Why Mt Etna?

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ABSTRACT

The Etna volcano is located in an apparently anomalous position on the hinge zone of the Apennines subduction and its Na-alkaline geochemistry does not favour a magma source from the deep slab as indicated for the Aeolian K-alkaline magmatism. The steeper dip of the regional foreland monocline at the front of the Apennines in the Ionian Sea than in Sicily, implies a larger rollback of the subduction hinge in the Ionian Sea. Moreover, the lengthening of the Apennines arc needs extension parallel to the arc. Therefore, the larger southeastward subduction rollback of the Ionian lithosphere with respect to the Hyblean plateau in Sicily, should kinematically produce right-lateral transtension and a sort of vertical 'slab window' which might explain (i) the Plio-Pleistocene alkaline magmatism of eastern Sicily (e.g. the Etna volcano) and (ii) the late Pliocene to present right lateral transtensional tectonics and seismicity of eastern Sicily. The area of transfer of different dip and rollback occurs along the inherited Mesozoic passive continental margin between Sicily and the oceanic Ionian Sea, i.e. the Malta escarpment.

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Introduction

Eastern Sicily is characterized by active destructive seismicity and intense magmatism (e.g. Baratta, 1910; Hirn *et al.*, 1997). The tectonic activity and magmatism are concentrated mostly along the Malta escarpment (Fig. 1), an inherited Mesozoic continental margin (Scandone *et al.*, 1981; Casero *et al.*, 1984). The Ionian ocean opened probably during the middle–late Mesozoic and aborted at some time during the Tertiary (Catalano *et al.*, 2001). The seismicity and the Etna volcano (Sharp *et al.*, 1980; Tonarini *et al.*, 1995; Armienti *et al.*, 1996; Azzaro and Barbano, 1996; Bonaccorso, 1996; Hirn *et al.*, 1997; Tanguy *et al.*, 1997; Cocina *et al.*, 1998; Azzaro *et al.*, 1999; Azzaro, 1999; Murru *et al.*, 1999; Chiarabba *et al.*, 2000) are sited at the front or in the foreland of the Apennines accretionary wedge (Bianchi *et al.*, 1987) in an anomalous external position with respect to the arc magmatism and back-arc spreading zones associated with the Apennines subduction (Fig. 2). In this paper, new data are presented on the dip of the foreland monocline and its age, supporting an ongoing subduction below both northern Sicily and Calabria. The variable dip of the top of the slab appears to be determined by the different composition of the downgoing foreland lithosphere, i.e. denser or oceanic in the Ionian sea and continental in Sicily. This idea of differential rollback was proposed by Doglioni *et al.* (1998), and a similar model was confirmed by Gvirtzman and Nur (1999). However, there are several main differences between these two approaches: (i) evolution and dip of the foreland monocline are used in Doglioni *et al.* as main indicators, whereas the reasoning of Gvirtzman and Nur is based mainly on gravity reconstructions; (ii) the subduction below Sicily and its northern offshore region are considered crucial in Doglioni *et al.* for determining the geodynamics of the area, but not in Gvirtzman and Nur; and (iii) only Doglioni *et al.* include the lengthening of the arc and its right-lateral transtension in their model.

Brief history of Mt Etna

Mt Etna is the largest subaerial active volcano in Europe. It has a roughly elliptical base (38 × 47 km) and a maximum elevation of about 3300 m (Chester *et al.*, 1985; Kieffer and Tanguy, 1993). It comprises a series of nested strato-volcanoes, often characterized by summit calderas, the most important one being the Ellittico Caldera, formed about 14–15 Ka (Condomines *et al.*, 1995). The strato-volcanoes and the associated small scattered eruptive centres grew on a lava basement, produced by fissural flows of tholeiitic/transitional composition (Corsaro and Cristofolini, 1997; Clocchiatti *et al.*, 1998), for which an age of about 500 kyr has been determined (Gillot *et al.*, 1994). Although the plateau was almost completely covered by the recent volcanics, it is still recognizable morphologically in the southern part of the volcano (Favalli *et al.*, 1999). The eruptive axis of the largest central volcanoes has shifted westward through time; the volcanic edifice resulting from the coalescence of the various apparata is dissected by the Valle del Bove, a huge horseshoe-shaped depression (up to 6.5 km long and 5 km wide) opening toward the Ionian Sea, and frequently draining the recent lava flows (for a discussion of the Valle del Bove origin, see Guest *et al.*, 1984; McGuire *et al.*, 1985).

Throughout its history, Mt Etna has been characterized essentially by effusive activity; however, several pyroclastic deposits related to sub-Plinian and Plinian eruptions have been identified in the Holocene sequence (Coltelli *et al.*, 1998). The exposed magmatic rocks have an affinity varying from tholeiitic to mildly Na-alkaline. The Etnean volcanic products show a composition (Fig. 3) varying from picritic basalt and alkali basalt to trachytes, with hawaiites being the dominant rocks (D'Orazio, 1994).

Geodynamic setting of Mt Etna

Several authors have proposed alternative settings for the development of the volcanic edifice, including a hot spot origin (Tanguy *et al.*, 1997; Clocchiatti *et al.*, 1998), an asymmetric rifting process (Continisio *et al.*, 1997), the dislocation between the

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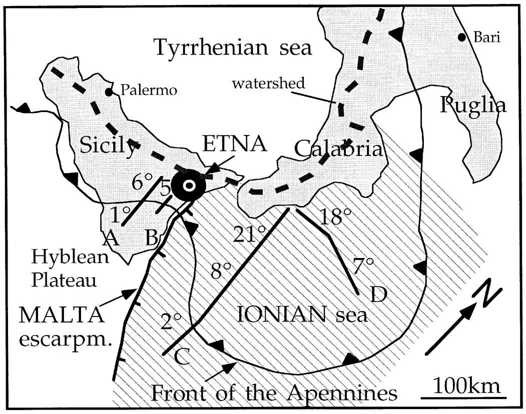

Fig. 1 Schematic tectonic map of the Mt Etna area and location of the representative sections where the foreland dip has been measured and shown as Fig. 4.

'Malta–Sicilian block' and the Ionian basin (Gillot *et al.*, 1994), and several other tectonic features intersecting in the Etna area (Lanzafame *et al.*, 1997; McGuire *et al.*, 1997). Many authors recognize the most important feature as the Malta Escarpment and its northward extension as the Messina–Giardini fault zone (Lo Giudice and Rasà, 1986; Lanzafame and Bousquet, 1997; McGuire *et al.*, 1997). The Malta escarpment is the southwestern margin of a Mesozoic basin which has been interpreted mainly as oceanic; however, a few papers question its nature (Farrugia and Panza, 1981; Biju-Duval *et al.*, 1982; Finetti, 1982; Makris *et al.*, 1986; Suhadolc and Panza, 1989; de Voogd *et al.*, 1992; Catalano *et al.*, 2001).

The Etna volcano is located in the hanging wall of the Apennines accretionary prism (Fig. 2), and therefore its deep sources competed and compete with the advancing basal decollement of the prism. The depth of the decollement is probably close to the crystalline basement–sedimentary cover interface (5–15 km). The eastern Sicily thrust belt architecture and seismicity indicate a compressional, N–S orientated, tectonic setting for the Etna volcano (Cocina *et al.*, 1997, 1998; Lanzafame *et al.*, 1997). However, on the eastern side of the volcano, from the 15°E meridian, the stress field is more complicated and no unique tectonic setting is observed (Cocina *et al.*, 1997). In fact, on the eastern side of Mt Etna and eastern Sicily, extensional tectonics are documented (Azzaro *et al.* 2000). Monaco *et al.* (1997) proposed a dilatation strain on the footwall of an E-facing normal fault in the 'Siculo-Calabrian rift zone' where WNW–ESE-directed regional extension takes place. Active tectonics with a normal component to the south-east of Mt Etna have been described by Torelli *et al.* (1998). Moreover, a right-lateral component of movement has been described along the NNW-trending normal faults (Azzaro, 1999). Other deformations and seismicity are associated with uprising magma (Cocina *et al.*, 1998) and the gravitational collapse of the volcanic edifice toward the deep Ionian Sea to the east. One example is the E–W-trending Pernicana fault (Azzaro *et al.*, 1998), which operates as a left-lateral transfer to the volcanic collapse. In summary, apart from these last features associated with the evolution of the volcano, structural and seismic data indicate that the regional deformation in the Etnean area is generally dominated by N–S compression; however, this coexists on the eastern side with a roughly E–W extension or right-lateral transtension concentrated along the Malta fault system, both offshore and onshore (Timpe fault).

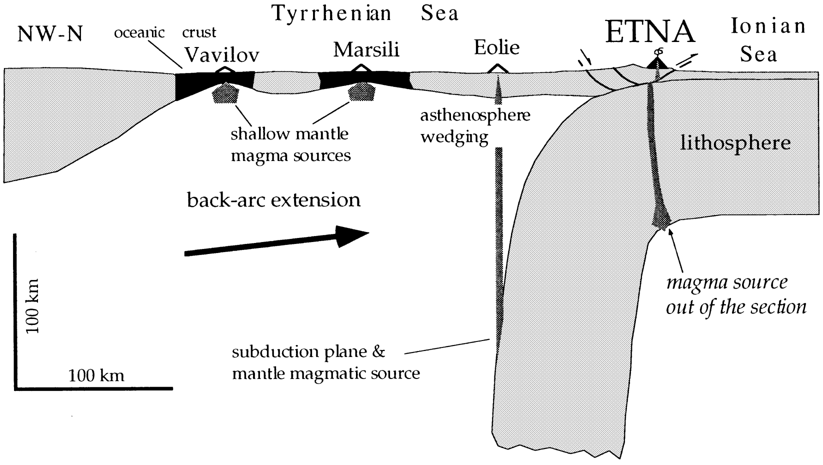

Fig. 2 The Etna volcano is located anomalously close to the hinge zone of the Apennines subduction, in the hanging wall of the accretionary wedge. It is not classically sourced by the slab, as are the Aeolian calkalcaline volcanoes, or by the shallow backarc asthenosphere of the alkaline-tholeiitic Marsili and Vavilov volcanic seamounts. Thick arrows indicate inferred mantle flow.

The subduction zone underneath the Apennines has been imaged by earthquakes, tomographic studies, gravity, magmatism and structural geology (Cristofolini *et al.*, 1985; Serri *et al.*, 1993; Scarascia *et al.*, 1994; Selvaggi and Chiarabba, 1995; Piromallo and Morelli, 1997). The 'eastward' retreat of the Apennines slab kinematically implies asthenospheric replacement (Fig. 2) beneath the belt (Doglioni, 1991), which is supported by seismological studies (Calcagnile and Panza, 1981; Mele *et al.*, 1997). Moreover, the lengthening of the Apennines arc includes extension parallel to the subduction arc (Doglioni, 1991). Doglioni *et al.* (1998) proposed that the Etna volcano is sourced by a 'window' associated with the differential rollback of the Apennine subduction zone between Sicily and the Ionian Sea. Recently, Gvirtzman and Nur (1999) similarly proposed that the asthenospheric wedge beneath the Calabrian arc is responsible for decompression and melting of the mantle sourcing the

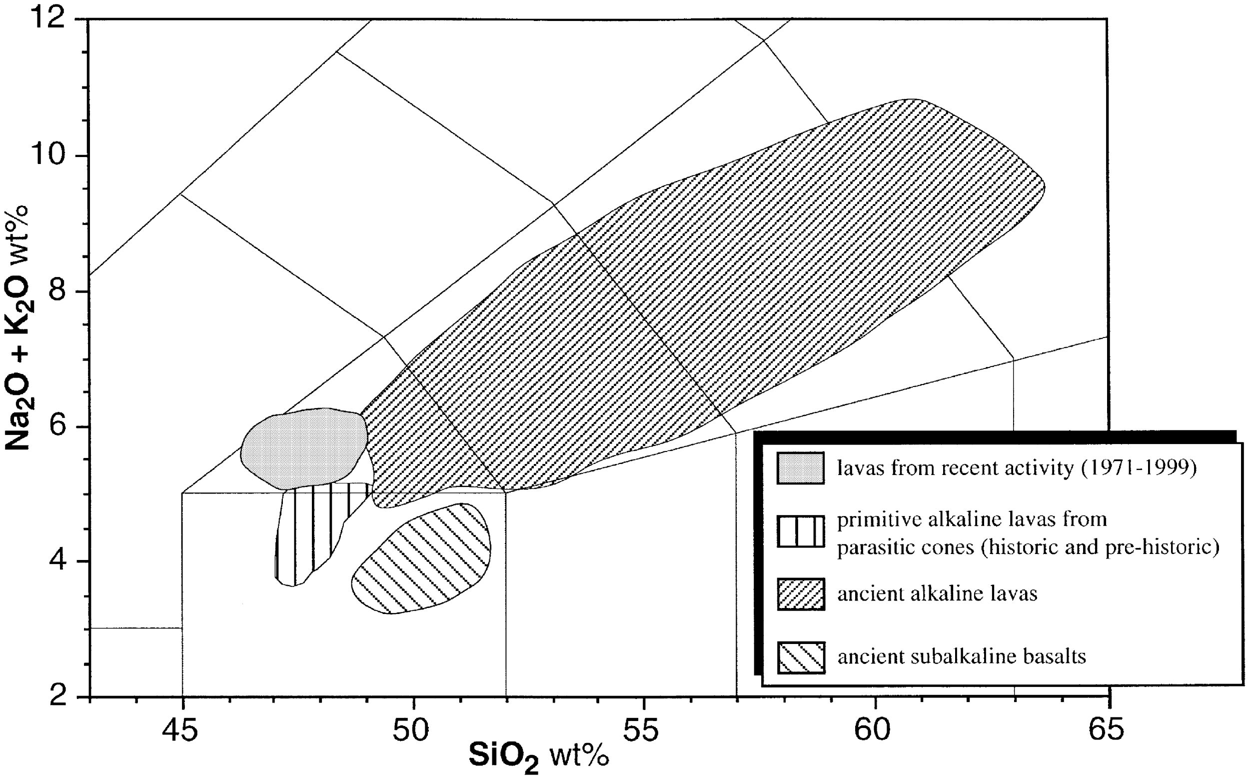

Fig. 3 Total alkali vs. silica diagram for the volcanic rocks of Mt Etna (data from D'Orazio, 1994; authors' database).

volcano. In their model, there is no subduction north of Sicily. In contrast, the present authors recognize that a similar mantle wedge occurs underneath the entire Apennine arc, even beneath northern Sicily, as well as in other areas of the Apennines uplifted even more than Calabria. This appears to be constrained by shortening in the Sicilian accretionary wedge and by mantle tomography results (Piromallo and Morelli, 1997). The paucity of slab seismicity below northern Sicily and its northern Tyrrhenian offshore can be ascribed to the continental nature of the slab, which behaves plastically at temperatures of 300–350 °C, unlike the Ionian oceanic lithosphere, which is brittle up to about 600 °C.

Dip of the regional foreland monocline

The foreland regional monocline is a structure typical of any thrust belt or accretionary wedge (e.g. Bally, 1983). The dip of the monocline records the subsidence rates associated with the flexure of the foreland and formation of the related foredeep. These dips were measured on seismic reflection profiles at the front of the Apennines in eastern Sicily (Bello *et al.*, 1998) and in the Ionian Sea (Cernobori *et al.*, 1996). The dip at the Apennines front (Mariotti and Doglioni, 2000) in eastern Sicily is on the order of about 1–2° in the Hyblean plateau, and increases to about 4–6° below the thrust sheets of NE Sicily (Fig. 4). The front of the Apennines is normalized to the Apennines watershed in Fig. 4 to highlight how it is more advanced in the Ionian Sea than on the Hyblean plateau. Moving eastward into the Ionian Sea, offshore southern Calabria, the monocline becomes rapidly steeper, with an inclination of more than 20° (Fig. 5). The separation between the two different angles of foreland flexure occurs along the inherited Mesozoic passive continental margin of the Malta escarpment (Fig. 6). Stratigraphic and structural data suggest that this Mesozoic alignment was reactivated during the late Tertiary and Quaternary. The foreland monocline is the uppermost expression of the subduction and its activity is indicated by the dip.

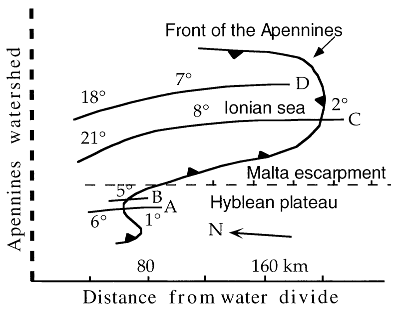

Fig. 4 Profiles of the top of the foreland monocline dip, two in the Hyblean plateau (A,B), and two in the Ionian Sea (C,D). Note the larger dips in the Ionian area moving along strike with respect to the Hyblean–Sicilian area. Location of the sections in Fig. 1.

Therefore, the present subsidence in the foredeep provides indirect evidence that subduction is active below both northern Sicily and Calabria, albeit at different rates.

Dip variations vs. seismicity

A relevant seismicity is found in the foreland of the Apennines belt

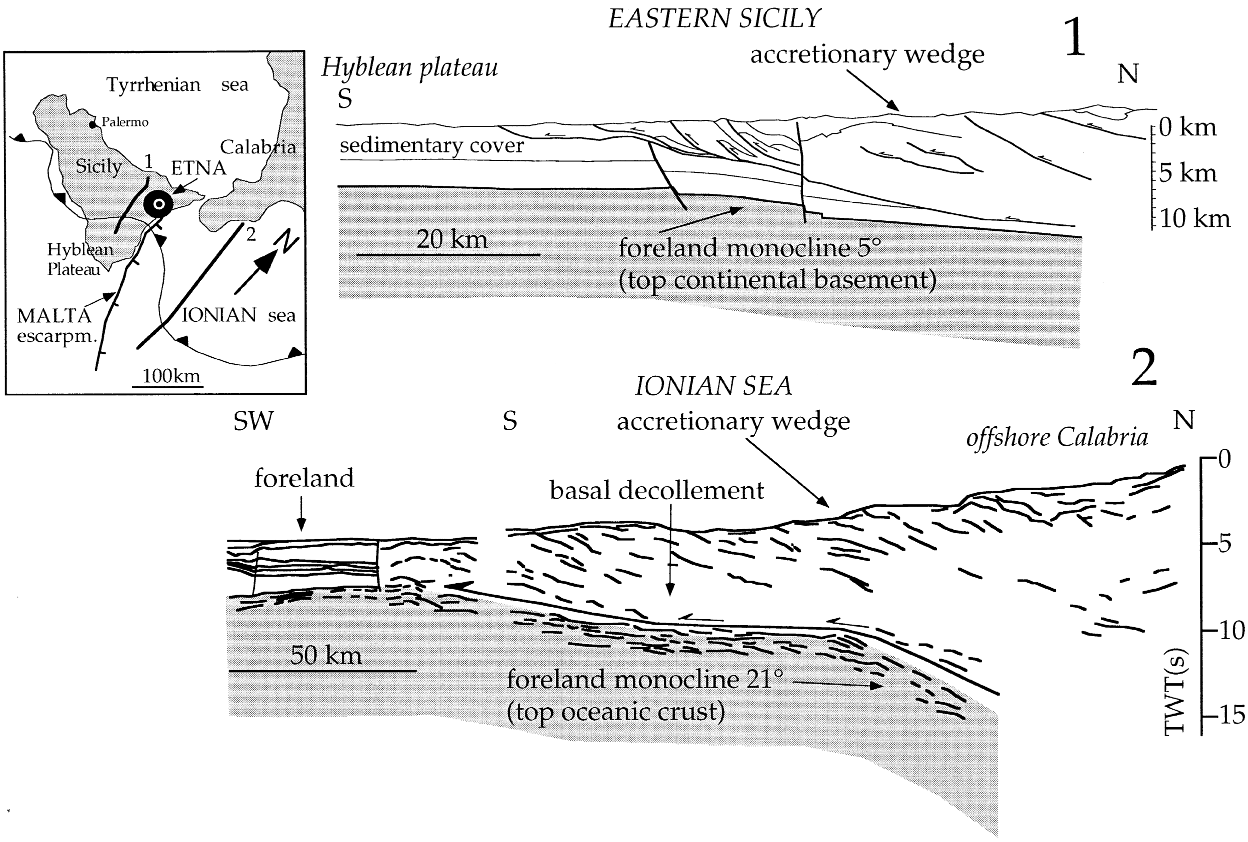

Fig. 5 Cross-sections of (1) eastern Sicily and (2) Ionian sea, redrawn and slightly modified after (1) Bianchi *et al.* (1987) and (2) Cernobori *et al.* (1996) with permission from Elsevier Science. Note the steeper dip of the foreland monocline in the Ionian section (2), even if the vertical scale is in time.

(Amato *et al.*, 1993). The most seismic zones are (i) north of Puglia (Tremiti alignment), (ii) eastern Sicily or western Ionian, and possibly (iii) other limited areas of the Po basin, not subject of this study. The north Puglia seismicity is thought to result from movement within a right-lateral transfer zone separating the more rapidly retreating central–northern Adriatic lithosphere from the lithosphere to the south in the Puglia area (Doglioni *et al.*, 1994). This differential retreat was likely generated during the Pleistocene as the subduction rate of the thicker, lighter and more buoyant Puglia lithosphere was slowed, while the northern Adriatic counterpart maintained its subduction rate. These different rates of retreat produced differences in the dip of the foreland monocline, which is steeper and located further eastward north of the transfer zone, where the Adriatic lithosphere was more subductable. A similar scenario is suggested in the Malta escarpment: the inherited Mesozoic margin between the continental crust in eastern Sicily (west) and the oceanic Ionian basin (east) shows different rates of rollback due to the higher density of the oceanic Ionian basin. The larger retreat of the subduction hinge in the Ionian Sea implies that the Mesozoic Malta escarpment was reactivated as a right-lateral transfer zone, thus accommodating the differential flexure of the foreland. This could explain kinematically the eastern Sicily seismicity, which is characterized by right-lateral strike-slip and tensional focal mechanisms and by the surface expression of these kinematics (Azzaro and Barbano, 1996; Torelli *et al.*, 1998; Azzaro, 1999). Moreover, the seismicity is an indication that differential rollback and subduction are both still active. Clear evidence of neotectonic seismogenetic faults occurs in the Messina Strait (Ghisetti, 1992). The Timpe fault system on the eastern flank of Mt Etna is the NNW inland prolongation of the Malta escarpment, which shows surficial evidence of activity where the normal component slip rate has been greater than 2.0 mm yr^{-1} during the last 80 kyr (Azzaro *et al.*, 2000).

The differential rollback should die out toward the foreland where the tip line of the rupture propagated (Fig. 7). This is consistent with seismicity that decreases moving southward into the lower Ionian sea, north of Libya. It is expected that the tip line of the differential rollback will continue to migrate southward with accompanying seismicity and magmatism.

Conclusions

The Malta escarpment was the Mesozoic boundary between the relict Mesozoic Ionian ocean to the east and continental Sicily to the west. During the Quaternary, this alignment was used for differential rollback of the Apennines subduction: the larger retreat of the Ionian lithosphere, suggested by the larger dip of the

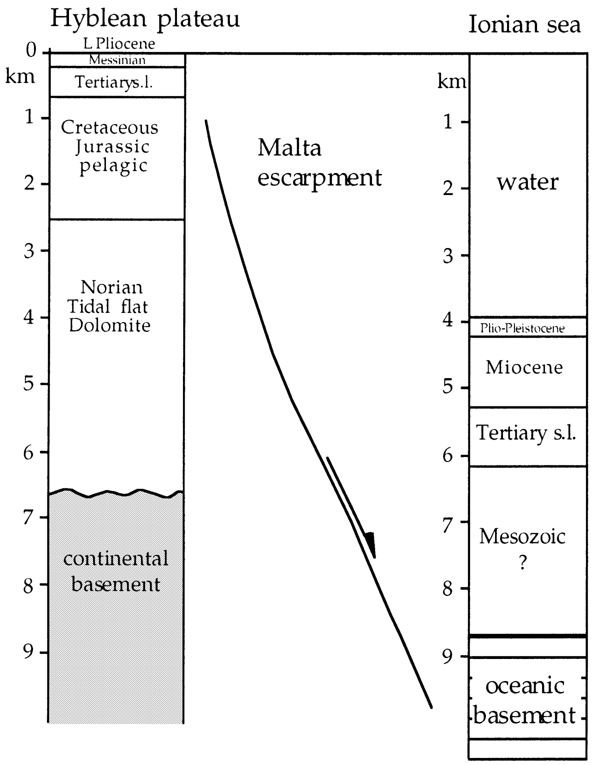

Fig. 6 Representative stratigraphic columns of the Hyblean plateau and the Ionian sea (after Catalano *et al.*, 2001).

foreland monocline at the front of the accretionary wedge in the Ionian Sea, would account for the right-lateral transfer zone along the Malta escarpment, which is seismically active. The lengthening of the Apennines arc is responsible for extension parallel to the arc itself. Therefore, the right lateral transfer along the Malta escarpment is a transtensional 'window' between the Sicilian and Ionian segments of the Apennines slab. This is a possible mechanism for mantle decompression and melting that allowed the ascent of the Etna magmas from the lower lithosphere or upper asthenosphere along a vertical 'window' in the slab. These kinematics could explain the anomalous external position and the Na-alkaline geochemistry of the volcano, which is not sourced by the slab but is in some way related to it. Similar ruptures resulting from differential rollback of the subduction hinge of other orogens could explain intraplate 'anorogenic' magmatism, deformation and seismicity in foreland environment.

The model used herein, although developed using a different dataset, is 'similar' to that of Gvirtzman and Nur (1999). However, the present model differs from Gvirtzman and Nur's in the sense that the mantle source for the Etna magmas is interpreted herein as a 'window' along a more continuous slab around the entire Apennines arc, and subduction underneath northern Sicily is not disregarded. Mantle wedging occurs all along the hinge zone of the Apennines subduction (Doglioni, 1991). The mantle tomography (Piromallo and Morelli, 1997), the Neogene and Pleistocene shorten-

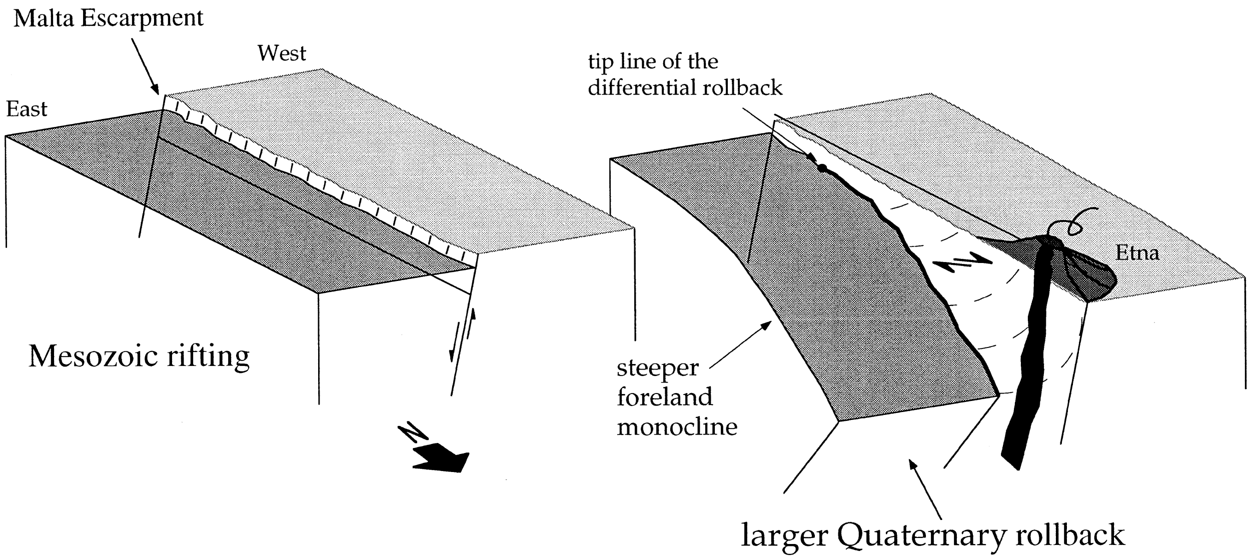

Fig. 7 Cartoon of the tectonic evolution of the eastern Sicily–Ionian Sea transition, and related emplacement of the Etna volcano along the active right-lateral transtensional fault, resulting from the differential rollback in the footwall of the accretionary wedge (omitted for simplicity).

ing in the Sicilian belt, and the Pleistocene dip of its foreland monocline all indicate a subduction process below northern Sicily as well as below Calabria.

The Etna volcano must also be progressively detached from its mantle source because it is located on the hanging wall of an active S-verging thrust sheet of the Apennines accretionary wedge.

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