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# Magmatectonic Zonation of Italy: A Tool to Understanding Mediterranean Geodynamics

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## 1. Introduction

The Cenozoic magmatic activity of Italy is characterized, from the Alps to the Aeolian Islands, by an abundance of SiO<sub>2</sub>-undersaturated potassic to ultra-potassic rock-types (leucite-phonolites, leucitites, kamafugites and lamproites). Rocks of sodic character, mainly sub-alkaline transitional and alkaline basaltic in composition plus some isolated lamprophyres, are situated along the western and southern side of the Tyrrhenian basin (Sardinia, Ustica, Sicily Channel, Etna) and eastward of it, within the Padan-Adriatic-Hyblean foreland (Veneto, la Queglia-Pietre Nere and Hyblean plateau). Although the sodic and potassic products belong to the same magmatotectonic domain, i.e. the Mediterranean “wide-rift system” and its shoulders, they have been attributed in the literature to contrasting geodynamic environments, one anorogenic and intra-plate, and the other orogenic and subduction-related (see Lustrino and Wilson, 2007 and references therein).

There is widespread acceptance that the sodic magmatism is intra-plate in character, but in the case of the potassic suites there is no unanimity (Lustrino et al., 2011 and references therein). Models for the origin of the potassic rocks centre around the nature of the metasomatic components which might result from dehydration or decarbonation of a slab as it is subducted into the mantle or from the upwelling of deep mantle melts and/or fluids associated with hot spots/plumes. Some papers address the problem from a geochemical point of view comparing the radiogenic isotopic signatures, especially Sr, Nd and Pb, with the composition of well-known, world-wide, mantle components (Bell et al., 2006 among many others). Another category of papers address the problem from a tectonic-structural point of view, discussing the geological and seismological proof for or against subduction (Lavecchia and Creati, 2006 and references therein).

Here, we provide an overview of the Paleocene to Present Italian igneous rocks in relationship to their tectonic setting at the time of their emplacement, and then evaluate possible alternative geodynamic scenarios for their origin, mainly based on integrated geophysical/geological and geochemical parameters.

## 2. The Mediterranean deformation history

The present tectonic setting of the Western and Central Mediterranean “wide-rift” system (e.g. Ligurian-Provençal and Tyrrhenian basins) and of the surrounding, outward-verging, Apennine-Maghrebian thrust belt (Fig. 1) results from a long history of deformation characterized by the alternation and/or the overprinting of contractional and extensional tectonic phases. Such a history, developed during the last 35 Ma, started while the Alpine-Betic orogeny was undergoing its final collisional stage (Faccenna et al., 2004).

Beginning from Late Cretaceous times, the Alpine Tethys ocean progressively closed with generation of the Alpine orogenic belt, presently exposed in the Alps, northwest Corsica, Calabria and in the Betics (southeast Spain) (Stampfli and Borel, 2004). By the end of the Paleocene (~55 Ma ago), the oceanic and/or ultra-thinned continental Tethyan lithosphere had been completely underthrust beneath the African continental plate. Shortening, however, along the Alpine-Betic belt continued at least to the end of the late Eocene. The Alpine collisional activity occurred together with a localized intra-continental extensional phase, which generated the Cenozoic “narrow-rift” system of eastern and central Europe (Fig.1) (Ziegler, 1992). With the beginning of the early Oligocene (~35 Ma ago), extension started to dominate again over compression. A regional, east-dipping, extensional fault system developed along the south-westward prolongation of the Central Europe Rift System, along the western border of the Western Mediterranean basin, between Corsica-Sardinia and the Provençal region (Fig. 1).

During early Miocene times (from ~22 to ~16 Ma ago), the Corsica-Sardinia block, which belonged to the European continental lithosphere, started to undergo a counter-clockwise rotation around a pivot point situated more or less north of present-day Corsica (star in Fig. 2), which led to the opening of Ligurian-Provençal basin. After a period of tectonic quiescence of a few million years, in middle Miocene times (~13 Ma ago) the extensional process started again to the east of the Corsica-Sardinia block. The Adriatic foreland rotated counter-clockwise giving birth to the progressive opening of the Tyrrhenian basin (Fig. 1a). The extensional process was mainly achieved through easterly-dipping, low-angle, and antithetic, high-angle, normal faulting which produced an extensive stretching and thinning of the crust and mantle lithosphere, with localised areas of mantle unroofing and/or the accretion of new oceanic crust (Fig. 1b). The extensional process progressively migrated eastward and is now active and seismogenic along the axis of peninsular Italy (Lavecchia, 1988; Chiarabba et al., 2005). Both the Ligurian-Provençal and the Tyrrhenian extensional phases were characterized by the development of contemporary coeval and co-axial outward-verging fold-and-thrust structures that nucleated at the outer border of the extended regions (Carminati et al., 1998; Finetti et al., 2001).

## 3. Magmatic phases

Each of the tectonic phases listed above was characterized by distinctive magmatic activity (Figs. 1, 2 and 3). The Late Cretaceous to Paleocene Alpine orogenic phase was substantially amagmatic, accompanied by isolated lamprophyric activity, mainly consisting of dyke swarms situated on both the African and European continental sides of the closing Tethys (Vichi et al., 2005; Stoppa, 2008 and references therein). Known Italian occurrences are located in southern Tuscany (~110-90 Ma), in the south-eastern Alps (Calceranica and Corvara in Badia, 70-68 Ma), in south-eastern Sardinia (Nuraxi Figus 62-60 Ma), in the

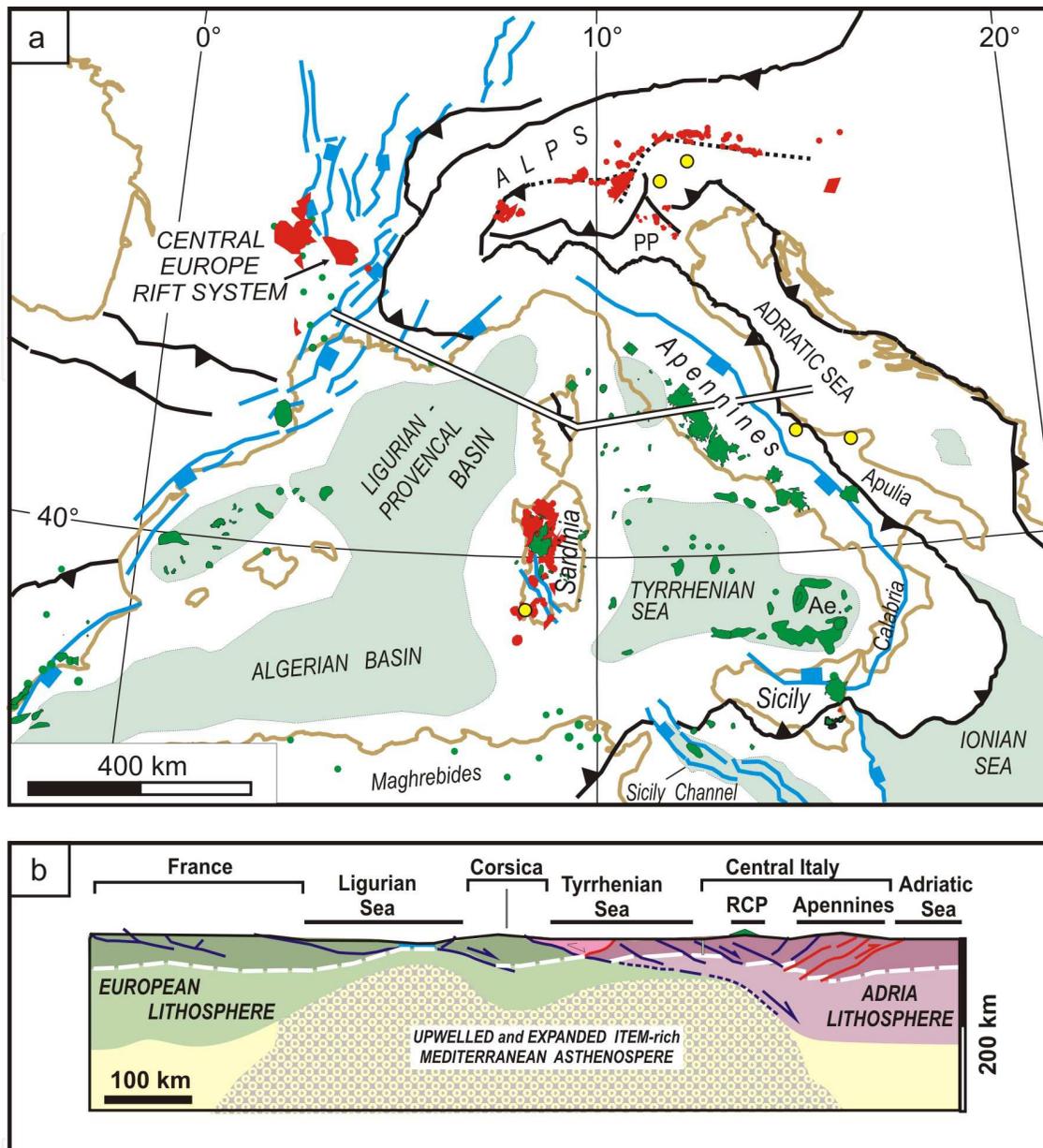


Fig. 1. a) The map shows the Western (e.g. Ligurian-Provençal) and Central (e.g. Tyrrhenian) Mediterranean extensional basins and surrounding regions, with associated volcanic occurrences and major tectonic structures. Key: A = Aeolian volcanic arc; PP = Padan Plain; blue lines = normal and normal oblique faults; black lines with triangles = major thrust fronts; green areas and spots = volcanic occurrences younger than 25 Ma; red areas = volcanic occurrences aged between 25 and 45 Ma; yellow spots = Italian volcanic occurrences older than 45 Ma. The light green basinal areas refers to regions with oceanic and ultra-thinned continental crust (Moho depth  $\leq \sim 20$  km).

b) The section shows a schematic view of the crustal and lithospheric structure of the Ligurian and Tyrrhenian “wide-rift” basins; the trace of the section is given in the map. The European and the Adriatic lithospheric domains are distinguished with different colours; the Moho discontinuity (white dashed line) is from Locardi and Nicolich (1988); the lithosphere thickness is from Suhadolc *et al.* (1990); the adopted structural style is from Lavecchia and Stoppa (1989) and Lavecchia *et al.* (2003).

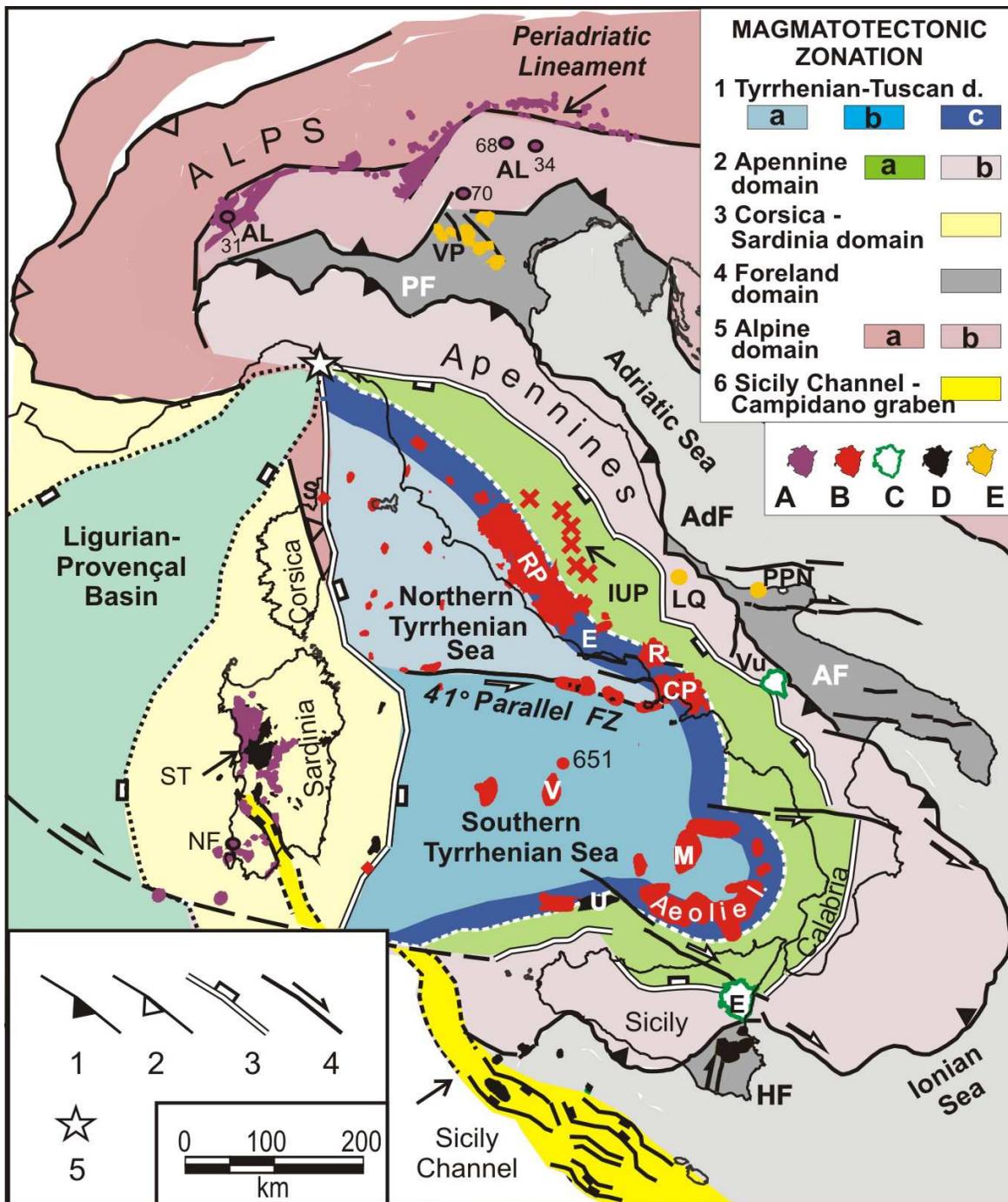


Fig. 2. Major “Magmatotectonic Domains” defined on the basis of both the compositional character and age of the igneous occurrences and the thickness and tectonic setting of the crust and the lithosphere at the time of the volcanic emplacement (after Lavecchia and Stoppa, 1996; Bell et al., submitted). The features of the various domains numbered 1, 2, 3, 4, 5 and 6 in the legend, and their subdivision in sub-domains (a, b, c), are described within the main text. The occurrences labelled A, B, C, D and E at the base of the legend in the upper right side of the figure are distinguished with different colours based on their age, composition and major features in terms of radiogenic isotopic arrays. Labels A, B and C refer to centres lying within the FOZO-ITEM isotopic array in Fig. 6; labels D and E refer to centres lying within other isotopic arrays in the same figure (possible FOZO-EM1 and

FOZO-HIMU) Key: A = late Eocene-early Miocene calc-alkaline magmatism widely distributed along the Periadriatic Lineament and the Sardinian Trough (ST) plus individual lamprophyric occurrences, with their average ages in Ma, in the eastern and western Alps (AL = Alpine lamprophyres) and in south-western Sardinia (NF = Nuraxi Figus); B = Plio-Quaternary Tuscan-Tyrrhenian and intra-Apennine magmatism, from sub-alkaline transitional in the Tyrrhenian Sea (V = Vavilov, M = Marsili, 651 = ODP drilling site), to prevalently calc-alkaline, K-alkaline in the Aeolian islands, to HK-alkaline and ultra-alkaline in peninsular Italy (RP = Roman Province, E = Ernici; R = Roccamonfina, CP = Campanian Province which includes Vesuvius and the Phlegrean Field; IUP = Intramontane Ultra-alkaline Province); C = volcanoes lying in between the outer extensional and the outer compressional fronts (Vu = Vulture, Etna = E); D = late Miocene to Quaternary Na-alkali basalts of Sardinia, the southern Tyrrhenian border (U = Ustica), the Sicily Channel and the Hyblean plateau; E = Late Paleocene-Oligocene Na-alkaline to ultra-alkaline occurrences (VP = Veneto Province, LQ = La Queglia, PPN = Punta delle Pietre Nere) lying within the foreland domain (PF = Padan Foreland, AdF = Adriatic Foreland, AF = Apulia Foreland, HF = Hyblean foreland). The legend in the lower left corner refers to: 1 = active thrust front; 2 = Alpine thrust front; 3 = outer limit of active extension; 4 = major transcurrent fault systems; 5 = pivot point during the Mio-Pliocene opening of the triangular shaped Ligurian-Provençal and Tyrrhenian basins.

Gargano region (Punta delle Pietre Nere, 62-58 Ma) and in Abruzzo (La Queglia, 62-54 Ma) (Figs. 2 and 3).

The prevalently Eocene Alpine collisional phase was characterized mostly by calc-alkaline and K-alkaline magmatism concentrated along the Periadriatic Lineament that extends across the entire Alpine belt in an approximate E-W direction (Macera et al., 2008) (Fig. 2). Such activity occurred in middle Eocene - late Oligocene times (~42 to 24 Ma), climaxing in the early Oligocene (~34 to 28 Ma). Isolated lamprophyric activity also occurred in the south-eastern (Val Fiscalina, 34 Ma) and in the south-western Alps (Sezia-Lanzo, Combin and Biellese, ~29 to 33 Ma) (Fig. 3). In addition, extensive Paleocene-early Oligocene volcanism of primarily basaltic composition occurred in the Veneto foreland region of south-eastern Alps (e.g. Macera et al., 2003).

The Oligocene-early Miocene Western Mediterranean extensional phase was characterized by prevalent calc-alkaline magmatic activity mainly developed between ~38 and 15 Ma, with the peak of activity taking place between ~22 and 18 Ma. Such a climax was more or less contemporary with the maximum opening of the Ligure-Provençal basin, from ~21 to 16 Ma. The magmatic products extensively outcrop within the Sardinian Trough, which extends for nearly 220 km along the western side of Sardinia (Figs. 1 and 2), and partially along the French coast (Provence, ~34 to 16 Ma) (Savelli, 2002; Cherchi et al., 2008). It is interesting to note that the early Oligocene magmatic activity within the Sardinian Trough is contemporary with the peak of activity along the Periadriatic Lineament.

The middle Miocene-Quaternary volcanism in the Tyrrhenian Sea is characterized by a wide range of products, whose distribution, age and petrology neatly fits with the progressive, eastward-migrating process of crustal extension and lithospheric stretching. At any given site, the magmatic activity post-dates the beginning of extensional activity by up to 2-3 Ma (Lavecchia and Stoppa, 1996). Details about the Tyrrhenian and circum-Tyrrhenian magmatic activity are given below.

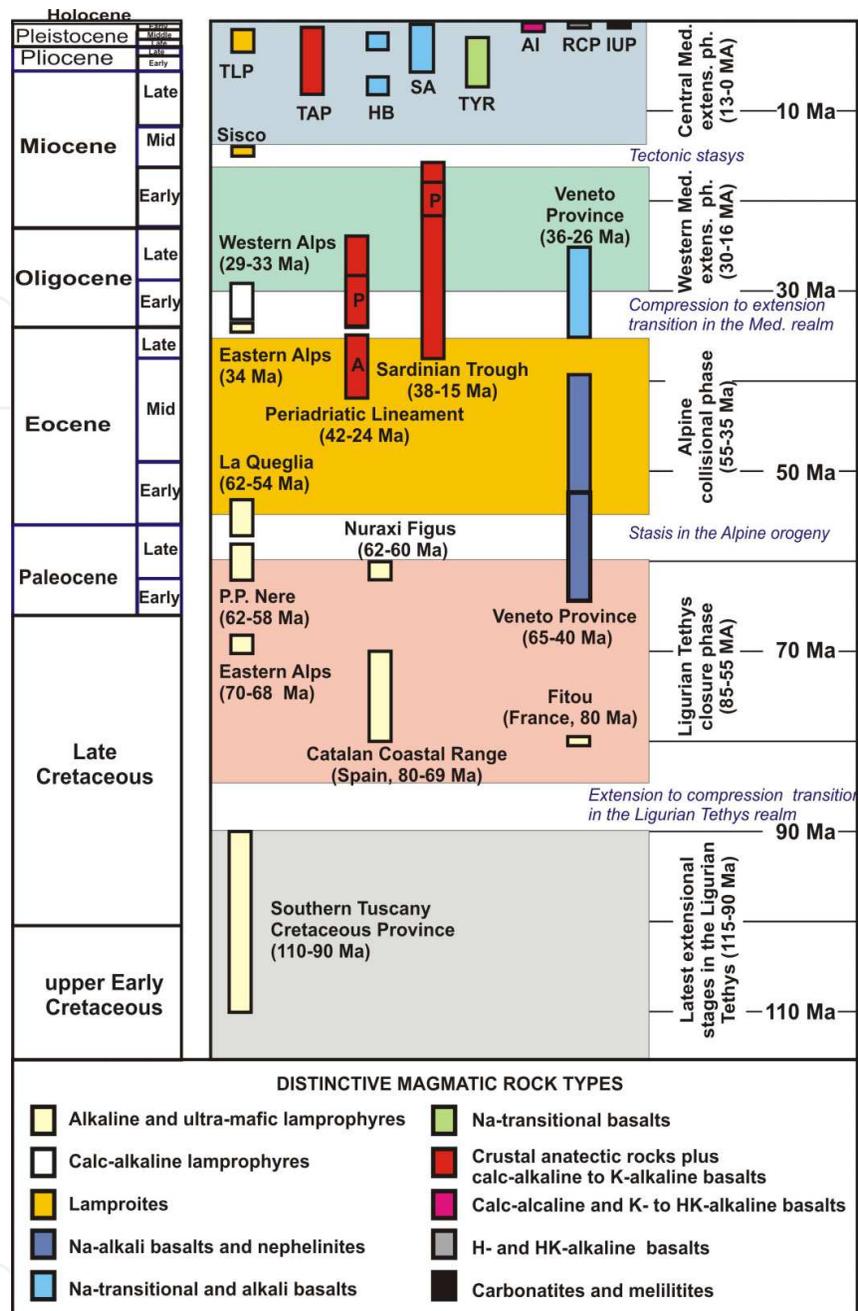


Fig. 3. Schematic chronostratigraphic chart with major tectonic and magmatic events in Italy since Late Cretaceous times. Key: A = Adamello batholith; AI = Aeolian Islands; HB = Hyblean plateau; IUP = Intramontane Ultra-alkaline Province; P = peak of magmatic activity along the Periadriatic Lineament and within the Sardinian Trough; P.P. Nere = Punta delle Pietre Nere; RCP = Roman-Campanian Province; SA = Sardinia; TAP = Tuscan Anatectic Province; TLP = Tuscan Lamproitic Province; TYR = Tyrrhenian basin.

#### 4. Magmatotectonic domains

We define the term 'Magmatotectonic domain' as a lithospheric-scale structural domain which is homogeneous from the geometric-kinematic point of view, and closely associated with one or more well-defined igneous province. An igneous province, as considered here,

consists of specific igneous associations, relatively discrete in time and space, characterized by distinctive major, minor and trace elements, as well as isotopic compositions. In Italy, the close spatial relationship between the surface distribution of the igneous provinces and well-defined, structural domains indicate that the magmatic activity is strongly controlled by the tectonics of the lithosphere. We define six major magmatotectonic domains. These are schematically shown in Figure 2.

1. The Tyrrhenian-Tuscan domain, that consists of the basinal area and its eastern onshore shoulder in Tuscany, Latium and Campania, underwent progressive eastward extension starting in late Miocene times along the eastern side of the Corsica-Sardinia block. This process progressively migrated eastward, with present activity occurring along the axis of the Apennine mountain chain (Lavecchia, 1988). The domain mainly lies within the boundary of the 50 km depth contour line that corresponds to the lithosphere-asthenosphere boundary (Panza and Suhadolc, 1990). The lithospheric stretching is mainly achieved through low-angle, east-dipping normal faulting and antithetic, high-angle faults (Fig. 1b). The consequential crustal thinning and mantle upwelling is associated with thermal highs with nodes situated mainly in the Latium and southern Tuscan regions and in the southern Tyrrhenian Sea (e.g. Rehault et al., 1987). Based on the geometry of the lithospheric structure and on the character of the magmatic occurrences, three major sub-domains can be identified, one (sub-domain 1a) northward of a nearly E-W lithospheric discontinuity known as "41° Parallel Fault Zone", one south of it (sub-domain 1b) and another running along the eastern Tyrrhenian side, from Tuscany to the Aeolian insular arc (sub-domain 1c). These sub-domains are shown in Figure 2.

Sub-domain 1a consists of the northern Tyrrhenian Sea and of the Tuscan onshore region; it is characterized by thinned crust (20-25 km) and lithosphere (~50 km) and is typically marked by the Tuscan Magmatic Province. This province consists of distinct magmatic associations: felsic rocks of crustal anatexis together with subordinate, sub-alkaline basalts, late Tortonian to early Pleistocene in age (Conticelli and Peccerillo, 1992; Serri et al., 1993), and rare lamproitic rocks of Pliocene-Pleistocene age (Orciatico-Montecatini 4.1 Ma, Torre Alfina 1.3 Ma). An isolated lamproitic outcrop of middle Miocene age (~14.5 Ma) is situated at Sisco, on the north-western Corsican coast. In southern Tuscany, alkali-lamprophyric rocks of Early-Late Cretaceous age are also found (Faraone and Stoppa, 1990).

Sub-domain 1b consists of the southern and south-eastern Tyrrhenian Sea, which is characterized by thinned to ultra-thinned continental crust (~20 to 5 km) and lithosphere (~50 to 30 km), the extension being largely achieved by top-to-the-east extensional, low-angle, normal faults. A mantle core complex of peridotitic rocks, overlain by a thin volcanic layer and by Pliocene sediments, characterizes the Vavilov basin (Masche et al., 1991). The volcanic rocks within this sub-domain mainly consist of Na-transitional basalts and range in age from late Miocene to early Pleistocene. Alkali basalts occur at the Magnaghi and Vavilov seamounts and at Ustica and Prometeo islands. At the south-eastern side of this sub-domain the Marsili basin, coinciding with ultra-thinned crust (~10-15 km), is surrounded by the Aeolian insular arc. The latter is emplaced on thin crust (~20 km thick) and belongs to sub-domain 1c.

Sub-domain 1c consists of the southern Latium and Campania onshore region, located in a transitional position between the Tyrrhenian rift basin and the Apennine Mountain belt. Northward of the "41° Parallel Fault Zone" (Fig. 2), it is typically marked by the

magmatism of the Roman-Campanian Province (RCP), which ranges in age from middle Pleistocene to Present. In this province, which mainly consists of large volcanoes with giant calderas, the most abundant rock types are leucite tephrites and leucitites, belonging to the so-called HK-series ( $K_2O/Na_2O-2 \gg 1$ ), (Appleton, 1972). They are also commonly associated with leucite-free, silica-saturated rocks ( $K_2O/Na_2O \cong 1$ ) belonging to the so-called K-series. Also belonging to this sub-domain is the Aeolian Insular arc. The latter consists of calc-alkaline to K-rich rocks with an increasing potassic character; HK-rocks occur at Vulcano, Vulcanello and Stromboli (Trua et al., 2004; Francalanci et al., 2004).

2. The Apennine domain, which surrounds the Tyrrhenian basin to the east and the south, has undergone outward-verging compression since late Miocene times. The compression is still active. Seismic activity occurs along the Padan-Adriatic and the Calabrian-Sicilian thrust fronts (Lavecchia et al., 2003, 2007). Since late Pliocene times, the intra-Apennine compressional structure domain has undergone normal and normal oblique extension, which is still active and responsible for large crustal extensional earthquakes (Chiarabba et al., 2005). This domain, characterized by thickened crust (up to 40-45 km) and unthinned underlying mantle lithosphere (~100-110 km) (Fig. 4) is virtually amagmatic. Few exceptions include the small monogenic volcanoes of the Intramontane Ultra-alkaline Province (IUP) of central Italy (Stoppa and Woolley, 1997; Bailey and Collier, 2000; Lavecchia et al., 2006) and two isolated large volcanoes, Mt. Vulture and Mt. Etna. The IUP consists of a number of small monogenetic kamafugitic (kalsilite foidites or kalsilite olivine melilitites) and/or carbonatitic centres of middle-late Pleistocene age (0.74 to 0.13 Ma) which lie within a narrow area (less than 20 km wide) extending NNW-SSE for a length of ~110 km, nearly 50 km eastward from the centers of the Roman Province. The known occurrences are sited in Umbria (San Venanzo, Polino, Collefabbri), in Latium (Cupaello) and in Abruzzo (Oricola, Grotta del Cervo). The beginning of the IUP activity post-dated the onset of the extensional tectonics (middle Pliocene times) by ~3.0 Ma. The end of the IUP activity occurred while the intra-Apennine extensional regime was still active.

Mt. Vulture is located in Lucania (southern Italy), nearly 100 km eastward from the Campanian Province, and lies between the active extensional and compressional thrust fronts, close to the boundary between the southern Apennine east-verging thrusts and the Adriatic foreland terrains (Fig. 2). The Mt. Vulture igneous rocks are trachyphonolite, phono-tephrite and melilitites. A swarm of carbonatitic maar-diatremes ~0.1 Ma years old are present in the Vulture area along the Ofanto line (Stoppa and Principe, 1998; Stoppa et al., 2009). The Etna volcano, in Sicily, also lies within the same structural position as Mt. Vulture, on the frontal thrust of the Apennine-Maghrebian chain. Etna is the largest active volcano in Europe, and its basaltic composition marks the compositional difference from the foiditic Mt. Vulture volcano.

3. The Corsica-Sardinia domain mainly coincides with the stable, on-shore and partially offshore, areas situated at the footwall of the east-dipping, normal fault system correlated with the Tyrrhenian opening (Fig. 1b). The domain, characterized by 25 to 30 km thick continental crust, is associated with widespread Na-alkaline basaltic volcanism, early Pliocene to Quaternary in age, occurring in eastern Sardinia and its offshore areas, as well as in the NW-SE striking Campidano graben (south-western

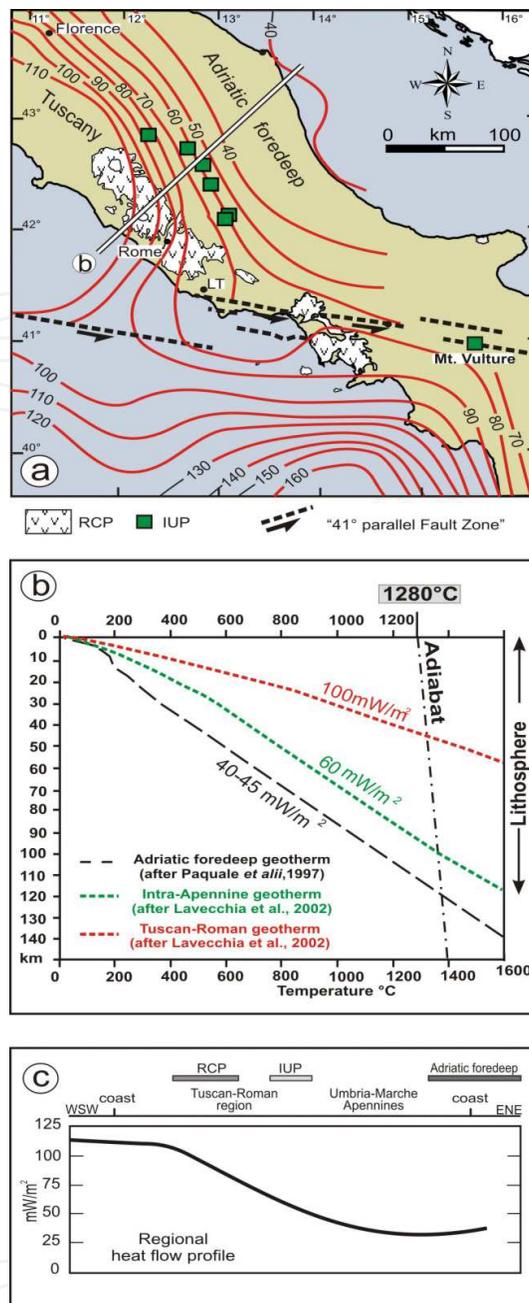


Fig. 4. a) Regional heat flow density map (mWm<sup>-2</sup>) of central-southern Italy and Tyrrhenian sea (after Mongelli et al., 1989; Pasquale et al., 1997).

b) Temperature-depth profiles for the Roman-Campanian Province (RCP) and the Intramontane Ultra-alkaline Province (IUP) (from Lavecchia et al., 2002). The geotherms have been calculated from inversion of the regional pattern of surface heat flow, assuming steady-state conditions. Thermal parameters used: mantle heat flow = 30 mWm<sup>-2</sup>; upper crust thermal conductivity  $k_{uc} = 2.7 \text{ Wm}^{-1}\text{K}^{-1}$ ; lower crust thermal conductivity  $K_{lc} = 2.1 \text{ Wm}^{-1}\text{K}^{-1}$ ; mantle thermal conductivity  $k_m = 2.6 \text{ Wm}^{-1}\text{K}^{-1}$ ; near surface exponential radiogenic production  $H_s = 2.0 \cdot 10^{-7} \text{ Wm}^{-3}$ ; constant radiogenic production  $H_c = 2.5 \cdot 10^{-6} \text{ Wm}^{-3}$ ; thickness of the layer with constant radiogenic heat production  $h_c = 17 \text{ km}$ ; characteristic length  $h_r = 10 \text{ km}$ .

c) Regional heat flow profile across the RCP and the IUP; the trace of the section is marked on the map.

- Sardinia). From early Oligocene to the beginning of middle Miocene (~30 to 15 Ma), the Sardinian Trough in western Sardinia, as well as the Provençal region on the east side of the Western Mediterranean basin, were the sites of crustal anatectic and sub-alkaline magmatism, tholeiitic to calc-alkaline in character. The magmatic activity culminated between ~22 and 18 Ma (Fig. 1). It post-dated the formation, in Aquitanian times, the Sardinian trough-rift system and was concomitant with the phase of counter-clockwise rotation of the Sardinia-Corsica block and opening of the Liguria-Provençal basin.
4. The Adriatic-Pelagian foreland domain, extending from the Padan Plain to the Adriatic Sea, Apulia and the Hyblean Mountains in south-eastern Sicily (Fig. 3), consists of part of the African plate unaffected by the Alpine and Apennine compressional deformation. It is characterized by 25 to 30 km thick continental crust and lies at the footwall of both the south Alpine and the Apennine frontal thrusts. It is locally affected by discrete and localized deformational zones, mainly with strike-slip kinematics and characterized by a number of isolated magmatic occurrences. The Veneto region (south-eastern Alps), west of the Schio-Vicenza line, was the site of mafic alkaline magmatic activity from Paleocene to middle Eocene times and of prevailing Na-transitional activity during late Eocene-early Oligocene times (Figs. 2 and 3). Alkali basalts, basanites and transitional basalts are the commonest rock types (Macera et al., 2003). During late Paleocene times the Gargano-Abruzzi foreland region was characterized by two lamprophyric occurrences, possibly situated along the same major lithospheric strike-slip fault zone extending across the Gargano area of the Apulia foreland (Punta delle Pietre Nere, ~62-58 Ma) and the Abruzzi region (La Queglia, ~58-54 Ma). From late Miocene to Pleistocene times, three cycles of magmatic activity, ranging in composition from tholeiitic to nephelinitic, occurred within the Hyblean foreland, in south-eastern Sicily (8-6 Ma, 3-2 Ma, 1.5-1.2 Ma) (Savelli, 2002). Intraplate volcanic activity with Na-alkaline affinity had also occurred in the same area from the Late Triassic to the Late Cretaceous (Beccaluva et al., 1998).
  5. The Alpine deformational domain resulted from south-verging compression associated with the Alpine Tethys closure during Late Cretaceous-early Paleocene times and from double-verging compression during the Neogene collisional phase between the African and European plates. Both crust and mantle lithosphere are thickened with values of nearly 50 km and 130 km, respectively (Stampfli and Borel, 2004). The region does not show magmatic activity associated with the main Alpine Tethys closure phase, but instead is characterized by an intense, widespread, calc-alkaline activity along the Periadriatic Lineament during early Oligocene (~30-32 Ma) times. Such activity was substantially coeval with the lamprophyric activity in the south-eastern Alps (Val Fiscalina, BZ, ~34 Ma) and in the south-western Alps (Sezia-Lanzo, Combin and Biellese, ~29 to 33 Ma). It was also coeval with the onset of the calc-alkaline activity in the Sardinian Trough.
  6. The Sicily Channel domain consists of a “narrow-rift” system, which extends north-westerly across the Pelagian Sea, south-westward of Sicily, with a possibly prolongation along the Campidano Graben in Sardinia. It is associated with moderately thin (~20-25 km) continental crust and characterized by normal and normal-oblique tectonic activity which dates back to the late Miocene (Beccaluva et al., 2004). The associated magmatism began in the early Pliocene and was still active in Holocene times. Most representative rock types are Na-alkaline and sub-alkaline transitional basalts, as well as peralkaline rhyolites at Pantelleria (e.g. Rotolo et al., 2006).

## 5. Depth and structural setting of the magmatogenic sources

No matter which of the above igneous provinces we consider, there is no general *consensus* about the composition and the depth of magma equilibration. Among the many sources proposed for the various magmatic occurrences are non-metasomatized and metasomatized lithosphere, metasomatized asthenosphere, and mesosphere. The problem is further complicated by the definition of lithosphere and asthenosphere, and whether the basis of their definition is rheological or chemical. In the case of the Quaternary igneous provinces, assuming that the present Italian lithosphere is similar to that during the Pleistocene, it is possible to speculate not only on the depth of equilibration of the magmas, based on compositional considerations, but also on the location of the sources themselves.

Following Lavecchia and Stoppa (1996), the Plio-Quaternary Tyrrhenian and peri-Tyrrhenian magmatic products may be schematically divided into two magmatogenetic groups, whose parental magmas equilibrated at different depths. The first included the Tyrrhenian transitional and sub-alkaline transitional basalts, the calc-alkaline to potassium series of the Aeolian Islands and part of the Roman-Campanian Province, as well as of the Na-series typical of Etna, the Sicily Channel and the Campidano Graben in Sardinia. These products are mainly SiO<sub>2</sub>-saturated and are attributed to parental melts derived from a non-metasomatized, depleted mantle source. These can be related to liquids equilibrated at pressures <22 kb (i.e. at a depth less than ~70 km) within a relatively homogeneous lherzolite containing variable amounts of spinel (Olafsson and Eggler, 1983; Peccerillo and Manetti, 1985). Both garnet and spinel-peridotites have been proposed for the Sicily Channel products (Rotolo et al., 2006).

The HK-series of the Roman-Campanian Province and the ultra-alkaline products of the IUP, which are strongly SiO<sub>2</sub>-undersaturated, highly potassic to ultra-potassic in composition with high <sup>87</sup>Sr/<sup>86</sup>Sr ratios, are assumed to have been generated from a radiogenic and metasomatized carbonate/phlogopite-bearing peridotite (Lavecchia and Stoppa, 1996; Bailey and Collier, 2000). These melts have been related to liquids equilibrated at pressures between 22 and 24 kb i.e. at a depth of 70-80 km (Peccerillo and Manetti, 1985), and those of the IUP to pressures in the range of 28-30 kb (Cundari and Ferguson, 1994), i.e. depths of 85-100 km. Direct evidence for the mantle source composition for the IUP group is given by mantle nodules found within the volcanic rocks that commonly consist of phlogopite-clinopyroxenite, phlogopite-wherlite, spinel-wherlite and phlogopitite (Conticelli and Peccerillo, 1992; Stoppa and Lupini, 1993; Rosatelli et al, 2007). A depth of ~75 km has been estimated for the mantle xenoliths sampled at Monticchio at Mt. Vulture (Jones et al., 2000).

Assuming a value of about 1280°C for the potential temperature (TP) at the lithosphere-asthenosphere boundary (LAB) (Cundari and Ferguson, 1994; Cella et al., 1998; Federico and Pauselli, 1998) and considering the regional heat flow values of 60 and 100 mW/m<sup>2</sup> which characterize the IUP and RCP areas, respectively (Pasquale *et al.*, 1997), Lavecchia et al. (2002) calculated the corresponding steady-state geotherms and the lithosphere thermal thickness (Fig. 4). The adiabatic curve corresponding to a TP of 1280°C intersects the RCP and the IUP geotherms at depths of ~45-50 and ~85-90 km, respectively. The same adiabatic curve intersects the geotherm of the Adriatic foreland area (heat flow of 45-50 mW/m<sup>2</sup>, Pasquale et al., 1997) at a depth of ~115 km and the geotherm of an average continental lithosphere (heat flow of 60 mW/m<sup>2</sup>, Zhou, 1996) at a depth of ~110 km. On the basis of these findings, parental melts could have equilibrated within the lithosphere, close to the LAB, or within the uppermost asthenosphere (Fig. 5) The difference in the regional geothermal gradient between the RCP and the IUP essentially corresponds to a sharp LAB

deepening in central Italy, moving from the thinned Tuscan lithosphere to the unthinned Adriatic lithosphere (Fig. 5). The lithospheric step is located beneath the transition area between the RCP and the IUP. The surface position of the RCP and the IUP corresponds to the surface projection of the upper and lower LAB-hinge zones, respectively. Beneath the IUP, a significant amount of melt generation would have been precluded by the almost unthinned lithosphere; beneath the RCP, it would have been allowed by the thinned lithosphere and related high stretching-factor. The different amount of melts may also be considered responsible for the different volcanic styles of the two provinces: giant calderas in the RCP and diatremes in the IUP; the latter is probably due to the small melt volume, fluidisation and gas exsolution during upward migration. In both provinces, the volcanic activity post-dates, by some millions of years, the beginning of the horizontal, extensional tectonics and occurred only after the onset in middle Pleistocene times of prevailing vertical tectonics with a regional uplift. The surface distribution in central Italy of the IUP and RCP occurrences along narrow NNW-SSE bands corresponds to the surface projection of the lower and upper LAB-hinge zones (Fig. 5). This suggests that the sharp lithospheric step and

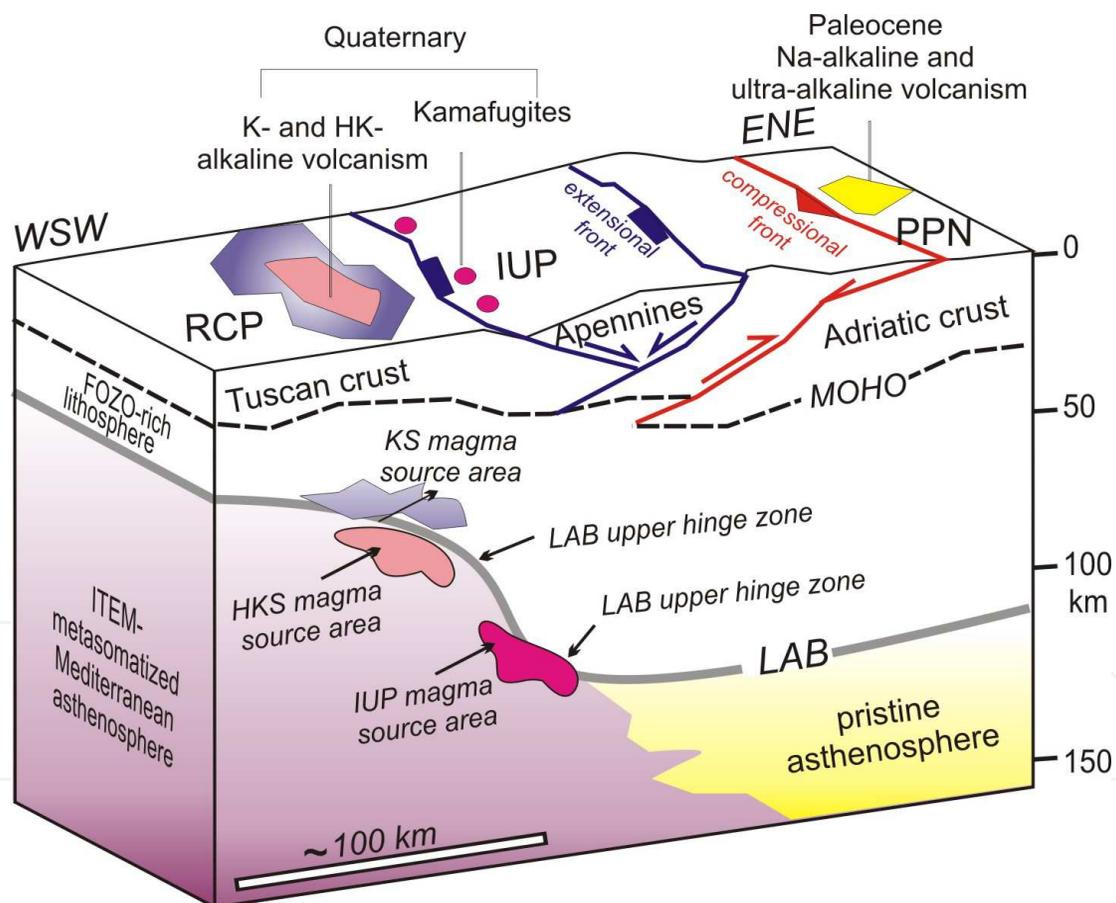


Fig. 5. Schematic block diagram across central Italy illustrating the present-day crustal and lithospheric structure and the relationships between the surface distribution of the various igneous provinces and magma types and the inferred mantle location of their parental melts (after Lavecchia and Stoppa, 1996; Lavecchia et al., 2003). Key: RCP = Roman-Campanian Province; IUP = Intramontane Ultra-Alkaline Province; PPN = Punta delle Pietre Nere. Note the inferred ITEM isotopic character of the upwelled Tyrrhenian asthenosphere.

lateral density contrast between the thinned Tyrrhenian and unthinned Adriatic lithosphere may have controlled the uprising of melts from asthenosphere reservoirs into relatively narrow bands across the lithosphere. In the case of Somma-Vesuvius and Vulture, the focusing of the volatiles from the mantle reservoir into one well-defined site might have been controlled by the intersection between the nearly E-W “41° Parallel Fault Zone” (see Figs. 2 and 4a) and the upper and lower LAB-hinge zone, respectively.

A source region close to the base of the lithosphere with normal temperatures is also proposed by Beccaluva et al. (2007) for the Paleogene Veneto province and for the other magmas of the Adria and Hyblean foreland domains. They considered that most of the magmas were equilibrated within the spinel-peridotite lithosphere mantle, from sources ranging in depth from about 30 to 100 km and with concomitant decrease in the degree of partial melting from (25% to 3%) from quartz-normative tholeiites to nephelinites. Two kinds of mantle mineralogy were identified: lherzolite-bearing amphibole with phlogopite for the tholeiites to basanites, and similar sources, but with the addition of some carbonatitic components for the nephelinites.

The origin of the late Eocene-early Miocene magmatic activity along the Periadriatic Lineament and along the Sardinia Trough can be interpreted as the result of melting due the presence of H<sub>2</sub>O and K-rich fluids during unloading processes. Such processes are commonly associated with the Ligurian-Provençal back-arc, extensional process in Sardinia and with the Alpine slab break-up in the case of the Periadriatic Lineament (Macera et al., 2008 and references therein). It is interesting to note that in the late Eocene-early Oligocene (that is before the opening of the Ligure-Provençal basin), the Periadriatic Lineament and the Sardinian Trough were nearly continuous along a common ENE-WNW direction. Also, considering the magmatic affinity between the two regions, we wonder if both might be related to the onset of extensional processes in the Western Mediterranean basin, with consequent lithospheric unloading. In such a case, the Periadriatic Lineament, corresponding to a pre-existing high-angle, northward-dipping, crustal discontinuity between the north-verging and the south-verging Alpine system, might have acted as a transfer fault to allow the eastward shift of the Adria foreland and the progressive opening of the Provençal basin.

## 6. Radiogenic isotopic compositions

The variation of the Italian igneous rocks in terms of Sr, Nd and Pb radiogenic isotopic is extreme, reflecting both depleted and very enriched sources, not only on a regional, but also on a local scale (Bell et al., 2005; Lustrino and Wilson, 2007; Lustrino et al., 2011; Bell et al., submitted). The compositional variations can be defined by a limited number of end-members that form well-defined binary mixing array (Fig. 6), that possibly reflect the magmatotectonic domains (Fig. 2). Two end-members are of widespread distribution and are considered to be plume-related. They are FOZO (Focus Zone) with low  $^{87}\text{Sr}/^{86}\text{Sr}$  (0.7025), high  $^{143}\text{Nd}/^{144}\text{Nd}$  (0.51315), moderate  $^{206}\text{Pb}/^{204}\text{Pb}$  (19.40) and HIMU (High  $\mu$  = high  $^{238}\text{U}/^{204}\text{Pb}$ ) with low  $^{87}\text{Sr}/^{86}\text{Sr}$  (0.70285), high  $^{143}\text{Nd}/^{144}\text{Nd}$  (0.51285), high  $^{206}\text{Pb}/^{204}\text{Pb}$  (22.00) (Hart et al., 1992, and reference therein). FOZO is considered to be a ubiquitous component of all of the analysed rocks from Italy, whereas an HIMU-like component is mainly restricted to occurrences lying within the Padan-Adriatic-Pelagian foreland and the Sicily Channel. Two other end-members range from very radiogenic (ITEM) to moderately radiogenic (possibly EM1) pointing to metasomatised mantle sources. ITEM (Italian Enriched Mantle) with very high  $^{87}\text{Sr}/^{86}\text{Sr}$  (0.7200), very low  $^{143}\text{Nd}/^{144}\text{Nd}$  (0.51185), low  $^{206}\text{Pb}/^{204}\text{Pb}$  (18.70) is widespread in the Italian mantle (Bell et al., 2005), while the EM1 component, with moderate  $^{87}\text{Sr}/^{86}\text{Sr}$  (0.70530), low  $^{143}\text{Nd}/^{144}\text{Nd}$  (0.51236) and very low  $^{206}\text{Pb}/^{204}\text{Pb}$  (17.50), is mainly observed in northern and central Sardinia.

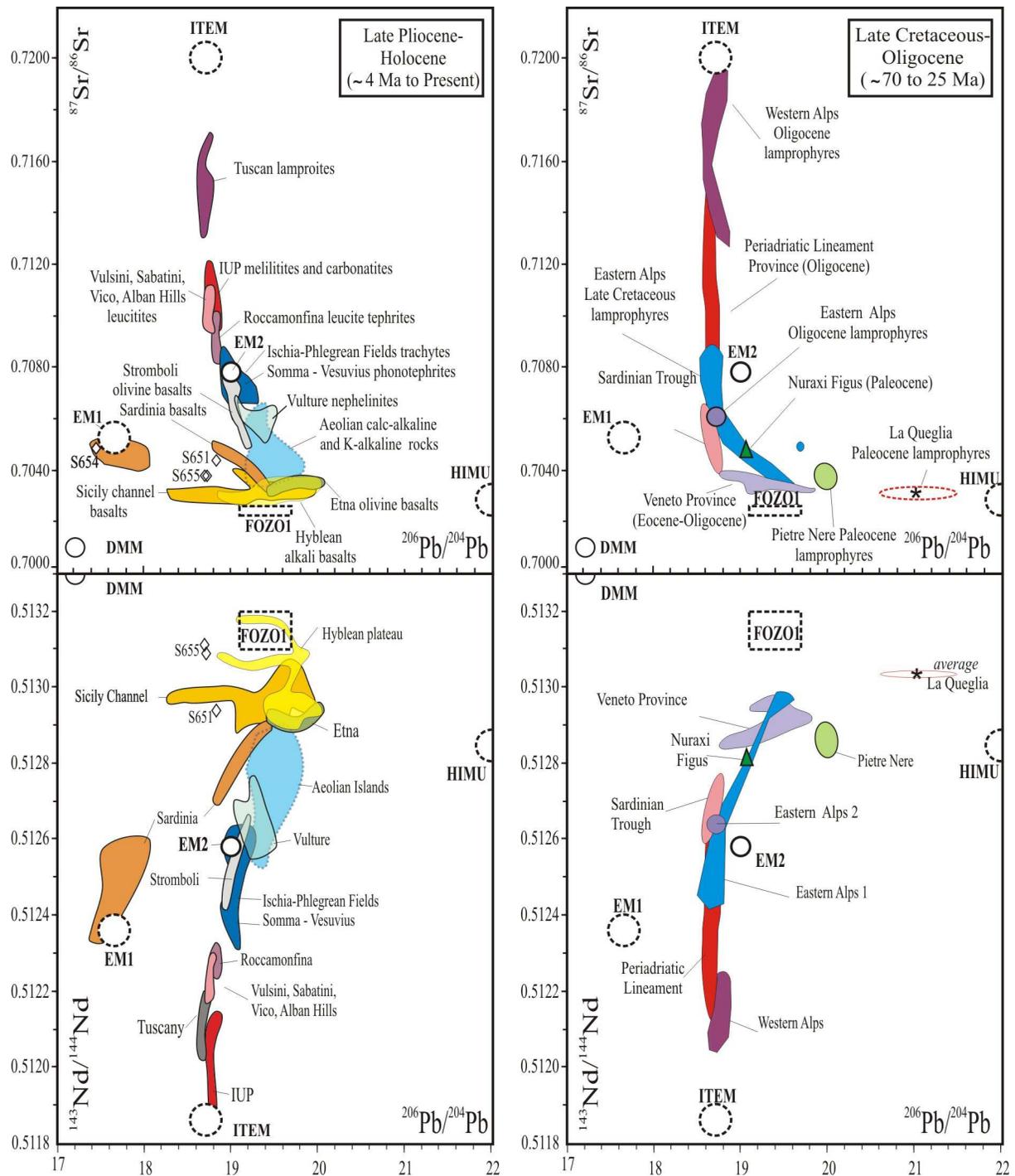


Fig. 6. Plots of  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $^{143}\text{Nd}/^{144}\text{Nd}$  against  $^{206}\text{Pb}/^{204}\text{Pb}$  for the Italian young (left side) and old (right side) volcanic occurrences. The diagram on the left side is from Bell et al., 2005; the diagram on the right side is from Bell et al., 2005 integrated with data from Owen, 2008; Beccaluva et al., 2007; Lustrino et al., 2011 and Bell et al., submitted. The identified isotopic distribution is compared with known world-wide, mantle end-members (EM1, EM2, HIMU, FOZO, (Hart et al., 1992, and references therein) and with the mantle Italian component ITEM (Bell et al., 2005 and 2006). We use the term FOZO1 in the diagram to refer to Hart et al's 1992 values since there are others in the literature.

The main mixing array is defined by FOZO-ITEM and includes data from the Tyrrhenian, the Apennine and the Alpine magmatotectonic domains (from Etna in Sicily to the Alps). A relevant increase in  $^{87}\text{Sr}/^{86}\text{Sr}$  (from 0.703 to 0.720), with a corresponding relevant decrease in  $^{143}\text{Nd}/^{144}\text{Nd}$  and a slight increase in  $^{206}\text{Pb}/^{204}\text{Pb}$  (from 19 to 20) is observed moving along the binary mixing array from ITEM to FOZO (Fig. 6). This mixing array essentially traces the isotopic compositions of a wide range of rocks, outcropping from north to south along the length of Italy and ranging in age from Late Cretaceous to Quaternary (Fig. 6 a and b). The most radiogenic Sr compositions are shown by the early Oligocene western and eastern Alpine lamprophyres ( $^{87}\text{Sr}/^{86}\text{Sr} \sim 0.72$ ); progressively decreasing values are observed moving towards the Plio-Quaternary Tuscany lamproites, the Oligo-Miocene Periadriatic calc-alkaline rocks, the Quaternary IUP carbonatites ( $\sim 0.712$ ), the Roman Province leucitites, the Campanian Province phonotephrites, the Vulture nephelinites and the Stromboli alkali basalts, down to the Aeolian calc-alkaline products and the alkali basalts from Etna (Fig. 6). The FOZO-HIMU-like mixing line almost exclusively consists of data from outcrops belonging to the Padan-Apulia-Pelagian foreland domain. Moving from HIMU-like to FOZO, we observe a relevant decrease in  $^{206}\text{Pb}/^{204}\text{Pb}$ , from an average value of  $\sim 21.5$  at la Queglia to a minimum of  $\sim 18.30$  at the Sicily Channel and rather constant values in  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios (0.703) and high radiogenic  $^{143}\text{Nd}/^{144}\text{Nd}$  (0.512-0.513). Along this array, we move from the Paleocene lamprophyres of La Queglia and Punta delle Pietre Nere in the Apulia foreland, to the Paleocene-Oligocene Na-alkali basalts of the Veneto Province in the Padan foreland, to the late Miocene-Pliocene Na-basalts in the Hyblean mountains within the Pelagian foreland, to the Na-alkali basalts of the Sicily Channel. A possible FOZO-EM1 mixing line constitutes a third subordinate array. It almost exclusively consists of data from Plio-Quaternary rocks from northern and central Sardinia.

## 7. The southern Tyrrhenian Benioff plane

The Tyrrhenian extensional basin is commonly considered a back arc-basin, developed at the rear of the NW-subducted Ionian lithosphere, with the Aeolian islands offshore of Calabria being considered the associated insular arc (Malinverno and Ryan, 1986; Doglioni et al., 1997). Such an interpretation is largely based on the presence of deep-focus earthquakes (up to depths of  $\sim 500$  km) supposedly associated with a westerly-dipping subduction plane (D'Agostino and Selvaggi, 2004; Chiarabba et al., 2005). As a matter of fact, the Southern Tyrrhenian Benioff Plane (STBP), analysed in terms of size, strain deformation pattern and spatial relationships with the overlying Aeolian volcanic arc appears to be in conflict with the classic geometric and kinematic configurations predicted by both active and passive subduction-related models (Isacks and Molnar, 1971).

The STBP depth contour lines in Fig. 7a were obtained by analysing the depth distribution of the sub-crustal ( $>35$  km) seismicity, in the time interval 1978 to 2008. The data were extracted from the International Seismological Centre database and projected along a set of radial sections across the plane, with an average semi-amplitude of 25 km. The hypocenters projected in Fig. 7b were extracted from the same dataset, assuming a semi-width of 60 km along the trace of the section.

In the map of Fig. 7a, the STBP depth contour lines show an average NE-SW direction in the southern sector, which then turns to NNE-SSW. The lack of a geometric correspondence with the shape of the Aeolian volcanic arc, which is tightly curved, is evident. In the section view of Fig. 7b, the Benioff plane is sub-vertical to deeply SE-dipping down to nearly 200

km and dips to the northwest, at an average dip angle of about  $50^\circ$ , at higher depths. Large portions of the slab are characterized by the presence of aseismic domains which prevail at depths greater than 350 km. The Aeolian volcanoes, projected along the trace of the section, are positioned both above the seismic and aseismic plane segments. The various volcanoes lie at different depths above the plane, from a minimum of ~150-200 km for Vulcano-Lipari, to depths of ~250-300 km for Filicudi-Alicudi and still more for Enarete-Sisifo (~400 km). It is evident that the Aeolian magma sources do not form a more or less continuous linear zone at a constant depth along the top of the subduction zone, as should be if they were connected to a down-going slab (Moores and Twiss, 1995).

Available focal mechanisms associated with the STBP show a predominant normal-faulting kinematics (Chiarabba et al., 2008). T-axes turn in azimuth perpendicularly to the slab direction and P-axes are usually parallel to the average plane dip direction (blue and red arrows in Fig. 7 b). Such evidence of slab down-dip compression enables us to exclude any model of retreating slab, which would be characterized by down-dip extension, due to the negative buoyancy of the subducting lithosphere. On the other hand, a process of active subduction, consistent with the down-dip compression, would imply fault plane solutions showing thrust faulting in the shallower depth range (0-100) km in the vicinity of the convergent boundary which are missing in the study area (Chiarabba et al., 2005).

The Southern Tyrrhenian Benioff zone is also unusual in terms of its size. Its lateral extension (nearly 250 km) is one of the smallest on Earth and its along strike length/along dip-length ratio is very low (about 0.5) unlike the circum-Pacific subduction planes (about 20). Furthermore, an along-strike length of a few hundred kilometres cannot help explain the length of the Apennine-Maghrebic belt, that would represent the associated accretionary prism extending for nearly 3500 km from northern Italy to the Gibraltar Arc, unless 90% percent of the subduction plane is considered aseismic.

Another interesting point concerns the balance between the along-dip length of the STBP (maximum length of 500 km) and the amount of shortening of the Apennine fold-and-thrust belt system. The volume of the entire Apennine crust in Calabria is smaller than the volume of the upper crust that would be involved in the formation of an accretionary prism, assuming that the upper crust had been scraped off during subduction (Doglioni *et al.*, 1999). In general, the compressional structures of both the central and the southern Apennines do not show the thin-skinned geometries typical of subduction-related complexes, but rather they are characterized by a thick-skinned style, typical of ensialic deformations, with basement largely involved in the deformation and with only limited amounts of horizontal shortening (van Dijk et al., 2000; Barchi et al., 2001; Noguera and Rea, 2000; Lavecchia et al., 2003).

Tomographic models of the mantle beneath the Apennines and the Tyrrhenian show the presence of a highly discontinuous, intra-asthenosphere, high-velocity body, usually assumed to be the Ionian lithosphere subducted in the course of the Apennine compressional phase, but images are very different in length, position and continuity (Spakman *et al.*, 1993; Cimini and De Gori, 2001; Piromallo and Morelli, 2003; Piromallo and Faccenna, 2004). Some alternative, very speculative, hypotheses have been advanced. Some authors interpret the structure of the Calabro-Sicilian Arc to krikogenesis rather than subduction (Wezel, 1981); others associate the STBP to seismic shearing along intra-asthenospheric remnants of a pre-existing Alpine subduction plane (Lavecchia and Creati, 2006), to asthenosphere dragging (Locardi and Nicolich, 1988), to deep-seated reverse faulting (Choi, 2004), and to dense mantle material rising towards the surface from a large body of lower mantle material trapped in the transition zone (Scalera, 2006).

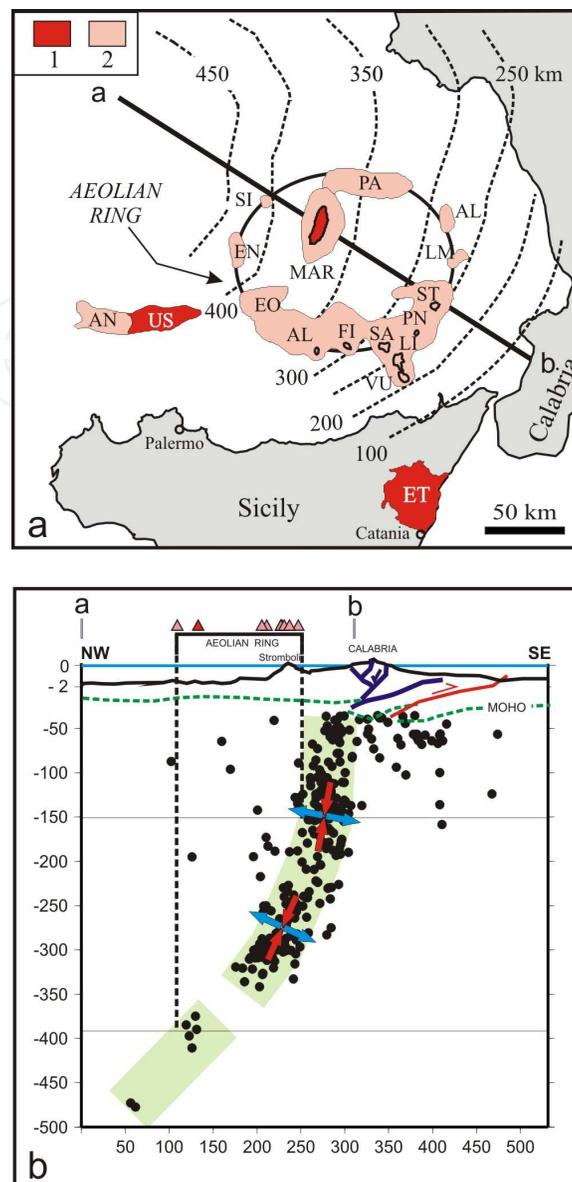


Fig. 7. a) Location of Quaternary igneous rocks in the southern Tyrrhenian Sea compared with the geometry of the Benioff plane off Calabria (from Bell et al., 2005). Key: 1) alkali basalts to trachybasalts; 2) olivine basalts, trachybasalts with shoshonites and calc-alkaline rocks; PA) Palinuro, AL) Alcione, LM) Lamentini, ST) Stromboli, PN) Panarea; SA) Salina, LI) Lipari, VU) Vulcano, FI) Filicudi, AL) Alicudi, EO) Eolo, EN) Enarete, SI) Sisifo, MAR) Marsili, AN) Anchise, US) Ustica, ET) Etna; dashed lines = reconstructed average depth contours of the Benioff plane labelled in kilometres.

b) Section view of the Southern Tyrrhenian Benioff plane along a SW-NE striking, transect assuming a semi-width of 60 km. The trace of the a-b segment of the section is given in the map. The hypocentral data set is from the International Seismological Centre (ISC); it consists of sub-crustal events registered at depth  $\geq 35$  km in the time interval 1978-2008 ( $M_b$  2.0 to 5.7). The red and blue arrows refer to average P- and T- axes, respectively, calculated from focal mechanisms extracted from the CMT catalogue and the RCMT catalogues, available on line. The pink triangles above the section represent the islands of the Aeolian volcanic ring projected along the trace of the section.

No matter which of the above alternative models is favoured, the ring-like configuration of the Aeolian islands at the surface is not governed by the geometry of the slab at depth, which is much more linear (Fig. 7). The Aeolian magmatism might simply be due to lithospheric stretching, unloading and associated partial melting in the thinned and stretched areas surrounding the Marsili mantle core complex, independently from any subduction.

## 8. Proposed model

### 8.1 The origin of the mantle radiogenic components

Among the isotopic mantle end-members identified in Italy, FOZO is ubiquitous and has been involved in the generation of all the igneous products since Late Cretaceous times (Fig. 6). It is very close in composition to FOZO of Hart et al. (1992) and is similar to other European and Mediterranean end-members, such as EAR (European Asthenospheric Reservoir, Granet et al., 1995; Wilson and Patterson, 2001), LVC (Low Velocity Component, Hoernle et al., 1995) and CMR (Common Mantle Reservoir, Lustrino and Wilson, 2007). The world-wide FOZO component was first identified on the basis of isotopic data from oceanic island basalts; it is anorogenic, independent of subduction and normally associated with intra-plate magmatism. The Italian ubiquitous FOZO end-member, first introduced by Bell et al (2003), has been considered a pure deep mantle component entrained within the Mediterranean lithosphere and asthenosphere *via* upwelling plumes (Bell et al., 2006; Cadoux et al, 2007). It might also represent an ancient phase of regional rifting which pre-dated the Late Triassic-Early Jurassic continental break-up of Europe and Africa (Bell et al., submitted).

In the Alps, the Apennines and the Tyrrhenian Sea, the ITEM component is just as ubiquitous as FOZO, and is involved to different degrees in the generation of almost all of the igneous rocks. Conversely, there is no trace of ITEM within the Alpine and Apennine foreland domain (Figs. 2 and 6). The ITEM involvement is lowest in Sicily and highest in the Alps. Given its high  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio it has commonly been interpreted as a crustal component released within the mantle during an inferred Apennine subduction process (Peccerillo, 1999). ITEM, however is most prevalent in the most primitive and extreme ultra-alkaline Italian rocks (carbonatites, melilitites, lamprophyres) that are not related to subduction. Its presence not only in the early Oligocene Alpine lamprophyres, but also in the Late Cretaceous-Paleocene lamprophyres from the western Alps and possibly in the Early-Late Cretaceous lamprophyres of southern Tuscany means that whatever process generated the mantle enrichment, it had to date back at least to Cretaceous times. This rules out any relationship with the perceived subduction of continental crust during the Mediterranean extensional phase.

In general, ITEM increases with an increase in Mg number, with an increase in K content and with an increase in depth of the magmatogenetic source. This might reflect depth-controlled variation in partial melting and in the mantle source composition, with ITEM being more common at deeper levels. The ITEM signature always co-exists with FOZO, requiring two distinct mantle reservoirs that are contiguous and hence able to communicate with one another. A vertical compositional variation, with a prevalently depleted lithosphere and an underlying metasomatised, ITEM-rich, asthenosphere enriched by plume-derived fluids is one possible solution, or a heterogeneous mantle plume another. According to Lavecchia and Creati (2006), the ITEM end-member could originate within the D'' layer, at the lower mantle/core transition, where it could have evolved to its extreme isotopic compositions and could have been transported within the asthenosphere *via* plumes, in recent times.

The HIMU-like composition is not as widespread as ITEM and FOZO, but is still regionally, fairly important since it is present in all of the occurrences within the Adriatic foreland. Beccaluva et al. (2007) explains the isotopic characteristics of the mantle sources within the Adriatic foreland regions, as due a variable mixing of HIMU and, to a lesser extent, EM2 metasomatic components with a pristine depleted-mantle lithosphere. Given its extreme isotopic compositions in radiogenic lead, HIMU has been interpreted as a lower mantle component which has experienced considerable ageing during long-term residence (Collerson et al., 2010). In the case of Italy, the HIMU-like end-member is found, together with FOZO, within the sodic-alkaline and ultra-alkaline suites of the Foreland domain and of the Sicily Channel domain. We could hypothesise a present residence of the HIMU-like component within the asthenosphere, in areas that have not been affected by the plume-generated ITEM metasomatic components.

The EM1-like component is rare in Italy and is found in the Plio-Pleistocene basalts of northern and central Sardinia. It is similar to that of the eastern Atlantic, northern Africa, and central Europe (Macera et al., 2003) and might be ascribed to melting of metasomatised veins enclosed within the European continental lithosphere.

Summarising, the FOZO component might reside within the lithosphere of both the Tyrrhenian-Tuscan stretched domain and the surrounding unstretched areas (Foreland domain and Sardinia-Corsica domain in Fig. 2) where perhaps it might have developed during plume-driven, rifting processes pre-dating the Pangea break-up. Conversely, both the ITEM and HIMU-like components could reside within the asthenosphere, in geographically and tectonically distinct magmatotectonic domains. ITEM could occur beneath the Tuscan-Tyrrhenian domain (Fig. 2) and, in general, beneath the widely extended Western and Central Mediterranean domain. The HIMU-like component might lie beneath the stable foreland domain, and beneath the "narrow-rift" domains, such the Sicily Channel and the Central Europe Rift System.

## 8.2 The Mediterranean trapped plume model

We do not consider the Western and Central Mediterranean regions as a back-arc basin developed on the rear of westward-subducting lithosphere, but instead propose an alternative hypothesis that involves lithospheric stretching driven by mantle asthenosphere expansion due to the growth of a plume head (Fig. 8) (Lavecchia and Creati, 2006; Bell et al., submitted). Because most plumes involve thermal highs, elevated topography and flood basalts, missing in the Mediterranean region, the plume head would have to be trapped within the transition zone between the asthenosphere and the mesosphere (~410 to 670 km depth). Such a mantle plume would carry radiogenic fluids/melts from the deep mantle in order to generate metasomatic agents with an ITEM signature that affected the host Mediterranean asthenosphere. Influxes in the upper mantle of fluids/melts associated with a plume enriched in CaO-CO<sub>2</sub>-K<sub>2</sub>O would generate a source capable of producing ultra-alkaline magmatism, and the deep-seated CO<sub>2</sub> emissions found in peninsular Italy. The progressive eastward growth of a large plume head trapped within the transition zone and the consequent asthenospheric volume increase would also cause stretching and large scale extension of the overlying lithosphere. The consequent lithospheric unloading would, in turn, control the Tyrrhenian and peri-Tyrrhenian magmatogenetic activity.

Given the Late Cretaceous age of the oldest Italian occurrences carrying the ITEM signature, the birth of such a plume should be older than the onset of the Mediterranean extensional phase, and perhaps related to the Alpine Tethys Jurassic extensional phase. We hypothesise a pulsating plume activity (Bell et al., submitted). We argue that during the Alpine

compressional phase, the plume was relatively quiescent and only produced minor upwellings that allowed the hot, low viscosity material to escape to upper levels, thus generating a number of isolated lamprophyric occurrences on both the European and the African sides of the Alpine orogenic zone, implying that their emplacement was not controlled by slab migration. During the Mediterranean phase, the plume was active again and controlled the magmatotectonic evolution of the Ligure-Provençal and Tyrrhenian basins.

The interpretation of the Mediterranean region in the framework of plume-driven mantle expansion also implies an unusual interpretation of the large-scale high-velocity anomaly, shown by tomographic data within the transition zone (410 to 670 km) (Piromallo and Morelli, 2003). The high-velocity body might not represent accumulated Alpine and Apennine subduction material, but rather the trapped plume head (Lavecchia and Creati, 2006). In such a case, the velocity anomaly would not result from thermal variations (cold subducted lithosphere), but rather from chemical/compositional variation (upwelled deeper mantle material) (Fig. 8). The low-velocity tomographic anomaly that characterizes the Mediterranean upper mantle down to 400 km, could in turn represent asthenospheric material that has been enriched, metasomatised and softened by the fluids released by the plume head.

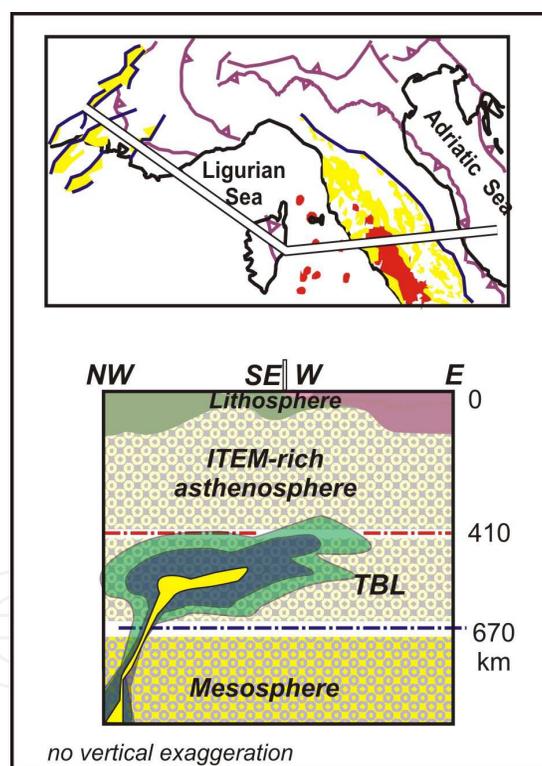


Fig. 8. Proposed interpretation of the mantle structure beneath the lithospheric section of Fig. 1b, assuming the trapped plume scenario discussed in the paper. The shape of plume head although speculative (from Lavecchia and Creati, 2006) is largely derived from Fig. 6 in Brunet and Yuen (2000). The plume head substantially coincides with a high-velocity anomaly highlighted by tomographic data beneath the Western and Central Mediterranean region (Piromallo and Morelli, 2003). In our sketch, the colours of plume head mark an hypothesised progressive outward increase of the  $V_p$  velocities, due to the loss of volatiles and light elements released within the overlying asthenosphere.

## 9. Final remarks

The geology of the Western and Central Mediterranean region, with all of its paradoxes and contradictions, presents an exceptional natural laboratory for assessing the cause-effect relationships between the tectonic/magmatic processes associated with crust, the mantle lithosphere and the underlying mantle. Rather than fitting all of the evidence that has been acquired during the last decades into a standard subduction model, we have attempted to find alternative solutions that might more easily explain the available data. The simple models of orogenic *versus* anorogenic, and active rifting *versus* passive rifting, although useful, may be more complex than we imagine, and we have sought alternative, more encompassing solutions that might explain the diverse tectonic and magmatic activity in Italy, during Tertiary and Quaternary times.

In the case of the progressive opening since Oligocene times of the Central and Western Mediterranean "wide-rift" basins, a model assuming the eastward growth of a plume head fed from the deep mantle and pinched within the transition zone (410 to 670 km depth) may be a reasonable alternative to one involving back-arc opening at the rear of a retreating subduction slab. In fact, closer evaluation of the evidence for subduction is not so convincing when looked at in detail. The unusual tectonic, petrographic and geochemical characters, such as extension dominating over compression, high potassic to ultra-alkaline suites predominating over calc-alkaline occurrences, and plume-related isotopic compositions, have been casually dismissed by subductionists as "anomalous" and "exotic" (Lustrino et al., 2011).

A trapped plume model may well explain (i) the fast lithosphere extensional rate (up to 5-6 cm/y, Faccenna et al., 2004), (ii) the cold continental geotherm (~1300°C at the lithosphere-asthenosphere boundary, Cella and Rapolla, 19987), (iii) the regional subsidence (bottom sea level reaching depths of less than 3000 km), and (iv) the lack of extensive basaltic magmatism. Because the plume head in our model does not reach the base of the lithosphere, it does not directly control the lithospheric tectonics and magmatism. Instead, the plume growth within the transition layer exerts an indirect control on the lithosphere tectono-magmatic activity. The highly radiogenic character (ITEM signature) of the fluids injected within the Mediterranean asthenosphere, and carried up to the surface during igneous activity, implies a long residence time in an isolated source that may coincide with the transition zone between the asthenosphere and the mesosphere (670 km depth) and/or with the D'' boundary layer at the core mantle/transition (2900 km depth).

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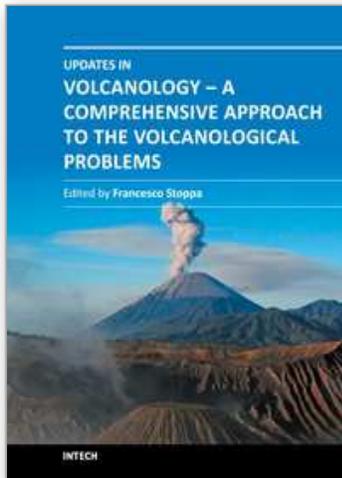
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## **Updates in Volcanology - A Comprehensive Approach to Volcanological Problems**

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