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E. MANTOVANI, D. ALBARELLO, D. BABBUCCI and C. TAMBURELLI

EXTRUSION TECTONICS IN THE CENTRAL MEDITERRANEAN AREA

Abstract. The post-Tortonian deformation pattern in the Central Mediterranean is explained as a result of the Africa-Eurasia convergence along roughly a SSW-NNE direction. This convergence was first accommodated by a considerable reduction of the Adriatic foreland, through the consumption of its eastern and western margins, and then by lateral expulsion of crustal wedges, accompanied by crustal thickening, in the zone between the Adriatic and African forelands. The lateral expulsion of the Calabria and Sicily blocks, towards the E/SE and NW respectively, was possible due to the presence of poorly constrained lateral boundaries corresponding to the thinned Ionian foreland and to the zone of crustal stretching in the Tyrrhenian basin. The proposed interpretation allows physically plausible explanations of a considerable amount of geological, geophysical and volcanological evidence in the framework of relatively simple and coherent tectonic mechanisms.

INTRODUCTION

The post-Tortonian evolution of the central Mediterranean region (Fig. 1) has been characterized by several major deformation events.

- Around the late Tortonian, the Giudicarie fault system in the Southern Alps was activated as a left-lateral transpressional fault and since then intense compressional deformations have only occurred in the eastern part of the Southern Alps (see, e.g., Semenza, 1974; Castellarin and Vai, 1986).

- Around the late Tortonian, the stress field in the zone lying between the Corsica-Sardinia block and the Adriatic foreland, which was mainly occupied by Alpine and Apenninic thrust belts, underwent a drastical change, passing from a compressional to an extensional regime, which caused crustal stretching with an E-W extensional trend. This led to the formation of the Tyrrhenian basin lying north of the Selli line (see Fig. 1).

- A continental collision took place on the Adriatic-Balkan border (Outer Hellenides) around the late Miocene (Mercier et al., 1979, 1989).

- From roughly the Messinian to the middle-upper Pliocene, the Apenninic belt experienced an overall migration of 100-200 km towards the Adriatic foreland (see, e.g., Di Nocera et al., 1976; Ortolani, 1979; Sartori, 1989; Patacca and Scandone, 1989). This migration was associated with compressional deformations and accretion along the external front of the chain, and by extensional tectonics in the internal, Tyrrhenian, margin. In the Southern Apennines, this phenomenon was much more intense than in the northern part of the belt.

- Simultaneously, a large part of the Adriatic-Ionian foreland was consumed, through a downward flexure, beneath the outward extruding Apenninic belt (Casnedi et al., 1982; Patacca

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University of Siena, Dept of Earth Sciences, Via Banchi di Sotto 55, 53100 Siena, Italy.

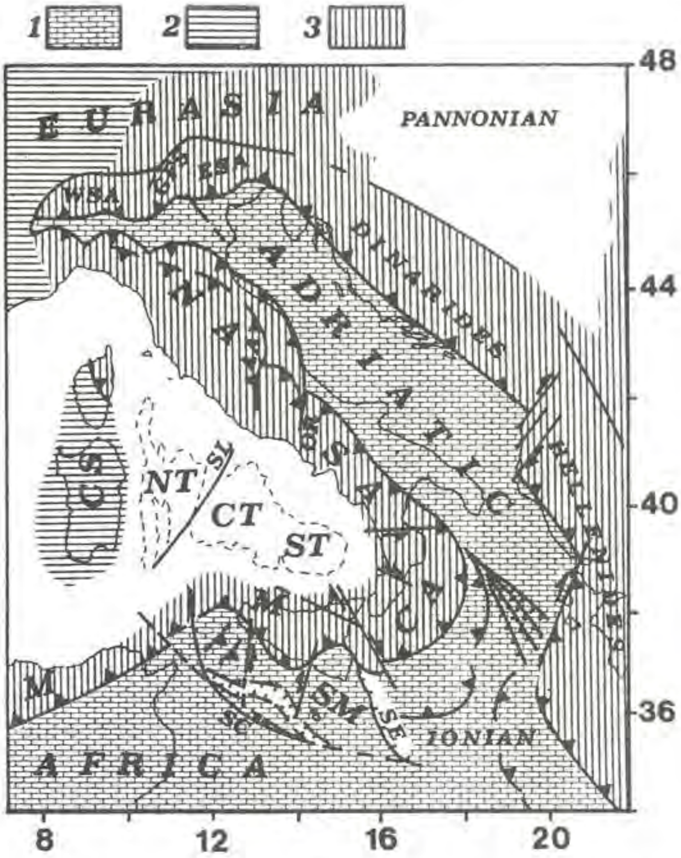


Fig. 1 - Main structural-tectonic elements in the central Mediterranean region 1) African-Adriatic domain 2) European domain 3) Main deformation belts. The dashed lines in the Tyrrhenian contour the zones of crustal stretching. WSA = Western part of Southern Alps, ESA = Eastern part of Southern Alps, GFS = Giudicarie fault system. NA = Northern Apennines, SA = Southern Apennines, AA = Ancona-Anzio line, OR = Ortona-Roccamonfina line, SL = Selli line, CA = Calabrian Arc, SM = Sicily microplate, SE = Siracusa escarpment, SC = Sicily Channel, CS = Corsica-Sardinia microplate, NT, CT, ST = Northwestern, central and southern parts of the Tyrrhenian basin, M = Maghrebides.

and Scandone, 1989; Patacca et al., 1990).

- From the Messinian to the middle-upper Pliocene, intense E-W crustal stretching took place in the central part of the Tyrrhenian zone, the present Magnaghi-Vavilov basin (see, e.g., Rehault et al., 1987; Sartori, 1989).

- Important deformations started in the zones surrounding Sicily around the late Messinian-early Pliocene. Extensional tectonics occurred in the Siracusa escarpment (Carbone et al., 1982; Grasso and Lentini, 1982; Sartori et al., 1992). A number of grabens began to develop in the Sicily Channel within the framework of a transcurrent mechanism (Finetti, 1984; Boccaletti et al., 1987; Cello, 1987; Jongsma et al., 1987; Reuther, 1987, 1990).

- Around the upper Pliocene, the outward migration of the Southern Apennines and the crustal stretching in the central Tyrrhenian bathyal plain slowed considerably (see, e.g., Ortolani and Aprile, 1977; Ciaranfi et al., 1983; Sartori, 1989; Patacca et al., 1990). Since then the Calabrian block has experienced a fast SE-ward drift at the expense of the thinned Ionian lithosphere, and crustal stretching took place in the southernmost Tyrrhenian, i.e., the present Marsili basin, with exposure of oceanic crust (Finetti and Del Ben, 1986; Kastens et al., 1988; Sartori, 1989).

- Since the Pleistocene, a fast uplift, with maximum rates of about 1.5 mm/y, occurred in Eastern Sicily, Calabria, Southern Apennines and the adjacent foredeep (Ghisetti and Vezzani, 1982; Ciaranfi et al., 1983).

- In the Quaternary a renewal of shortening took place in the Outer Hellenides (Mercier et al., 1979).

- The Corsica-Sardinia block has not been affected by any appreciable compressional deformation or lateral migration since the Tortonian.

The above mentioned tectonic events have never been explained all together within the framework of a coherent evolutionary model. A detailed discussion on the major outstanding problems of earlier attempts is given by Mantovani et al. (1992, 1993) and in the last section of this work.

Here we argue that all the major features listed above can be coherently interpreted as consequences of a succession of shortening mechanisms (also involving consumption of continental-like lithosphere) and block readjustments, driven by the convergence between Africa and Eurasia.

PROPOSED EVOLUTIONARY MODEL

It is assumed that the overall driving force of post-Tortonian deformations in the Central Mediterranean has been the convergence between Africa and Eurasia along a SSW-NNE direction. The arguments supporting this hypothesis are described by Mantovani et al. (1992, 1993) and Albarello et al. (1993, 1994). The block movements mentioned in the text refer to a fixed Eurasia plate, unless otherwise stated.

Paleomagnetic observations in the Mediterranean area have not been taken into account to reconstruct the positions of intermediate plates, since this kind of information may be affected by significant uncertainties (see, e.g., Marton, 1987, 1993). The proposed evolution of the central Mediterranean region is schematically illustrated by five paleogeographic maps (Fig. 2) which cover the time span from the upper Tortonian, prior to the Tyrrhenian extension, up to the present. The evolutionary model is divided into three main phases: late Tortonian-early Messinian, middle Messinian-middle Pliocene, upper Pliocene-present. The beginning of each phase is determined by a key tectonic event which produces a significant change of the shortening mechanism and related deformation pattern.

Magmatic and geological evidence suggests that large portions of the Adriatic-Ionian lithosphere have been consumed since the upper Miocene (see, e.g., Patacca et al., 1990, 1993). This implies that extensive sunk lithospheric edifices have been present for the last 10 My beneath the zones here considered, and that they might have significantly influenced the evolution and kinematics of shallow structures. As a consequence, any attempt at reconstructing the evolution of the Central Mediterranean cannot neglect the above problem and should at least provide some plausible hypotheses on how the presence of deep lithospheric roots may be reconciled with the proposed shallow deformation patterns.

In order to illustrate the speculative considerations reported in the text about this connection, a perspective sketch of the sunk lithosphere is given at the bottom of each paleogeographic map.

Tortonian (pre-Tyrrhenian)

Fig. 2a shows the presumed structural-tectonic setting in the Central Mediterranean zone after the opening of the Balearic basin and before the extensional phase in the Tyrrhenian region.

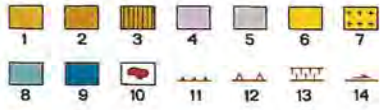
The African/Adriatic promontory was much larger than at present. The present shape is shown for reference in each phase by the dark brown area. The width of the Africa-Adriatic foreland successively consumed (light brown) has been tentatively chosen on the basis of shortening estimates across the Alps, the Dinarides, the Hellenides, the Apennines and the Maghrebides (see, e.g., Mercier et al., 1979, 1989; Burchfiel, 1980; Laubscher, 1983; Ghisetti and Vezzani, 1984; Horvath, 1984; Castellarin and Vai, 1986; Philip, 1987; Catalano et al., 1989; Patacca and Scandone, 1989; Sartori, 1989; Schmid et al., 1989; Patacca et al., 1990; Castellarin et al., 1992).

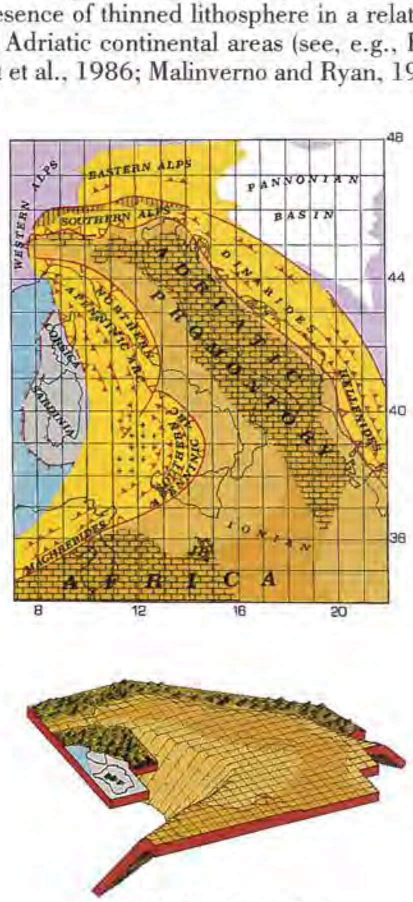
During this phase, the convergence of the Adriatic promontory (driven by Africa) and Eurasia was mostly absorbed by the consumption of the eastern Adriatic margin beneath the Dinarides and Hellenides (Mercier et al., 1979, 1989; Burchfiel, 1980) and by shortening in the Alps (Laubscher, 1983; Castellarin, 1984).

The northwestern protuberance of the Adriatic promontory was deeply indented into the Eurasian domain (see Fig. 3) after the main continental collision in the Western Alps (see, e.g., Semenza, 1974; Channell and Horvath, 1976; Laubscher, 1983). Due to this embedding, the northwestern Adriatic edge was most probably characterized by a very low mobility and, consequently, could have been a sort of hinge zone for a counterclockwise rotation of the Adriatic block.

The Corsica-Sardinia microplate was already in its present position and it was separated from the African-Adriatic foreland by an orogenic belt, constituted by Alpine and pre-Messinian Apenninic units (see, e.g., Biju-Duval et al., 1977; Dewey and Sengor, 1979; Scandone, 1979; Cohen, 1980; Rehault et al., 1985, 1987; Dercourt et al., 1986; Patacca and Scandone, 1989; Sartori, 1989).

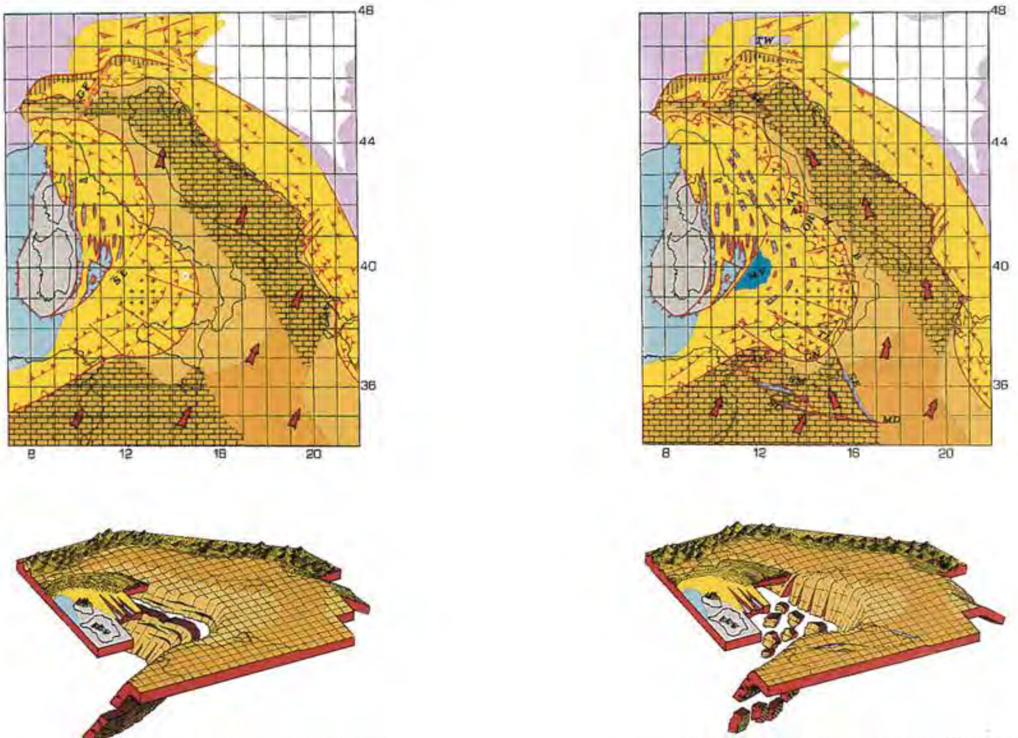
A feature of the Tortonian structural setting which significantly influenced the successive evolution of the Central Mediterranean was the presence of thinned lithosphere in a relatively narrow zone, the Ionian, between the African and Adriatic continental areas (see, e.g., Rossi and Sartori, 1981; Scandone et al., 1981; Dercourt et al., 1986; Malinverno and Ryan, 1986).





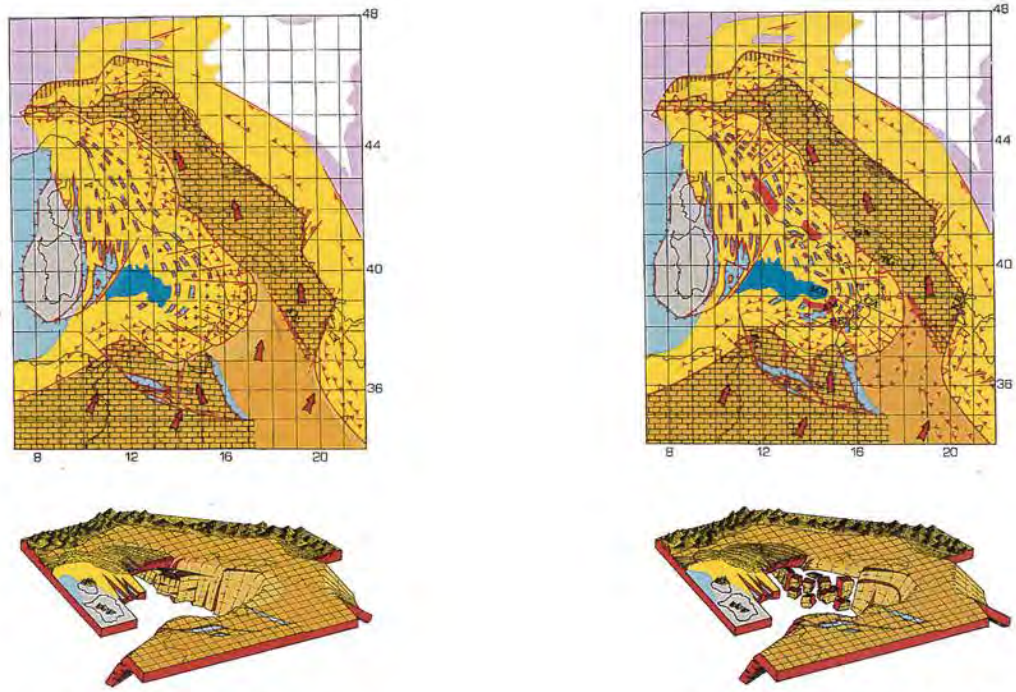
2A. Upper Tortonian

Fig. 2 - Proposed evolutionary scheme of the central Mediterranean area since Tortonian times. 1, 2) African-Adriatic foreland, the light tone indicates the zones which will be consumed during the successive evolution, and bricks identify the continental parts of the present foreland area. 3) Paleozoic crystalline basement in the Southern Alps. 4) Deformed European margin. 5) Corsica-Sardinia microplate. 6) Deformation belts. 7) Calabria. 8, 9) Zones affected by extension, the dark tone indicates intense stretching with exposure of oceanic crust. 10) Subduction related magmatism. 11) Main trends of compressional deformations. 12) External front of deformation belts. 13) Main tensional features. 14) Main trascurrent or transpressional fault systems. The red arrows tentatively indicate the major motion trends with respect to Eurasia. The movements of Africa are compatible with an Africa-Eurasia rotation pole located offshore Northern Portugal (see Mantovani et al., 1992 and Albarello et al., 1993, 1994). Present geographic contours and grid (thin black lines) are reported for reference. Dotted geographic contours indicate the presumed positions of some significant foreland zones during each evolutionary phase. The speculations which are reported in the text about deep tectonics are tentatively illustrated by perspective views of the subducted lithosphere. The accretionary belts which built up around the Adriatic plate during the period considered are represented by imbrication nappes. AA=Ancona-Anzio line, AE=Apulian escarpment, AL=Abruzzi-Lazio units, AM=Aeolian magmatic arc, AP=Adventure plateau, B=Basilicata region, C=Campania region, CA=Catanzaro fault system, EG=Egadi fault, GA=Gargano-Apulia zone, GF=Giudicarie fault system, GN=Gela nappes, IB=Iblean zone, KE=Kefallinia line, M=Molise region, MB=Marsili basin, MD=Medina seamounts, MV=Magnaghi-Vavilov basin, OR=Ortona-Roccamonfina line, P=Padanian region, PE=Peloritani block, SC=Sicily Channel, SE=Siracusa escarpment, SL=Selli line, SM=Sicily microplate, SV=Schio-Vicenza line, TG=Taranto gulf, TL=Taormina line, TW=Tauern window, VU=Vulcano fault.



2B. Late Tortonian - early Messinian

2C. Middle Messinian - early Pliocene



2D. Lower-middle Pliocene

2E. Upper Pliocene - Present

Fig. 2 - Continued.

OLIGOCENE MIOCENE MIDDLE PLIOCENE

Fig. 3 - Schematic tectonic evolution of the Adriatic-Eurasia interaction zone which has been proposed by Semenza (1974) to explain the geological evidence in the Alps and surrounding regions. G: Giudicarie fault system. SV: Schio-Vicenza line. The large arrows indicate the dominant motion of the Adriatic foreland with respect to Eurasia.

The Iblean foreland, i.e., the present southern part of Sicily, was still closely connected with Africa. The region corresponding to the present Sicily Channel and surrounding zones was affected by SW-NE compressional stresses (see, e.g., Reuther, 1987; Boccaletti et al., 1990; Barrier, 1992).

The distribution of Oligo-Miocenic calc-alkaline magmatic activity in Sardinia and North Africa, which ended about 10-15 My ago (see, e.g., Savelli et al., 1979; Bellon, 1981), suggests that after the opening of the Balearic basin an extended arcuate edifice of subducted lithosphere was present beneath the Apenninic and Maghrebian belts, as tentatively shown in the perspective view (Fig. 2a).

Late Tortonian- Early Messinian

The key event which, around the late Miocene, caused a profound change in the deformation pattern of the Central Mediterranean, was the activation, in the Southern Alps, of a transpressional sinistral fault system, the Giudicarie belt (see Fig. 2b), which allowed the decoupling of the main Adriatic promontory from its northwestern edge and thus from the Eurasian block. This hypothesis, advanced by Semenza (1974; see Fig. 3), can satisfactorily account for the pattern of deformations which have occurred in the Alps since the late Miocene and, in particular, for the fact that only weak deformations have affected the sector of the chain lying west of the Giudicarie belt, whereas the eastern Southern Alps have been affected by significant shortening (Semenza, 1974; Laubscher, 1983; Castellarin and Vai, 1986; Castellarin and Sartori, 1986). The time-space distribution of compressional deformations in the Southern Alps points out another significant feature supporting the supposed left-lateral transcurrency along the Giudicarie fault system: the relative shifting of crystalline Paleozoic basement units lying east and west of this belt. Laubscher (1988) argued that the offset along the Giudicarie fault system was probably accommodated by strong shortening, partly in the area of the Tauern Window and partly in the Southern Alps. Shortening in the Tauern Window area is indirectly confirmed by white mica and biotite fission track ages, which suggest that the western portion of the Tauern Window underwent acceleration of uplift from 10 My onwards (Grundmann and Morteani, 1985).

The age of the displacement along the Giudicarie fault system is in good agreement with that required to accommodate continued thrusting in the eastern block, after termination of thrusting in the western (Massari, 1990). A similar role was played by the sinistral NE-SW fault system bounding the Vienna Basin (Royden, 1985) accommodating part of the displacement between the active and inactive parts of the thrust belt in the western Carpathians.

After the wrenching along the Giudicarie fault system and the consequent decoupling from its hinge zone in the Western Alps, the Adriatic block moved into closer connection with Africa. As a consequence, the Adriatic-Eurasia rotation pole ceased to be located around the Western

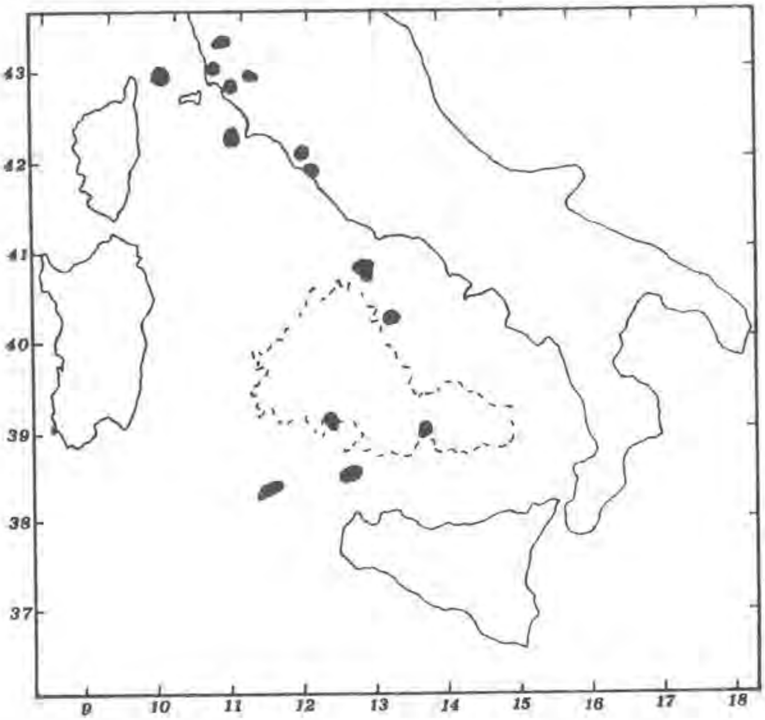


Fig. 4 - Messinian-Pliocene "subduction related" magmatism in and around the Tyrrhenian Sea (black spots), after Sartori (1986) and CNR-PFG (1989). The dashed line contours the Tyrrhenian bathyal plain.

Alps and shifted towards a position nearer to the Africa-Eurasia pole. This new pole implied a roughly S-N relative motion of the northern Adriatic block (see Fig. 2b), which caused the squeezing of the Eastern Alps against the Eurasian foreland. In response to this compression, the Alpine nappes underwent a lateral expulsion towards the weakly constrained eastern border, in correspondence to the northern edge of the Pannonian basin (see Fig. 2b). Crustal thickening and lateral flow of orogenic units, driven by sets of conjugate strike slip faults, caused tectonic denudation of the zone which had been affected by the most intense squeezing and uplifting, the present Tauern Window (see Fig. 2c). A very interesting modelling of this extrusion pattern has been described by Ratschbacher et al. (1991a, 1991b).

Further south, the collision of the Adriatic plate with the Balkan zones was mainly accommodated by the consumption of the remaining thinned Adriatic margin. The most intense shortenings occurred along the Outer Hellenides (Mercier et al., 1979, 1989), while minor deformations took place in the Dinaric sector of the belt (Channell and Horvath, 1976; Burchfiel, 1980). This difference is most probably connected with the differentiated kinematic behaviour of the North Aegean region, moving roughly westward, with respect to the more northern Balkanic zones (Rodope and Carpatho-Balkan systems). Furthermore, it should be noted that along the Dinarides the compression induced by the Adriatic drifting interplayed with the extensional regime which was affecting the Pannonian basin (see, e.g., Royden et al., 1983; Horvath, 1984).

The differential deformations of the Hellenides and Dinarides were accommodated by a dextral transcurrent fault system, which now corresponds to the evident shift between the Dinarides and Hellenides compressional fronts located in the Albanian zone (see Fig. 1).

The drifting of the Adriatic block also had significant consequences along its western margin. The divergence between the Adriatic foreland and the Corsica-Sardinia block produced a tensional regime in the region corresponding to the present northwestern Tyrrhenian basin, with the formation of several S-N trending troughs (see, e.g., Zitellini et al., 1986; Finetti and Del Ben, 1986; Kastens, Mascle et al., 1987; Sartori, 1989; Mascle and Rehault, 1990). These extensional

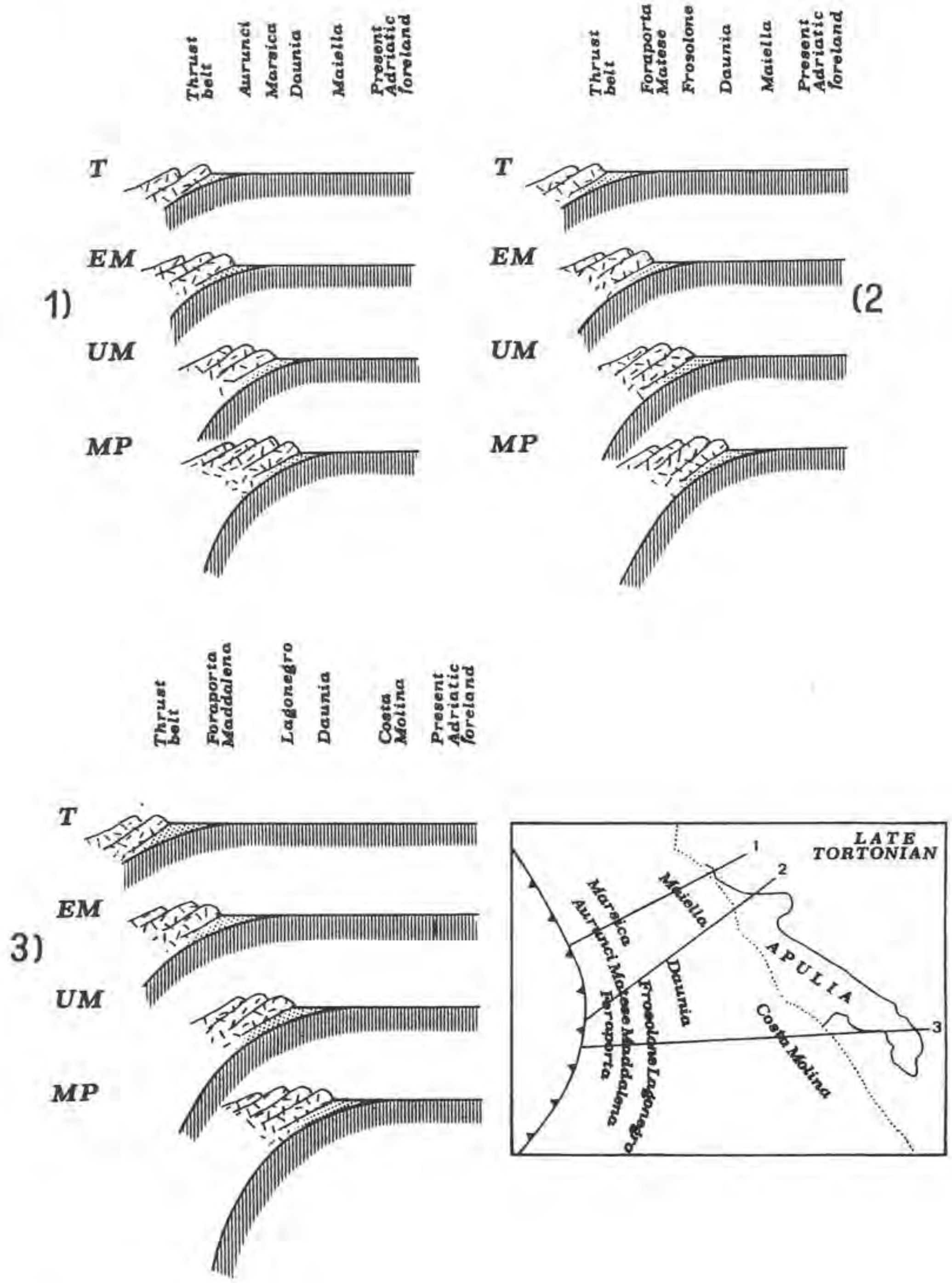


Fig. 5 - Tentative reconstruction of the outward migration of the thrust belt-foredeep system in the Southern Apennines and related flexural pattern of the adjacent Adriatic foreland, from the Tortonian (T) to the middle Pliocene (MP), through the early Messinian (EM) and the upper Messinian (UM), based on geological analysis (Patacca et al., 1990). The inset shows the location of the three cross-sections in the Late Tortonian paleogeographic setting (after Patacca et al., 1990).

tectonics were most probably responsible for the magmatic activity which occurred in the Northwestern Tyrrhenian from roughly 10 to 6 My (CNR-PFG, 1989).

During this phase, the Southern Apenninic Arc was lying between the African and Adriatic forelands, which were both moving NNE-wards (Fig. 2b), and thus no significant extension occurred in that part of the belt. In the Messinian, the Selli line was separating a deep basin to the NW from a more or less emergent land to the SE (Fabbri and Curzi, 1979; Sartori, 1989).

The hypothesis that the Adriatic block underwent displacement during this phase raises a major problem concerning the behaviour of its western subducted margin. Has this slab moved in close connection with the Adriatic platform? or has it remained trapped in the mantle and then been detached from the shallow Adriatic lithosphere? The first hypothesis seems unlikely, since the displacement through the mantle of such an extensive lithospheric body would have required the lateral flow of a huge volume of asthenospheric material. The second hypothesis, instead, appears to be more plausible from the physical point of view and, furthermore, it might explain the timing (roughly between 6 and 2.5 My ago) and the space distribution (see Fig. 4) of calc-alkaline magmatic activity in the Tyrrhenian area (Sartori et al., 1989; CNR-PFG, 1989). This magmatic episode might have been generated by the relatively fast lowering of pressure which would have accompanied the hypothesized tearing and stretching of the slab beneath the Tyrrhenian area (Fig. 2b).

Middle Messinian - Middle Pliocene

This phase involved considerable deformations of the shallow and deep structures so, in order to make their development over time clearer, we illustrate them with two paleogeographic maps and the related deep structural sketches (Figs. 2c and 2d).

The key event determining the beginning of this phase was a continental collision, in the Outer Hellenides (Mercier et al., 1979, 1989) which strongly reduced the eastward drift of the Adriatic plate into a minor movement roughly northwards.

A major effect of this kinematic change was the end of the divergence between the Adriatic foreland and the Corsica-Sardinia block, with the consequent cessation of crustal stretching in the northwestern Tyrrhenian basin (Finetti and Del Ben, 1986; Sartori, 1989).

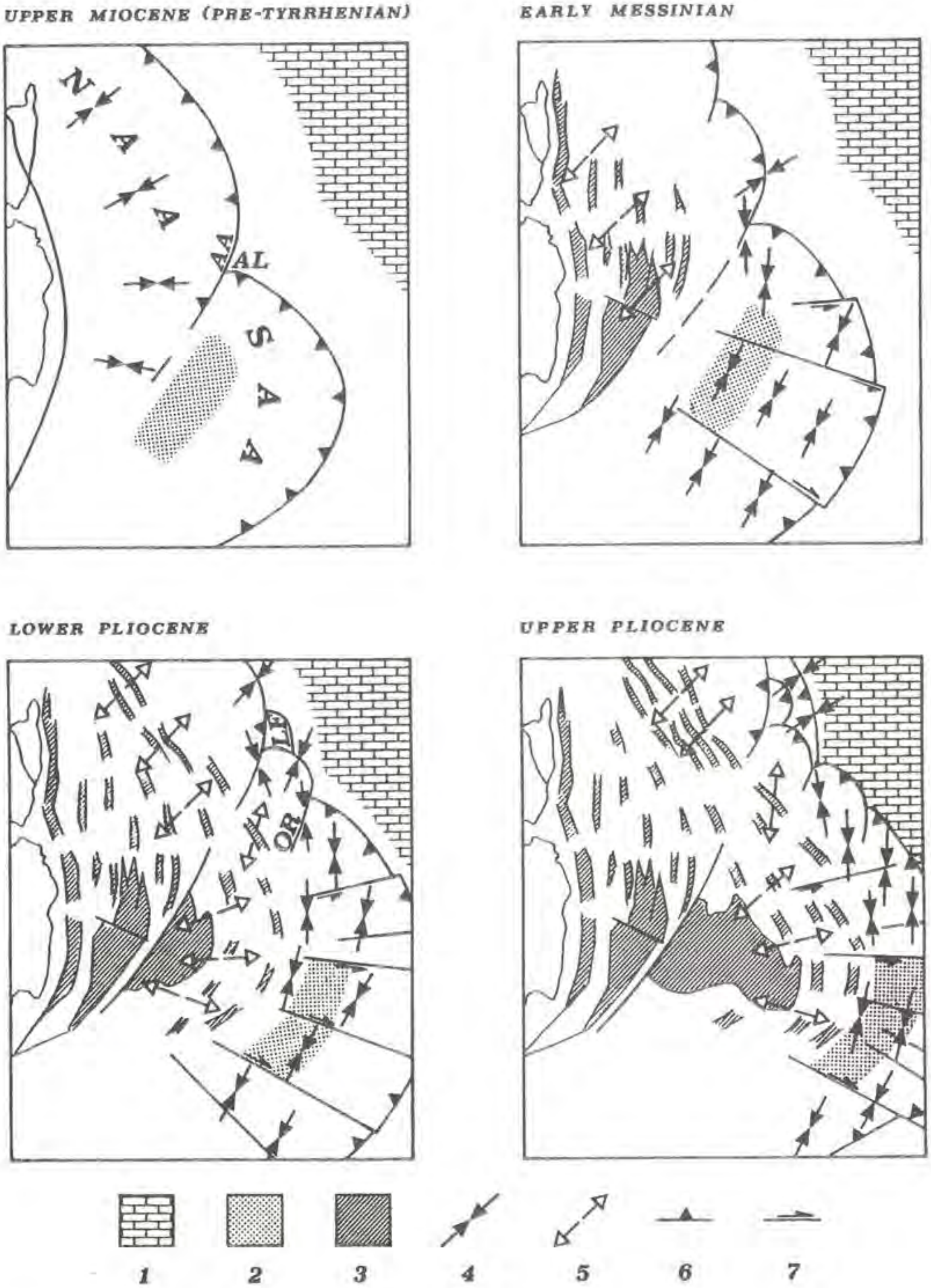
No longer absorbed by the lithosphere consuming process in the Hellenides, the NNE-ward displacement of Africa induced an intensification of compressional stresses and relative strains in the zone lying between the Adriatic and African continental forelands, i.e., the Southern Apenninic Arc and the Ionian zone.

This dynamic context caused the outward extrusion of Apenninic units, at the expense of the downward flexure of the Adriatic-Ionian lithosphere (see Figs. 2c, d). The occurrence of these deformations, from about the Messinian to the middle Pliocene, is well documented by geological data (Di Nocera et al., 1976; Casnedi et al., 1982; Mostardini and Merlini, 1986; Patacca and Scandone, 1989; Patacca et al., 1990). Fig. 5 shows the time pattern of the lithospheric flexure and eastward migration of the thrust belt-foredeep system, which has been reconstructed on the basis of sedimentary data along three cross-sections in the Southern Apennines.

The above compressional mechanism was responsible for the most intense tectogenetic pulses in the Apennines after the period of minor activity which followed the last orogenic phase in the Tortonian (see Di Nocera et al., 1976; Vai, 1987; Torre et al., 1988).

The violence of this tectonic phase is shown by the great shortening, estimated at about 150-300 km (Patacca and Scandone, 1989), by the counterclockwise rotation of the Southern Apennines with respect to the Northern Apennines, and by the fact that the Burdigalian-Tortonian units were thrust over the Messinian-Pliocene units through duplex mechanisms (see, e.g., Ortolani, 1979; Casnedi et al., 1982; Mostardini and Merlini, 1986).

The very evident eastward allocthonous character of the Southern Apenninic units, and the development of the adjacent foredeep seem to be mostly confined to the region lying south of the Ortona-Roccamonfina (OR) line (Casnedi et al., 1982). Given that the outward migration of the belt bore a close relationship to the downward flexure of the Adriatic foreland, one can



UPPER MIOCENE (PRE-TYRRHENIAN)

EARLY MESSINIAN

LOWER PLIOCENE

UPPER PLIOCENE

Fig. 6 - Proposed evolutionary pattern of stress regimes in the Apennines. 1) Present Adriatic foreland. 2) Calabrian Massif. 3) Extensional zones. 4, 5) Main trends of compressional and extensional stresses. 6) External fronts of the Apenninic belt. 7) Main transcurrent or transpressional faults. NAA = Northern Apenninic Arc. SAA = Southern Apenninic Arc. AA = Ancona-Anzio Line. AL = Abruzzi-Latium platform. LF = Laga Flysch. OR = Ortona-Roccamonfina Line.

reasonably assume that the OR line was reflected deep down by a lithospheric tear fault, which allowed those parts of the Adriatic slab lying south and north of this fault to have different flexural patterns (Royden et al., 1987; Patacca et al., 1990).

The SE-ward shift over time of the tectogenetic pulses and foredeep development in the Southern Apennines (Casnedi et al., 1982) seems to delineate a sort of migrating compressional phase which progressively affected more and more southerly zones of the belt, from the OR line to the Gulf of Taranto (Casnedi et al., 1982; Van Dijk and Okkes, 1991). This pattern could indicate that inside the Southern Apenninic Arc there was a body, most probably corresponding to the Calabrian crystalline massif, characterized by a greater rigidity than the surrounding orogenic units. The position over time of this rigid body can be reconstructed by analysis of the deformation pattern in the Southern Apennines. Around the early Pliocene, this body may have been just south of the Selli line, to account for the fact that the most intense compressional deformations in the Apennines were affecting the Molise sector (see Fig. 2c). Then this body, in response to the Africa-Adriatic compressional regime, underwent a progressive extrusion towards the SE, guided by transpressional fault systems. As a conseguence, the NE-ward compressional deformation in the Southern Apennines shifted from the Molise to the Campania sector, finally to reach the Basilicata zone and the Gulf of Taranto in the upper Pliocene.

In the wake of the outward migrating Apenninic units, there was crustal stretching in the central Tyrrhenian basin. The morphology of the troughs which openend up during this phase and the analysis of ODP/DSDP drilling data indicate that the dominant trend of extension was roughly E-W (Kastens, Mascle et al., 1987). This implies that the opening of the Magnaghi and Vavilov basins was mainly connected with the eastward displacement of the Southern Apennines units (Moussat et al., 1986; Sartori, 1989).

Significant constraints on the driving mechanism responsible for the evolution of Apennines can be inferred from the time-space evolution of deformation trends throughout the chain (Fig. 6). This pattern clearly indicates that the direction of orogenic forces changed considerably from the Aquitanian-Tortonian phases to the Messinian-middle Pliocene phases.

During the Aquitanian-Tortonian, the orogenic activity in the Apennines was dominated by a W-E compressional stress field, which was most probably connected with the convergent motion between the Corsica-Sardinia block and the Adriatic foreland. This phase determined the shape of the Northern Apenninic Arc (see, e.g., Parotto and Praturlon, 1975; Boccaletti et al., 1980; Catalano and D'Argenio, 1982).

Around the Late Tortonian, the dynamic context and stress pattern in the Apennines changed drastically (Figs. 2a, b). In the internal part of the Northern Arc, E-W compressional deformations ceased and were substituted by a tensional stress regime connected to the ceasing of the Corsica-Sardinia microplate drift and the beginning of the Adriatic's NE-ward drift. This phase determined the formation of the northwestern Tyrrhenian basin.

Around the Messinian, the Abruzzi-Latium carbonate platform began to be affected by a roughly NE-ward compressional regime, which caused the progressive closure of all preexistent SE-NW troughs and the formation of thrust fronts (Castellarin et al., 1978, 1982; Ghisetti and Vezzani, 1986). The Laga Flysch underwent strong bending and translation (Casnedi et al., 1982). Meanwhile, the zones lying just north of the Ancona-Anzio line (AA) were affected by a roughly S-N compressional regime which caused torsion of previous orogenic fronts. During this phase the AA line behaved as a lateral ramp for the further eastward migration of the Northern Apenninic units (Calamita and Deiana, 1988; Lavecchia et al., 1988).

Since the Messinian, the Northern Apenninic Arc (NAA) has been subject to compressional tectonics along the external fronts and tensional deformations in the internal area. Both types of phenomena underwent a progressive migration towards E/NE (Elter et al., 1975; Bartolini et al., 1983; Lavecchia, 1988). This deformation pattern in the Central-Northern Apennines was caused, in our opinion, by the S-N to SE-NW compression exerted by the Southern Apenninic Arc (SAA) and the Adriatic platform, which produced a progressive outward extrusion of Northern Apenninic units over the adjacent Adriatic foreland. This extrusion was guided by a number of transpressional faults transverse to the chain.

The hypothesis that the Plio-Quaternary deformations in the Northern Apennines, with particular reference to the series of arcs which formed along the external Padanian fronts (Pieri and Groppi, 1981), were caused by roughly S-N shortenings has also been advanced by Castellarin and Vai (1986).

The fact that the most intense post-Tortonian orogenic pulses in the Southern and Northern Apennines occurred during the same period (Messinian-Pliocene) supports the hypothesis that these deformations were closely connected with a unique driving mechanism, which in our opinion is represented by the SSW-NNE convergence between the African and Adriatic forelands.

The occurrence of significant Plio-Quaternary shortening along the northern Adriatic border, principally in the eastern Southern Alps (Castellarin, 1979; Castellarin and Vai, 1986), and the minor activity in the Outer Hellenides, from about early Pliocene to early Pleistocene (Mercier et al., 1989), suggest that, after the continental collision in the Outer Hellenides, the kinematics of the Adriatic plate were mainly characterized by a N/NW-ward motion.

We advance the hypothesis that the strong compressional phase which has affected the Africa-Adriatic interaction zone since the Messinian was also absorbed by another major tectonic event, the NW-ward extrusion of an African crustal wedge, hereinafter called the Sicily microplate (Fig. 2c).

The transpressional lateral guides for this extrusion were most probably, on one side, a fault system located between the Iblean zone and Tunisia (the present Sicily Channel) and, on the other side, the Taormina fault system, an old discontinuity which formed in the Miocene in connection with the overriding of the Calabrian Alpine units over the Maghrebian-Apenninic belt, and which was then reactivated as a transpressional fault (Amodio-Morelli et al., 1976; Scandone, 1982).

As discussed by Ratschbacher et al. (1991 a, b), the tectonic conditions which can produce lateral extrusion of crustal wedges are as follows: 1) an overall compressional regime, 2) a strong foreland in front of it, 3) the presence of a weak constraint along a lateral boundary and 4) an "extruding" body constituted by a previously thickened, gravitationally unstable, thermally weakened crust.

Such conditions can be recognized in the lateral extrusion of Sicily: 1) the compressional stress field was kinematically induced by the SSW-NNE Africa-Adriatic convergence. 2) the strong foreland was the Adriatic platform and the Balkan massifs lying behind it. 3) the weak lateral constraint was represented by the stretched crust in the Northwestern tyrrhenian basin. 4) the extruded crustal wedge was mainly formed from units of the Maghrebian-Apenninic belt, remnants of the Alpine chain and a tectonized fragment of Africa, for which it seems reasonable to suppose thermal conditions and gravitational instability of the type mentioned above.

The hypothesized NW-ward extrusion of the Sicily microplate can account for the deformations which occurred, starting in the late Messinian - early Pliocene, in the zones surrounding the Iblean foreland.

- The structural border between the Iblean foreland and the thinned Ionian area, i.e., the present Siracusa escarpment, was activated as a normal fault, with a throw of several hundred metres (Carbone et al., 1982; Grasso and Lentini, 1982; Sartori et al., 1992). Extensional activity was accompanied by basaltic magmatism along the Siracusa escarpment (see, e.g., Barberi and Innocenti, 1980). The part of the Ionian zone affected by subsidence during this phase was bounded to the south by the seamounts of the Medina Rise, which are interpreted as "horsts of sedimentary rocks standing up after the general lowering of the Ionian bathyal plain" (Rossi and Zarudski, 1978; Jongsma et al., 1987). This extensional event may be interpreted as an effect of the divergent motion between the Sicily microplate, which was drifting roughly NW-ward, and the Ionian region, which was probably moving in close connection with Africa (Fig. 2c).

- Compressional deformations trending SW-NE, i.e., perpendicular to the drifting direction of the Sicily microplate, developed in the Adventure plateau and western Sicily. In addition, the Gela nappes underwent further bowing and migration towards the Iblean foreland (Lentini, 1982; Ghisetti and Vezzani, 1984; Argnani et al., 1986; Grasso et al., 1990; Argnani, 1993).

- The border between the Iblean foreland and the Calabrian massif, i.e., the Taormina

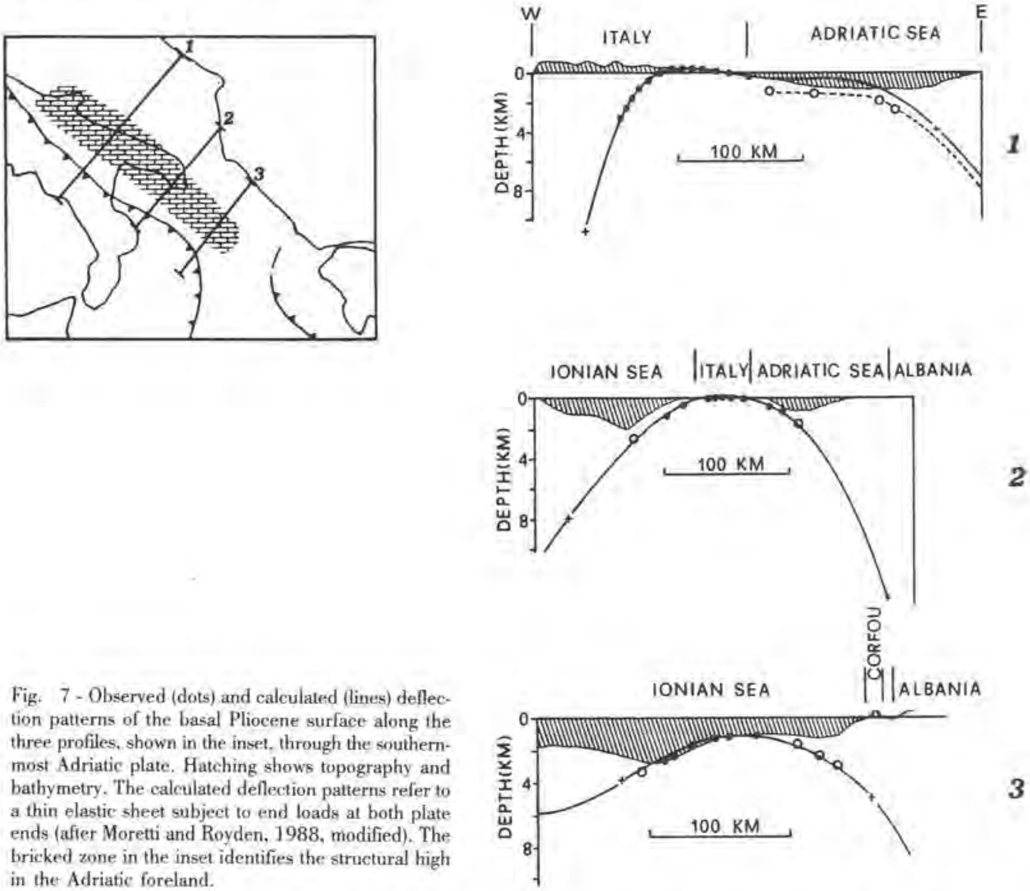


Fig. 7 - Observed (dots) and calculated (lines) deflection patterns of the basal Pliocene surface along the three profiles, shown in the inset, through the southernmost Adriatic plate. Hatching shows topography and bathymetry. The calculated deflection patterns refer to a thin elastic sheet subject to end loads at both plate ends (after Moretti and Royden, 1988, modified). The bricked zone in the inset identifies the structural high in the Adriatic foreland.

fault, was characterized by transpressional movements (see, e.g., Patacca and Scandone, 1989). This allowed decoupling between the Sicily and Calabria blocks, which were moving towards the NW and SE respectively.

- The Sicily Channel was affected by strike-slip tectonics in a compressional stress regime. This type of deformation was accompanied by the formation of pull-apart troughs (Finetti, 1984; Boccaletti et al., 1987; Cello, 1987; Jongsma et al., 1987; Reuther, 1987, 1990). The complex fracturing pattern in the Sicily Channel has led to different interpretations of the stress orientation and regional shear mechanism. Argnani (1993) suggests that the Plio-Quaternary extensional tectonics which affected the Sicily Channel and the simultaneous compressional deformations in the adjacent Gela belt-foredeep system can be explained as consequences of a roll-back mechanism, or of a mantle delamination process. These types of interpretations, however, encounter great difficulties in explaining some major features in the zones surrounding the Sicily Channel, as argued in the last section of this work.

As regards the deep structures, this phase was characterized by the formation of a new slab beneath the Tyrrhenian basin, through the consumption, by a downward flexure, of the Adriatic and Ionian forelands (see Figs. 2c, d). As argued earlier, the two sectors of the slab lying south and north of the Ortona-Roccamonfina line underwent different flexural patterns, due to the greater consumption of the southern part with respect to the northern one.

Upper Pliocene-present

Around the middle-upper Pliocene, the southern Adriatic foreland reached a critical stage of deformation, beyond which any further downward bending began to encounter noticeable resistance. This condition developed after the southern part of the Adriatic plate, i.e., the one most directly stressed by the African displacement, has experienced a bilateral consumption (see Fig. 7), first beneath the Hellenides, in the late Tortonian-Messinian phase, and then beneath the Apennines, in the Messinian-middle Pliocene phase (see Moretti and Royden, 1988). By the upper Pliocene, the southern Adriatic plate had been reduced to its bulge zone, i.e., the present structural high in the Apulia region (the bricked area in Fig. 7). Consequently, the downward flexuring of lithosphere beneath the Southern Apennines underwent a progressive slowdown.

The above hypothesis is suggested by the fact that since the middle-upper Pliocene the outward migration of the rift basin-thrust belt-foredeep system in the Southern Apennines and in the adjacent Tyrrhenian basin has considerably decreased (Patacca et al., 1990; Sartori, 1989). After this event, the Africa-Adriatic convergence, no longer absorbed by the downward bending of the Adriatic margin beneath the southern Apennines, was mainly accommodated by the lateral expulsion of crustal wedges, in particular the SE-ward migration of Calabria, at the expense of the downward bending Ionian foreland (see e.g., Rossi and Sartori, 1981; Sartori, 1989; Patacca et al., 1990; Van Dijk and Okkes, 1991).

In the wake of Calabria, crustal stretching, with a NW-SE extensional trend, occurred in the southernmost Tyrrhenian, i.e., the Marsili basin, with exposure of oceanic crust (Finetti and Del Ben, 1986; Kastens et al., 1988; CNR-PFG, 1989; Sartori, 1989).

Since the Pleistocene, a fast uplift with maximum rates of about 1.5 mm/y, has taken place in eastern Sicily, Calabria, the Southern Apennines and the adjacent foredeep (Ciaranfi et al., 1983; Ghisetti and Vezzani, 1982). This phenomenon might imply that the lateral extrusion of crustal wedges during this phase was accompanied by crustal thickening.

Around the late Pliocene-early Quaternary, the northern part of Calabria collided with the Apulian margin, in the Gulf of Taranto. After this event, Southern Calabria has had the greatest mobility, in terms of SE-ward drifting (Barone et al., 1982). The transpressional lateral guides which were decoupling this last sector from the adjacent ones, i.e., Northern Calabria and the Peloritani block, corresponded respectively to the Catanzaro and Vulcano fault systems (Ghisetti and Vezzani, 1982; Finetti and Del Ben, 1986).

Since the middle-upper Pliocene, normal movements have occurred along the Apulian escarpment (Auroux et al., 1985; Finetti and Del Ben, 1986). This could mark the vertical decoupling between the continental Adriatic foreland, which was not affected any longer by downward bending, and the Ionian foreland, which continued to sink under the SE-ward migrating Calabrian block.

The intensity of the SW-NE Quaternary compressional phase (Barbano et al., 1978; Bousquet and Philip, 1986; Van Dijk and Okkes, 1991) affecting the Calabrian Arc and the southern Adriatic area is also shown by the reactivation of compressional deformations along the Adriatic-Balkan border, in the Outer Hellenides (Mercier et al., 1989).

We advance the hypothesis that since the middle-upper Pliocene the drift trend of the Sicily microplate has undergone a significant variation, passing from roughly NW-ward (see Fig. 2d) to northward (Fig. 2e). This hypothesis can account for the tectonic events which have occurred around this block:

- Lateral motions ceased along the Taormina line, while transpressional tectonics began at the near by Vulcano fault, roughly oriented SSE-NNW (Finetti and Del Ben, 1986; Patacca and Scandone, 1989). Something similar might have occurred on Sicily's other lateral guide, in the northern part of the Sicily Channel, where an almost S-N trending transcurrent discontinuity, the Egadi fault, was activated after the middle Pliocene (Finetti and Del Ben, 1986; Reuther, 1987).

- Geological observations indicate that post-late Pliocene thrust fronts in the Maghrebian belt lying north of Sicily have developed at high angles with respect to the previous phases, and that SW-NE folding ceased in the Adventure plateau and Western Sicily (Catalano et al., 1989; CNR-PFG, 1989).

- Along the Siracusa escarpment extensional activity slowed down considerably (Reuther, 1987). This might be a consequence of the fact that the new motion of Sicily was more parallel to that of the Ionian region, thus implying a lower divergence rate (see Fig. 2e) at the border between these two blocks, i.e., the Siracusa escarpment.

- In the Sicily Channel extensional activity has slowed down since the middle Pliocene (Finetti, 1984; Cello, 1987; Jongsma et al., 1987; Calanchi, et al., 1989). In particular, Argnani (1990) suggested that only minor extension has occurred in this zone since the upper Pliocene. This might be another consequence of the post-middle Pliocene motion of Sicily, which, being more parallel to the drift direction of Africa, involved a lower transcurrent motion along the SE-NW fault system in the Sicily Channel and, consequently, a reduced extensional activity in the pull-apart troughs associated with these faults.

- Around the upper Pliocene, extensional activity began in the Messina Straits, leading to a progressive decoupling between the Peloritani block and Southern Calabria (Barbano et al., 1978; Ghisetti and Vezzani, 1982). Before the upper Pliocene, the Peloritani block was moving in close connection with Calabria and was separated from the Sicilian Maghrebian units by the transpressional Taormina fault. Since the upper Pliocene, when Sicily began to move northward (Fig. 2e), the transcurrency along the Taormina fault has been replaced by a prevalently compressional regime, which has led to the detachment of the Peloritani block from Calabria and to the opening of an angular trough, the Messina sphenocasm.

- The middle Pliocene change in the drift direction of Sicily might also have had some effect on the deformation pattern of deep lithospheric structures. This hypothesis could explain the occurrence and the space-time evolution of the Aeolian calc-alkaline magmatic episode (see e.g., Beccaluva et al., 1982; 1985a). In this regard, it is interesting to note that the Aeolian magmatic activity started and developed along an arc roughly between the Taormina and Vulcano faults, i.e., just in the zone where one would expect the maximum deformation, in terms of wrenching and steepening, of the Ionian subducted lithosphere stressed by the lithospheric roots of the Sicily microplate. This deep collisional pattern only occurred after the change in the Sicily microplate direction. Before this event, the motion of Sicily was parallel to the retreat of the Ionian foreland, towards SE, and, thus, there was no compressional interaction between the Ionian slab and the Sicilian lithospheric block. The hypothesized deformation pattern of the Ionian sunk lithosphere is consistent with the chronological zonation, the ring-like distribution and the general tendency of both calc-alkaline and shoshonitic volcanism to become younger moving counterclockwise in the Aeolian Arc. These features, in fact, have been interpreted as the result of a considerable torsion, segmentation and lateral stretching, accompanied by progressive steepening of the deep plate (Beccaluva et al., 1982; 1985a).

We suggested earlier that the extrusion of the Sicily microplate in the Messinian, and the direction of its lateral expulsion, was allowed, or at least strongly favoured, by the presence of a weak constraint in the Northwestern Tyrrhenian. Coherent with this way of thinking, one might suppose that the change in the expulsion direction of the Sicily microplate was determined by the fact that around the middle-upper Pliocene the zone of crustal stretching in the Tyrrhenian (and thus the weak lateral constraint) was reaching more to the east, after the formation of the central-Tyrrhenian basin (Fig. 2d).

During this phase, the stress regimes and the consequent deformation patterns were significantly different in the Southern and Northern Apennines. The southern part of the chain was no longer directly involved in the Adriatic-Africa interaction zone and started to experience transtensional tectonics, driven by the divergent motion between the Adriatic plate and the Tyrrhenian region (Fig. 2e). The Northern Apennines, however, being stressed by the N/NW displacement of the Adriatic platform, have continued to undergo a NE-ward extrusion, at the expense of the downward flexure of the adjacent foreland.

Fig. 2e shows a tentative reconstruction of the remnant subducted lithosphere beneath the region under consideration, which is also based on structural seismological investigations and on the distribution of deep earthquakes in the southern Tyrrhenian area.

Over the past few years, seismic tomographic analyses have been done in the Central Mediterranean (Spakman, 1990; Amato and Alessandrini, 1991; Cimini and Amato, 1993). The results reported by Spakman (1990) indicate the presence of relatively rigid lithosphere down to depths of some hundreds of km, beneath the southernmost Tyrrhenian in correspondence to the region where deep seismicity occurs, and of a low velocity zone in the depth range 0-200

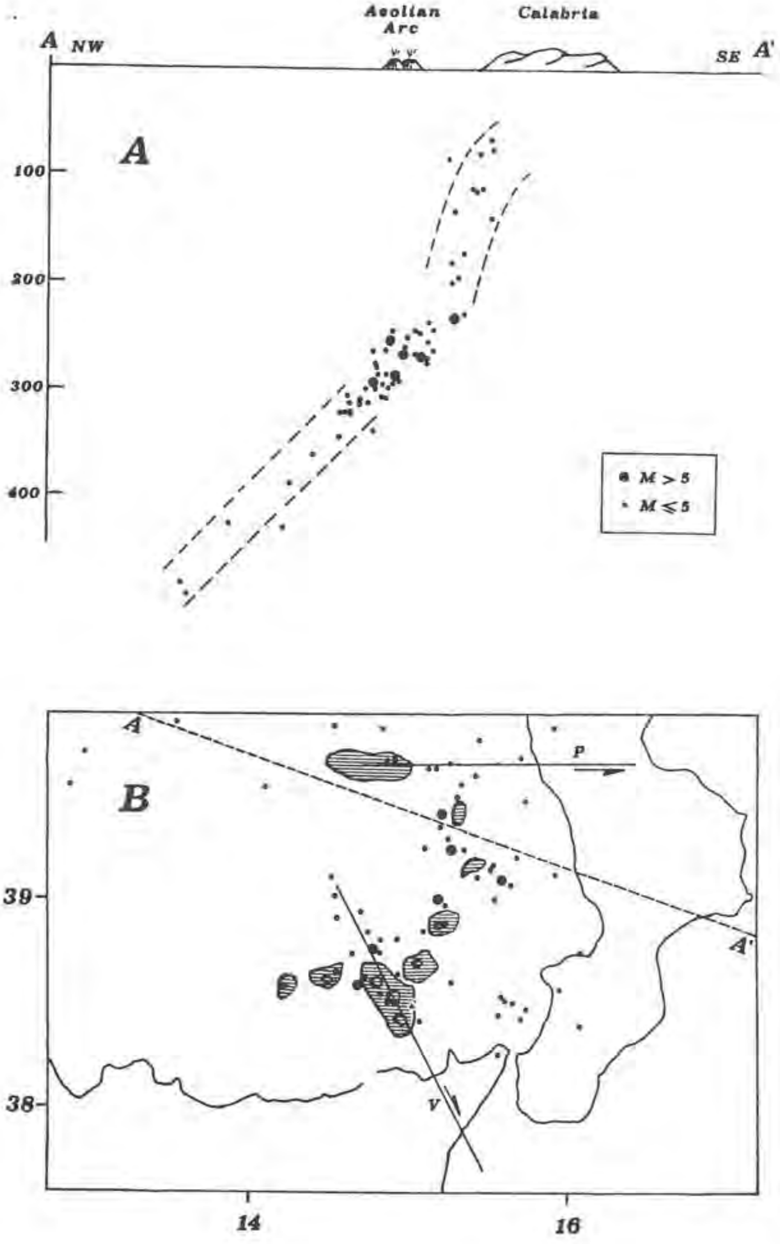


Fig. 8 - A) Distribution versus depth of deep seismicity (h ⩾ 60 km) beneath the southernmost Tyrrhenian along the cross-section (AA') indicated in the map below (after Anderson and Jackson, 1987, modified). At the top of the section the location of the Aeolian volcanic Arc and Calabria are shown. The vertical correspondence between the zone of maximum bending and seismic energy release in the slab and the calc-alkaline volcanic arc at the surface might corroborate the hypothesis that the sources of the calc-alkaline and shoshonitic magmas are closely connected with the most intense deformation of the subducted lithosphere.
B) Epicentres of the deep earthquakes shown in the cross-section. It is interesting to note that most epicentres, and in particular the ones of strongest shocks (M > 5, larger dots), lie within a narrow belt roughly corresponding to the Aeolian Arc. This belt is interrupted north and SW by possible alignments of epicentres along two trends, the Volcano fault (V) and the Palinuro fault (P), respectively, which might correspond to deeply-seated fracture systems (see, e.g., Colantoni et al., 1981; Beccaluva et al., 1982; Finetti and Del Ben, 1986; Gabbianelli et al., 1990). Recent volcanic activity (0.6 My) is indicated by dashed spots.

km beneath the Tyrrhenian-Apennines system. A low rigidity of the slab beneath the Southern Apennines has also been suggested by Giardini and Velonà (1991) on the basis of travel-time residuals from deep Tyrrhenian events.

The results of Amato and Alessandrini (1991) suggest higher velocities, with respect to Spakman (1990), beneath the northernmost Apennines, which could account for the occurrence of some subcrustal earthquakes (h=50-100 km) in that zone.

To explain the uprising of considerable amounts of "subduction related" magmas in the Roman and Neapolitan provinces (Fig. 2e) during the Quaternary (see, e.g., Di Girolamo, 1978; Peccerillo and Manetti, 1985; Beccaluva et al., 1985b; 1989; Conticelli et al., 1986; Di Girolamo et al., 1988; Civetta et al., 1989; CNR-PFG, 1989; Serri et al., 1991) we advance the tentative hypothesis that since the middle-upper Pliocene the slab has undergone considerable deformation and fracturing beneath Central Italy.

This new deformation pattern of the Adriatic sunk lithosphere was determined by two tectonic events. One was the slowdown cessation of the downward flexure beneath the Southern Apennines and the other was the change in the Sicily drift trend from NW-ward to roughly northward. The first event interrupted a mechanism which was allowing the Adriatic-Ionian subducted foreland lying south of the OR line to absorb the motion of Africa, and the second event strengthened the SSW-NNE compression of the Sicily-Africa blocks on the above slab. As discussed earlier, this new dynamic context caused deep compressional interactions at the contact of the Adriatic-Ionian subducted lithosphere with the Sicilian lithosphere. We assume that a similar collisional pattern occurred beneath Central Italy, i.e., at the contact between the two decoupled parts of the Adriatic sunken margin lying beneath the Southern and Northern Apennines, respectively. The sketch shown in Fig. 2d illustrates one possible geometry of the slab's fracturation compatible with the hypothesized dynamic setting. The stretching and wrenching of the deep lithosphere which is implied by the mechanism described above might be responsible for the generation of the magmas which reached the surface in the Quaternary.

The uprising of magmas through and around the sunken lithosphere might have caused a significant acceleration in the heating and disruption of the slab (Nur et al., 1991). This could explain the presence, beneath the western margin of Italy, of an extended low velocity zone, evidenced by tomographic investigations, and by the lack of intermediate earthquakes beneath the Southern Apennines.

The presence of rigid lithosphere beneath the Southern Tyrrhenian, as implied by the occurrence of intermediate-deep earthquakes, is consistent with the fact that along this sector of the belt the building of the slab continued through the Quaternary, by downward flexure of the Ionian lithosphere.

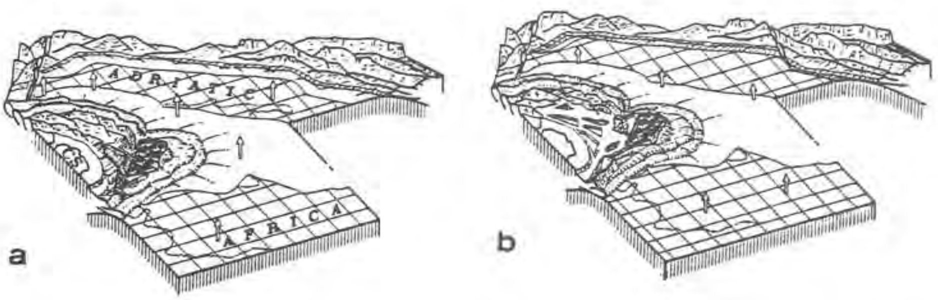
Recent analyses of deep shocks (Anderson and Jackson, 1987; Giardini and Velonà, 1991) have pointed out two major features of the "Tyrrhenian Benioff zone": the concentration of energy release in the depth range 250-300 km and a significant change in the dip of the slab, from about 70°, in the shallower part, to 50°, in the deeper roughly located where the maximum energy release occurs (see Fig. 8).

These features coud be interpreted as consequences of an impending fracturation of the sunk lithosphere, as schematically indicated in Fig. 2e. This fracturation could be due to the fact that the shallowest part of the Ionian slab, being squeezed between the African and Adriatic forelands, tends to steepen and bend downwards. This deformation, however, cannot easily be absorbed by the deeper part of the slab, which is probably trapped in the mantle, and thus some decoupling has to occur between the shallow and deep parts of the subducted lithosphere.

The most intense seismicity being in the depth range 250-300 km might be a consequence of this decoupling mechanism, which seems to be dominated by almost horizontal shear stresses, as suggested by focal mechanisms of deep shocks (Anderson and Jackson, 1987; Giardini and Velonà, 1991). A similar fracturing in the slab beneath the Calabrian Arc has also been suggested by Van Dijk and Okkes (1991) from independent considerations.

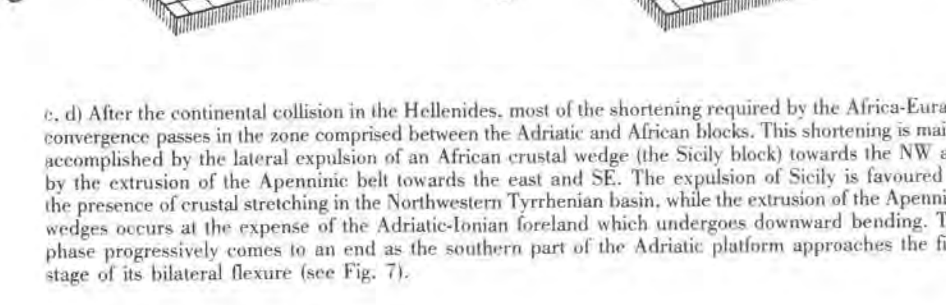
Fig. 9 - Sketch of the shortening mechanisms which accomodated the SSW-NNE Africa-Eurasia convergence in the Central Mediterranean during the three main post-Tortonian evolutionary phases.
For each phase, two sketches are given to illustrate the structural tectonic settings corresponding to the early and late parts of the period considered. The large grid identifies the present size of the Adriatic and African continental domains. The darker mountains inside the Southern Apenninic Arc tentatively indicate the position of the Calabrian massif. The arrows indicate the presumed motion of blocks with respect to Eurasia. CS: Corsica-Sardinia microplate.

FIRST PHASE (late Tortonian to early Messinian)
SHORTENING PROCESSES ALONG THE NORTHERN-EASTERN ADRIATIC BORDER



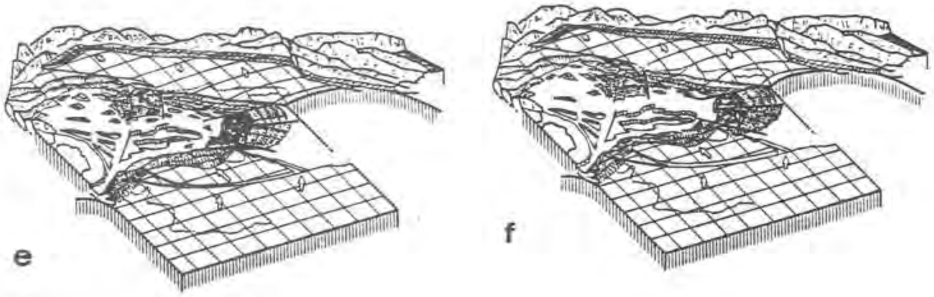
a, b) The activation of the Giudicarie transpressional fault system in the Southern Alps allows the decoupling of the Adriatic block from Eurasia. Driven by the SSW-NNE motion of Africa, the Adriatic plate drifts towards the Balkan zones causing shortening in the Alps, Dinarides and Hellenides. The remaining thinned margin of the Adriatic plate along its eastern border is almost completely consumed during this phase. The divergence between the Adriatic block and the stable Corsica-Sardinia microplate produces extensional tectonics in the interposed belts, causing the formation of the Northwestern Tyrrhenian basin. The progressive slowdown/cessation of this extensional phase is determined by the development of a continental collision in the Hellenides, which considerably decreases the eastward drifting rate of the Adriatic block.

SECOND PHASE (middle Messinian to middle Pliocene)
OUTWARD EXTRUSION OF THE APENNINIC BELT, CONSUMPTION OF THE ADRIATIC-IONIAN FORELAND AND EXTRUSION OF THE SICILY BLOCK.



c, d) After the continental collision in the Hellenides, most of the shortening required by the Africa-Eurasia convergence passes in the zone comprised between the Adriatic and African blocks. This shortening is mainly accomplished by the lateral expulsion of an African crustal wedge (the Sicily block) towards the NW and by the extrusion of the Apenninic belt towards the east and SE. The expulsion of Sicily is favoured by the presence of crustal stretching in the Northwestern Tyrrhenian basin, while the extrusion of the Apenninic wedges occurs at the expense of the Adriatic-Ionian foreland which undergoes downward bending. This phase progressively comes to an end as the southern part of the Adriatic platform approaches the final stage of its bilateral flexure (see Fig. 7).

THIRD PHASE (upper Pliocene to present)
LATERAL EXPULSION OF CALABRIA AND SICILY AND CRUSTAL THICKENING



e, f) No longer absorbed by the consumption of the southern Adriatic foreland beneath the Southern Apennines, the Africa-Adriatic convergence can only be accommodated by the opposite lateral expulsions of the Calabrian block, at the expense of the downward flexing Ionian foreland, and of the Sicily block towards the stretched Tyrrhenian zone. During this phase, the extension in the Tyrrhenian area can only occur towards SE, in the wake of the Calabrian block. The rapid uplift which has affected Sicily, Calabria, Southern Apennines and the adjacent foredeep since roughly the Pleistocene seems to suggest that during this last phase the Africa-Adriatic convergence has been also accommodated by crustal thickening. This tectonic phase is still going on, even though the major mobility of the Calabrian block is now confined to its southern part.

CONCLUSIONS AND DISCUSSION

Proposed evolution

It is hypothesized that a large number of the major and minor deformation events in the central Mediterranean region since the late Miocene can be coherently interpreted in the framework of SSW-NNE convergence between Africa and Eurasia. The shortening required by the Africa-Eurasia convergence has been accommodated by a complex distribution in space and time of lithosphere consuming processes and lateral extrusion of crustal wedges towards weakly constrained borders, as schematically illustrated in Fig. 9 and summarized in the related captions.

One might wonder whether the estimated migrations of the Southern Apennines and the Calabrian Arc towards the Adriatic-Ionian foreland are compatible with the SSW-NNE shortening implied by the Africa-Eurasia convergence (about 150-200 km) that we have assumed in our reconstruction. A rough estimate of the extrusion rates which can be produced by a SSE-NNW shortening of 200 km in a more simplified structural context, suggests that the hypothesized SE-ward migration of the Calabrian Arc for about 400 km cannot be easily accounted for by such a driving mechanism. However, one must remember that extrusion of the Southern Apenninic Arc developed in a geometrical situation involving a progressive narrowing of the lateral confinement, in between the Adriatic and Africa forelands. In Fig. 9 it can be seen, for example that in the Messinian the extruding belt lied between continental walls (the Adriatic and Africa-Sicily forelands) about 500 km apart, whereas in the Quaternary the same belt was being extruded through a "corridor" about 300 km wide. As known from Fluid-Dynamics, a funnel shaped guide increases the extrusion flow rate. The plausibility of this effect is not clearly demonstrated in the case of rock extrusion, but it seems reasonable to suppose that this mechanism might have played a significant role in the evolution of the Calabrian Arc.

For the development of tensional tectonics in the Sicily Channel, three main types of physically plausible mechanisms have so far been proposed: active rifting (Grasso and Pedley, 1985; Grasso and Reuther, 1988; Pedley and Grasso, 1992), slab pull (Argnani, 1993) or mantle delamination (Channel and Mareschal, 1988) and pull-apart mechanisms along transcurrent fault systems

(Finetti, 1984; Cello, 1987; Cello et al., 1985; Mantovani et al., 1985, 1990, 1992, 1993; Boccaletti et al., 1987; Jongsma et al., 1987). In our opinion, the first two types of tectonic mechanism can hardly account for the major deformation in the peri-Sicilian zones during the main extensional phase of the Sicily Channel, i.e., the late Messinian-middle Pliocene period. Both the "slab-pull" and "active rifting" hypotheses would imply a motion of the Sicilian fragment (mainly represented by the Iblean foreland) roughly towards the NE, that is along a direction perpendicular to the main orientation of the troughs in the Sicily Channel. This direction of motion would have required the presence of lateral transcurrent guides oriented routhly SW-NE, to allow the decoupling of the Sicily block from the adjacent regions. However, no evidence of these guides can be recognized in the geological information available for this zone. On the contrary, the presence of extensional tectonics in the Siracusa escarpment, the transcurrent regime along the Taormina fault, the SW-NE orientation of compressional fronts in western Sicily and the Adventure plateau, and the clear presence of strike-slip tectonics in the Sicily Channel can hardly be reconciled with a NE-ward motion of the Iblean foreland. The same features, instead, can all be coherently interpreted as connected with motion of the Iblean foreland roughly towards the NW, as argued before.

In our Africa-Eurasia kinematic model, we have assumed that the convergence between these two plates has progressively slowed over the last 10 My. This is suggested by the fact that the late Miocene-middle Pliocene deformation rates can be satisfactorily accounted for by an Africa-Eurasia convergent motion of about 2 cm/y, whereas the post-middle Pliocene deformations suggest a convergence rate around 1 cm/y. A slowing of the Africa-Eurasia convergence might plausibly be a consequence of the fact that, from the late Miocene to middle-upper Pliocene, the "consumable" margins of the Adriatic promontory have progressively disappeared and thus, shortening processes have become ever more difficult and slow.

Deep tectonics and magmatic activity

As regards deep tectonic processes, we advance the tentative hypothesis that the episodes of subduction-related magmatism in the Tyrrhenian and surrounding regions have been connected with two main circumstances: the occurrence of profound fractures or deformations in the underlying slab, caused by tensional and wrenching mechanisms, and the contemporaneous presence of extensional tectonics in the overlying crustal structure.

Different geodynamic interpretations of magmatic evidence in the Tyrrhenian and peri-Tyrrhenian regions have been proposed in the recent literature (see, e.g., Serri, 1990; Serri et al., 1991). These hypotheses suggest that the petrogenesis and time-space distribution of the upper Tortonian-to-present magmatism is consistent with a model of roll-back subduction and back-arc extension, driven by gravitational sinking of the subducted lithosphere. Following this hypothesis, the formation and eruption of calc-alkaline and shoshonitic magmas from deep mantle sources previously modified by subduction would have been produced by intense rifting, developed along the internal zones of the Apenninic belt during a post-collisional extensional phase (Di Girolamo et al., 1988; Beccaluva et al., 1991). The different composition of magmas between the magmatic provinces lying north and south of the Ortona-Roccamonfina line is explained by supposing that they are related to the subduction of an oceanic lithosphere in the south, and to subduction/deformation of a continental lithosphere in the north (Serri, 1990; Serri et al., 1991).

The major problem in the above interpretative scheme is that it assumes that magma generation was produced by tectonic processes which also occurred in other regions where no or little magmatic activity is observed. For example, geological data clearly indicate that the Southern Apennines have been affected by a roll-back of the Adriatic lithosphere, accompanied by an eastward migration of the rift basin-thrust belt-foredeep system (Patacca and Scandone, 1989). It is not easy to understand why this type of tectonic mechanism, which has been described as responsible for "subduction related" volcanism in the Central-Northern Apennines, has produced almost no magmatic activity in the Southern Apennines, south of the Campania province.

Moreover, the hypothesis that the subduction process south of the Ortona-Roccamonfina line involved oceanic lithosphere contrasts with the conclusions of Casero et al. (1988) and

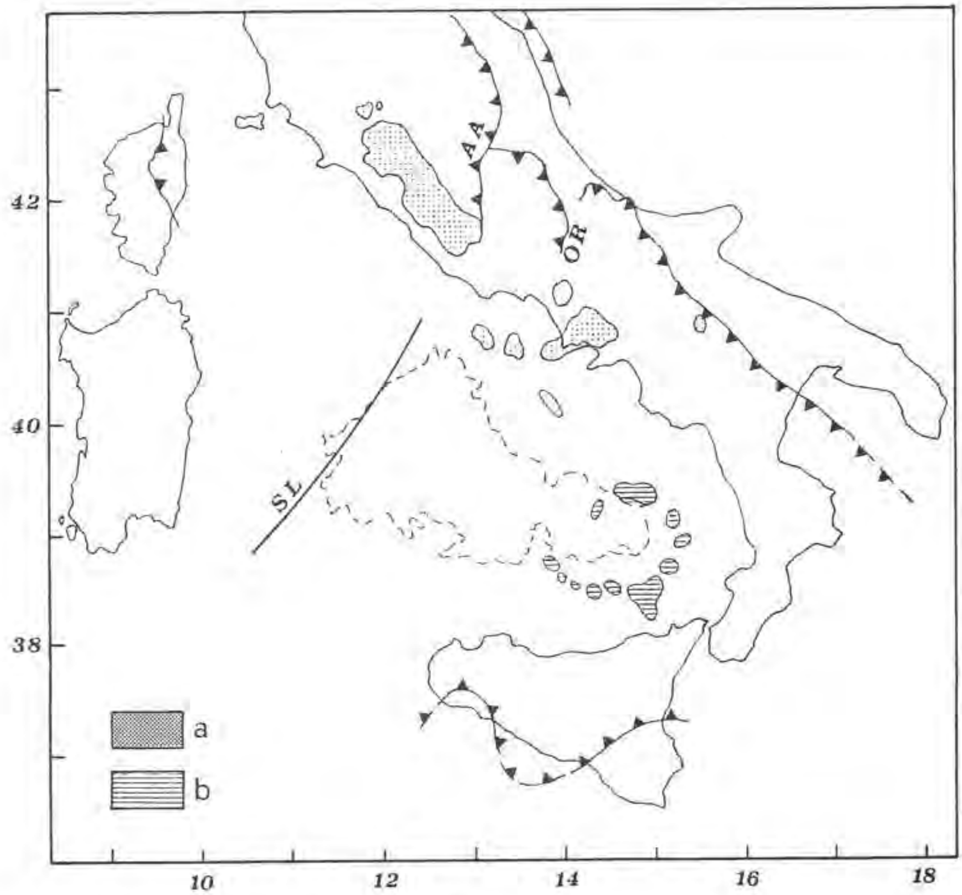


Fig. 10 - Pleistocene subduction-related volcanism in and around the Tyrrhenian Sea (CNR-PFG, 1989). a) Roman and Neapolitan Province; b) Southern Tyrrhenian Province. AA = Ancona-Anzio line; OR = Ortona-Roccamonfina Line; SL = Selli line. The dashed line contours the Tyrrhenian bathyal plain.

Patacca et al., (1990), who, on the basis of geological data, suggested that a continental lithosphere was consumed beneath the Southern Apennines.

More in general, we think that if the generation of calc-alkaline and shoshonitic magmas was simply connected with roll-back subduction and extensional tectonics in the overlying crust, one should expect a more regular and continuous distribution in space and time of volcanic activity along the western side of Italy and in the Tyrrhenian basin. On the contrary, the subduction-related activity has mainly occurred in relatively small zones (Central Italy and the Aeolian Arc) and during relatively short time intervals: a Pliocene phase in the Tyrrhenian (Sartori, 1989), and a Quaternary phase, in Central Italy and in the southernmost Tyrrhenian.

We advance the hypothesis that the discontinuous distribution of volcanic activity in space and time can be better explained as an effect of particular thermo-baric conditions which developed in the subducted lithosphere, during its tectonic evolution. In our scheme we have supposed that these "particular conditions" were connected with stretching or wrenching of the slab, since such mechanisms seem to be the most probable in the geodynamic framework here proposed. The Pliocene calc-alkaline magmatic activity in the Tyrrhenian just followed the period of greater mobility of the Adriatic plate (Fig. 2c). It appears plausible, from the mechanical point of view, to assume that the displacement of the Adriatic plate induced E-W extensional stresses and stretching in its subducted margin, favouring melting processes and consequent uprising of magmas through the Tyrrhenian crust, which by that time was experiencing an extensional regime.

A new phase of subduction-related magmatism occurred extensively in the Quaternary, along the Tyrrhenian side of Italy and in the southernmost Tyrrhenian (see Fig. 10). We suppose that the causal mechanism of this new magmatic episode was analogous to that of the Pliocene episode, i.e., connected with stretching and wrenching of subducted lithosphere. In this last case the fracturing slab was the one built up during the Messinian-middle Pliocene tectonic phase. The stress regime which led to this fracturation of the slab beneath central Italy started approximately in the middle Pliocene, when the downward bending of the southern Adriatic foreland ended (see Fig. 2d). After this event, the displacement of Africa, no longer accommodated by the consumption of the Adriatic lithosphere beneath the Southern Apennines, caused an increase of stress over the whole subducted Adriatic margin, which could have produced the deep deformations tentatively reconstructed in Fig. 2d,e, with the consequent melting and generation of magmas. The proposed connection between slab deformation/fracturing and the generation of subduction-related magmas seems to be corroborated by the good spatial correspondence between the zone of maximum deep seismicity and the Aeolian volcanic arc (see Fig. 8).

Previous evolutionary models

Whoever presents a new evolutionary hypothesis, as we do in this work, has to provide some plausible explanation of why the model should be preferred to the previous ones. Otherwise any new interpretation risks increasing ambiguity about the Mediterranean geodynamic evolution rather than reducing it.

In this respect, we refer to the discussion on alternative models which is given by Mantovani et al. (1992). Here we only devote some further remarks to the hypotheses which describe the roll-back of Adriatic-Ionian lithosphere and consequent opening of the Tyrrhenian basin as effects of gravitational sinking (see e.g., Malinverno and Ryan, 1986; Royden et al., 1987; Patacca and Scandone, 1989), or of pushing by an eastward mantle flow (Doglioni, 1991), which are often mentioned in the recent literature.

These kinds of hypothesis can account for the downward flexure of the Adriatic-Ionian foreland beneath the Apenninic Arc, but cannot easily explain other major Plio-Quaternary deformation events in the surrounding regions.

As the opening of the Tyrrhenian basin and the evolution of the Apenninic belt have developed in three main phases, characterized by rather different tectonic conditions, it seems opportune to analyse the plausibility of the "gravitational sinking" and "mantle push" models for each single phase.

The first extensional phase, which approximately occurred from the late Tortonian to the Messinian in the Northwestern Tyrrhenian, can hardly be interpreted in the framework of the above two hypotheses, since for this time interval, there is no clear evidence of intense outward migration of the chain, or of orogenic activity in the Northern Apennines and downward bending of the adjacent Adriatic foreland (see, e.g., Vai, 1987; Castellarin et al., 1992). Moreover, from the geometry of the Oligo-Miocene calc-alkaline arc and other tectonic considerations on the opening of the Balearic basin, it seems reasonable to believe that in Tortonian times, prior to the Tyrrhenian opening, the subducted lithosphere was mainly beneath the most arcuate sector of the belt, i.e. that lying south of the Selli line (see Fig. 2a, b). Given this structural premise, one would expect that the maximum effects of the "gravitational sinking" or "eastward mantle push mechanism", have occurred in the southern Tyrrhenian.

The second extensional phase developed in the central Tyrrhenian region from the Messinian to the middle-upper Pliocene and was accompanied by roll back of the Adriatic foreland (see e.g., Patacca et al., 1990). However, if this event and the evolution of the surrounding regions are explained as an effect of "gravitational sinking" or of "mantle push", it is not easy to explain the presence of a SW-NE compressional stress regime in the zone comprising Sicily, the Calabrian Arc, and the Southern Apennines, and the occurrence of roughly S-N oriented compression in the Central Apennines. Other major evidence which does not seem compatible with the above mechanisms is the deformation pattern around the Sicily block, which took place from the

Messinian to the middle Pliocene, as argued earlier in this paper.

Furthermore, one could ask why during this phase the gravitational sinking or mantle push driving mechanisms had significant effects in the central Tyrrhenian only, in spite of the fact that subducted lithosphere was present in the adjacent sectors of the Adriatic-Ionian foreland (see Fig. 2a).

In the last extensional phase (upper Pliocene to present), crustal stretching only occurred in the southernmost Tyrrhenian (Marsili basin), with a SE-ward extensional trend, in connection with downward bending of the Ionian lithosphere. Eastward migration of the rift-thrust belt-foredeep system had instead ceased in the Southern Apennines. How can the gravitational sinking or mantle push mechanisms explain these different flexural behaviours of the Adriatic and Ionian forelands during this last phase? Furthermore, these driving mechanisms cannot account for the presence of a SSW-NNE compressional regime in the Calabrian Arc and Southern Apennines, and for the fast uplift of these regions over the last million years. Such types of deformation cannot easily be attributed to the downward flexure of the Ionian margin. Even if one can find a plausible answer to this problem, it remains to be understood why uplift has also occurred in the Southern Apennines where the roll-back mechanism had already ceased or at least considerably slowed down.

Concerning the mantle push mechanism, it is not clear how the application of this hypothesis to the evolution of the Tyrrhenian region (Doglioni, 1991) can take into account perturbations of the mantle flow regime, which result from the presence of large slabs at depth.

For example, it seems reasonable to expect that beneath the Tyrrhenian the supposed eastward flow of the mantle is strongly deformed by the presence, in front of it, of a large lithospheric edifice plunging down to a depth of 400-500 km. The consequences of these deep perturbations on the shallow tectonic pattern should be predicted and compared with observed deformations.

More in general, the main problem of the gravitational sinking or mantle push hypotheses appears to be the difficulty in explaining why the roll-back of the Adriatic foreland has successively occurred in certain places and at certain times. In our opinion, this difficulty is due to the fact that the above hypotheses are partial concepts, which only recognise the second stage of the complete real mechanism. The sinking of continental-like lithosphere cannot occur if it is not preceded by another tectonic process, the decoupling between the upper and lower crust, which considerably decreases its buoyancy (see, e.g., Molnar and Gray 1979). Consequently, the distribution in space and time of lithospheric sinking is mainly conditioned by the occurrence of collisional patterns, and consequent scraping off processes, which can turn a buoyant continental plate in a "subductable" lithosphere. Thus, to understand why and where downward bending of the Adriatic margin occurred, it is first necessary to recognize the mechanism which led the Alpine-Apenninic belt to collide with the adjacent Adriatic foreland. Royden (1993) classifies the Adriatic-Apenninic system as a "retreating plate boundary" and states: "subduction occurs in this type of boundary only when the downgoing plate has a sufficiently high density that gravity can drive the subduction process. An important consequence of this is that subduction at retreating plate boundaries generally ceases shortly after the entry of thick buoyant continental crust into the subduction zone". This view, however, contrasts with the fact that a considerable part of the Adriatic foreland which disappeared beneath the Southern Apennines during Messinian-Lower Pliocene times had most probably a continental-like structural character (Casero et al., 1988; Patacca et al., 1990). The above difficulty could be removed if one modifies the concept described by Royden (1993) as follows: "Subduction at retreating plate boundaries ceases when the collisional pattern in the trench zone, and thus the scraping off of the descending lithosphere, is interrupted by local structural-tectonic circumstances". For instance, the slowdown/cessation of thrusting in the Southern Apennines in the upper Pliocene-Quaternary might have been determined by local effets, such as the previous strong flexure of the southern Adriatic foreland, as argued earlier in this work.

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