter cut across the Hyblean Foreland (Figg.1 and
95 2). Lastly, north of Mt. Etna, discontinuities develop along the NNW-SSE and NNE-SSW trends;
96 the latter is the main seismotectonic alignment of the Strait of Messina and of Southern Calabria
97 (Fig. 2) (Catalano et al. 2008).

98

99 **3. Evolution of scientific thought on etnean volcanism**

100

101 The volcanism in the etnean area seems to be associated with the fourth and final distension phase
102 of the central Mediterranean which occurred between the Neogene and the Quaternary (Finetti,
103 1982), during which various magmatic intrusions and volcanic eruptions affected the northern edge
104 of the Hyblean Foreland, the Catania Plain, the Ionian Sea and the Canal of Sicily (Fig.1) (Tanguy,
105 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;

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

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

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

158 Di Stefano et al. (1999) inverting P-wave arrival times from local and regional earthquakes,
159 calculated a Vp model in the lower crust and uppermost mantle of Eastern Sicily. A velocity
160 reduction weaker than 5% was found in the lower crust beneath the Chiancone and bordering areas
161 (Fig.4A), which are affected by the Siculo-Calabrian Rift Zone (Monaco et al., 1997; Monaco &
162 Tortorici, 2000). It is probable that in the past there was a migration towards the surface of magma
163 and magmatic fluid in this crust along the numerous discontinuities which cut across the low eastern
164 side of Etna. This hypothesis is supported by the strong emissions of magmatic-derived CO₂
165 recognized in the Chiancone area by Aiuppa et al. (2004) (Fig. 4B). Moreover, La Delfa et al.
166 (2007) have shown that the rise of high temperature aqueous fluids derived from the magma to the
167 crustal levels ever closer to the surface during the 2002-2003 eruption, in the Chiancone zone, has
168 led to alteration in the rheology of the crust and in October 2002 triggered shallow earthquakes
169 (Depth < 6 Km). The geo-electric data confirm the observations previously made. The results of an
170 E-W Resistivity Cross Section, obtained through the interpretation of axial dipole geo-electric
171 soundings (Loddo et al., 1989) (Fig.4C), show the existence of a lower level of resistivity which

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

188 Lastly, the strong magnetic anomalies measured in Ionian area near eastern Sicily, suggest the
189 existence of crustal volumes rich in magnetic minerals inside the regional discontinuities. These are
190 the anomalies shown on the maps of the southern areas close to the African coast, which come from
191 a collection of magnetic surveys acquired by Getech of Leeds (UK), as part of a study of the
192 African Magnetic Mapping Project (sponsored by major World Oil Companies). Bernardelli et al.
193 (2005) using these data, propose a map of the residual magnetic field reduced to the pole. This
194 shows many different magnetic anomalies localised in the northern and southern sector of the
195 Hyblean Foreland, in the Catania Plain to the North, in the Hyblean-Maltese Escarpment, and
196 inland and offshore of the etnean area (Fig. 4D and Fig. 1).

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

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

224

225 **5. Morphological evidence and petrographical features of submarine volcanism**

226

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

238 In a recent survey carried out offshore of Riposto, a location situated on the Chiancone, the authors
239 have found new evidence supporting submarine volcanism. Using a cartographic type GPS linked to
240 an echo sounder (Lowrance LMS-337C), the sea bottom in a rectangular area 1.5Km x 1.0Km was
241 explored to a depth of 150m. The bathymetric profiles recorded and the relative geo-referential
242 traces gave the necessary data to draw up a detailed bathymetrical chart in 3D (Fig. 5B). The three-
243 dimensional bathymetrical chart shows two ridges, one with a NE-SW linear development, about
244 1500m long in the surveyed area (Fig. 5Ba), and the other of a conical shape with its top cut off
245 (Fig. 5Bb). The two ridges are linked by a saddle-shaped hump (Fig. 5Bc) running NW-SE. These
246 bulges are traditionally known as the “Shoal of Riposto” located two kilometres from the Ionian
247 coast (Fig. 5C, white rectangle) near the western edge of an underwater structure in the shape of a
248 WNW-ESE oriented amphitheatre which develops, in the area under study, between 500m and
249 2000m b.s.l. (Fig. 5Cd). This structure is shown up by the seafloor level contours determined from
250 the chart of quoted points on sheet n°22 of the ‘Istituto Idrografico della Marina Italiana’ which are
251 more frequents nearer the coast.

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

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

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

279 Analysis on thick sections highlight the presence of severely altered lavas (very probably due to
280 exposures to environmental conditions for a long time) immersed in a very fine matrix similar to
281 clay; therefore it has not been possible to carry out geochemical analyses. However it is known that
282 the etnean volcanism, on the whole, shows a series of magmas which are quite continuous and
283 homogeneous, to which can be ascribed tholeiitic, alkaline and all the intermediate petrographic
284 types of terms. The columnar lavas outcropping between the Timpa di Don Masi and Santa Maria
285 La Scala are sub alkaline basalts (Corsaro and Pompilio, 2004), whose composition can be
286 compared to that of etnean products indicated as tholeiitic transitional (Atzori, 1966; Tanguy,
287 1967,1978; Cristofolini, 1972; Corsaro & Cristofolini,1997). These compositions constitute the
288 most evolved terms in the area under study and outcrop on the north western edge of the underwater
289 ridge oriented roughly E-W (Fig 5Cf). According to Corsaro et al. (2002) the fluid inclusions in
290 mafic minerals of these sub- alkaline basalts, suggest a trapping pressure ranging from 0.35 to 0.45
291 GPa corresponding to crustal storage depths between 11 Km and 17 Km.

292

293 **6. Discussion**

294

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

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

306 225 Ky and 142 Ky B.P. To the south, inland between the Timpa di Don Masi and Capo Mulini
307 some as yet undated dykes outcrop (on a marine terrace), which in some cases have fed the
308 subaerial lavas mostly submerged by the sea, due to changes in sea level during last 200 Ky
309 together with a seaward gravitational sliding. The seafloor just off Capo Mulini shows, moreover, a
310 well evidenced ridge to at least 1500m b.s.l., which develop E-W following the average orientation
311 of the dykes found on this marine terrace. The SW edge of this ridge includes Acicastello and
312 Acitrezza's underwater tholeiitic volcanics, which are the most ancient in the etnean area
313 (Cristofolini, 1972; Tanguy, 1980; Tanguy et al., 1997). Also in this area fissures injected with
314 magma, breccias and lava pillows have been found, but there is no proof of ancient central rising
315 eruptive apparatuses. Moreover, the underwater volcanic bodies outcropping in the Acicastello area
316 show extensive fractures oriented ENE – WSW (Corsaro & Cristofolini, 2000) like the direction of
317 dykes found north of Capo Mulini (Fig. 5A). North of S.M. La Scala, in the Chiancone area, there is
318 only indirect proof of a current volcanism. In fact, in the western zone of the Chiancone, high
319 concentrations of CO₂ in the soil and in the groundwater were recorded before the summit eruption
320 of 1991-1993. The values of these concentrations together with the thermal anomalies measured
321 were consistent with the rise of hot fluids released by ascending magma (Aiuppa et al., 2004). La
322 Delfa et al. (2007) made similar considerations when studying the seismic swarm of 29 October
323 2002 associated to the summit eruption of 2002-2003. According to these researchers, during the
324 eruption, the fracturing mechanisms appear to be linked to the mutation of the mechanical crust
325 properties below a depth of 6 Km, which goes from brittle to ductile as a consequence of rising high
326 temperature aqueous fluids derived from the magma in the western sector of the Chiancone. Finally,
327 this latter shows a sedimentary substratum formed by massive flysch terrains embedded with
328 quartzite and limestone, whose resistivity varies from 40 000 Ωm to a few thousand Ωm from W to
329 E (Loddo et al. 1989). The drastic reduction in resistivity revealed by the axial dipole geo-electric
330 soundings in the Chiancone area, in our opinion, could be determined by the presence of extremely
331 altered ancient volcanic rocks injected into the sedimentary terrains. The vast fracturing of this area
332 due to the crossing of regional fault systems could have favoured magma rise in the past and hot
333 magmatic fluid migration in the present. East of the Chiancone, seafloor takes on the morphology of
334 a ring shaped structure open towards the SE which reaches a depth of 2800 b.s.l. It interrupts the
335 quite irregular trend of the Hyblean – Maltese Escarpment and the Fiumefreddo-Messina Line one,
336 and it lies where the two morphotectonic structures cross each other. Moreover, this type of
337 morphology is unique all along the escarpment which bounds eastern Sicily and is located east of
338 the etnean volcanic apparatus. The ring shaped structure circumscribes another smaller structure in
339 the shape of an amphitheatre also open towards the SE, as is shown by contouring and by the DEM.

340 In our opinion the two morphologies belong to an ancient volcanic edifices, probably formed by the
341 coalescence of more than one caldera. The geometry of these presumed calderas is analogous to the
342 development of calderic rims outcropping on the eastern flank of Etna (Fig. 5Ch) (Patané et al.,
343 2006), both constrained by the prevailing NW-SE structural trend.

344 The “Shoal of Riposto” (80 m depth), represents the highest point of the ring shaped
345 structure, on its top there is evidence of beaches ascribable to marine terraces, formed during the
346 last glaciation (Wurm: 70-20 Ky). By considering the general uplift of the eastern etnean area of
347 about 2 mm/yr (Monaco et al., 1997), the above mentioned marine terraces, currently at a depth of
348 80 m, was at about 120 m below the present sea level, undergoing an uplifting of 40 m during the
349 last 20 ky. Therefore the Shoal of Riposto, which is older than 20 Ky, was very probably formed in
350 the last phases of a volcanism which involved that area. By considering the large extension of the
351 remaining ring structure (20 km in diameter and up to -2.4 km deep), it is possible to hypothesise
352 that it was formed over a longer time span.

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

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

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

390

391 **7. Conclusions**

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

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

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422

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424

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654 **Figure Captions**

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

660

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

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

669

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

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

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

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

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

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

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

689

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

696

697 **Fig. 6.** Sketch of the temporal and spatial evolution of volcanism along the eastern etnean coast, inland and
 698 offshore. The ages of the lavas marked (a) and (b) are taken from (a) Branca et al., 2008; (b) Gillot et al.,
 699 1994.

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701

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

704

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

