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A mantle plume head trapped in the transition zone beneath the Mediterranean: a new idea

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We compare subduction and plume models for the Apennines and the Western Mediterranean. The impingement of a hot plume on the base of the Mediterranean lithosphere is ruled out due to the lack of distinctive signatures, such as excess topographic elevation, deep thermal regime and extensive flood basalts. However, a progressively eastward-grown plume head confined within the transition zone (between the 670 km and 410 km discontinuities), fed from the core-mantle boundary and controlled by the circulation in the upper mantle is considered to be a reasonable hypothesis. A simple area balance methodology is used in order to predict the size of such a plume along a regional transect extending from the Gulf of Lyon to Calabria. Equivalence is assumed to exist between the area of the plume head that enters within the transition zone and the area of the asthenosphere that is pushed laterally. The eastward-expanding asthenosphere drives the stretching of the overlying lithosphere and, therefore, the amount of net lithospheric extension (l_{final}-l_{initial}) is a direct expression of the amount of lateral asthenospheric expansion. The past sizes of the plume, before the onset of the Tyrrhenian phase (about 16 Myr ago) and at the beginning of the Ligurian-Provençal phase (about 30 Myr ago), are evaluated using the same balancing criteria. The possible shapes of the Mediterranean plume at the different deformation stages are supposed and depicted integrating the balancing technique with inputs from the literature on the geometry of numerically modelled plume heads trapped within the transition zone. The Apennine-Maghrebian fold-and-thrust belt is interpreted as an indirect plume product due to rift push forces which developed at the outer border of the Mediterranean stretched and thinned lithosphere. The peculiar geochemical and isotopic composition of the Italian Quaternary high-K and ultra-alkaline magmatic products is interpreted as strictly related to the enrichment of the mantle source by metasomatising fluids released within the asthenosphere by the plume head. The large-scale tomographic velocity pattern detected in the Mediterranean region might be compatible with the proposed trapped plume model if interpreted in terms of chemical variations rather than of thermal variations.

5.1. INTRODUCTION

A large variety of subduction models have been proposed in the literature for the geodynamic evolution of the Mediterranean and the Apennines of Italy. Processes mainly range from active subduction, to slab roll-back (with trench retreat and back-arc opening), to lateral migration of slab detachment (Scandone, 1980; Scandone and Patacca, 1984; Finetti and Del Ben, 1986; Malinverno and Ryan, 1986; Royden *et al.*, 1987; Doglioni, 1991; Doglioni *et al.*, 1997, 1999, 1998; Lonergan and White, 1997; Carminati *et al.*, 1998; Jolivet and Faccenna, 2000; Wortel and Spakman, 2000; Mantovani *et al.*, 2002; Rosembaum *et al.*, 2002; Faccenna *et al.* 2003, 2004 among many others). All of these models assume the westward subduction of the Adriatic-Ionian lithosphere as a primary feature in controlling the evolution of the Mediterranean and the Apennines.

In this paper, we do not intend to compare and discuss the above models, but to open a discussion on alternative solutions. With this aim, we compile a brief list of the major problems that arise assuming the westward subduction of the Adriatic-Ionian lithosphere. Then, we consider a plume model proposed by Bell *et al.* (2003, 2004, 2006) to explain the peculiar geochemistry and isotopic features of the volcanic activity in Italy. We try to develop their model further, defining the possible size, depth and time evolution of such a plume in the Western Mediterranean. The basis for the definition of a possible shape and growth pattern for this plume derives from the comparison with numerically modelled mantle plumes in the literature (Brunet and Yuen, 2000).

5.2. SOME OF THE PROBLEMS WITH SUBDUCTION IN ITALY

In our opinion, the occurrence of a west-dipping subduction plane (the so-called Adria slab) controlling the development of the Tyrrhenian-Apennine system is not likely for a number of different reasons.

1) Available deep crust seismic reflection and refraction data show that during the Late Cretaceous-Eocene Alpine tectonic phase, the Tethyan oceanic lithosphere was southeasterly subducting beneath the Adriatic continental plate (Scarascia *et al.*, 1994; Finetti *et al.*, 2001). In order to justify a westerly dip for the Adriatic lithosphere during the Oligocene to Quaternary Apennine tectonic phase, it is necessary to flip the subduction polarity from east to west-directed (Doglioni *et al.*, 1997, 1998). This flip is hard to accept as it would have had to occur at around 35 Myr ago, when the NNW-SSE Africa-Europe convergence had decreased to less than 1 cm/yr (Doglioni *et al.*, 1999 and references therein) and when between the European and African plates there was no more available oceanic lithosphere to be subducted, other than the paleo-Ionian corridor east of Sardinia.

2) If the Ionian crust is really oceanic or if it is a thinned and attenuated continental crust is still a matter of debate (de Voogd *et al.*, 1992; Cernobori *et al.*, 1996). In any case, the subduction of the Ionian lithosphere beneath the Calabria arc has an along-strike length of a few hundred kilometres and, thus, it cannot help to explain the entire Apennine-Maghrebian belt that extends for about 3500 km from the Monferrato Arc to the Gibraltar Arc (fig. 5.1c).

3) Although a subduction process involving the continental lithosphere in the rear of a subducting oceanic lithosphere is considered possible (Ranalli *et al.*, 2000), a subduction process that involves *ab initio* the continental lithosphere would be incapable of starting, due to the lack of the necessary negative buoyancy. In order to justify a W-directed subduction of the Adria continental lithosphere during the Neogene-Quaternary Apennine phase, it would be much easier to propose a single west-dipping subduction process running since the onset of the Alpine phase in Late Cretaceous times (Jolivet and Faccenna, 2000; Faccenna *et al.*, 2003, 2004). But, in this case the problem still remains as to why the westernmost extensional basins of the Mediterranean (*e.g.*, Alboran, Valencia and Provençal basins), that would be a direct expression of the Adria slab retreat, developed obliquely to the trend of the Alpine-Betic orogen (fig. 5.1a). The Alboran Basin developed within the Betic Chain, whereas the Valencia and Provençal basins nucleated behind the Alpine NW-verging front and within the European foreland zone (Doglioni *et al.*, 1997). In addition, the progressive SE-ward roll-back of the Adriatic lithosphere implies an along-strike extension of the subduction plane from an initial length of about 1500 km, measured from the Gibraltar Arc to the Ligurian Region at about 30 Myr ago (fig. 5.1a), to a present length of about 3500 km (fig. 5.1c). This would imply evident slab segmentation achieved by strike-slip faulting and/or by normal faulting. Consequently, the Apennine-Magrebian fold-and-thrust belt, genetically linked to the retreating slab, would be highly discontinuous along the strike. On the contrary, it is substantially continuous.

4) Assuming a model of progressive along-strike slab detachment (Carminati *et al.,* 1998; van der Meulen *et al.*, 1998; Worthel and Spakman, 2000), we would expect a consequent variation in vertical motions, stress fields and magmatism along the strike of the Apennines mountain chain. However, the Apennines thrust-foredeep system has a clear eastward trench migration; extensional tectonics and magmatism rejuvenate eastwards, as well (Kastens and Mascle, 1990; Patacca *et al.*, 1990; Savelli, 2002).

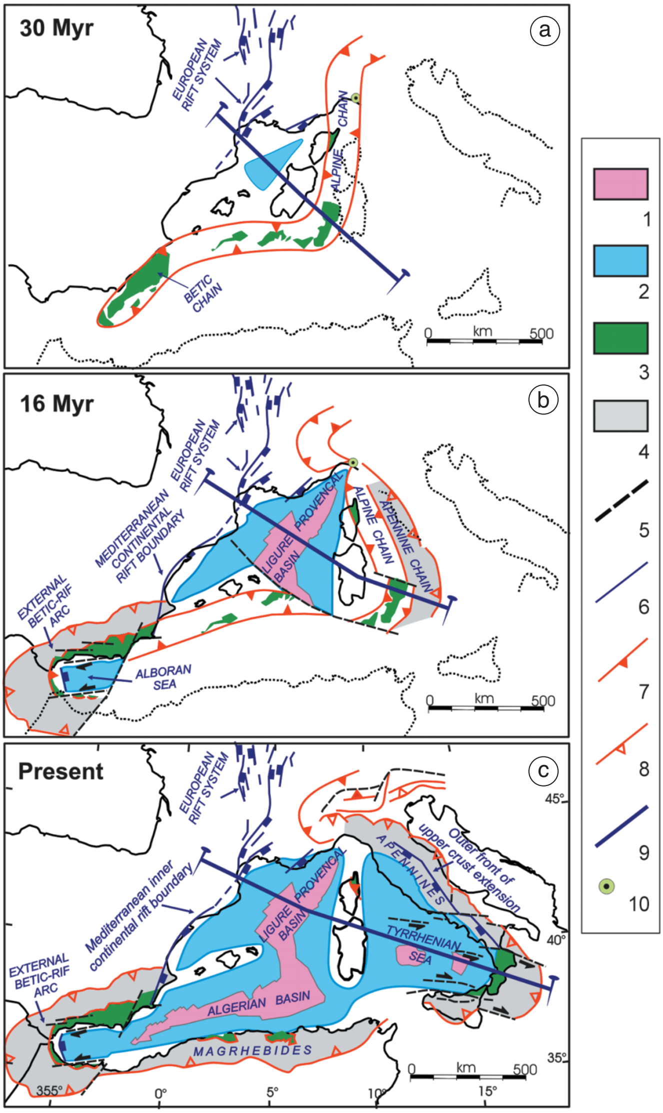

Fig. 5.1a-c. Schematic map of the Western Mediterranean extensional basins and of the Apennine-Maghrebian fold-and-thrust belt system at different deformation stages (after Scandone and Patacca, 1984; Patacca *et al.*, 1990; Doglioni *et al.*, 1999; Gelabert *et al.*, 2002; Speranza *et al.*, 2002; Faccenna *et al.*, 2004) with trace of the sections of fig. 5.2a-c. a) Tectonic scenario during the first stage of the Ligurian-Provençal phase in Early Oligocene times; b) tectonic scenario after the end of the Ligurian-Provençal phase and before the onset of Tyrrhenian phase at the end of Burdigalian times; c) present tectonic scenario. Key: 1 – ultra-thinned crust (<15 km); 2 – thinned continental crust (<25 km); 3 – relicts of the Alpine-inner Betic orogenic belt; 4 – Apennine-Maghrebian and External Betic-Rif compressional domain; 5 – lithospheric transfer faults; 6 – outer boundaries of the Mediterranean extensional domain; 7 – Alpine-inner Betic thrust fronts; 8 – Apennine-Maghrebian and External Betic-Rif thrust fronts; 9 – traces of the section in fig. 5.2a-c; 10 – pivot point during the Ligurian-Provençal and Tyrrhenian tectonic phases.

5) There is no balance between the along-dip length of the Adriatic subduction plane (maximum length of ~600 km offshore Calabria; Selvaggi, 2001) and the shortening of the Apennine fold-and-thrust belt system. The area of the entire Apennine crust in Calabria is smaller than the area of the only upper crust that would be involved in the accretionary prism (Doglioni *et al.*, 1999). Still, a thick-skinned style of the deformation, with basement largely involved in the deformation and with limited amounts of horizontal shortening, characterises both the Central and the Southern Apennines (Barchi *et al.*, 1998; Noguera and Rea, 2000; van Dijk *et al.*, 2000; Lavecchia *et al.*, 2003).

6) The Aeolian insular arc, a key element of the subduction hypothesis, cannot be related to the subduction as it has a ring-like shape which does not correspond to the much larger radius of curvature of the Southern Tyrrhenian Benioff plane (Selvaggi, 2001). Magma sources connected to a down-going slab would form a more or less continuous volcanic zone at a constant depth along the subduction zone. The distribution at the surface of the Aeolian volcanic centres demonstrate that it is not governed by the geometry of the slab at depth. Although a calc-alkaline activity has been claimed for the Aeolian magmatism, at closer inspection it appears to be more closely related to within-plate magmatism (Bell *et al.*, 2006). Furthermore, the Quaternary magmatic occurrences of Ustica and Promoteo, that are sited to the Aeolian Islands, within the Southern Tyrrhenian Basin and above the Benioff plane, share OIB-type geochemical features with the Etna and the Hyblean Plateau volcanoes, that are independent from subduction being sited on the rear of the subduction hinge zone (Trua *et al.*, 2003).

7) The intramontane ultra-alkaline province is characterised by a rare carbonatite-kamafugite rock association that is exclusively find in intra-continental extensional tectonic settings far from subduction (Lavecchia and Stoppa, 1996; Stoppa and Woolley, 1997; Lavecchia *et al.*, 2006). In addition, the high-potassic alkaline magmatism of the Roman-Campanian Province is characterised by an extreme enrichment of incompatible elements that can be hardly reconciled with a subduction-related environment (Cundari, 1979, 1994; Bell *et al.*, 2006). In general, the peri-Mediterranean magmatism is dominantly non-calc-alkaline and the major active volcanoes (Stromboli, Etna, Vesusius) erupt basaltic lavas typical of plume activity (Gasperini *et al.*, 2002).

8) The subcrustal seismicity (<100 km) beneath the Central Apennines and the deep seismicity (up to ~600 km) off Calabria are commonly considered one of the most striking evidence of the on-going subduction of the Adriatic lithosphere beneath the Tyrrhenian Sea (Selvaggi, 2001, among many). As a matter of fact, this seismicity does not conform to standard subduction models (Giardini and Velonà, 1991). The subcrustal seismicity beneath the Central Apennines appears to be independent of subduction and, instead, it reflects the activity of a SW-dipping, intra-lithospheric, reverse shear-zone (Lavecchia *et al.*, 2003). The seismicity off Calabria defines a Benioff plane which in plan view has a very limited lateral extent (about 250 km) and in section view has a rather unusual concave shape. The seismogenic volume is slightly ESE-dipping in the depth range between 30 and 180 km and has a WNW-ward dip of about 70° beneath about 200 km (fig. 3 in Milano *et al.*, 1994; fig. 1 in Selvaggi, 2001). Tomographic models of the mantle beneath the Apennines show the presence of an intra-asthenosphere high-velocity body, but the images are very different in length, position and continuity (Spakman *et al.*, 1993; Mele *et al.*, 1998; Lucente *et al.*, 1999; Cimini and De Gori, 2001; Piromallo and Morelli, 2003; Piromallo and Faccenna, 2004). Overall, seismicity and tomographic data do not prove the westward subduction of the Adriatic lithosphere.

9) As pointed out by Scalera (2006), a fundamental difficulty of subduction models in the Mediterranean and surrounding regions comes from the need for an incredibly high number of downgoing slabs, sited in relatively small space and time and having different dips, strikes and kinematics. In particular, the WNW-dipping Benioff plane off Calabria and the NE-dipping Aegean Benioff planes are close in contact, at a distance of 50 km, and perform non-compatible simultaneous movements.

10) As a matter of fact, when looking at the Mediterranean-Apennine region it is evident as the amount of contraction does not equal the amount of extension, the last being enormously in advantage. Then, given that since Oligocene times extension has acted as the primary plate tectonic process in the region, why not to look for an extensional-type deep-sited engine rather than subduction?

5.3. THE PLUME HYPOTHESIS

5.3.1. Pioneer models on active mantle upwelling and plume in Italy

About twenty five years ago, a few authors (Cundari, 1979; Wezel, 1981; Locardi, 1982) proposed, as an alternative to subduction, mantle upwelling as the driving force for the geodynamic and magmatogenetic processes in the Western Mediterranean and related fold belts. They mainly considered vertical mantle motions, with prevailing midplate domal upward; the outward moving topography was thought to generate thrusts and gliding nappes. Such a model was not popular because of the growing force of the subductionist approach, but also because it was strongly based on a vertical tectonic concept. This was in contrast with the evidence in the Mediterranean region of a prevailing horizontal tectonics, testified by the extreme eastward migrating stretching of the continental crust and lithospheric mantle.

About seventeen years ago, Locardi and Nicolich (1988) noticed that no subduction-related structures had been outlined from deep seismic refraction (DSS) data, either in the Tyrrhenian Basin or in the Apennine area. In their opinion, DSS data available at that time rather showed the presence beneath the Northern and Southern Tyrrhenian basins of two upwelled mantle domains (asthenolithes), possibly due to the transformation of the lithospheric mantle enhanced by heat and fluids from below. The thinning of the Tyrrhenian Sea and the tectonic evolution of the Apennines were interpreted as related to the eastward flow of the asthenolitic domes.

About ten years ago, Hoernle *et al.* (1995), based on global upper-mantle seismic tomography and isotope geochemistry of Cenozoic volcanic rocks, showed a large low-velocity anomaly extending across the Western Mediterranean and Western European lithosphere. This anomaly was related to a wet metasomatised upwelled mantle. In the same year, Granet *et al.* (1995) proposed a thermal and chemically anomalous mantle plume beneath the Massif Central in France during Tertiary times.

About five years ago, Goes *et al.* (1999) and Ritter *et al.* (2001) identified by global tomography a broad anomaly (500×500 km^2) in the lower mantle below Central Europe and interpreted it as a deep plume-like structure trapped in the transition zone (between the 670 and 410 km discontinuities). In their opinion, this plume represented a common source for the active upper-mantle plumes beneath the Massif Central, the Eifel volcanic field (Germany) and possibly other Tertiary volcanic fields in Europe.

In recent years, Gasperini *et al.* (2000, 2002), based on the geochemistry of Plio-Quaternary Italian basaltic volcanics, considered the storage of a plume head in the deep mantle and the rise of deep mantle material through a broad slab window in the west-dipping Adriatic lithosphere. The same research group also proposed a possibly plume-related origin for the Tertiary alkaline basaltic volcanism of the Veneto region, in the South-Eastern Alps foreland (Macera *et al.*, 2003). A plume-modified asthenospheric mantle source has also been considered by Coulon *et al.* (2002) in association with the emplacement of typical Plio-Quaternary within-plate alkaline basalts in Oranie (Algeria).

Lastly, Bell *et al.* (2003, 2004, 2006) demonstrated that the Sr-Pb-Nd isotope signature found in Italian rocks and commonly attributed to involvement of recycled and aged limestone and other upper crust carbonate-rich material is not a crustal component, but a deep mantle component. They attributed the entire post-Oligocene Italian magmatism to low degrees of partial melting of a volatile-rich plume head underlying the Tyrrhenian Sea, independent of any subduction.

5.3.2. The opportunity of a plume model in Italy

The impingement of a plume head on the base of the continental lithosphere would produce a number of distinctive features (Condie, 2001) that are not observed in the Mediterranean. It would dynamically support regionally high topographic elevation, such as it is seen, for example, in the East African Rift System (Lithgow-Bertellon and Richards, 1998). The African Plateau has an average elevation of 1 km, the US Cordillera exceeds 1.5 km, whereas the Mediterranean stands on average 1.2 km beneath the sea-level. In addition, an anomalous deep thermal regime in the Central Mediterranean is excluded by gravity modelling of the litho-asthenosphere system (Cella *et al.*, 1998) and by experimental petrology data (Cundari and Ferguson, 1991; Panina *et al.*, 2003; Stoppa *et al.*, 2003) that indicates a geotherm typical of continental lithosphere (Bailey and Collier, 2000; Lavecchia *et al.*, 2002). Still, in the Mediterranean, a sufficient amount of flood basalts is not produced and the time-space relationships between extensional tectonics and magmatism are not typical of active mantle doming. In fact, at any given place the magmatism always follows the normal faulting in time (Lavecchia and Stoppa, 1996).

For all of these reasons, in previous papers we excluded a plume beneath the Tyrrhenian Basin and proposed a model of passive asthenospheric upwelling driven by stretching and thinning of the continental lithosphere (Lavecchia and Stoppa, 1996; Lavecchia *et al.*, 2002). This model needs an engine able to drive the eastward extension of the lithosphere. For the previously discussed reasons, we exclude the retreat of the Adriatic-Ionian slab as the likely driving mechanism. Alternatively, the extension of the lithosphere might be driven by horizontal far-field forces associated with an eastward motion of the Adria microplate (Adria pull), but this does not fit with available data on large-scale plates motion. Since Late Cretaceous times, the motion of Africa relative to Eurasia has been converging and WNW to NNW oriented (Faccenna *et al.*, 2003, and references therein). Space geodesy data confirm a present-day NW-ward motion of Africa relative to Eurasia, at an average convergent rate of about 0.5 $\mathrm{cm\,yr^{-1}}$ (McClusky *et al.*, 2003). Therefore, it is necessary to identify an engine acting within the Mediterranean system. This necessity, together with the geochemical evidence of a possible plume-related magmatic activity in Italy (Gasperini *et al.*, 2002; Bell *et al.*, 2003, 2004, 2006) as well in the Northern African margin (Coulon *et al.*, 2002), has forced us to re-consider the possibility of a plume model for the Mediterranean and the Apennines.

5.3.3. Brief introduction to plumes

Plumes are narrow, low-viscosity conduits in a variable-viscous fluid, up which buoyant material preferentially rises until flattening in a large plume head (Condie, 2001). Plumes can be of variable size, temperature and depth of origin (Ernst and Buchan, 2002, and references therein). Some plumes are believed to be generated at the thermal boundary layer at the top of the lower mantle, others to arise from the D'' thermal boundary layer at the core-mantle interface. The spinel to olivine phase transition at the core-mantle interface induces the ejection of very fast plume material within a very thin vertical channel towards the surface (Brunet and Yuen, 2000). When the plumes arrive at the 670 km discontinuity, they may be detained from further rise creating a large plume head that grows within the transition zone (between the 670 and 410 km discontinuities). The asymmetric growth of the plume material trapped in the transition zone is controlled by the large scale circulation of the upper mantle (Zhao, 2001). Two main types of plumes detaching from the core-mantle boundary may be identified: stable vertical plumes, which extend throughout the mantle for several hundred million years, such as the Emperor-Hawaiian one, and, unstable fast moving plumes, which are bent and move relative to the global circulation, such as those in the super swell area in the South Pacific (Brunet and Yuen, 2000). Fast moving plumes can generate several reservoirs of plume material in the transition zone. The process of injection of new material from the lower mantle in the transition zone may repeat itself with a period of some tens of million years; this pulsating mechanism may be responsible for the periodicity of intraplate volcanism (Brunet and Yuen, 2000).

5.4. THE MEDITERRANEAN TRAPPED PLUME

5.4.1. Plume typology and size

In our opinion, a model of fast moving plume that arises from the core-mantle interface (D''-layer) and stagnates within the transition zone, where it progressively grows eastward, might be sufficient to explain the birth and temporal evolution of the Mediterranean basins and of the Apennine-Maghrebian thrust belt. The asymmetrical shape of the plume head would be governed by the eastward-directed large-scale circulation of the upper mantle (Zhao, 2001); the size would be governed by the process of injection of new material from the lower mantle in the transition zone. The deep-mantle material injected from the D''-layer within the Mediterranean plume head would have an extremely high concentration of volatile elements (Ti, Al, Fe, Mn, Ca, Na, K, H_2O and CO_2, Rb. Sr, Y, Zr, Nb, Ba) and rare Earth elements (Cundari, 1979, and references therein). The isotopic elements would be highly radiogenic coming from older and undepleted regions of the mantle. While stagnating within the transition zone, the plume head material would progressively release H_2O- and CO_2-rich fluids to the overlying asthenosphere.

Such a type of plume would not produce meaningful flood basalts (Bell *et al.*, 2003) and thermal anomalies; it would be capable of causing asthenospheric metasomatism and of driving asymmetrical lithospheric extension. The rift push forces, developed at the outer border of the extending lithosphere, due to the strong differential lithospheric thinning between the thinned and unthinned regions, might be responsible for the nucleation of fold-and-thrust belt structures (Turcotte and Emernan, 1983; Lavecchia *et al.*, 1995). It is possible, therefore, that, the Apennines and the Maghrebides are not related to subduction, but represent a recent example of «plume-induced orogenesis». Ancient orogenesis driven by plumes has been proposed for the Late Paleozoic «Ancestral Rockies» deformation in the South-Western United States and for the Early Mesozoic Gondwanide fold belt of South America, Southern Africa and Antarctic (Dalziel *et al.*, 2000).

If a plume is trapped within the transition zone beneath the Mediterranean, what would be its shape, size and temporal evolution? In order to find a very preliminary answer to this question, we consider that the injection of plume-material within the transition zone would cause an increase in volume of the asthenosphere; this, in turn, would drive stretching of the overlying lithosphere. Assuming conditions of mass conservation, a balance would exist between the amount of the asthenospheric excess volume and the amount of the lithospheric extension.

Applying the considerations outlined above to a lithospheric section across the Mediterranean, from the Gulf of Lyon to the outer front of the Apennines thrust belt in Calabria (fig. 5.2a-c), we try to predict the size in section view of the here hypothesised Mediterranean plume. The geometry of the crust and the lithosphere along the transect have been reconstructed using data from the literature (Panza, 1984; Locardi and Nicolich, 1988; Kastens and Mascle, 1990; Cella *et al.*, 1998; Rollet *et al.*, 2002, among many others). A crustal-area balancing of the transect has been performed by restoring the crust to an average pre-extensional thickness of 30 km, with the exception of the segment of the section which extends across the Tyrrhenian Sea. For this segment, we have assumed a pre-extensional crustal thickness of 40 km, corresponding to an average thickness of the pre-existing Alpine Chain. The area occupied in the section by basaltic plateaux and post-rift sediments has been subtracted. The finite crustal extension ($e=\Delta l=l_{\text{final}}-l_{\text{initial}}$) calculated along the transect is of ~600 km. Extrapolating this value to the lithospheric extension and assuming a depth of 670 km for the Asthenosphere-Mesosphere Boundary (AMB), the area occupied by the crust and upper mantle region along the Δl segment would be equal to Δl multiplied by AMB, that is about $4\cdot10^5$ km^2 (Lavecchia *et al.*, 2006). Following our reasoning, a roughly equivalent area would be occupied by the plume head within the transition zone. In the very speculative sketch of fig. 5.2c, we have depicted a plume head roughly having such a size. The shape of the plume has been inspired by the geometry of plumes trapped in the transition zone numerically modelled by Brunet and Yuen (2000).

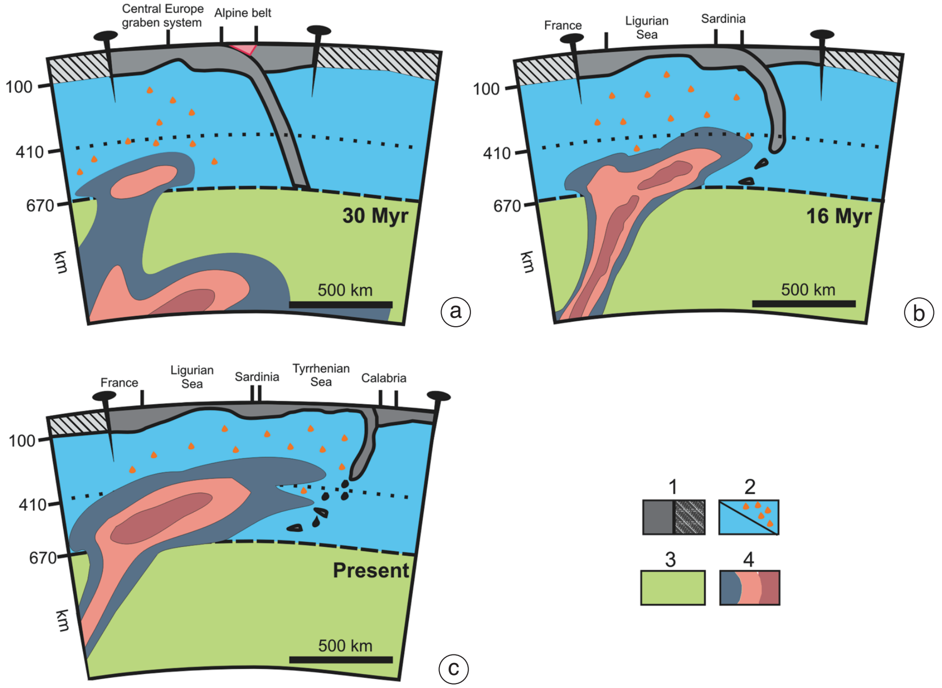

Fig. 5.2a-c. Kinematic model illustrating the proposed trapped plume scenario along a transect from the Gulf of Lyon to Calabria; the model comprise three steps dated at the Early Oligocene (a), at the end of Burdigalian (b) and at present times (c); the trace of the transect at each deformation stage is given in fig. 5.1a-c. The present-day crustal structure (c) is from Kastens and Mascle (1990); Rollet *et al.* (2002); the present-day lithospheric structure is from Suhadolc *et al.* (1990); the geometry of the plumes in the three sections (a, b, c) is highly speculative and largely derived from fig. 6 in Brunet and Yuen (2000). Key: 1 – Crust and underlying lithospheric mantle; 2 – Normal asthenosphere and enriched asthenosphere (small drops) with low-viscosity fluids, containing highly radiogenic isotopes, released from the plume head; 3 – mesosphere; 4 – depleted and degassed plume head trapped within the transition zone, the colour marks the decrease of the temperature moving from the outer zone to the inner one in the plume.

5.4.2. Deformation history

The Alpine-Betic tectonic phase started in Late Cretaceous times, with the subduction of the Tethyan oceanic lithosphere beneath the African continental lithosphere, and ended in Middle Eocene times, with the collision of the African and Eurasian plates (von Blankenburg and Davies, 1995; Schmid *et al.*, 1997; Piromallo and Faccenna, 2004). From Late Eocene-Early Oligocene (about 40-35 Myr ago) times onward, the geodynamic scenario changed and the dominance of the contractional process was replaced by the dominance of the extensional process. A narrow rift system started to develop along the SW-ward prolongation of the Rhine-Rhone Rift System, obliquely across the pre-existing Alpine-Betic belt (Ziegler, 1992). At the end of the Early Oligocene (about 30 Myr ago), a SE-dipping extensional fault system was well developed at the inner border of the Western Mediterranean region and the Provençal region had started to undergo low-angle extension and counterclockwise block rotation (fig. 5.1a).

During Aquitanian-Burdigalian times (from about 22-21 Myr to about 16 Myr ago), a relatively fast low-angle extensional process led to the opening of the Ligurian-Provençal «wide rift» system (Speranza *et al.*, 2002) (fig. 5.1b). After a tectonic stasis of about 3 Myr (F. Brozzetti, personal comunication, 2005), in Middle Serravallian times (about 13 Myr ago) the extensional process had a new pulse and gave birth to the Algerian Basin and to the Tyrrhenian wide rift system (fig. 5.1c). The extension is now active along the axis of peninsular Italy.

Both the Ligurian-Provençal and the Algerian-Tyrrhenian extensional phases were characterised by the development of coeval and co-axial outward-verging fold-and-thrust structures that nucleated at the outer border of the extended regions. Whereas the initial continental break-up of the Western Mediterranean did not follow pre-existing structures, but developed obliquely to the Africa-Eurasia suture zone, the site of the Apennine-Maghrebian fold-and-thrust belt was controlled by the pre-existing lithospheric architecture as it followed closely the Alpine-Betic belt.

5.4.3. The plume temporal evolution

Applying simple area techniques, we have very schematically restored the present Gulf of Lyon-Calabria lithospheric section (fig. 5.2c) to its configuration before the onset of Tyrrhenian phase (end Burdigalian times, about 16 Myr ago, fig. 5.2b) and, subsequently, to its configuration at the beginning of the Ligurian phase (end of Early Oligocene times, about 30 Myr ago, fig. 5.2a). The size of the plume head at each step has been calculated applying the considerations outlined in Section 5.4.1. The plume shape at each step depicted in fig. 5.2a-c is obviously highly speculative, but it is an almost faithful reproduction of the geometry and temporal evolution of the trapped plume head numerically modelled in the literature (fig. 6 in Brunet and Yuen, 2000).

In the restored sections of fig. 5.2a-c, we also hypothesise the possible past configuration of the Southern Tyrrhenian lithospheric slab. Given that the Benioff plane off Calabria is vertical to slightly SE-ward dipping in the uppermost 200 km and dips NW-ward at higher depths (Milano *et al.*, 1994; Selvaggi, 2001), we speculate that its concave shape might be the result of a process of progressive overturning of the Tethyan oceanic lithosphere that during the Alpine tectonic phase was dipping SE-ward beneath the African foreland. The progressive eastward growth of the Mediterranean plume head, trapped in the transition zone and impinged beneath the pre-existing SE-dipping Tethyan slab, might have caused the progressive bending and overturning of the deeper portion of such a slab.

5.5. FINAL CONSIDERATIONS

On the basis of isotopic data, Bell *et al.* (2003, 2006) demonstrate that the overall Italian magmatism may be plume- rather than subduction-related. Integrating their isotopic constraints with our geological-geometric considerations, we feel confident enough to hypothesize that, starting with Late Eocene-Early Oligocene times, the progressive growth of an asymmetric plume head within the transition zone played an active role in the fragmentation of the European and African continents that, at that time, were sutured together along the Alpine-Betic Chain. We consider the Mediterranean an independent micro plate growth in the last 35-40 Myr above an ESE-ward growing plume head. This microplate has a triangular shape, which reflects the plan view of the plume head. The north-western side corresponds to the Mediterranean extensional breakaway fault zone (inner Mediterranean continental rift boundary in fig. 5.1), the north-eastern side corresponds to the outer front of the Apennines, the southern side corresponds to the E-W outer front of the Maghrebian Chain and it is possibly controlled by the geometry of the E-W plate boundary north of the Nubia Plate (see fig. 6 in McClusky *et al.,* 2003).

The Mediterranean plume head developed independently from pre-existing lithospheric structures: in fact, basin extension started on a NE-SW striking discontinuity trending obliquely with respect to the pre-existing Alpine-Betic structures. The outer front of the extending Mediterranean system, that is the Apennine-Maghrebian thrust system, was strongly controlled by the tectonic inheritance of the Alpine-Betic Chain.

In the model we propose, the plume is mainly confined beneath the 410 km discontinuity and for this reason no deep thermal anomaly is observed at the surface. A prevailing horizontal extensional tectonics, rather than a vertical tectonics, is associated with the progressive eastward asymmetric growth of the plume head, driven by large-scale circulation of the upper mantle. The eastward growth of the plume pushes laterally the asthenosphere that is forced to migrate eastward as testified by the asymmetric heat-flux pattern and thermal history, the subsidence pattern, the magmatic asymmetry and the upper mantle anisotropy observed across the Mediterranean Basin (Barruol and Granet, 2002; Pasquale *et al.*, 2002; Savelli, 2002; Zito *et al.*, 2003). We also suggest that a balance is ultimately achieved between plume size and lithospheric extension with the amount of extension directly reflecting the size of the plume.

Still, we hypothesise that deep-mantle H_2O- and CO_2-rich fluids, containing highly radiogenic isotopes, are released by the plume head in the uppermost asthenosphere. They produce the necessary conditions in order to explain the peculiar isotopic and geochemical composition of the Quaternary Italian leucititic and carbonatitic-melilititic products (Cundari, 1979, 1994; Lavecchia and Stoppa, 1996; Lavecchia *et al.*, 2006, and references therein), the abundance in Central Western Italy of regional aquifers with mantle-derived CO_2 emissions (Chiodini *et al.*, 1999; Bell *et al.*, 2006) and in general the Sr-Nd and Pb-isotopic content of the Italian magmatic rocks (Bell *et al.*, 2003, 2004, and references therein). The process of injection of new material from the lower mantle in the transition zone may repeat itself in a period of some tens of million years (Brunet and Yuen, 2000). Then, this mechanism might be responsible for older pulses of ultra-alkaline activity, such as that occurring in Italy between 50-70 Myr and generating lamprophyres in Central-Eastern Italy (Pietre Nere, ~60 Myr and La Queglia, older age 54 Myr), South-Eastern Alps (~70 Myr) and South-Western Sardinia (~62 Myr) (see fig. 4.1 in Bell *et al.*, 2006). It might also be responsible for the Tertiary alkaline basaltic volcanism of the Veneto region, in the South-Eastern Alps foreland (Macera *et al.*, 2003). In a similar manner to the model here proposed, a connection of an upper mantle plume with a broad reservoir in the transition zone has been suggested for the Eifel plume (Ritter *et al.*, 2001).

One of the main problems that our plume-model may encounter is the interpretation of the tomographic velocity pattern detected in the Mediterranean region (Spakman *et al.*, 1993; Piromallo and Morelli, 2003). The tomographic images well show a large-scale high-velocity anomaly placed in the transition zone at the bottom of the upper mantle, beneath the whole Western Mediterranean area. This is coupled with a large-scale low-velocity anomaly extending from the Eastern Atlantic Ocean to Northern Africa, Central Europe and the Western Mediterranean. Still, an almost continuous NW-dipping high velocity body dipping is observed off Calabria, from surface to a depth of ~600 km. In order to attempt an explanation of the tomographic images, we follow Choi (2005) and Scalera (2006), in considering that the detected velocity pattern might correspond to the mantle's chemical anomalies rather than to thermal variation. In our opinion, the high-velocity body within the transition zone represents deep-mantle plume material which, once it arrived within the transition zone, had lost low-viscosity volatiles and fluids that escaped upwards. In turn, the low velocity heterogeneity that characterises the Mediterranean upper mantle down to 400 km might represent asthenospheric material enriched, metasomatised and softened by the fluids released by the plume head. The high-velocity body beneath the Apennines and off Calabria (Spakman *et al.*, 1993; Mele *et al.*, 1998; Lucente *et al.*, 1999; Cimini and De Gori, 2001) might be interpreted as an overturned remnant of the originally SE-dipping Alpine lithospheric slab (fig. 5.2a-c). Alternatively, following Scalera (2006), it might be interpreted as a tongue of deep-mantle plume material ejected from the transition zone.

To conclude, we stress that we are simply suggesting a preliminary and over-simplified hypothesis, which needs testing and modelling. We are also aware that the plume model we propose implies an «expansion» in the Mediterranean. Is the expansion compensated by shortening somewhere else or is it an aspect of the global expansion claimed by a few isolated researchers (Scalera and Jacob, 2003, and papers therein; Scalera, 2006)? We really do not have an answer, but we do know that the time has come to open a discussion on possible new frontiers in the Earth's sciences.

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REFERENCES

BAILEY, D.K. and J.D. COLLIER (2000): Carbonatite-melilitite association in the Italian collision zone and the Ugandan rifted craton; significant common factors, in *Carbonatite Thematic Set,* edited by A.P. JONES (Mineralogical Society, London, U.K.), **64**, 675-682.

BARCHI, M.R., G. MINELLI and G. PIALLI (1998): The Crop 03 profile: a synthesis of result on deep structures of the Northern Apennines, *Mem. Soc. Geol. It.*, **52**, 383-400.

BARRUOL, G. and M. GRANET (2002): A Tertiary asthenospheric flow beneath the Southern French Massif Central indicated by upper mantle anisotropy and related to the West Mediterranean extension, *Earth Planet. Sci. Lett.*, **202**, 31-47.

BELL, K., F. CASTORINA, G. ROSATELLI and F. STOPPA (2003): Large-scale, mantle plume activity below Italy: Isotopic evidence and volcanic consequences, *Geophys. Res. Abstr.*, **5**, 14217.

BELL, K., F. CASTORINA, G. LAVECCHIA, G. ROSATELLI and F. STOPPA (2004): Is there a mantle plume beneath Italy?, *Eos, Trans. Am. Geophys. Un.*, **85** (50), 541 and 546-547.

BELL, K., F. CASTORINA, G. ROSATELLI and F. STOPPA (2006): Plume activity, magmatism and the geodynamic evolution of the Central Mediterranean, *Annal. Geophysics*, **49** (suppl. to no. 1), 357-371 (this volume).

BRUNET, D. and D. YUEN (2000): Mantle plumes pinched in the transition zone, *Earth Plan. Sci. Lett.,* **178** (1-2), 13-27.

CARMINATI, E., M.J.R. WORTEL, W. SPAKMAN and R. SABADINI (1998): The role of slab detachment processes in the opening of the Western-Central Mediterranean basins: some geological and geophysical evidence, *Earth Planet. Sci. Lett.*, **160**, 667-679.

CELLA, F., M. FEDI, G. FLORIO and A. RAPOLLA (1998): Gravity modelling of the litho-asthenosphere system in the Central Mediterranean, *Tectonophysics*, **287**, 117-138.

CERNOBORI, L., A. HIRN, J.H. MCBRIDGE, R. NICOLICH, L. PETRONIO, M. ROMANELLI and STREAMERS/PROFILES WORKING GROUPS (1996): Crustal image of the Ionian Basin and its Calabrian margins, *Tectonophysics*, **264**, 175-189.

CHIODINI, G., F. FRONDINI, D.M. KERRICK, J. ROGIE, F. PARELLO, L. PERUZZI and A.R. ZANZARI (1999): Quantification of deep CO_2 fluxes from Central Italy. Examples of carbon balance for regional aquifers of soil diffuse degassing, *Chem. Geol.*, **159**, 205-222.

CHOI, D.R. (2005): Deep earthquakes and deep-seated tectonic zones: a new interpretation of Badati-Benioff Zone, *Boll. Soc. Geol. Ital.*, **5**, 79-118.

CIMINI, G.B. and P. DE GORI (2001): Non-linear *P*-wave tomography of subducted lithosphere beneath Central-Southern Apennines (Italy), *Geophys. Res. Lett.,* **28**, 4387-4390.

CONDIE, K.C. (2001): *Mantle Plumes and their Record in Earth History* (Cambridge University Press, Cambridge, U.K.), pp. 306.

COULON, C., M. MEGARTSI, S. FOURCADE, R.C. MAURY, H. BELLON, A. LOUNI-HACINI, J. COTTON, A. COUTELLE and D. HERMITTE (2002): Post-collisional transition from calc-alkaline to alkaline volcanism during the Neogene in Oranie (Algeria): magmatic expression of a slab breakoff, *Lithos*, **62**, 87-110.

CUNDARI, A. (1979): Petrogenesis of leucite-bearing bavas in the Roman Volcanic Region, Italy, *Contrib. Mineral. Petrol.*, **70**, 9-21.

CUNDARI, A. (1994): Role of subduction in the genesis of potassic rocks: a discussion paper on the unfashionable side of the role, *Mineral. Petrol. Acta*, **37**, 81-90.

CUNDARI, A. and A.K. FERGUSON (1991): Petrogenetic relationship between melilitite and lamproite, *Contrib. Mineral. Petrol.*, **107**, 343-357.

DALZIEL, I.W.D., L.A. LAWVER and J.B. MURPHY (2000): Plumes, orogenesis and supercontinetal fragmentation, *Earth Planet. Sci. Lett.,* **178**, 1-11.

DE VOOGD, B., C. TRUFFERT, N. CHAMOT-ROOKE, P. HUNCHON, S. LALLEMANT and X. LE PICHON (1992): Two-ship deep seismic soundings in the basins of the Eastern Mediterranean Sea (Pasiphae cruise), *Geophys. J. Int*., **109**, 536-552.

DOGLIONI, C. (1991): A proposal of kinematic modelling for *W*-dipping subductions – Possible applications to the Thyrrenian-Apennine system, *Terra Nova*, **3**, 423-434.

DOGLIONI, C., E. GUEGUEN, F. SABAT and M. FERNANDEZ (1997): The Western Mediterranean extensional basins and the Alpine orogen, *Terra Nova*, **9**, 109-112.

DOGLIONI, C., F. MONGELL and G. PIALLI (1998): Boudinage in the Alpine belt in the Apenninic backarc, *Mem. Soc. Geol. It*., **52**, 457-468.

DOGLIONI, C., E. GUEGUEN, P. HARABAGLIA and F. MONGELLI (1999): On the origin of west-directed subduction zones and applications to the Western Mediterranean, in *The Mediterranean Basins: Tertiary Extension within the Alpine Orogen* edited by B. DURAND, L. JOLIVET, F. HORVATH and M. SERANNE, *Geol. Soc. London, Spec. Publ.*, **156**, 541-561.

ERNST, R.E. and K.L. BUCHAN (2002): Maximum size and distribution in time and space of mantle plumes: evidence from large igneous provinces, *J. Geodyn.,* **34**, 309-342.

FACCENNA, C., L. JOLIVET, C. PIROMALLO and A. MORELLI (2003): Subduction and depth of convection in the Mediterranean mantle, *J. Geophys. Res.,* **108** (B2), 2099, doi: 10.1029/2001JB001690.

FACCENNA, C., C. PIROMALLO, A. CRESPO-BLANC and L. JOLIVET (2004): Lateral slab deformation and the origin of the Western Mediterranean arcs, *Tectonics*, **23**, TC1012, doi: 10.1029/2002TC001488.

FINETTI, I.R. and A. DEL BEN (1986): Geophysical study of the Tyrrhenian opening, *Boll. Geofis. Teor. Appl*., **28**, 75-155.

FINETTI, I.R., M. BOCCALETTI, M. BONINI, A. DEL BEN, R. GELETTI, M. PIPAN and F. SANI (2001): Crustal section based on CROP seismic data across the North Tyrrhenian-Northern Apennines-Adriatic Sea, *Tectonophysics*, **343**, 135-163.

GASPERINI, D., J. BLICHERT-TOFT, D. BOSCH, A. DEL MORO, P. MACERA, P. TELOUK and F. ALBAREDE (2000): Evidence from Sardinia basalt geochemistry for recycling of plume heads into the Earth's mantle, *Nature*, **408**, 701-704.

GASPERINI, D., J. BLICHERT-TOFT, D. BOSCH, A. DEL MORO, P. MACERA, P. TELOUK and F. ALBAREDE (2002): Upwelling of deep mantle material through a plate window: evidence from the geochemistry of Italian basaltic volcanics, *J. Geophys. Res.*, **107**, 2367, doi: 10.1029/2001JB000418.

GELABERT, B., F. SÀBAT and A. RODRIGUEZ-PEREA (2002): A new proposal for the Late Cenozoic geodynamic evolution of the Western Mediterranean, *Terra Nova*, **14**, 93-100.

GIARDINI, D. and M. VELONÀ (1991): The deep seismicity of the Tyrrhenian Sea, *Terra Nova*, **3**, 57-64.

GOES, S., W. SPAKMAN and H. BIJWAARDM (1999): A lower mantle source for Central European volcanism, *Science*, **286**, 1928-1931.

GRANET, M., M. WILSON and U. ACHAUER (1995): Imaging mantle plume beneath the French Massif Central, *Earth Planet. Sci. Lett.,* **136**, 281-296.

HOERNLE, K., Y.S. ZHANG and D. GRAHAM (1995): Seismic and geochemical evidence for large-scale mantle upwelling beneath the Eastern Atlantic and Western and Central Europe, *Nature*, **374**, 34-38.

JOLIVET, L. and C. FACCENNA (2000): Mediterranean extension and the Africa-Eurasia collision, *Tectonics*, **19**, 1095-1106.

KASTENS, K. and J. MASCLE (1990): The geological evolution of the Tyrrhenian Sea: an introduction to the scientific results of ODP Leg 107, *Proc. Ocean Drill. Progr. Init. Rep.*, **107**, 3-26.

LAVECCHIA, G. and F. STOPPA (1996): The tectonic significance of Italian magmatism: an alternative view to the popular interpretation, *Terra Nova*, **8**, 435-446.

LAVECCHIA, G., C. FEDERICO, G.D. KARNER and F. STOPPA (1995): La distensione tosco-tirrenica come possibile motore della compressione appennnica, *Studi Geologici Camerti*, **1995/1** (spec. vol.), 489-497.

LAVECCHIA, G., N. CREATI and P. BONCIO (2002): The Intramontane Ultra-alkaline Province (IUP) of Italy: a brief review with considerations of the thickness of the underlying lithosphere, *Boll. Soc. Geol. It.*, **1**, 87-98.

LAVECCHIA, G., P. BONCIO and N. CREATI (2003): A lithospheric-scale seismogenic thrust in Central Italy, *J. Geodyn.*, **36**, 79-94.

LAVECCHIA, G., F. STOPPA and N. CREATI (2006): Carbonatites and kamafugites in Italy: mantle-derived rocks that challenge subduction, *Ann. Geophysics*, **49** (suppl. to no. 1), 389-402 (this volume).

LITHGOW-BERTELLONI, C. and M.A. RICHARDS (1998): The dynamics of Cenozoic and Mesozoic Plate motions, *Rev. Geophys.,* **36**, 27-78.

LOCARDI, E. (1982): Individuazione delle strutture sismogenetiche dall'esame dell'evoluzione vulcano-tettonica dell'Appennino e del Tirreno, *Mem. Soc. Geol. It.*, **24**, 569-596.

LOCARDI, E. and R. NICOLICH (1988): Geodinamica del Tirreno e dell'Appennino Centro-Meridionale: la nuova carta della Moho, *Mem. Soc. Geol. It.,* **41**,121-140.

LONERGAN, L. and N. WHITE (1997): Origin of the Betic-Rif mountain belt, *Tectonics*, **16**, 504-522.

LUCENTE, F.P., C. CHIARABBA, G.B. CIMINI and D. GIARDINI (1999): Tomographic constraints on the geodynamic evolution of the Italian region, *J. Geophys. Res.,* **104**, 20307-20327.

MACERA, P., D. GASPERINI, C. PIROMALLO, J. BLICHERT-TOFT, D. BOSCH, A. DEL MORO and S. MARTIN (2003): Geodynamic implications of deep mantle upwelling in the source of Tertiary volcanics from the Veneto Region (South-Eastern Alps), *J. Geodyn.*, **36**, 563-590.

MALINVERNO, A. and W.B.F. RYAN (1986): Extension in the Tyrrhenian Sea and shortening in the Apennines as result of arc migration driven by sinking of the lithosphere, *Tectonics*, **5**, 227-245.

MANTOVANI, E., M. VITI, D. ALBARELLO, D. BABBUCCI, C. TAMBURELLI and N. CENNI (2002): Generation of back arc basins in the Mediterranean region: driving mechanism and quantitative modelling, *Boll. Soc. Geol. It.*, **1**, 99-111.

MCCLUSKY, S., R. REILINGER, S. MAHMOUD, D. BEN SARI and A. TEALEB (2003): GPS constraints on Africa (Nubia) and Arabia Plate motions, *Geophys. J. Int.*, **155**, 126-138.

MELE, G., A. ROVELLI, D. SEBER, T.M. HEARN and M. BARANZAGI (1998): Compresional velocity structure and anisotropy in the uppermost mantle beneath Italy and surrounding regions, *J. Geoph. Res.,* **103** (B6), 12529-12543.

MILANO, G., G. VILARDO and G. LUONGO (1994): Continental collision and basin opening in Southern Italy; a new plate subduction in the Tyrrhenian Sea?, *Tectonophysics*, **230**, 249-264.

NOGUERA, A.M. and G. REA (2000): Deep structure of the Campanian-Lucanian Arc (Southern Apennine, Italy), *Tectonophysics*, **324**, 239-265.

PANINA, L.I., F. STOPPA and L.M. USOLTSEVA (2003): Genesis of melilite rocks of the volcano Pian di Celli from data of melt inclusion studies, *Russian J. Petrol*, **4**, 365-382.

PANZA, G.F. (1984): Structure of the lithosphere-asthenosphere system in the Mediterranean region, *Ann. Geophysicae*, **2**, 137-138.

PASQUALE, V., M. VERDOYA and P. CHIOZZI (2002): A possible mechanism for thermal asimmetry of the Ligurian Basin, *Terra Nova*, **14**, 484-490.

PATACCA, E., R. SARTORI and P. SCANDONE (1990): Tyrrhenian Basin and Apenninic arcs: kinematic relations since Late Tortonian times, *Mem. Soc. Geol. It.*, **45**, 425-451.

Piromallo, C. and C. Faccenna (2004): How deep can we find the traces of Alpine subduction*?, Geophys. Res. Lett.,* **31**, L06601, doi: 1029/2003GL019288.

Piromallo, C. and A. Morelli (2003): *P*-wave tomography of the mantle under the Alpine-Mediterranean area, *J. Geophys. Res.,* **108**, 2065, doi: 10.1029/2002JB001757.

Ranalli, G., Pellegrini R. and S. D'Offizi (2000): Time dependence of negative buoyancy and the subduction of the continental lithosphere, *J. Geodyn.,* **30**, 539-555.

Ritter, J.R.R., M. Jordan, U.R. Christensen and U. Achauer (2001): A mantle plume below the Eifel volcanic field, Germany, *Earth Planet. Sci. Lett*., **186**, 7-14.

Rollet, N., J. Déverchère, M.O. Beslier, P. Guennoc, J.P. Réhault, M. Sosson and C. Truffert (2002): Back arc extension, tectonic inheritance and volcanism in the Ligurian Sea, Western Mediterranean, *Tectonics*, **21**, 6,1-6,23.

Rosenbaum, G., G.S. Lister and C. Duboz (2002): Reconstruction of the tectonic evolution of the Western Mediterranean since the Oligocene*, J. Virtual Explorer*, **8**, 107-126.

Royden, L., E. Patacca and P. Scandone (1987): Segmentation and configuration of subducted lithosphere in Italy: an important control on thrust belt and foredeep-basin evolution, *Geology*, **15**, 714-717.

Savelli, C. (2002): Time-space distribution of magmatic activity in the Western Mediterranean and peripheral orogens during the past 30 Myr (a stimulus to geodynamic considerations), *J. Geodyn*., **34**, 99-126.

Scalera, G. (2006): The Mediterranean as a slowly nascent ocean, *Annal. Geophysics*, **49** (suppl. to no. 1), 451-482 (this volume).

Scalera, G. and K.H. Jacob (2003): '*Why Expanding Earth? A Book in Honour of Ott Hilgenberg*', *Proceedings of the 3rd Lautenthaler Montanistisches Colloquium, Mining Industry Museum*, Lautenthal (Germany), May 26, 2001 (INGV, Roma), pp. 465.

Scandone, P. (1980): Origin of the Tyrrhenian Sea and Calabrian Arc, *Boll. Soc. Geol. It*., **98**, 27-34.

Scandone, P. and E. Patacca (1984): Tectonic evolution of the Central Mediterranean, *Ann. Geophysicae*, **2**, 139-142.

Scarascia, S., A. Lozej and R. Cassinis (1994): Crustal structures of the Ligurian, Tyrrhenian and Ionian seas and adjacent onshore areas interpreted from wide-angle seismic profiles, *Boll. Geofis. Teor. Appl.*, **36**, 5-19.

Schmid, S.M., O.A. Pfiffner, G. Schonborn, N. Froitzheim and E. Kissling (1997): Integrated cross section and tectonic evolution of the Alps along the eastern traverse, in *Results of NPR 20, Deep Structure of the Swiss Alps*, edited by O.A. Pfiffer, P. Lehner, P. Heitzman, S. Mueller and A. Steck (22 Birkhaeuser Verlag, Basel, Switzerland), 289-304.

Selvaggi, G. (2001): Strain pattern of the Southern Tyrrhenian slab from moment tensors of deep earthquakes: implications on the down-dip velocity, *Ann. Geofis.*, **44** (1), 155-165.

Spakman, W., S. van der Lee and R. van der Hilst (1993): Travel-time tomography of the European-Mediterranean mantle down to 1400 km, in *Structure and Evolution of the European Lithosphere and Upper Mantle; 7th Conference of the European Union of Geoscience,* edited by R.C. Snieder and V. Poupinet, *Physics of the Earth and Planetary Interiors*, **79**, 3-74.

Speranza, I., I.M. Villa, L. Sagnotti, F. Florido, D. Cosentino, P. Cipollari and M. Mattei (2002): Age of Corsica-Sardinai rotation and Liguro-Provençal Basin spreading: new paleomagnetic and Ar/Ar evidence, *Tectonophysics*, **347**, 231-251.

Stoppa, F. and A.R. Woolley (1997): The Italian carbonatites: field occurrence, petrology and regional significance, *Mineral. Petrol.*, **59**, 43-67.

Stoppa, F., A. Cundari and G. Rosatelli (2003): Melilitolite occurrences: their relationship with alkaline silicate rocks and carbonatites, *Period. Mineral.*, **1**, 223-251.

Suhadolc, P., G.F. Panza and S. Mueller (1990): Physical properties of the lithosphere-asthenosphere system in Europe, *Tectonophysics,* **176**, 123-135.

Trua, T., G. Serri and M.P. Marani (2003): Lateral flow of African mantle below the nearby Tyrrhenian Plate: geochemical evidence, *Terra Nova*, **15**, 433-440.

TURCOTTE, D.L. and S.H. EMERMAN (1983): Mechanics of active and passive rifting, *Tectonophysics*, **94**, 39-50.

VAN DER MEULEN, M.J., J.E. MEULENKAMP and M.J.R. WORTEL (1998): Lateral shifts of Apenninic foredeep depocentres reflecting detachment of subducted lithosphere, *Earth Planet. Sci. Lett.,* **154**, 203-219.

VAN DIJK, J.P., M. BELLO, G.P. BRANCALEONI, G. CANTARELLA, V. COSTA, A. FRIXA, F. GOLFETTO, S. MERLINI, M. RIVA, S. TORRICELLI, C. TOSCANO and A. ZERILLI (2000): A regional structural model for the northern sector of the Calabrian Arc (Southern Italy), *Tectonophysics*, **324**, 267-320.

VON BLANKENBURG, F. and J.H. DAVIES (1995): Slab break off: a model for syn-hcollisional magmatism and tectonics in the Alps, *Tectonics*, **14**, 120-131.

WEZEL, F.C. (1981): The structure of the Calabro-Sicilian Arc: krikogenesis rather than subduction, in *Sedimentary Basin of Mediterranean Margins,* edited by F.C. WEZEL, 485-487.

WORTEL, M.J.R. and W. SPAKMAN (2000): Subduction and slab detachment in the Mediterranean-Carpathian region, *Science*, **290**, 1910-1917.

ZHAO, D. (2001): Seismic structure and origin of hotspots and mantle plumes, *Earth Planet. Sci. Lett.,* **192**, 251-265.

ZIEGLER, P.A. (1992): Europe Cenozoic Rift System, *Tectonophysics*, **208**, 91-112.

ZITO, G., F. MONGELLI, S. DE LORENZO and C. DOGLIONI (2003): Heat flow and geodynamics inn the Tyrrhenian Sea, *Terra Nova*, **15**, 425-432.