The Southern Tyrrhenian subduction system: recent evolution and neotectonic implications

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Abstract
Geological and geophysical data have been integrated with the aim of presenting a new evolutionary model for the Southern Tyrrhenian and adjacent regions. The Southern Tyrrhenian backarc basin opened within a plate convergence regime because of sinking and rollback of the oceanic Ionian lithosphere. On the basis of seismological observations, I infer that the sinking slab was torn apart on either side in the last 2 Ma and this process controlled the neotectonics of the Southern Apennines - Tyrrhenian region. On the north-eastern side the slab broke off from NW to SE and this process triggered volcanism and NW-SE extension along the Eastern Tyrrhenian margin, and strike-slip tectonics along NW-SE trending faults in Northern Calabria. On the south-western side the slab broke off from W to E along the Aeolian Island alignment, although the tear has currently been reoriented along the NNW-SSE Malta escarpment. During its sinking the subducted slab also detached from the overriding plate, favouring the wedging of the asthenosphere between the two plates and the regional uplift of the Calabrian arc and surroundings. This regional uplift promoted gravitational instability within the orogenic wedge, particularly towards low topography areas; the large-scale sliding of the Calabrian arc towards the Ionian basin can be the cause of CW rotation and graben formation in Calabria. Also the E-dipping extensional faults of the Southern Apennines can be related to accommodation of vertical motions within the fold-and-thrust belt. The pattern of recent seismicity reflects this neotectonics where crustal-scale gravity deformation within the orogenic wedge is responsible for extensional earthquakes in Calabria and the Southern Apennines, whereas Africa plate convergence can account for compressional earthquakes in Sicily.

Key words *subducted slab – lithospheric tears – neotectonics – vertical motions – seismicity*

1. Introduction

The Central Mediterranean was shaped during the convergence between Africa and Europe that has been going on since the late Cretaceous (*e.g.*, Dewey *et al.*, 1973, 1989). Arcuate mountain belts and deep basins originated within this convergence setting and the intense neotectonics of this region is indicated by the great deal of seismic and volcanic activity (McKenzie, 1972).

The Tyrrhenian basin and the adjacent regions (fig. 1) originated mainly during the last 10-20 Ma and several papers have described the evolution of this region or parts of it, often with different approaches and assumptions (*e.g.*, Doglioni, 1991; Patacca *et al.*, 1992; Mantovani *et al.*, 1997). To what extent the presently observed tectonic regime is representative of the longer-term evolution of this region is, however, an open question. A review of the geological events that affected the SouthernTyrrhenian

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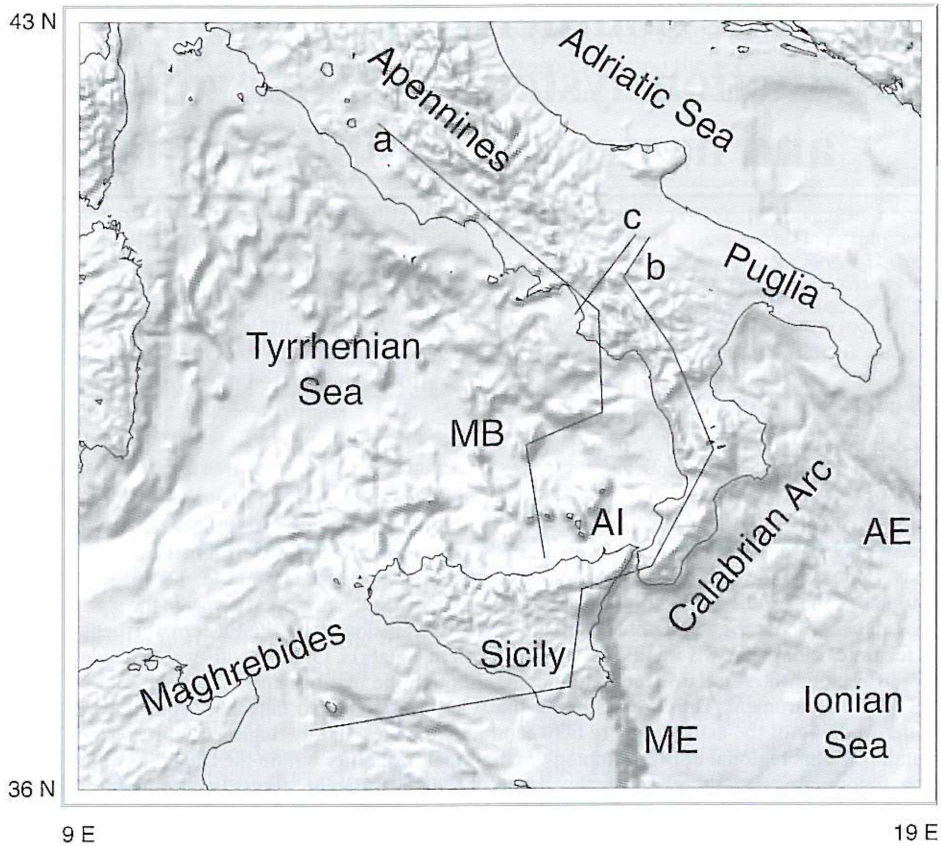


Fig. 1. Topographic map of the Central Mediterranean with the main geographic features of the study area. AI indicates the Aeolian Islands and MB the Marsili Basin. Note the steep Malta (ME) and Apulia (AE) escarpments on the western and north-eastern side of the Ionian Sea, respectively. The indicative trace of the schematic profiles of fig. 2 (a, b) and of the cross section of fig. 7 (c) are also indicated.

and adjacent regions suggests that major changes in the volcano-tectonic regime took place in the last 2 Ma (fig. 2). It seems that during this time interval vertical motions, both uplift and subsidence, overtook the previously dominant horizontal motions, and volcanic activity also became particularly intense. For instance, volcanic activity has extensively affected Central and Southern Italy, with products covering a wide range of magma types (Serri, 1990; Peccerillo, 1999), and recent K-Ar datings strongly suggest that the main eruptive centres of Italy, from Southern Tuscany to Sicily and its offshore, developed in the last 0.7 Ma (Gillot, 2000).

This paper aims to summarize the principal geological events that affected the SouthernTyrrhenian and adjacent regions in the last 2 Ma, and offer a tentative interpretation of the tectonic evolution and of the inferred geodynamic regime.

2. Geological setting

Given the great geological complexity of this region, reflected in a huge amount of literature, only the relevant pieces of evidence are reviewed in the following (fig. 2).

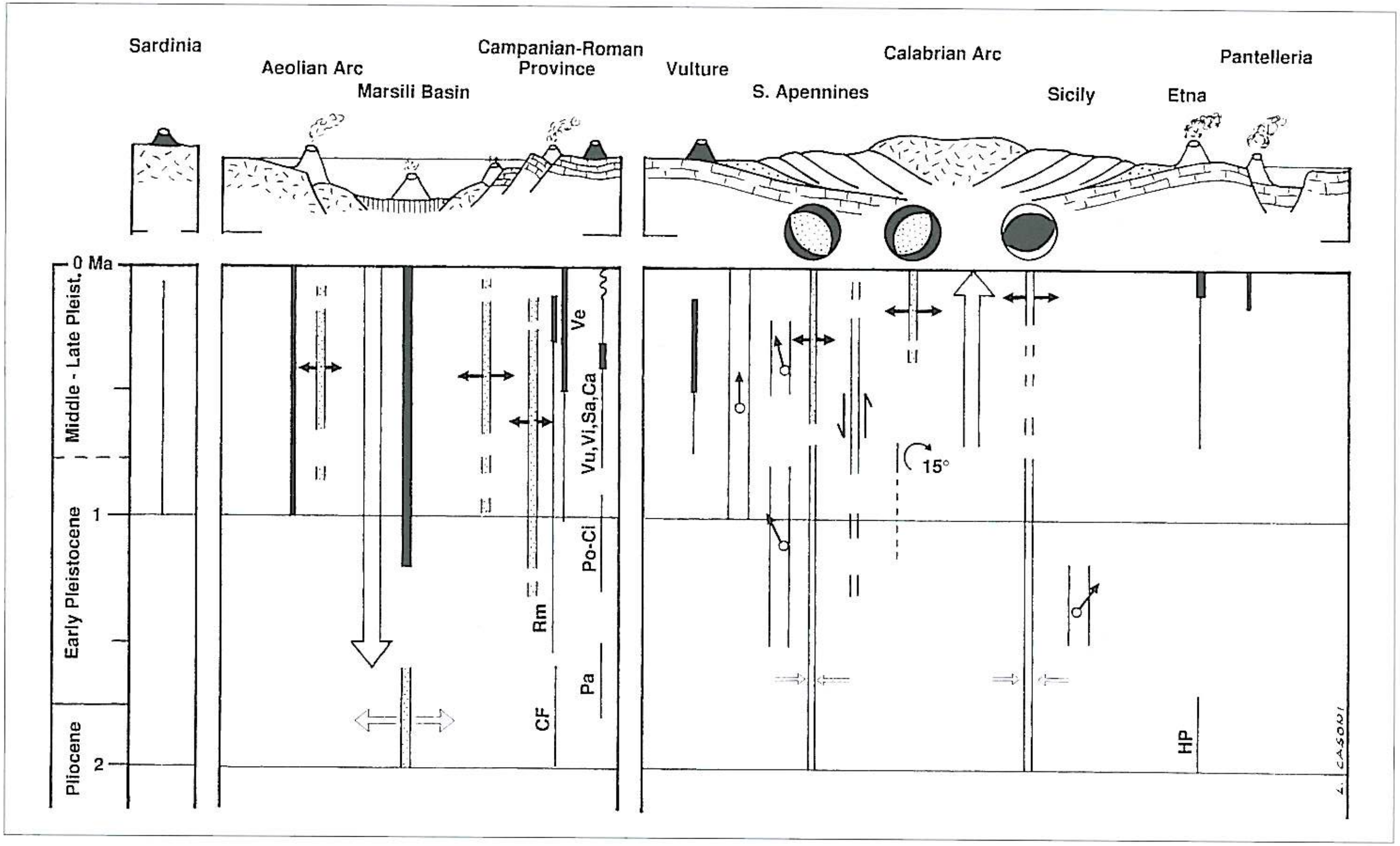


Fig. 2. Time frame of major geological events in the Southern Apennines and Tyrrhenian region. The upper panels represent Sardinia and two profiles, one indicative of the Marsili basin and its margins and one crossing the fold-and-thrust belt and the foreland (see fig. 1). Average focal mechanisms for the Southern Apennines, Calabria and Sicily are also shown (Pondrelli *et al.*, 1995). In the lower panels the timing of volcanic and tectonic events and paleomagnetic rotations are indicated with vertical bars. Horizontal arrows represent extension and shortening, whereas vertical arrows represent uplift and subsidence. Small arrows with open dot at one end represent sediments subsequently undergoing paleomagnetic rotations; whereas the circular arrow under Calabria indicates calculated timing and amount of rotation. The events represented are discussed at more length in the text. Volcanics of the Roman and Campania Provinces: CF = Campi Flegrei; Rm = Roccamonfina; Ve = Vesuvio; Pa = Palmarola; Po-Ci = Ponza and Cimini; Vu = vulsini; Vi = Vico; Sa = Sabatini; Ca = Colli Albani. HP = Hyblean Plateau.

2.1. *Subducted slab*

A seismic slab is present under the Marsili basin (Anderson and Jackson, 1987a; Giardini and Velonà, 1991; Selvaggi and Chiarabba, 1995) and the hypocentral distribution of the most accurately located events depicts a continuous slab dipping *ca.* 70 degrees to the NW down to a depth of *ca.* 500 km (Selvaggi and Chiarabba, 1995; fig. 3). This slab is also very narrow, having a width of *ca.* 200 km. Inspection of profiles from subducted slab world wide strongly suggests that only the oceanic lithosphere can be subducted to 500 km depth and with such a steep angle (Isacks and Barazangi, 1977; Stein and Stein, 1996). Both seismological (Selvaggi and Chiarabba, 1995; Frepoli *et al.*, 1996) and tomographic (Piromallo and Morelli, 1997; Cimini, 1999) data suggest a connection between the subducted slab and the Ionian lithosphere, which has been proven to be oceanic (de Voogd *et al.*, 1992), further supporting the inference that the Tyrrhenian slab is of oceanic nature. A study of *S*-wave propagation from intermediate to deep earthquakes (Mele, 1998) indicates that the slab is also physically attached to the African plate, as *S*-waves have not been attenuated when travelling along the Tyrrhenian slab, that acts as a wave guide, towards the Apulian and Hyblean foreland (fig. 4; Mele, 1998). Recent work on *S*-wave propagation across the Eastern Mediterranean confirms this interpretation (Mele, 2000, personal communication). An additional result obtained studying *S*-wave amplitudes concerns the suggestion of lateral tears on either side of the subducted slab. In fact, *S*-waves could not efficiently reach many stations located in the Southern Apennines and Western Sicily because they were attenuated when travelling through the asthenosphere (fig. 4; Mele, 1998). Another indication of the presence of lateral discontinuities in the subducted slab comes from seismic tomography that shows the absence of cold lithosphere underneath the Southern Apennnines and most of Sicily in the first 100-200 km depth (Amato *et al.*, 1993a,b; Spakman *et al.*, 1993; Piromallo and Morelli, 1997; Mele *et al.*, 1998; Lucente *et al.*, 1999; Hearn, 1999; Piromallo *et al.*, 2000). In addition, teleseismic traveltime tomography (Cimini, 1999) shows that the lateral extent of the high velocity slab increases with depth, indicating that the oceanic lithosphere, and therefore the subductive margin, was previously more extended than the narrow corridor actually present underneath Calabria.

Island arc magmatism in the Aeolian arc is younger than 1.2 Ma (fig. 2) and mainly calcalkaline (Barberi *et al.*, 1974), although Na-Alkaline products of within-plate affinity have been found at Ustica. Geochemical data suggest that this magmatism is compatible with a mantle wedge of transitional MORB/OIB type enriched by fluids, and in some cases also sediments, derived from a subducted oceanic crust (Serri, 1990). Also the magmatic rocks of the Central Campania province (fig. 2), that includes the Campi Flegrei high potassium calcalkaline (2.0-1.6 Ma), the Campi Flegrei, Ischia and Procida shoshonites (100 ka - Present), and the Vesuvius leucitite and leucitite basanite (1 Ma - Present), show elemental ratios (Ba/La, Nb/Y and Nb/Zr) suggestive of affinity with island arc magmatism (Peccerillo, 1999). On the other hand, lower Sr (87/86) isotope ratios and higher Nd (143/144) and Pd (206/204) isotope ratios indicate a minor involvement of continental crustal rocks with respect to the Roman province, located to the north of the Central Campanian province.

Magmatic rocks from Central Campania and the Aeolian volcanic arc have comparable geochemical features suggesting a similar OIB mantle source enriched by components derived from subducted oceanic lithosphere (Serri, 1990), as opposed to the magmatism of the Roman province that reflects a mantle source metasomatised by upper crustal material, likely subducted (Serri, 1990; Peccirillo, 1999). Therefore, the distribution of magmatic products offers further evidence that the Southern Tyrrhenian and the adjacent regions were under the influence of oceanic subduction (Serri, 1990, 1997).

2.2. *Extension and compression*

Geological and geophysical data suggest that in the Southern Apennines the main horizontal motion ended or faded out in the last 1 Ma, giving way to dominantly vertical motions (West-

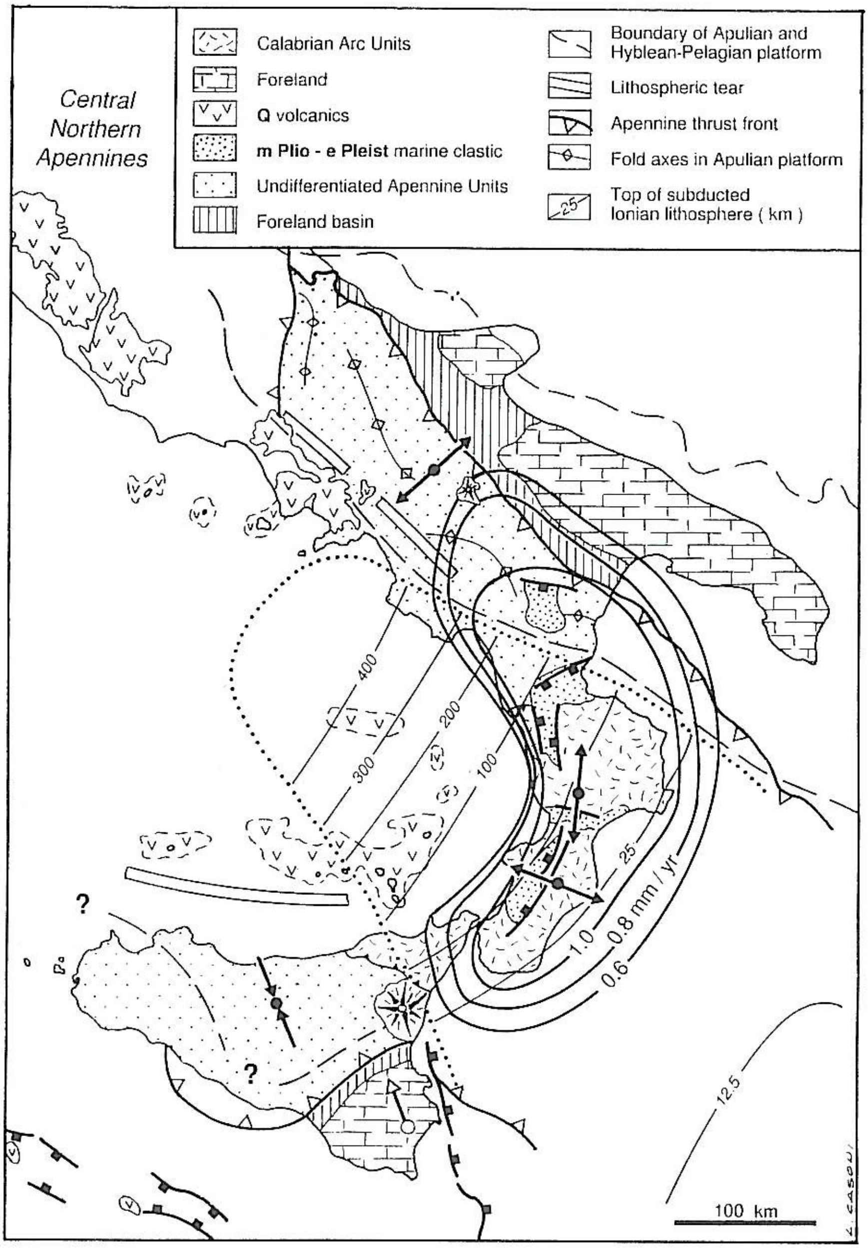


Fig. 3. Simplified geological map of the Southern Tyrrhenian region and adjacent fold-and-thrust belts with the isobaths in kilometers of the top of subducted slab (after Selvaggi and Chiarabba, 1995) and the position of the inferred lithospheric tears on either side of the slab. Contours of the rate of uplift (in mm/yr) in the Calabrian arc for the last 0.7 Myr (Westaway, 1993a) are superposed, together with directions of strain derived from seismic moment tensor summation (black double arrow with black dot; Selvaggi, 1998). The Nouvel-1 plate motion of Africa is also added in the Hyblean foreland of Sicily (arrow with open dot at an end; De Mets *et al.*, 1990).

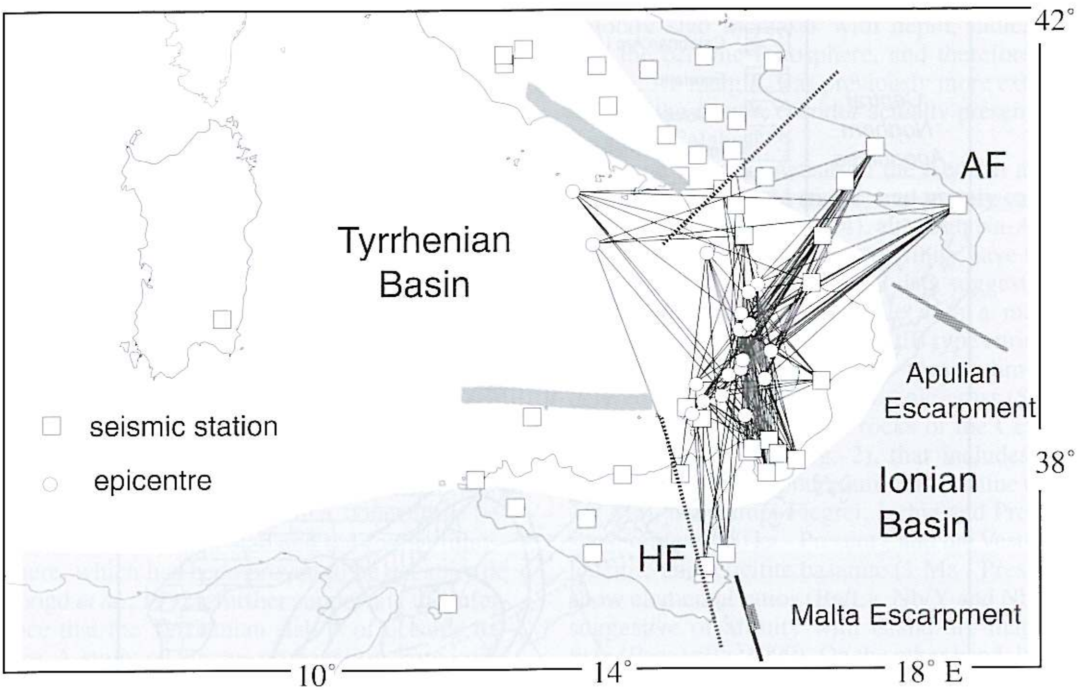


Fig. 4. Pattern of efficient *S*-wave propagation from intermediate to deep earthquakes in the Southern Tyrrhenian domain. It indicates the presence of lithospheric discontinuities on either side of the Tyrrhenian slab. Dashed lines indicate the original author's interpretation (Mele, 1998) of these discontinuities, whereas the interpretation here preferred for the position of lithospheric tears is shown with thick grey bands. The Apulian and Hyblean foreland regions, AF and HF respectively, are also indicated, and the African plate domain is shaded. Modified after Mele (1998). See text for discussion.

away, 1993a; Bordoni and Valensise, 1998). The present extensional tectonic regime is indicated by the focal mechanisms of recent earthquakes (Pondrelli *et al.*, 1995; Selvaggi, 1998; Frepoli and Amato, 2000) and supported by studies of well breakouts (Amato and Montone, 1997; Montone, 1997; Montone *et al.*, 1997, 1999). An extensional rate of 1.6 mm/yr with NE-SW direction has been estimated on the basis of moment tensor summation (Selvaggi, 1998; fig. 3). Furthermore, geological evidence constrains the end of compression in the Southern Apennines at about 0.8 Ma (Scandone *et al.*, 1990), whereas microtectonic studies (Hippolyte *et al.*, 1994) suggest that the tectonic regime switched from compressional to extensional about 0.8 Myr ago. Seismically active faults trend NW-SE along the Apennines, and so does the belt of crustal seismicity. However, close to the Tyrrhenian coast a system of NE-SW-trending extensional faults with associated Pleistocene grabens is present from the river Volturno to Salerno (fig. 5; Finetti and Morelli, 1974; Mariani and Prato, 1988; Hippolyte *et al.*, 1995; Bruno *et al.*, 1998). This fault system accommodated a NW-SE extension.

In the Calabrian arc focal mechanisms give extension both parallel and perpendicular to the arc (Selvaggi, 1998; Frepoli and Amato, 2000) and geological data (Tortorici *et al.*, 1995) indicate that extension along NE-SW and NW-SE faults has been going on since the middle Pleistocene. As a result, grabens trending both NE-SW and NW-SE have been originated. Studies on fault scarps indicate slip rates of 0.6-1.1 mm/yr for the last 0.7 Myr. Seismic moment tensor

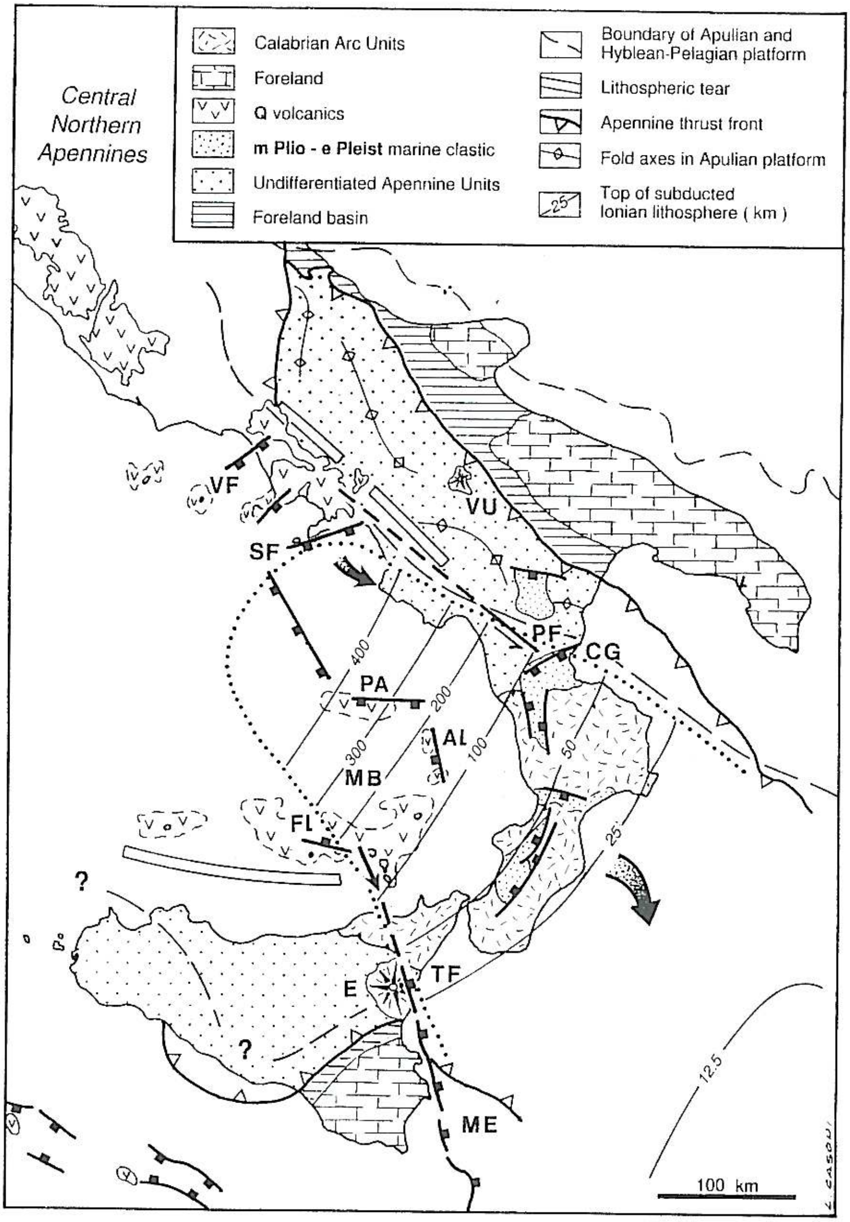


Fig. 5. Tentative neotectonic sketch for the Southern Apennines - Southern Tyrrhenian region. The arrow in the Aeolian Islands indicates the direction of drop in age of the volcanic edifices (Mazzuoli *et al.*, 1995). Note the change in direction from the *ca.* E-W Aeolian trend to the NNW-SSE Malta escarpment which is considered the most recent segment of the lithospheric tear. VF = Volturno Fault; SF = Salerno Fault; PF = Pollino Fault; TF = Timpe Fault; E = Etna volcano; VU = Vulture volcano; ME = Malta Escarpment; CG = Crati Graben; PA = Palinuro volcanic system; Al = Alcione volcano and fault; Fl = Filicudi fault; MB = Marsili Basin. The Sant'Arcangelo basin is the large basin located just north of the Crati graben.

summation indicates a slightly higher extensional rate of 1.7 mm/yr with direction of WNW-ESE, although a minor longitudinal extension is also present (Selvaggi, 1998).

The Crati graben is located at the boundary between the Southern Apennines and the Calabrian arc (fig. 5). This graben has an upside down *L* shape, trending *ca.* N-S in the southern part and NE-SW in its northern portion, and detailed microtectonic analyses show that this basin is dominated by E-W to WNW-ESE extension (Lanzafame and Tortorici, 1981). The northern part of the Crati graben is in close connection with the NW-SE-trending Pollino fault zone (fig. 5), which displays sinistral strike slip (Catalano *et al.*, 1993; Schiattarella, 1996). Typically, the Pleistocene basins of the Southern Apennines and Calabria do not show any significant Bouguer gravity anomaly, indicating a limited sedimentary thickness; only the Sant'Arcangelo basin and the offshore extension of the Crati graben present a Bouguer anomaly of –60 mgal (Bigi *et al.*, 1990). Whereas the Crati graben is an extensional basin, the origin of the Sant'Arcangelo basin, filled with *ca.* 4 km of Pleistocene sediments, is not fully understood; proposed structural settings range from transtensional (Turco *et al.*, 1990; Merlini and Cippitelli, 2000) to piggyback (Hippolyte *et al.*, 1991, 1994; Pieri *et al.*, 1994).

Farther to the south along the mountain belt, the front of the Sicilian Maghrebides has been inactive since the early Pleistocene (Argnani, 1987; Likorish *et al.*, 1999) but thrusting apparently moved in the inner part of the belt (Likorish *et al.*, 1999) where earthquake focal mechanisms also indicate compression with the direction of the *P* axis that approximates the vector of Africa-Europe convergence (Anderson and Jackson, 1987b; Pondrelli *et al.*, 1995; Kiratzi and Papazachos, 1995).

The Strait of Sicily has been the site of extensional tectonics, mainly during the Pliocene (Argnani, 1990). Volcanism occurred in relation to rifting in the Strait of Sicily, with both submarine and subaerial activity (fig. 2). The large volcanic islands of Pantelleria and Linosa have an age of 300-150 ka to the Present. However, previous submarine volcanic activity with the same within-plate geochemical characters has affected the area since Tortonian (Calanchi *et al.*, 1989). The limited amount of volcanic products (less than a few cubic kilometers) characterises the Strait of Sicily as a low-volcanicity rift (Calanchi *et al.*, 1989). Magmatic activity with similar geochemical features occurred in the Hyblean plateau (fig. 2) where volcanism is characterised by products of within-plate affinity erupted mainly from small submarine centres (Schminke *et al.*, 1997). The age of volcanics ranges from 2 to 1.7 Ma.

2.3. *Rotations about vertical axes*

Paleomagnetic studies have greatly contributed to the understanding of the tectonics of the Southern Apennines and the Maghrebian belt of Sicily (*e.g.*, Meloni *et al.*, 1997; Channell *et al.*, 1990; figs. 2 and 6). In the Southern Apennines fold-and-thrust belt lower Pleistocene sediments show a rotation of *ca.* 20 degrees CCW in several localities (Sagnotti, 1992; Scheepers *et al.*, 1993) and in some cases, as in the Mercure basin, even middle Pleistocene sediments are rotated *ca.* 12 degrees CCW (Scheepers and Langereis, 1994; Meloni *et al.*, 1997). The sediments of the Bradanic foredeep, instead, do not show any rotation (Scheepers, 1992). It is noteworthy, as an eception to the general picture, that lower Pleistocene sediments near Salerno (locality Eboli), that is in the internal part of the Southern Apennines, do not show rotation.

Significant rotations have also been recorded in the Calabrian arc. A 15 degree CW rotation during the Pleistocene has been recognised by several authors all along the arc (Scheepers *et al.*, 1994; Speranza *et al.*, 2000), and recent studies claim that this rotation occurred in a very short time interval, from 0.7-0.8 Ma (Duermeijer, 1999). This last interpretation implies very fast horizontal motion and poses some questions concerning the geological reliability of such high rates of motion.

In Sicily a CW rotation of about 30 degrees affected the lower Pleistocene sediments in the Southwestern Gela Nappe basin (Speranza *et al.*, 1998, 1999).

In detail palemagnetic rotations in Sicily and Calabria display some more complexities that,

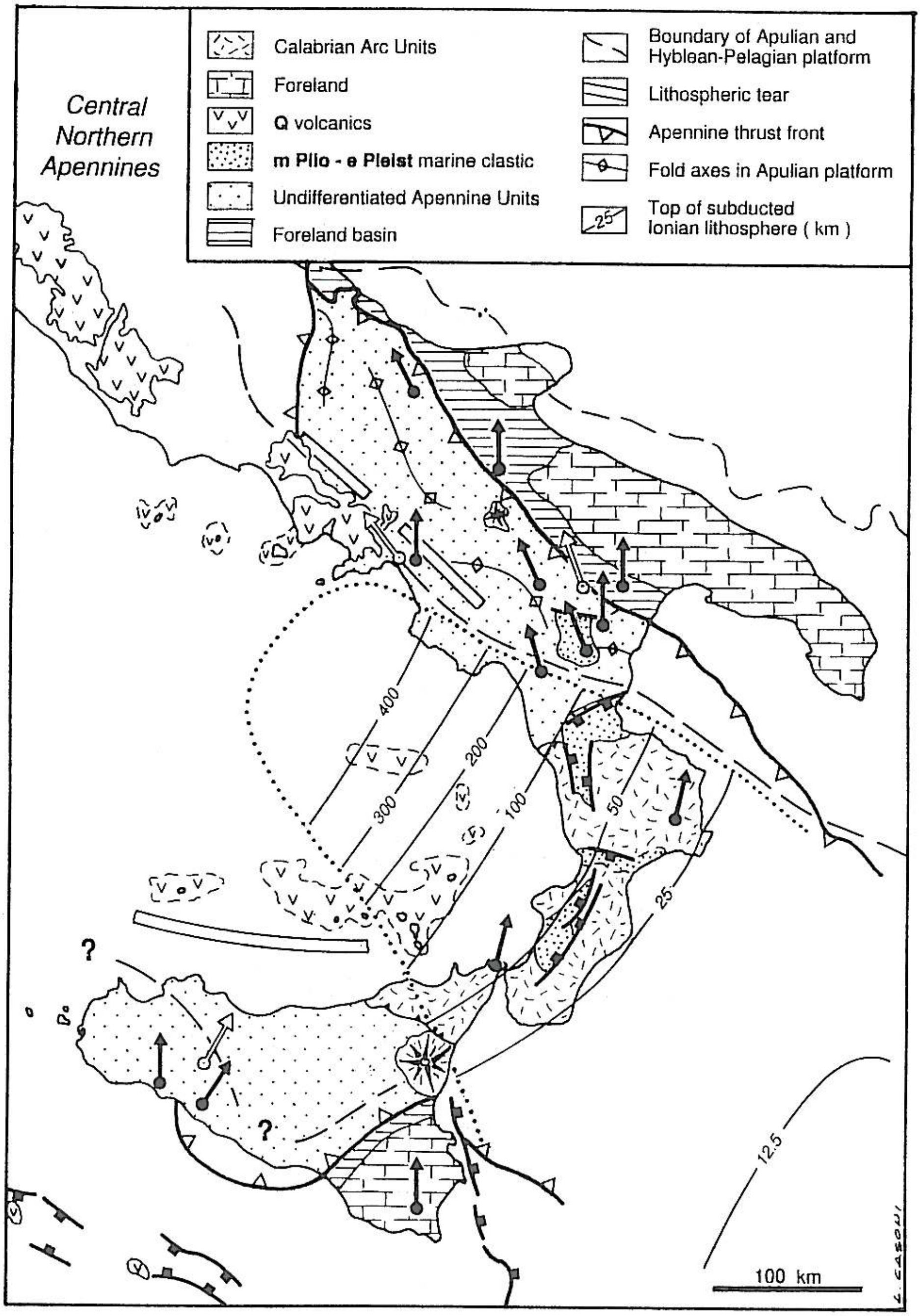


Fig. 6. Simplified geological map with shape of the subducted slab. Arrows with dots at one end indicate paleomagnetic rotations of Pliocene (open dots) and Pleistocene (filled dots) sediments.

nevertheless, represent just variations of the regional pattern described above. The scope of this paper can be fulfilled by the simplified picture here presented; details of paleomagnetic rotations in Sicily and Calabria are found elsewhere (Duermeijer, 1999; Speranza *et al.*, 1999, 2000).

2.4. *Vertical motions*

Recent uplift characterises the Calabrian arc and the adjacent Southern Apennines and Sicily (fig. 3). A critical review of data on marine terraces of Tyrrhenian age shows that the maximum uplift for the past 125 ka has been recorded in Calabria with rates up to 1.2 mm/yr that decrease on either side of the Calabrian arc (Bordoni and Valensise, 1998). Several pieces of data, although less uniform, suggest that the uplift of this region was mainly accomplished in the last 2 Myr with an acceleration in the last 1 Myr (Ghisetti, 1981, Westaway, 1993a).

In the same time interval the Marsili basin was subsident, as indicated by paleo-water depth estimates in the ODP well 650 that give a subsidence rate of *ca.* 1 mm/yr (Kastens *et al.*, 1988; Kastens and Mascle, 1990; Argnani and Savelli, 1999). Steep normal faults with large vertical throws and exposed scarps characterise the margins of the Marsili basin and are often associated with volcanic edifices. The most relevant examples are the E-W Filicudi fault, the NNW-SSE Alcione fault, the WNW-ESE Palinuro fault and the large fault scarp north of the Palinuro fault (fig. 5; Finetti and Del Ben, 1986; Argnani and Trincardi, 1988).

The Marsili basin (fig. 1) is the youngest portion of the Tyrrhenian backarc basin and is characterised by the presence of large volcanic seamounts (Marsili, Palinuro, Alcione and other smaller apparata). These submarine volcanoes are very recent and the Marsili basin itself is 2 Ma old (Savelli, 1988; Kastens *et al.*, 1988; Argnani and Savelli, 1999). Within the evolution of the Tyrrhenian Sea episodes of basin extension alternate with episodes of no extension accompanied by calcalkaline volcanism in the arc (Argnani and Savelli, 1999). The large edifices were built during the non-extensional episodes and are likely due to concentration of magma outpouring along the major magmatic conduits, as opposed to the diffuse intrusion/effusion that characterised the extensional episodes. The fast rate of stretching characterising the Southern Tyrrhenian opening (Patacca *et al.*, 1992) likely promoted the focussing of melting within the basin (Harry and Bowling, 1999). This localisation of melting, in turn, explains the limited magmatism of the Tyrrhenian margin during extension; the volcanic activity surrounding the Tyrrhenian basin is, in fact, essentially younger than the basin formation.

3. Discussion

Geophysical data indicate that Adria has a continental crust (Scarascia *et al.*, 1994), but is connected to Africa by the oceanic Ionian lithosphere (de Voogd *et al.*, 1992). Paleomagnetic data, in fact, indicate that Adria has behaved as a promontory of Africa throughout its motion towards Europe (Channell, 1996). Further support of this interpretation comes from reliable VLBI data, integrated with GPS measurements, indicating that there is no relative motion between the stations of Matera (Apulian foreland of Southern Apennines) and Noto (Hyblean foreland of Sicily) (Devoti *et al.*, 1999).

The Ionian oceanic lithosphere continued NW-ward, in what is at present the subducted Tyrrhenian slab, and it is here proposed that this oceanic portion of the African plate played a major role in the Neogene geodynamic evolution of the Central Mediterranean.

The deep Algero-Provençal and Tyrrhenian backarc basins have opened in the Western Mediterranean since the Oligocene, during plate convergence (Rehault *et al.*, 1984; Faccenna *et al.*, 1997; Gueguen *et al.*, 1998). These basins originated because of sinking and rollback of a dense oceanic lithosphere. A weak coupling is expected in the Tyrrhenian subduction as the convergence rate was low and the subducted lithosphere quite old (Ruff and Kanamori, 1983) and this condition likely promoted the observed fast rollback. The slab actually present underneath the Tyrrhenian basin (Selvaggi and Chiarabba, 1995; Frepoli *et al.*, 1996) represents the final stage of this process. The fact that this slab is physically attached to the Ionian oceanic lithosphere, as previously discussed, gives further support to its oceanic nature. It follows that most of the pre-Pliocene evolution of the Southern Apennines can be fitted within a setting of oceanic subduction (Argnani, 2000) and it is only in post Pliocene times that the Southern Apennine accretionary wedge thrusted on the Apulian platform, which rests on the continental basement (Patacca *et al.*, 1992; Menardi Noguera and Rea, 2000).

The evolution of the Southern Apennines and of the Maghrebides of Sicily records a progressive elimination of the oceanic lithosphere in Messinian-early Pliocene times (Argnani, 2000). In the above mentioned regions the ensuing involvement in the subduction of buoyant continental lithosphere (Cloos, 1993) slowed the process of rollback. The dense oceanic lithosphere of the Ionian basin, however, continued to sink and was torn off the adjacent continental lithosphere. The presence of lateral tears on either side of the subducted Tyrrhenian slab has been suggested by the presence of inefficient *S*-wave propagation from intermediate to deep earthquakes (Mele, 1998). It is here proposed that a lithospheric tear propagated from NW to SE along the Southern Apennines and affected both volcanism and neotectonics. As a result of reduced horizontal motions, vertical isostatic re-equilibrations dominated the regional geodynamics, as reflected in the intense recent uplift that affected a large area surrounding the Calabrian arc (Westaway, 1993a; Bordoni and Valensise, 1998). The relevant aspects for this tentative reconstruction are discussed in the following.

3.1. *Lateral lithospheric tears*

Lithospheric tearing has been inferred to affect the subducted slab. Within such an inference the lithospheric tear would, therefore, be a deep-seated process, and its response at surface is likely diffused over a broad zone. Several lines of geological and geophysical evidence suggest that some regional discontinuities do exist in the Southern Apennines - Tyrrhenian system and that these discontinuities can be related to deep sited tears in the subducted slab. An additonal effect of lateral tearing of the subducted slab is that of favouring the rollback of the slab as sideways asthenospheric flow counteracts the suction produced by corner flow (Nur *et al.*, 1993; Dvorkin *et al.*, 1993). The fast rollback velocity estimated for the Tyrrhenian subduction (Patacca *et al.*, 1992; Faccenna *et al.*, 1997) can be explained by the contribution of lateral tearing.

The Pannonian/Eastern Carpathians system offers an analogue for this process of lithospheric tear. In this region andesitic volcanism migrated about 200 km from NW to SW, in a time interval between 11 and 0.2 Ma, along the inner side of the Carpathian fold-and-thrust belt. This propagation in time has been interpreted as due to the progressive tearing and rolling back of the subducted slab (Linzer, 1996). In fact, the Vrancea slab that is located at the apex of the Carpathian arc is narrow (40 km wide), *ca.* 80 km in length and almost vertical (Fan *et al.*, 1998), very much like the Tyrrhenian slab.

a) *Lateral tear in the Southern Apennines* – The western margin of the Cretaceous Apulian carbonate platform has been reconstructed in the subsurface of the Southern Apennines using exploration data (Mostardini and Merlini, 1986). This platform margin continues southward in the Ionian offshore, on the western side of the Apulian ridge, where it appears as a steep erosional carbonate slope (Biju-Duval *et al.*, 1982) passing in a short distance to the deep Ionian basin. If we assume that a similar situation existed all along the western margin of the Apulian platform, the platform to basin transition becomes a candidate for lithospheric tearing, and this location would be compatible with the pattern of *S*-wave propagation (figs. 4 and 5). Going from NW to SE along this belt which is inferred to be the surface expression of deep lithospheric tearing we find: i) intense volcanic activity with well defined volcanic edifices in the Campania Province; ii) Pleistocene basins on the Tyrrhenian coast showing NW-SE extension (Volturno-Salerno system), and at the southward end, iii) the sinistral strike-slip Pollino fault zone, trending NW-SE (Schiattarella, 1996).

Geological data, therefore, indicate that along this belt some relative SE-ward motion was accomplished with respect to the Southern Apennines. Besides the Pollino sinistral strike-slip fault zone, NW-SE-trending sinistral strike-slip faults have been reported to bound the northern part of the Sant'Arcangelo basin (Hippolyte *et al.*, 1995); these faults might also be connected with the Salerno graben as part of a complex sinistral shear zone. The lack of a well defined strike-slip fault is in some way expected as we are not dealing with a proper transform fault but rather a diffuse deformation at surface that only reflects a deep-seated process of tearing that propagated in a scissor way. The presence of abundant volcanic products younger than 2 Ma in the Central Campania Province suggests the occurrence of deep fractures tapping mantle reservoirs, further supporting the lithospheric scale of this discontinuity. Seismological and mesostructural data from the Somma-Vesuvius volcanic complex show that this apparatus is mainly controlled by NW-SE-trending discontinuities (Bianco *et al.*, 1998), in agreement with the regional trend of the inferred lithospheric tear. Beside volcanism, substantial heat input toward the base of the crust is expected following lithospheric tearing. The low *P*-wave velocity observed in the lower crust of the Southern Apennines (Di Stefano *et al.*, 1999) is a further evidence in agreement with such a process.

It is noteworthy that the efficient *S*-wave paths cross the SE portion of the inferred lithospheric tear, from Salerno to the Pollino Fault (figs. 4 and 5). This segment corresponds to the youngest part of the propagating tear, where the process is likely in an incipient stage. Considerations on the *S*-wave attenuation due to a hypothetical break within the subducted slab suggest that a gap as small as 25 km can be resolved (Mele, 1998) and, therefore, it can be reasonably assumed that the extent of the tear in the Salerno-Pollino segment is below this value.

b) *Relations between the Southern Apennines and the Calabrian arc* – The two differing directions of extension observed in the Southern Apennines and Calabrian arc require the presence of some compatiblity structure. The Crati graben, trending *ca.* N-S in the southern part and NE-SW in its northern portion may represent such a compatibility structure. This basin is dominated by E-W to WNW-ESE extension, and paleomagnetic data indicate that north of the Crati graben CCW rotations affected the Pleistocene sediments, whereas south of the Crati graben rotations in the Pleistocene sediments of the Calabrian arc are CW. Further to the north the boundary between the early Pleistocene CCW and CW rotational domains can be taken as running along the complex Pollino fault zone, which displays sinistral strike slip (Catalano *et al.*, 1993; Schiattarella, 1996) and along which the lower Pleistocene sediments of the Mercure basin were rotated CCW. The Pollino fault zone continues NW-ward in the Volturno-Salerno graben system and in the belt of the Central Campania volcanic centres.

It is noteworthy that lower-middle Pleistocene sediments near Salerno (Eboli) show no rotation whereas Pliocene sediments are strongly CCW rotated (Scheepers and Langereis, 1994). This observation might reflect a progressive disactivation of the shear as lithospheric tearing proceeds SE-ward in time.

Statistical analyses of crustal seismicity in Southern Italy suggest that a stress pulse propagated NW-ward from North Calabria along the Southern Apennines at a rate of 13 km/yr (Marzocchi and Mulargia, 1995). The origin of this earthquake-generating stress pulse could be in the active lithospheric tearing occurring at the northern side of the Tyrrhenian slab near the northern tip of Calabria. This would imply some sort of interrelation among tectono-magmatic processes (*e.g.*, Spence, 1977; Nostro *et al.*, 1998) that, however, is not fully assessed or accepted.

c) *Lateral tear offshore Northern Sicily* – The southern tear of the Tyrrhenian slab is much less obvious. Lacking reliable evidence on land the E-W Aeolian island alignment seems to be the best candidate. Along such an alignment abundant volcanic activity has occurred in the last 2 Myr (Savelli, 1988; Argnani and Savelli, 1999), and magnetic anomalies are also well evident all along this trend, both in the aeromagnetic (Agip, 1994) and in the onshore-offshore magnetic (Speranza and Chiappini, 2000) maps of Italy. A lithospheric tear along the Aeolian alignment would in fact fit the *S*-wave propagation pattern (fig. 4) and would explain the abundance of volcanic features observed along this trend. The tear presumably progressed towards the Calabrian arc, following some pre-existing discontinuity. As the most obvious discontinuity on the southern side of the Ionian ocean is represented by the NNW-SSE-trending Malta escarpment (Scandone *et al.*, 1981) a re-orientation of the tear from E-W to NNW-SSE should be expected.

It is worthy of note that in the Aeolian Islands the age of the onset of volcanic activity falls along the Salina-Vulcano NNW-SSE alignment (Mazzuoli *et al.*, 1995), with volcanism that started *ca.* 450 ka at Salina, 223 ka at Lipari, and 120 ka at Vulcano. Mt. Etna is located on the same alignment, and with its age of *ca.* 100 ka it would be the youngest edifice along the trend. Volcanic activity in the Etna region started as fissured eruption at *ca.* 700 ka with rocks of tholeiitic affinity. This initial activity was followed by small isolated centres at 200 ka, and finally by the building of the present central edifice at *ca.* 100 ka. These last events are characterised by rocks of Na-alkaline affinity. The magma feeding this edifice, that rests on the subducted plate, comes from a mantle not affected by subduction processes and the origin of their somewhat odd location is still a matter of debate (*e.g.*, Gvirtzman and Nur, 1999b).

The SE-ward fall in age of volcanic activity along the Salina-Vulcano-Etna alignment (Mazzuoli *et al.*, 1995), the recent NNW-SSE trending extensional faults (with minor dextral component) in the Timpe region, on the eastern flank of Mt. Etna (Tortorici *et al.*, 1995; Bousquet *et al.*, 1997; Lanzafame and Bousquet, 1997), and the earthquakes along the Malta escarpment offshore the Hyblean plateau, with associated tsunamis (Piatanesi and Tinti, 1998), all indicate that this reorientation of the lithospheric tear is currently occurring. The portion of the tear along the Malta escarpment is crossed by the *S*-wave paths (fig. 4). As for the Southern Apennines, it is assumed that the tear, being a recent feature, is not large enough to attenuate the *S*-wave propagation.

3.2. *Dynamics of vertical motions*

The outcropping part of the Calabrian arc is characterised by a thin crust (Scarascia *et al.*, 1994), less than 25 km thick, which is mainly composed of a thrust stack of basement rocks within the wider Calabrian arc accretionary wedge. This region has been affected by almost 2 km of uplift in the last 2 Ma and the process causing such uplift is not been fully understood. The isostatic rebound following the breakoff of the subducted slab has been proposed as a viable mechanism (Wortel and Spakman, 1992; Westaway, 1993a; Yoshioka and Wortel, 1995), but hypocentres distribution (Selvaggi and Chiarabba 1995; Frepoli *et al.*, 1996), *S*-wave propagation (Mele, 1998), and *P*-wave tomography (Piromallo and Morelli, 1997; Cimini, 1999; Lucente *et al.*, 1999) suggest that the presence of a discontinuity along the slab is unlikely.

Within isostatic equilibrium, the limited buoyancy of the thin Calabrian crust would require some deep mass deficit to support the elevation (Lachenbruch and Morgan, 1990), and the recent hypothesis of an isostatic support from an asthenospheric wedge caused by the rollback of the Ionian lithosphere (Gvirtzman and Nur, 1999a) has some appeal. However, the relatively low heat flow in the Calabrian arc (*ca.* 60 mW/m^2) does not fit completely with such a shallow asthenosphere (Lachenbruch and Morgan, 1990). It should be mentioned, however, that heat flow measurements in Calabria are rather scanty and might also be influenced by meteoric water circulation. Within these uncertainties, calculations using the measured heat flow of 60 mW/m^2 (Mongelli and Zito, 1994) and the observed crustal thickness of 20 km (Scarascia *et al.*, 1994) suggest that a lithospheric mantle *ca.* 50 km thick should be present under the Calabrian arc in order to have such a low heat flow, assuming a steady geothermal regime. The resulting lithospheric thickness (*ca.* 70 km), would just fit the top of the subducted slab as imaged by earthquake hypocentres that increases from 40 to 80 km underneath Calabria. Such a lithospheric structure, however, would result in an elevation of -0.8 km (*i.e.* below sea water) assuming isostatic equilibrium, which is not compatible with the topography of Calabria.

Therefore, either the heat flux has not reached equilibrium because of the recent tectonics, or some dynamic force is sustaining the elevation of Calabria.

Two-dimensional finite element modelling of theTyrrhenian subduction showed that a substantial amount of dynamic uplift can be created by the pull of the subducted slab when the upper plate is almost decoupled by the lower plate (Giunchi *et al.*, 1996). These models also reproduce the high rollback velocity and subsidence in the Marsili basin, although they are significant on a short time scale (*ca.* 100 kyr) and the long term response is not guaranted. However, the concomitance of fast rollback, and rapid vertical motions is in contrast with the observation that fast rollback and opening of the Tyrrhenian backarc basin occurred earlier than the uplift of the Calabrian arc, which characterises the last 2 Ma (Argnani and Savelli, 1999).

Van der Meulen *et al.* (1998) recognise a lateral shift in the Apennines foredeep depocentres from the Oligocene to the Present and explain their observation with the migration of a lithospheric tear towards the Calabrian arc. Subsidence in the foreland of the unaffected slab is supposed to increase in response to the excess pull exerted by the adjacent and broken off lithosphere (Wortel and Spakman, 1992; Yoshioka and Wortel, 1995). Their analysis concerns the whole of the Apennines; the evidence they present of lateral migration of a lithospheric tearing along the Southern Apennines is in fact limited as there is only one depocentre of Pleistocene age. Furthermore, the model they apply requires a vertical rebound of the upper plate after slab break off has occurred. The observation that the subducted slab is still continuous underneath the Calabrian arc (Mele, 1998), where the uplift has been maximum (Bordoni and Valensise, 1998), seems to contradict the applicability of their model.

The analysis of tectonic and magmatic events in the Tyrrhenian basin supports an evolution where rollback is active in pulses (Argnani and Savelli, 1999). A possibility is that isostatic support takes over dynamic support as subduction slows down or stops, with the upper plate lifted up by the asthenospheric wedge intruding above the subduction zone, as indicated by Gvirtzman and Nur (1999a,b). However, it should be considered that the uplifted region spans a great length of the fold-and-thrust belt, from the Southern Apennines to Sicily through Calabria, *i.e.* both parts of the belt under which the slab is continuous (Calabria) and parts under which the slab has apparently been broken off (Southern Apennines) have been uplifted. Studies on the upper mantle velocity in the Central Mediterranean show a low velocity anomaly underneath most of the uplifted area (Piromallo and Morelli, 1997; Mele *et al.*, 1998; Lucente *et al.*, 1999; Piromallo *et al.*, 2000), suggesting that the isostatic support can be a feasible mechanism.

The subsidence that affected the Marsili basin in the last 2 Myr brought the basin basement to a depth typical of backarc basins (Kobayashi, 1984; Park *et al.*, 1990; Argnani and Savelli, 1999) which is about 1 km deeper than the normal oceanic floors. It has been proposed that the dense slab present under the basin can contribute to this additional subsidence (Anderson, 1989). Given the concomitant uplift in the Calabrian arc and surroundings and subsidence in the Marsili basin it is likely that the dynamics of the sinking slab has some relevance in the system. For instance, the lateral tearing of the slab promoted its sinking and therefore the subsidence in the Marsili basin, but also the rise in the asthenosphere that substituted the broken off slab under the Southern Apennines and that wedged between the two plates under the Calabrian arc (Gvirtzman and Nur, 1999a,b).

3.3. *Seismically active faults and neotectonics*

a) *Southern Apennine seismicity* – Seismic activity on extensional faults characterises the present tectonic regime of the Southern Apennines (Pondrelli *et al.*, 1995; Selvaggi, 1998; Frepoli and Amato, 2000).

The ruptures related to the 1980 Irpinia earthquake are likely the best studied among the Southern Apennine active extensional faults. Teleseismic data show an E-dipping fault with strike ranging between 305 and 330 degrees N, dip comprised between 53 and 63 degrees to NE, and almost pure dip-slip motion (Giardini, 1993). The largest moment release occurred at a depth ranging from 8 to 13 km, *i.e.* within the upper crust. The fault plane seems to be steeper in the upper part, *ca.* 60 degrees, and then flattens downdip to an angle of *ca.* 20 degrees (Westaway and Jackson, 1987; Bernard and Zollo, 1989; Westaway, 1993b; Amato and Selvaggi, 1993). As the flat basal portion of the fault ruptured *ca.* 20 s after the main shock, this has been taken as an example of triggered low-angle normal fault (Axen, 1999) and might indicate the presence of some flat laying mechanical discontinuity. A steep (70 degrees), antithetic fault, that ruptured 40 s later, is also present. Typically, geological cross sections in the region of the earthquake show no evidence of E-dipping faults (Mostardini and Merlini, 1986; Menardi-Noguera and Rea, 2000); in fact, extensional faults are only present on the Tyrrhenian side of the Southern Apennines with SW dip. The seismically active E-dipping extensional faults, therefore, can be considered very recent features.

A kinematic model that links E-dipping thick-skinned extension and asthenosphere-crust shear within a regional eastward asthenospheric flow has been proposed (Doglioni *et al.*, 1996, 1999). In this model the extension, that is localised very close to the hinge of the subduction zone, is related to slab retreat. However, if this were the way upper plate extension and slab retreat are related it would be difficult to explain how a backarc basin, with its own conjugate margins, can originate. As backarc basins, including the Tyrrhenian basin, commonly originate behind retreating subduction (Tamaki and Honza, 1991) a somewhat different mechanics is required to explain the present Southern Apennine extension.

This faulting has also been taken as evidence of incipient rifting between Adria and the Tyrrhenian region (Scandone and Stucchi, 1999; Slejko *et al.*, 1999), implying that the whole Adriatic lithosphere is cut through by the extensional fault. Such a rifting is considered part of the boundary of an Adria plate detached from Africa. In this interpretation the pole of rotation for Adria is located in NW Italy and extension across the plate boundary should increase southward. However, there is not much evidence, either on seismicity and neotectonics, of the northern and southern continuations of this incipient plate boundary as extension in the Southern Apennines is confined within the fold-and-thrust belt. A lithospheric decoupling between Adria and Africa located in the Southern Adriatic, as proposed by Anderson and Jackson (1987b), is not supported by geological and seismological data (Argnani *et al.*, 2000) and the proposal of a decoupling running along the Malta escarpment (Slejko *et al.*, 1999) faces the lack of both seismological and geological evidence for the presence of a southern boundary of Adria in the Eastern Mediterranean. The absence of a decoupling between Adria and Africa is also supported by VLBI results as no significant relative motion has been observed between the stations of Matera and Noto (Devoti *et al.*, 1999).

The Southern Apennine seismicity concentrates along a narrow seismic belt, as opposed to the seismicity diffused over broad areas where block tilting occurs in regions of continental extension (England and Jackson, 1989; Scholz, 1990). As the seismically-active E-dipping extensional faults of the Southern Apennines present relatively steep angles and are not sustaining a system of tilted blocks, the main result of slip along their fault planes is to accommodate vertical motion. It seems therefore that the overall geological setting suggests that re-equilibration due to vertical motion within the fold-and-thrust belt can be the most likely explanation for the observed neotectonics. In fact, measured uplift rates up to 1.2 mm/yr (Bordoni and Valensise, 1998) compare pretty well with the seismically derived estensional rates of 1.6-1.7 mm/yr (Selvaggi, 1998). The narrow seismically active belt is located above the region of low velocity anomaly (high temperature) in the lower crust (Di Stefano *et al.*, 1999), and such a recent thermal effect can contribute to or cause isostatic perturbations within the Southern Apennines belt. The hypocentral depths of the 1980 Irpinia earthquakes fall towards the base of the fold-and-thrust belt (fig. 7), suggesting that the deformation is localised within the orogenic wedge. The present day topography of the Southern Apennines appears to be controlled by the recent uplift (Bordoni and Valensise, 1998), with the higher relieves located where uplift has been maximum, and the closeness between high reliefs and seismicity (Selvaggi, 1998) suggests that a gravitational accommodation within the uplifted orogenic wedge can be the cause of the *E*-dipping faulting in the Southern Apennines (fig. 7).

b) *Calabrian arc seismicity* – The crustal seismicity of the Calabrian arc is characterised by small earthquakes for which no reliable fault plane solution is available. A WNW-ESE extensional strain rate has been derived by seismic moment tensor summation, with a possible minor NNE-SSW extensional strain (Selvaggi, 1998; Frepoli and Amato, 2000; fig. 3). Recent faults trend both parallel and perpendicular to the arc (fig. 5), in agreement with the calculated strain directions.

Orthogonal directions of extension and concomitance of extension and uplift strongly suggest a relation between the two processes. Gravitational instability of the uplifted orogenic wedge and gliding towards the deep Ionian basin can drive NW-SE extension and also extension along the arc as uplift causes arc-parallel elongation (fig. 5). This process can be compared to gravitational spreading (Merle, 1986) with the brittle upper crust deforming in response to ductile flow of the underlying rocks (fig. 8a)

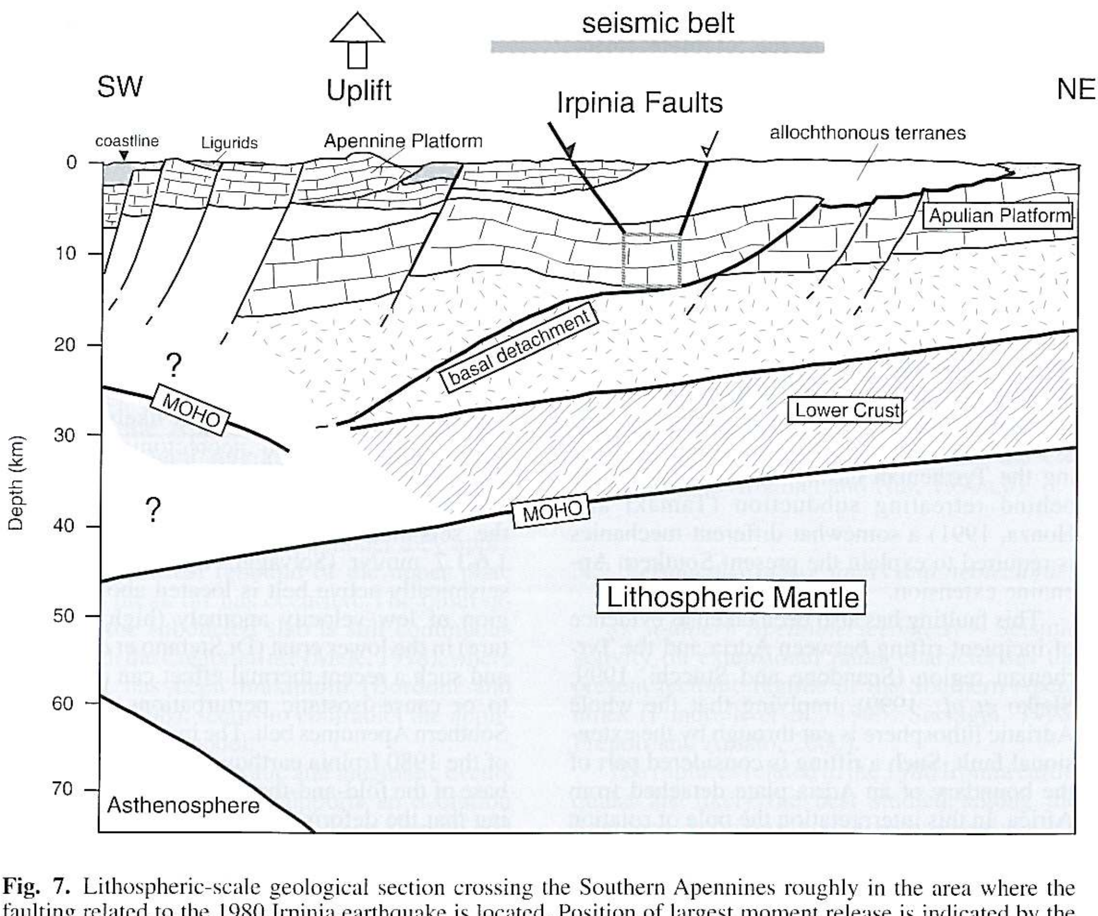
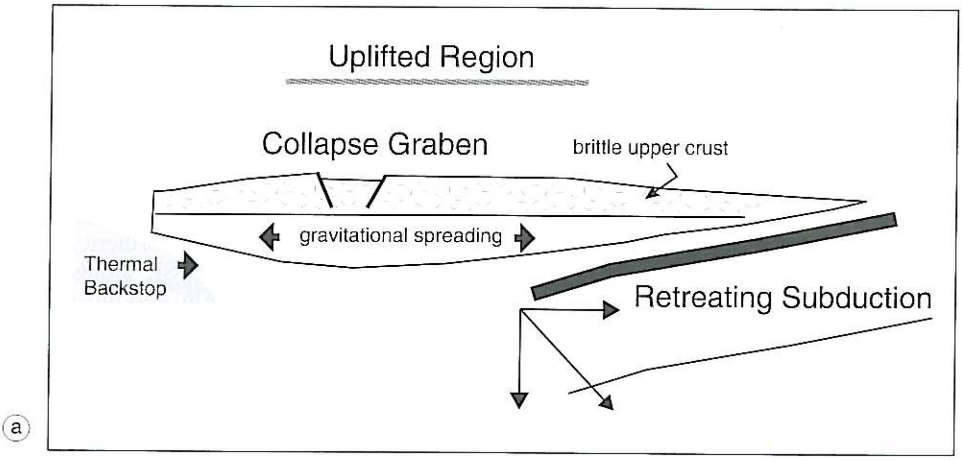


Fig. 7. Lithospheric-scale geological section crossing the Southern Apennines roughly in the area where the faulting related to the 1980 Irpinia earthquake is located. Position of largest moment release is indicated by the grey box which is located above the basal detachment. Geology of the upper 10 km modified after Mostardini and Merlini (1986).



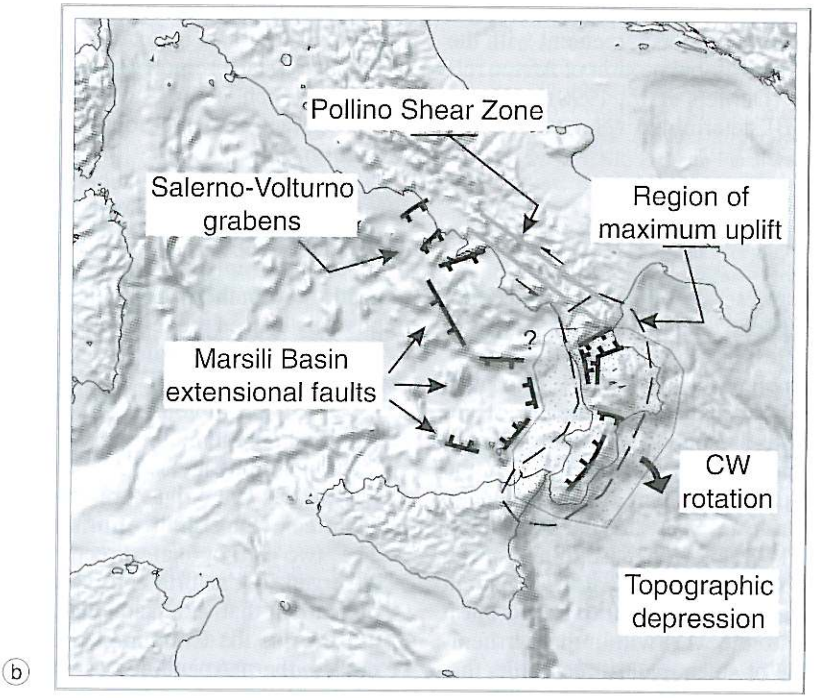


Fig. 8a,b. a) Schetch illustrating the proposed origin of the Calabrian arc grabens. The retreating subduction releases the upper plate from compressional stresses and the gravitational spreading of the uplifted orogenic wedge towards the Ionian basin causes the formation of collapse grabens. As the Calabrian arc is also stretching longitudinally, grabens perpendicular to the arc originate as well. b) The grabens of Calabria (Crati, Cosenza and Catanzaro) are located in the region of maximum uplift of the arc. The regional rotation of Calabria is possibly accommodated to the west by the large and steep extensional faults that bound the Marsili basin. In this simplified sketch the Pollino sinistral shear zone and the Salerno-Volturno grabens represent the northern boundary of the kinematic system.

and might be favoured by the regional extensional stress originated by the retreating subduction.

c) *Seismicity in the Maghrebides of Sicily* – The crustal seismicity of the Maghrebian belt of Sicily is characterised by compressional earthquakes, whose *P* axes, derived from the CMT catalog for the region encompassing North Africa and Sicily, trend NNW-SSE (Pondrelli *et al.*, 1995) and are *ca.* parallel to the Africa Europe convergence as reconstructed from global motions (DeMets, 1990; fig. 3). Seismic deformation accounts for 10 to 30% of the expected shortening. Other authors obtained slightly different *P* axes directions (Kiratzi and Papazachos, 1995), trending NNE-SSW with seismic rates of *ca.* 1 mm/yr. Altogether these directions are in pretty good agreement with the NNW-SSE Nuvel-1 global motion of Africa relative to Europe (DeMets *et al.*, 1990) and with the similar VLBI determined velocity of Noto (Ward, 1994).

3.4. *Rotation of Calabria*

Despite the presence of active extensional faults, paleomagnetic data indicate that Calabria rotated more or less as a single block (Scheepers *et al.*, 1994; Speranza *et al.*, 2000). The push originated by the asthenospheric uprise of the Tyrrhenian basin, as shallow as 30 km (Panza *et al.*, 1980), and the forces originated from the sinking and retreating Ionian slab combine to move the Calabrian arc SE-ward (fig. 8a). Clockwise rotation likely arose because of an uneven distribution of forces along the arc. The extent of the rotated terrane is difficult to assess but it likely stretches to the west within the Tyrrhenian Sea. The line of steep extensional faults that bound the eastern margin of the Marsili basin shows a northward increase in width of the fault scarp and can possibly accommodate the vertical axis rotation of the Calabria terrane (fig. 8b). In this tentative kinematic sketch the Pollino shear zone and the Volturno-Salerno grabens represent the northern boundary of the rotated terrane, corresponding to the surface expression of the deep seated lithospheric tear.

4. Conclusions

To summarise, the neotectonics of the Southern Apennines - Southern Tyrrhenian region can be tentatively synthesized in the following model.

In the last 1-2 Ma the old and dense (oceanic) subducted slab was torn apart on either side during its sinking; on the northern side the slab broke off from NW to SE along the former Apulian platform margin, and this process triggered volcanism and NW-SE extension along the eastern Tyrrhenian margin, and strike-slip tectonics along NW-SE trending faults in Northern Calabria. On the southern side the slab broke off from W to E along the Aeolian Island alignment; at present it seems that the tear has been reoriented along the NNW-SSE Malta escarpment. Progressive break off on either side of the subducted slab promoted sideways asthenospheric flow which, in turn, favoured the fast rollback that characterises the Southern Tyrrhenian subduction.

The sinking slab detached from the overriding plate favouring the wedging of the asthenosphere between the two plates and hot asthenosphere also replaced the broken off slab underneath the Southern Apennines; these processes possibly caused the regional uplift of the Calabrian arc and surroundings (Gvirtzman and Nur, 1999a).

Uplift promoted gravitational instability within the orogenic wedge, particularly towards low topography areas. The gravitational spreading of the Calabrian Arc towards the Ionian basin can cause graben formation in Calabria. The two orthogonal directions of extension observed in Calabria can be taken as a further indication that extension has been driven by uplift. Also the E-dipping extensional faults of the Southern Apennines can be related to accommodation of vertical motions within the fold-and-thrust belt, although in this case gliding is partly impeded by the closeness of the Apulian foreland. This gravity tectonics is radial with respect to the fold-and-thrust belt, and the Crati graben (and perhaps the Sant'Arcangelo basin) represents the compatibility structure between two domains with different potential of gliding.

Recent seismicity reflects this neotectonic picture: crustal-scale gravity tectonics within the orogenic wedge is responsible for extensional earthquakes in Calabria and the Southern Apennines, whereas Africa-Europe convergence is responsible for compressional earthquakes in Sicily.

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