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# VOLCANIC ACTIVITY FROM THE NEOGENE TO THE PRESENT EVOLUTION OF THE WESTERN MEDITERRANEAN AREA. A REVIEW

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## ABSTRACT

The Neogene to Present geodynamic and magmatological evolution of the western Mediterranean area may be summarized as follows: 1) Paleocene to Present volcanic activity in the Massif Central, France, related to the presence of a mantle plume in the Alpine foreland; 2) roughly continuous W-NW subduction of the Adria Plate from the Oligocene under the southern European margin; 3) development of a subduction-related back-arc basin during the Oligocene (Ligurian-Provençal Basin); 4) split of the Sardinia-Corsica Block from the Provençal basement; 5) collapse of the Betic orogen, with rapid exhumation of deep crustal and mantle rocks and development of volcanic activity in SE Spain (~30-2 Ma); 6) subduction-related magmatism in Sardinia (28-15 Ma) and eastern Spain (24-15 Ma); 7) a mid-Miocene 'leap' in the subduction system, from the Ligurian-Provençal Basin to the Tyrrhenian Sea, with a shift from Hercynian to Alpine terrane overthrusts; 8) opening of the Tyrrhenian Sea as a back-arc basin; 9) Neogene-Quaternary eastward-moving distensive and compressive tectonic waves and coeval magmatism along the western and southern margins of the Italian peninsula (Tuscan, Roman and Campanian Provinces and Aeolian Islands); 10) volcanic activity in the Betic foreland (Calatrava Province, ~9-1 Ma); 11) Plio-Pleistocene development of rift systems and coeval magmatism in Sardinia, northern and eastern Sicily (Mt. Etna and Hyblean Mts.) and the Strait of Sicily.

Intense volcanic activity accompanied the evolution of the last 30 Ma in the western and central Mediterranean, with a wide range of magmatic products which may be grouped into: a) oceanic floor basalts (Ligurian-Provençal Basin and Tyrrhenian bathyal plain with Magnaghi, Vavilov and Marsili seamounts), whose compositions vary from N-MORB to E-MORB and pure low-K calc-alkaline basalts; b) subalkaline series with both tholeiitic and calc-alkaline affinities; c) alkaline products with extreme compositions ranging from mildly alkaline types with sodic affinity to strongly $SiO_2$-undersaturated with both sodic and potassic to ultrapotassic affinity, possibly including also carbonatitic lithotypes. The Sr-Nd-Pb isotopic compositions of these products comprise virtually all the most common worldwide reservoirs and testify to the extremely heterogeneous compositions of the mantle sources of this sector of European lithosphere/asthenosphere system.

## INTRODUCTION

From about 30 Ma ago, the lithosphere under the area now occupied by the Western and Central Mediterranean Sea started to thin. In several zones (e.g., Ligurian-Provençal Basin, Tyrrhenian Sea), this process ended with the formation of pure oceanic crust, whereas in other places (e.g., Rhine-Rhone graben, "Fossa Sarda" graben in Sardinia, Strait of Sicily), oceanization was not completed but the thickness of the continental lithospheric was definitely reduced (Lustrino, 2000). Zones of lithospheric thickening (e.g., Alps, Apennine chain, Betic-Rifian zone) are associated with this lithospheric thinning. The reason for these processes in an overall compressive domain squeezed between Africa and north Europe is not yet completely understood (Séranne, 1999).

All these modifications were accompanied by volcanic activity of exceptionally wide compositional range. Both alkaline and subalkaline melts were emplaced: sodic, potassic and ultrapotassic alkaline products are spatially and temporally correlated, like tholeiitic and calc-alkaline volcanic rocks. Strongly $SiO_2$-undersaturated to $SiO_2$-oversaturated through $SiO_2$-critically saturated products were produced.

This paper reviews the most important igneous activity from Neogene to Present in the circum-Western Mediterranean area, highlighting, where possible, the various and often contrasting relations proposed to explain magmatic activity in relation with geodynamic environments.

From west to east, the magmatic provinces examined here (Fig. 1) are: Spain (Internal Betics, Valencia trough, Calatrava, Olot), Morocco (Gourougou Mts.), France (Massif Central, Provence) and Italy. The Italian provinces discussed in this paper are: the Oligo-Miocene and Plio-Pleistocene volcanic districts of Sardinia, southern Tuscany, northern Latium and Campania, Mt. Vulture, Aeolian Archipelago, Sicily (Mt. Etna, Hyblean Mts.), the islands of Pantelleria, Linosa and Ustica and Tyrrhenian Sea volcanic rocks.

The genesis and evolution of the volcanic records are reviewed in the light of modern geodynamic models of evolution. For each province, only the main features are described, exhaustive treatment of magma genesis and evolution in the Mediterranean area being beyond the scope of this paper.

## GEODYNAMIC SETTING OF WESTERN MEDITERRANEAN

At the end of the Paleogene, the northern sector of the Mediterranean area reached a continental collisional stage, after the total consumption of the Ligurian-Piedmontese ocean (Tethys). (For a more detailed review of the geodynamic models proposed for this area, see Lustrino, 2000). The closure of Tethys is the first evidence of the ongoing Alpine orogenesis (eo-Alpine phase), characterized by subduction of oceanic lithosphere and followed by continent-continent collision between Africa and Europe. The way in which this ocean was consumed is still a matter of debate and may be summarized in the following two points: a) closure via the formation of a westward-dipping subduction zone east of the southern European margin, represented by the Sardinia-Corsica Batholith. In this model, "Alpine" Corsica is linked to the northern Apennine system as an accre-

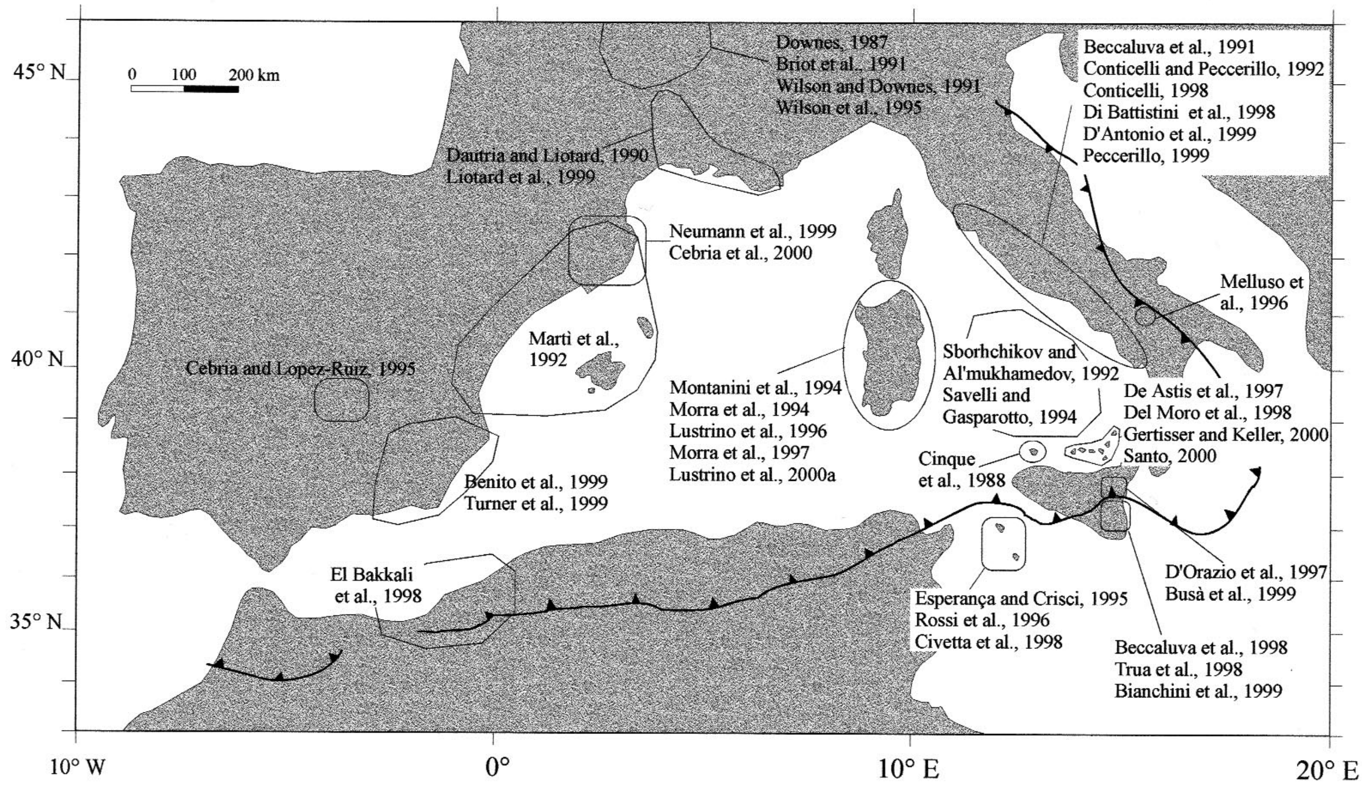

Fig. 1 - Sketch-map of main Neogene to Present volcanic rock outcrops of western Mediterranean area with most significant and the latest references for each region. (For a more complete list of references, see text).

tionary wedge (Carmignani et al., 1995; Muttoni et al., 1998); b) closure via the formation of an eastward-dipping subduction zone east of the Sardinia-Corsica block. According to many authors (e.g., Guerrera et al., 1993; Doglioni et al., 1997), the Alpine nappes of Corsica are the southern continuation of the Western Alps with European vergence and African back-thrusts. The suture line between European and African Plates now occurs only in NE Corsica. According to this hypothesis, Sardinia and Corsica were the Alpine foreland and Apennine interland.

During the Late Oligocene, Africa and Europe reached a continent-continent collisional stage in the SW (Betic orogen) and NW Mediterranean (Alpine Corsica and Northern Apennine chain). Tethyan oceanic crust was still present between these two realms. According to Gueguen et al. (1998), the continental collision stage reached by the SE-directed subduction system during the Late Oligocene lies at the base of the flip of the subduction zone from east- (eo-Alpine phase) to west-directed (neo-Alpine phase) towards the Alpine back-thrust belt, where Tethyan crust was still present.

In about the Paleogene-Neogene boundary, a rift system, extending from the shores of the North Sea through the Rhine-Rhöne-Bresse graben in Central Europe and the Limagne graben in the French Massif Central, down to the Algerian-Provençal-Ligurian Basin and Valencia trough, developed along the whole of Europe. These rifting processes had various moving forces: a) different stress release in the Alpine-Betic chain foreland (Rhine-Rhöne rift system (Germany; Mayer et al., 1997) and Calatrava Province (central Spain; Cebria and Lopez-Ruiz, 1995)), b) ascent of an asthenospheric plume (French Massif Central; Zeyen et al., 1997); c) slab roll-back-related subsidence (Western and Central Mediterranean areas; Gueguen et al., 1998; Doglioni et al., 1999).

The main petrological and geochemical characteristics of volcanic activities related to this geodynamic evolution of Western Mediterranean are summarized below.

## SPAIN

Neogene-Quaternary volcanism in Spain occurred in four zones: Internal Betics (SE Spain ; 30-2 Ma), Valencia trough (24-0 Ma), Calatrava Volcanic Province (~ 9-1 Ma) and Olot zone (NE Spain; 10-0 Ma).

### Internal Betics (SE Spain)

During the Late Cretaceous-Early Tertiary, the convergence between Africa and Europe reached a continental stage and resulted in the formation of the Betic orogen in SE Spain. During this phase, crustal staking developed and the lithospheric root reached a thickness of more than 50 km (Vissers et al., 1995). A rapid phase of extension during the Early Miocene followed by rapid unroofing (> 3km/Ma) is recorded in the core complexes of the Ronda (South Spain) and Beni Bousera (Morocco) peridotites (e.g., Zeck, 1997).

The Miocene extensional phase recorded in the Betic chain, within the general compressional regime, remains an unresolved problem for which several hypotheses have been proposed: a) convective removal of the lower part of the lithospheric mantle (thermal boundary layer; Platt and Vissers, 1989; b) delamination of the lithospheric mantle (i.e., Docherty and Banda, 1995); c) retreat of the westward slab in a back-arc setting (Lonergan and White, 1997); d) detachment of a subducting oceanic slab (Zeck, 1997; Carminati et al., 1998); e) interference between E-directed Betic subduction and W-directed Apennine subduction along the backthrust belt of the pre-existing orogen (Doglioni et al., 1999).

Within this complex geodynamic evolution, magmatic activity lasting from ~30 to 2 Ma developed in SE Spain, with extremely variable geochemical compositions (Zeck, 1997; Turner et al., 1999). Products range in composition from tholeiitic to calc-alkaline and high-K calc-alkaline character, up to real cordierite-garnet-bearing anatectic crustal melts. Ultrapotassic products (shoshonitic to lamproitic) also occur (Benito et al., 1999; Turner et al., 1999). The chemistry of these products has been alternatively related to subduction-related settings (e.g., Torres-Roldan et al., 1986) variably modified by crustal contamination (Benito et al., 1999) or mainly crustal contamination of a variably metasomatized mantle source (Turner et al., 1999).

Both asthenospheric and lithospheric mantles are thought to have melted. In particular, the first evidence of volcanism in SE Spain (tholeiitic dykes) is related to decompression melting within the asthenosphere, following removal of lithospheric keel. This process also produced crustal anatexis and calc-alkaline magmatism. The following alkali basalts and lamproites may reflect sediment-enriched lithospheric sources (Turner et al., 1999). Radiogenic isotopes reflect the variable sources (crust, enriched lithosphere and asthenosphere) involved in the genesis of these rocks ($^{87}Sr/^{86}Sr$ = 0.705-0.720; $^{143}Nd/^{144}Nd$ = 0.5119-0.5129; $^{206}Pb/^{204}Pb$ = 18.57-18.83). Enrichment of mantle sources is alternatively hypothesized to be ancient (Proterozoic?; Turner et al., 1999) or Late Cretaceous-Oligocene (Benito et al., 1999).

### *Valencia troug*

The Western Mediterranean started to open roughly during the Late Oligocene (~30 Ma; Séranne, 1999). The first evidence of this formation is the Late Oligocene-Early Miocene Alboran, Valencia and Ligurian-Provençal Basins, followed in time and space eastward by the formation of the Middle to Late Miocene Balearic and Algerian Basins and the Late Miocene-Pleistocene formation of the Tyrrhenian Sea (Gueguen et al., 1998).

The opening of the Ligurian-Provençal Basin separated the Sardinia-Corsica batholith from Provence during two major tectonic events: a Late Oligocene drift stage, followed by relative counterclockwise rotation of the Sardinia-Corsica block. The splitting of Sardinia and Corsica from Provence was induced by W-NW-dipping slab roll-back with related back-arc opening (Doglioni et al., 1997; Faccenna et al., 1997; Séranne, 1999) and oceanic crust formation. During the Early to Middle Miocene (24-19 Ma), calc-alkaline volcanism developed in the central to eastern offshore areas of the Valencia trough and on Mallorca. This volcanic cycle comprises mainly pyroclastic products emplaced in a sub-aerial environment. Only a few analyses are available for these rocks (Martì et al., 1992), showing compositions ranging from dacite to rhyolite, with trace element distributions typical of calc-alkaline associations.

From the Middle Miocene to Present (10-0 Ma) a new volcanic cycle developed in the Valencia trough area. Its products are mainly represented by poorly differentiated alkaline rocks with intraplate affinity (Martì et al., 1992). Olivine-nephelinite, basanite, alkali basalt and hawaiite, some containing mantle xenoliths, are the commonest lithologies. Their character is sodic, with strongly HREE-depleted compositions compared with LREE. Complete isotopic systematics of this volcanic cycle are lacking.

Decompression melting of mantle rocks (of both lithospheric and asthenospheric affinity) caused by the extensional tectonics is thought the origin of this second volcanic cycle of the Valencia trough (Martì et al., 1992).

### Calatrava Volcanic Province (Central Spain)

Mafic undersaturated alkaline lavas (Late Miocene-Quaternary) also occur in central Spain (Calatrava volcanic province) over an area of about 4000 km$^2$ (Cebria and Lopez-Ruiz, 1995). These products are roughly coeval with the late products in SE Spain (Benito et al., 1999; Turner et al., 1999) and the alkaline rocks of the Valencia trough (Martì et al., 1992). The Calatrava volcanic province is made up of undersaturated (alkali basalt and nephelinite) to strongly undersaturated (melilitite and leucitite) potassic alkaline rocks. A common source, relatively enriched in incompatible trace elements, has been proposed for the alkali basalt, nephelinite and melilitite suites, the latter forming through a lower degree of partial melting (5%) compared with alkali basalt (~ 17 % F). For the K-Rb-Ba-rich composition of leucitite, low melting degrees (~ 4%) of an anomalously enriched lithospheric mantle source, without any direct modification related to the Alpine-Betic orogenesis, has been proposed (Cebria and Lopez-Ruiz, 1995). Trace element abundances suggest the participation of lithospheric sources variously modified by a mantle diapir component with affinities to HIMU sources (Cebria and Lopez-Ruiz, 1995).

### Olot zone (NE Spain)

The volcanic rocks of NE Spain are emplaced in extensional basins and graben-type structures oriented NE-SW (following the Cenozoic European rift system; Ziegler, 1992) and NW-SE. These are leucite basanite, nepheline basanite and alkali olivine basalts (Cebria et al., 2000); an outcrop o trachyte is also present (Martì et al., 1992). The presence of mantle xenoliths in all groups (with the exception of trachyte), coupled with their relatively high MgO (> 7 wt. %), mg# (58-68) and Ni (> 100 ppm) strongly support the hypothesis that at least the more mafic lavas of the Olot zone represent primitive partial melts. Geochemically, the Olot volcanic rocks are almost homogeneous, with HIMU-OIB-like pattern in primitive mantle-normalized diagrams (e.g., overall bell-shaped pattern with positive peaks at Ta-Nb); the constant positive anomalies of Ba are, however, more typical of EMI-OIB-type end-member.

The entire spectrum of composition of the mafic products has been related to variable degree of partial melting (4 to 16 %) of a lithospheric mantle metasomatized by few percent (~5 %) of asthenospheric mantle partial melts (Cebria et al, 2000). Isotopic data indicate depleted LILE and LREE time-integrated isotopic character ($^{87}Sr/^{86}Sr$ = 0.7036-0.7038; $^{143}Nd/^{144}Nd$ = 0.51271-0.51283) and radiogenic Pb compositions ($^{206}Pb/^{204}Pb$ = 18.88-19.47; Neumann et al., 1999; Cebria et al., 2000). The overall isotopic and trace element signature is thus intermediate between HIMU and EMI mantle end-members. Mafic cumulates associated with such products show $^{87}Sr/^{86}Sr$ (0.7035-0.7036) and $^{143}Nd/^{144}Nd$ (0.5127-0.5128) overlapping with the host lava, but are shifted to more unradiogenic Pb compositions ($^{206}Pb/^{204}Pb$ = 18.10-19.10; Neumann et al., 1999).

## MOROCCO

During the Neogene to Pliocene, two contrasting volcanic cycles developed in the Eastern Rif. The first comprises a suite of orogenic rocks with calc-alkaline, high-K calc-alkaline to shoshonitic and alkaline serial character (13.1-5.4 Ma); the second is represented by alkali basalt with sodic affinity (5.6-1.5 Ma; El Bakkali et al., 1998). The products of the first cycle are basaltic andesite, andesite, shoshonite, latite, and trachyte to rhyolite, and show typical features of subduction-related magma (e.g. low Nb content and depleted HFSE (Ti, Y) compositions relative to MORB, coupled with enrichment in LILE (Sr, Rb, Ba, Th). El Bakkali et al. (1998) also showed the LILE-enriched character of Pliocene basalt from Gourougou magmatic field. These rocks were emplaced in a post-collisional tectonic setting and follow previous Miocene calc-alkaline to high-K calc-alkaline to shoshonitic volcanic activity. The geodynamic evolution of the eastern Rif (North Morocco) shares similarities with the Oligo-Pleistocene volcanic evolution of Sardinia and the Valencia trough (see below), both regions being characterized by terranes reworked during the eo-Alpine phase. However, during the Oligo-Miocene, Sardinia collided and overrode the oceanic Tethyan crust, whereas the Betic-Rif Orogen suffered continent-continent collision (Africa against Iberia) during Eocene-Early Miocene. Calc-alkaline and potassic calc-alkaline rocks were emplaced in both regions in post-collisional times and were followed by Pliocene sodic within-plate magmatism, sometime with K-rich character (e.g., Lustrino et al., 1996; El Bakkali et al., 1998; Lustrino, 1999).

The last noteworthy point is explanation of the geochemistry of the Miocene orogenic rocks (i.e., high $K_2O$ and LILE; low Nb). El Bakkali et al. (1998) hypothesized a mantle source modified by previously subducted slabs, without addressing more precisely the nature and timing of such processes. The slightly anomalous chemistry of the Pliocene volcanic rocks (which peak at Ba rather than Nb in primordial mantle-normalized diagrams and sometimes reach potassic rather than sodic affinities) cannot be related to purely anorogenic settings, but must require some enriched sources, probably lithospheric rather than asthenospheric.

## FRANCE

The most recent (30-0 Ma) activity of France is concentrated in two areas: over the Hercynian basement of the Massif Central in central France and around the gulf of Provence (SW France). Geochemically these rocks belong to tholeiitic and alkaline series, with both sodic and more rare potassic affinities. No calc-alkaline or ultrapotassic volcanism has been documented. From a geodynamic point of view, the magmatic activity developed during the formation of the European Continental Rift System formation (e.g., Ziegler, 1992).

### *Massif Central*

In the French Alpine foreland, magmatic records dated from Paleocene to Recent (65-0 Ma) are reported within the Hercynian batholith of the Massif Central (Downes, 1987), located in the main N-S trending Limagne graben system. Many individual volcanic provinces are identified within the Massif Central; the most important are: Cantal, Mont Dore, Aubrac, Chaine des Pyus and Velay (Chauvel and Jahn, 1984). With the exception of a few occurrences, most of this activity developed from the Miocene onwards and peaked at ~10-2 Ma. Mafic and evolved types occur, with both $SiO_2$-undersaturated (basanite, tephrite, phonolite) and $SiO_2$-saturated characters (alkali basalt, hawaiite, mugearite, benmoreite, trachyte, rhyolite) with mainly sodic affinity (Chauvel and Jahn, 1984; Downes, 1987; Briot et al., 1991; Wilson et al., 1995). Magma mixing and minor crustal contamination, via AFC processes, are common processes recorded in the intermediate to evolved products (Briot et al., 1991), although rhyolite (Mont Dore and Cantal) are considered to be differentiation products of the saturated series and not anatectic crustal melts, as proposed for those in Tuscany (Downes, 1987; Peccerillo et al., 1987; see below). The greatest topographic elevation of all the European Hercynides, the strong magmatic activity, and the presence of a low-velocity zone identified by 3D seismic tomography imaging, favour the interpretation of a mantle plume beneath the Massif Central (Granet et al., 1995; Zeyen et al., 1997; Zangana et al., 1999), whose asthenospheric (OIB-like) melts variously interacted with the overlying heterogeneous lithosphere in order to produce the entire spectrum of rocks (Wilson et al., 1995). In this context, note should be taken of the contrasting results of Ziegler (1992), according to whom the magmatic records of the Cenozoic rift system "[…] preclude a contribution from mantle plumes rising from the deep mantle […]" (Ziegler, 1992). The Massif Central volcanic rocks show large variations of radiogenic and unradiogenic isotopic ratios ($^{87}Sr/^{86}Sr = 0.7034\text{-}0.7046$, $^{143}Nd/^{144}Nd = 0.51277\text{-}0.51299$, $^{206}Pb/^{204}Pb = 18.64\text{-}19.72$, $^{207}Pb/^{204}Pb = 15.52\text{-}15.67$, $^{208}Pb/^{204}Pb = 38.81\text{-}39.44$, $\delta^{18}O = +5.6$ to $+8.1$ ‰) thought to reflect both various degrees of assimilation of granitic material during the formation of shallow magmatic reservoirs and mantle metasomatism shortly before of magmatism (Chauvel and Jahn, 1984; Downes, 1987; Briot et al., 1991; Wilson and Downes, 1991; Wilson et al., 1995).

### *Provence*

During the late stages of Ligurian-Provençal basin opening, volcanic activity developed along the French Mediterranean margin. This cycle is grouped into three districts: Aix-en-Provence (made up of mildly mafic alkaline basanite and transitional basalts of Miocene age; ~18.2 Ma), Toulon (tholeiitic basalt; 6.7-5.8 Ma) and Agde (transitional basalt; 1.3-0.6 Ma) (Dautria and Liotard, 1990). A common source for alkaline, transitional and tholeiitic rocks has been proposed, the first ones corresponding to lower degrees of partial melting (Dautria and Liotard, 1990).

Unlike the basalt of tholeiitic affinity of the French Mediterranean margin, the Plio-Quaternary volcanic district of southern France (Bas-Languedoc) is represented by alkaline mafic rocks. These products are ultimately related to the same thermal anomaly responsible for the Massif Central Paleocene-Quaternary volcanic rocks. The Bas-Languedoc volcanic rocks are represented by basanite, nephelinite and leucite-nephelinite on the basis of the nature and amount of normative feldspathoids (Liotard et al., 1999). These are high-Mg# rocks (Mg# = 59-70) with variable $Na_2O/K_2O$ (1.4-4.1) and bell-shaped patterns in primitive mantle-normalized diagrams, peaking at Nb-Ta. With few exceptions, the $^{87}Sr/^{86}Sr$ isotopic ratios show a narrow range from

0.70308 to 0.70337, whereas $^{143}Nd/^{144}Nd$ ranges from MORB-like (0.51300) to less radiogenic values (0.51286) (Liotard et al., 1999). Sr and Nd isotopic ratios fall within the field of French Massif Central lavas, but are shifted to slightly more Sr unradiogenic and Nd radiogenic compositions. $^{206}Pb/^{204}Pb$ ranges from 18.74 to 19.38 (in seven out of eight samples >19); $^{207}Pb/^{204}Pb$ ranges from 15.57 to 15.68, while $^{208}Pb/^{204}Pb$ ranges from 38.63 to 39.17. All samples plot above the NHRL of Hart (1984). Trace element compositions and Sr-Nd-Pb isotopic ratios are thought to be controlled by three end-member types of mixing: asthenosphere (with high $^{206}Pb/^{204}Pb$ [19.9-20] and low $^{87}Sr/^{86}Sr$ [~0.7030-0.7034]), lithosphere (with slightly lower $^{206}Pb/^{204}Pb$ [~18.75] and similar $^{87}Sr/^{86}Sr$) and a sedimentary component (with relatively low $^{206}Pb/^{204}Pb$ [18.25] and high $^{87}Sr/^{86}Sr$ [0.7065]) (Liotard et al., 1999).

## ITALY

The neo-Alpine cycle resulted in the formation of the Apennine chain, whose northern sector (~North of 41°N) evolved in an ensialic environment (Serri et al., 1993; Gualteri and Zappone, 1998), whereas in the southern chain Mesogean (?) oceanic crust recycling with a related back-arc spreading west of Sardinia occurred (Faccenna et al., 1997; Gueguen et al., 1998). In particular, the formation of the Oligocene Ligurian-Provençal Basin (Séranne, 1999) and the development of the Neogene to present Tyrrhenian Sea (Gueguen et al., 1998) are linked by the same crustal suction forces (Faccenna et al., 1997; Cella et al., 1998). The orogenic (s.l.) volcanic cycle now recorded along the western branch of the Apennine chain may thus find its parallel in the Oligo-Miocene orogenic magmatism of western Sardinia and eastern Spain (Martì et al., 1992; Brotzu, 1997; Morra et al., 1997), although strong geochemical and, to a lesser extent, isotopic differences do exist between these two cycles (Lustrino, 1999).

### Oligo-Miocene volcanism of Sardinia

Widespread volcanic activity developed in Sardinia from 28 to 15 Ma. This cycle is thought to be related to the W-directed subduction system of Tethyan crust (Brotzu, 1997; Morra et al., 1997). Activity mainly occurred along the master faults of the N-S directed continental rift system of the Fossa Sarda (Morra et al., 1997).

The first products of the Oligo-Miocene volcanism of Sardinia (Brotzu et al., 1997) are represented by effusive basalt and andesite. The NW-directed subduction system below Sardinia (with respect to its actual position) was originally thought to represent the main tectonic feature in controlling the composition of volcanic records. In particular, the increases in $K_2O$ contents from SE to NW and in the LREE/HREE ratio in northern Sardinia compared with southern Sardinia volcanic outcrops was related by Dostal et al. (1982) to NW-ward deepening of the Benioff zone and to mobilization of a spinel-facies peridotite to the south and a garnet-facies peridotite (with stronger LREE/HREE fractionation to the north, the HREE being retained in residual garnet). However, the discovery of low-K picrite in NW Sardinia (Montresta area; Morra et al., 1997) and calc-alkaline volcanism in southern Sardinia (Mt. Arcuentu, Brotzu et al., 1997) ruled out such a simple petrogenetic model, excluding geochemical gradients throughout the island.

It is important to note that much of the volcanic activity (calc-alkaline or, better, orogenic s.l.) is coeval with the main extensional phases (e.g., formation of the Fossa Sarda). Thus, the serial affinity of the volcanic products and their geochemical signature (low HFSE/LILE ratios) were inherited from a subduction-modified mantle source, activated by decompression during distensive stresses (Morra et al., 1997). The occurrence of volcanic activity with a subduction signature during extensional phases is a common aspect also recorded in the western (e.g., SE Spain; Turner et al., 1999) and central Mediterranean areas (e.g., Roman Comagmatic Province, Peccerillo, 1999; see below).

Oligo-Miocene volcanic activity occurred only in the western sector of Sardinia along the “Fossa Sarda”, which represents a continental rift cutting the island N-S for about 220 km and which developed during the counterclockwise rotation of the Sardinia-Corsica block (Brotzu, 1997). Both pyroclastic (ignimbrite) and effusive (lava flows and domes) facies are present and are mainly concentrated in the 23-17 Ma interval. Ignimbrite of peralkaline affinity occurs in the SW sector of Sardinia (island of St. Pietro; Morra et al., 1994). Calc-alkaline volcanic rocks are mainly represented by andesite with minor basalt, dacite, rhyodacite and rhyolite. High-MgO picrite (MgO up to 12 wt. %) is reported both from the northern (Montresta area) and southern (Mt. Arcuentu) sectors of the island.

### Formation of the Tyrrhenian Sea

The 15-13.5-Ma-old Sisco lamproite on NE Corsica signs the first stage of the opening of the Tyrrhenian Sea: from the Paleozoic terranes of the Provençal Basement (Sardinia-Corsica block), the overthrusts changed to the thrusts (and back-thrusts) of the eo-Alpine chain. The polarity of the subduction system (roughly W-directed) did not change (Doglioni et al., 1999). The counterclockwise rotation of the Sardinia-Corsica block stopped during the Aquitanian-Burdigalian (24-20 Ma, Séranne, 1999) or Burdigalian-Serravalian (18-13 Ma, Vigliotti and Langenheim, 1995). A magmatological period of quiescence started for Sardinia and lasted about 10 Ma, until the end of the Oligo-Miocene volcanic cycle.

Magmatic activity in the Mediterranean area did not stop, as the youngest ages measured in orogenic rocks from Sardinia (Langhian-Serravalian, Lecca et al., 1997) overlap with the first Tyrrhenian Sea opening-related volcanic rocks. The evolution of the Tyrrhenian may be divided into two sectors: the northern part (above ~41°N) opened after the continent-continent collision between Africa (Adria Plate) and Europe (Corsica-north Sardinia; Argnani and Savelli, 1999); in the southern part Tethyan oceanic crust was still present (Gueguen et al., 1998; Doglioni et al., 1999). The northern sector opened at a rate of about 1.3 cm/a, much more slowly than the southern one (~4.8 cm/a; Argnani and Savelli, 1999). The E-directed extensional wave of these realms was accompanied by a contemporaneous eastward compressional front, which resulted in the formation of the Apennine chain. During this eastward wave, both Hercynian and Alpine (eo-Alpine) slices were pushed and dragged to the east, and are now recognizable along the Italian peninsula. These are the Hercynian terranes of Calabria and the Peloritani Massifs (e.g., Duermeijer et al., 1998), the Ligurid ophiolite of the Northern Apennine, and the Frido Unit in the Southern Apennine (e.g., Di Girolamo et al., 1992; Rampone et al., 1998).

During the E-directed opening of the Tyrrhenian Sea, there was a contemporaneous E-ward shift of volcanic activity. The slab-retreating model can account for the temporal and spatial evolution of the Tyrrhenian and associated igneous activity (Doglioni et al., 1999). The chemical and thermal perturbations induced by the NW-directed Tethyan oceanic plate subduction recorded in the Oligo-Miocene magmatism of Sardinia (e.g., Brotzu, 1997, Morra et al., 1997) have also been identified in other offshore and onshore areas of the Tyrrhenian realm.

Evidence of SE-ward migration of calc-alkaline (s.l.) magmatism from Sardinia (~28-15 Ma) to the Aeolian Islands (1-0 Ma) has recently been pointed out by Argnani and Savelli (1999). According to these authors, subduction front migration was intermittently accompanied by magmatic activity in Sardinia (~28-15 Ma), along a presumed Pliocene magmatic arc (5-2 Ma) located in the central Tyrrhenian between the Vavilov and Marsili basins (to which the volcanic products of the Anchise and Glauco seamounts and those south of Ventotene and the Island of Ponza belong), up to its present position near the Aeolian Islands (Argnani and Savelli, 1999). The increase in $K_2O$ in volcanic rocks from Sardinia (arc-tholeiitic to calc-alkaline) to the Aeolian Islands (calc-alkaline to shoshonitic) is related to slab steepening during slab retreat (Argnani and Savelli, 1999).

The back-arc opening of the Tyrrhenian reached an oceanization stage near two basins: the northern Vavilov basin (8-2 Ma) and the southern Marsili basin (2-0.1 Ma) (Argnani and Savelli, 1999). Within these two sub-basins, two large volcanic structures have been identified: the Vavilov (~3-2 Ma) and Marsili seamounts (1-0.1 Ma), whose composition deviates from N-MORB types towards E-MORB-calc-alkaline basalt (Sborshchikov and Al'mukhamedov, 1992; Savelli and Gasparotto, 1994). These compositions are thought to be related to mantle sources metasomatized by interaction with the retreating Calabria subduction zone.

## Southern Tuscany

The onshore volcanic activity associated with the northern and southern Tyrrhenian is quite different: in the Northern Apennine sectors, volcanic rock associations mainly consist of crustal anatectic, hybrid, ultrapotassic (lamproite and kamafugite) and potassic rocks (e.g. Peccerillo et al., 1987; Conticelli and Peccerillo, 1992; Conticelli, 1998). The petrogenesis of the northern Apennine rocks (southern Tuscany and northern Latium) share many similarities with the Neogene voclanic rocks of SE Spain. Indeed, for both provinces, strong crustal contamination of mantle-derived rocks up to pure crustal anatectic melts has been proposed (cordierite-garnet-bearing dacite and strongly radiogenic rhyolite; Peccerillo et al., 1987; Benito et al., 1999). A mantle origin for lamproite from both areas is suggested on the basis of high Mg# (~0.70-0.80), Cr and Ni. The incompatible element-enriched character and radiogenic Sr ($^{87}Sr/^{86}Sr$ ~0.716-0.720) and unradiogenic Nd ($^{143}Nd/^{144}Nd$ ~0.5119-0.5120) compositions have been related to ancient subduction-related modification of the lithospheric mantle (Conticelli, 1998; Peccerillo, 1999; Turner et al., 1999). The Tuscan volcanic rocks occurs as dykes, necks and lava flows, with only a few large volcanic edifices (e.g., Mts. Amiata and Cimini). Their age ranges from ~8.7 to 0.3 Ma and younger eastwards (Peccerillo et al., 1987). The great variety in lithologies and in geochemical and isotopic features cannot be related to a single source, but require highly anomalous and heterogeneous sources.

## Roman Comagmatic Province

The geochemical features of the Roman Comagmatic Province (R.C.P.) have been the subject of heated debate since the early 1970s. In particular, under discussion are the geodynamic setting of emplacement of magmas and the geochemical and isotopic signatures of the mantle beneath Italy. Contrasting opinions relate to the puzzling evolution of the Mediterranean Sea and are still far from a single solution. In particular, on geophysical, geological and geochemical grounds, there are two main solutions hypothesized for the formation of the Tyrrhenian Sea and its related magmatism:

1) Asthenospheric diapir-related origin emplaced on an eastward-migrating rift system (e.g. an "East Africa rift"-like setting; Stoppa and Lavecchia; 1992; Stoppa and Cundari, 1995; Morelli, 1998) or a complex extensional asymmetric megafissures-related in a plastic-rigid deformation of the continental crust (Boccaletti et al., 1990), without involvement of any subduction system.
2) Subduction of Tethyan and Adrian crust (e.g., Conticelli and Peccerillo, 1992; Serri et al., 1993; D'Antonio et al., 1999). However, some aspects (e.g. scarcity of calc-alkaline rocks in the Italian Neogene-Quaternary province and the regular regional trend of radiogenic and unradiogenic isotopes) are still unresolved and unexplained by this theory. In fact, if the general idea of a W-directed subduction system active under the Italian Peninsula is assumed, isotopic as well as geochemical variations between foreland and interland are to be expected, whereas the greatest differences in the Italian magmas have been noted parallel to the tectonic arc, with constant rises in $\varepsilon_{Sr}$, $\delta^{18}O$ and $\delta^{13}C$ and constant decreased in $\varepsilon_{Nd}$, $^{206}Pb/^{204}Pb$, $^{3}He/^{4}He$ from Mt. Etna to the Tuscan Province through the Aeolian Islands and the Roman Province (e.g., Turi aand Taylor, 1976; Vollmer, 1990; Tedesco, 1997). The variable isotopic composition of the Italian orogenic rocks has been related to different material subducted along the trench system (e.g., Peccerillo, 1990). However, as already noted by Vollmer (1990), if different crustal material were subducted in the northern (continental crust) and southern sectors (Mesogean oceanic crust), irregular isotopic compositions rather than the monotonous isotopic climax would be expected.

In the context of geodynamic evolution of the Mediterranean area, the model of Hoernle et al. (1995) is important. According to these authors, seismic and geochemical evidence exists for the presence of a giant plume beneath the eastern Atlantic and Wstern and Central Europe. Hoernle et al. (1995) identified a low S- and P-wave velocity anomaly zone about 2500 km wide in the NNE direction, extending about 4000 km ESE below the North Atlantic to the central Mediterranean. The convergence of the isotopic compositions of Cenozoic European volcanic rocks (both within-plate and orogenic s.l. products) towards radiogenic Pb ($^{206}Pb/^{204}Pb$ ~20) and Nd compositions ($^{143}Nd/^{144}Nd$ ~0.5129) and unradiogenic Sr ($^{87}Sr/^{86}Sr$ ~0.7035) was considered by the above authors as evidence of a common asthenospheric (plume-related) origin of the European volcanics.

However, the presence of an active asthenospheric plume or diapir to explain the origin of the Tyrrhenian Sea as an active rift has recently been ruled out by Cella et al. (1998).

These authors exclude the presence of active plume material as the origin of the Tyrrhenian Sea and incline for passive thinning processes.

Once the presence of a thermal anomaly below the Tyrrhenian area is excluded, the driving power that led to the formation of this basin must be found. In particular, of the four following proposed models, all need the presence of a subduction system. These are:

1. Gravitative collapse of thickened lithosphere after Alpine crustal stacking (e.g., Serri et al., 1993). In this case, Tyrrhenian extension developed along a variously thickened suture zone flanked by a compressive zone.
2. Lateral expulsion of crustal wedges (Mantovani et al., 1997 and references therein) as hypothesized for the Oligo-Miocene evolution of Sardinia and the formation of the Aegean.
3. Passive subduction due to gravitative sinking of the Adria Plate and punctuated tearing processes of the subducted slab (Royden, 1993; van der Muelen et al., 1998);
4. Slab roll-back and relative lack of lithospheric material replaced by new, hotter asthenospheric material. This model includes several complexities, is based to the westward motion of lithosphere with respect to the asthenosphere, and is fully treated in numerous papers by Doglioni and coworkers (e.g., Gueguen et al., 1998).

Currently, the potassic, ultrapotassic and calc-alkaline magmatism of Italy is best interpreted in the light of syn- to post-subduction settings and its geochemical signature is thought to reflect mantle wedge sources metasomatized by fluids/melts released by the subduction plate (e.g., Conticelli and Peccerillo, 1992; D'Antonio et al., 1999).

The reason for the debate is the major, trace element and isotopic similarities between potassic and ultrapotassic rocks of Italy (volumetrically dominant over the calc-alkaline products) and volcanic rocks from the western branch of the East Africa Rift system (e.g., Toro-Ankole and Virunga Igneous provinces; Davies and Lloyd, 1989; Rogers et al., 1998). Here, potassic to ultrapotassic rocks (with kamafugitic affinity) were emplaced in a continental rift setting. In this case, the K- and incompatible element-rich compositions are thought to be the results of partial melting of a metasomatized mantle source, whose original pyrolitic paragenesis was shifted towards phlogopite-bearing clinopyroxenite (e.g. Lloyd et al., 1996). The metasomatizing agents are unrelated to subduction zones and have a deep origin, associated with the rising plume of asthenospheric material (e.g. see Wang and Takahashi, 2000). The presence of ultrapotassic (also with kamafugitic affinity) and potassic lithologies in Italy, closely associated with extensional tectonic movements, led some authors to propose an East Africa-like setting (e.g. Stoppa and Lavecchia, 1992), not considering some strong trace element and isotopic differences between African and Italian potassic/ultrapotassic volcanic rocks (Rogers, 1992). Recently, for the less evolved potassic and ultrapotassic rocks from central Italy (Montefiascone volcanic complex, Vulsini district), Di Battistini et al. (1998) proposed an origin from a phlogopite- and clinopyroxene-rich veined lithospheric mantle metasomatized by very low-degree partial melts rising from the asthenosphere, making unnecessary the need to invoke the addition of a crustal component to the mantle via subduction. The origin of the high LILE/HFSE ratios of the potassic and ultrapotassic Italian volcanic rocks has been interpreted in terms of the key role of Ti-phases (e.g. rutile, ilmenite and other titanates) during magma production (Di Battistini et al., 1998).

To complicate the interpretation of the geodynamic contest of this area is the presence of carbonate-rich rocks classified either as carbonatite by Stoppa and Cundari (1995) and Castorina et al. (2000), and thus rift-related, or as mixture of silicate magma and geochemically barren limestone (e.g., Peccerillo, 1998).

The Roman Comagmatic Province outcrops in the western sector of central-southern Italy (Latium and Campania regions). It comprises several volcanic districts (Vulsini, Sabatini, Albani, Ernici, Roccamonfina, Neapolitan province), with potassic and ultrapotassic compositions; high-K calc-alkaline basaltic andesite and andesite rarely occur exclusively as drilled samples, buried under potassic alkaline volcanics near the Phlaegraean Fields in Campania (Beccaluva et al., 1991). The volcanic activity ended between 0.05 and 0.1 Ma in Latium and north Campania (Mt. Roccamonfina), whereas it is still present around the Gulf of Naples (Mt. Vesuvius, Phlaegraean Fields, Ischia).

In the Roman Province, there are few magmas with Mg#, Ni and Cr compatible with unfractionated liquids in equilibrium with mantle peridotite. Rare exceptions are Vulsini (e.g. leucite-basanite; Di Battistini et al., 1998), San Venanzo (olivine-leucitite melilitite of kamafugitic affinity; Stoppa and Lavecchia, 1992) and the islands of Procida and Ventotene (shoshonitic basalt; D'Antonio et al., 1999).

A summary of all the models proposed to explain the petrogenesis of the most mafic volcanic rocks requires the existence of a variably metasomatized phlogopite-bearing mantle, but the origin itself is still a matter of debate. In particular, for the origin of the enrichment in K and other incompatible trace elements, together with their isotopic compositions, the following have been proposed: a) mixing processes involving mantle and continental crust rocks of variable compositions (Turi and Taylor, 1976); b) development of K-alkaline melts originating at the base of the thermal boundary layer within upwelling metasomatized asthenosphere (Stoppa and Lavecchia, 1992); c) plume-derived melts triggering continental rifting; in this case, K-rich magmas need not rely on contemporaneous subduction processes (Cundari, 1994; Ayuso et al., 1998); d) very old enrichment events, unrelated to the subduction that preceded the Roman magmatism (Conticelli, 1998; Di Battistini et al., 1998; Castorina et al., 2000); e) an active to recent subduction system beneath Italy which variably enriched the lithospheric wedge after source contamination by subducted crustal material (e.g. Beccaluva et al., 1991; D'Antonio et al., 1999).

## Mt. Vulture

Mt. Vulture (0.8-0.13 Ma) is considered the easternmost volcanic centre of the R.C.P. (Melluso et al., 1996) although many aspects (e.g., tectonic setting, major and trace element compositions, mineralogy) deviate from the Roman products. First of all, Mt. Vulture is located in a foreland position very close to the front of the overthrusts of the Southern Apennine chain, whereas all the R.C.P. products lie more internally (interland). Secondly, Mt. Vulture is mainly dominated by notably more Na-rich $SiO_2$-undersaturated compositions (predominantly basanite and trachyphonolite, with minor amounts of tephrite, phonolitic tephrite and melilitite) compared with similar rocks of the R.C.P.; moreover, the Mt. Vulture products show rather transitional trace element patterns in primordial mantle-normalized diagrams with low HFSE but also with relatively low LILE abundance. Overall, the Mt. Vulture magma sources indicate within-plate affinity, although this character is coupled with a subduction-related signature (Melluso et al., 1996). Thirdly, it is the only volcanic complex of the R.C.P. in which haüyne is the most common feldspathoid and leucite is present only in smaller amounts (Bindi et al., 1999). Ultramafic xenoliths, both cumulates (Bindi et al., 1999) and mantle fragments (Jones et al., 2000) are commonly found. Few isotopic data are available for the Mt. Vulture volcanic rocks; Sr isotopic ratios are slightly radiogenic ($^{87}Sr/^{86}Sr$ = 0.70569-0.70718), whereas Pb isotopes show strong radiogenic compositions ($^{206}Pb/^{204}Pb$ = 19.15-19.31; $^{207}Pb/^{204}Pb$ = 15.67-15.72; $^{208}Pb/^{204}Pb$ = 39.11-39.37; Vollmer, 1976; Vollmer and Hawkesworth, 1980).

## Aeolian Islands

The Aeolian Islands emerge in the southern Tyrrhenian, representing a Quaternary volcanic arc extending for about 200 km and lying on a 20-km-thick continental crust. Of the seven main islands, Stromboli and Vulcano are the only active volcanic edifices. The geochemical and isotopic characteristics of these islands have been interpreted as reflecting a heterogeneous mantle source without significant crustal contamination of melts *en route* to the surface (e.g. Francalanci et al., 1993), although open-system evolution models have been also proposed, at least for Vulcano and Salina (Del Moro et al., 1998; Gertisser and Keller, 2000). In particular, Del Moro et al. (1998) performed calculations on the basis of the AFC (assimilation and fractional crystallization) and AFCB (assimilation fractional crystallization batch replenishment) models and obtained isotopic and trace element correlations consistent with the liquid line of evolution of Vulcano's products, using both lower and upper crustal lithologies assimilated (generally < 15%) by Etnean-Hyblean-type basalts.

The wide compositional spectrum of the volcanic products include arc-tholeiitic through calc-alkaline, high-K calc-alkaline to shoshonitic series (Francalanci et al., 1993). The Aeolian arc is related to the NW-dipping Benioff zone of the Calabrian subduction system. Primitive compositions are subordinate with respect to intermediate and evolved types. The wide compositional variability of the Aeolian islands is related to mantle heterogeneity coupled with varying cumulating phases during fractional crystallization processes and to assimilation of both lower and upper continental crust in shallow magma reservoirs (Gertisser and Keller, 2000; Santo, 2000). The spiked patterns of the least evolved rocks in primitive mantle-normalized diagrams with LILE, U, Th and Pb enrichment relative to HFSE have been related to mantle sources variably modified by the addition of slab-derived components (e.g. De Astis et al., 1997; Gertisser and Keller, 2000). Sr and Nd isotopic compositions span from the depleted quadrant ($^{87}Sr/^{86}Sr$ <0.7044; $^{143}Nd/^{144}Nd$ >0.51264) towards more enriched compositions ($^{87}Sr/^{86}Sr$ up to 0.7052; $^{143}Nd/^{144}Nd$ up to 0.51254). Lead isotopes show radiogenic compositions and $\Delta 7/4 > 0$ ($^{206}Pb/^{204}Pb$ ~18.9-19.6; $^{207}Pb/^{204}Pb$ ~15.50-15.87; $^{208}Pb/^{204}Pb$ ~38.7-39.8).

## Mt. Etna

Mt. Etna rises on the eastern coast of Sicily, near the contact between the African foreland and the Apennine chain, in an interland position. The volcanic activity of Mt. Etna started about 0.6 Ma ago, with tholeiitic to transitional products and evolved with time towards more alkaline compositions. The most recent products display a mildly alkaline (sodic) affinity and have slightly evolved compositions: hawaiite to trachyte through benmoreite. The scarcity of near-primitive melts is mainly attributable to shallow-level fractionation processes (D'Orazio et al., 1997; Busà et al., 1999). Moderate assimilation of crustal lithologies and heterogeneity of mantle sources are revealed by the variability of Sr and Nd isotopic and trace element ratios ($^{87}Sr/^{86}Sr$ = 0.7030-0.7037; $^{143}Nd/^{144}Nd$ = 0.51285-0.51297), which match the compositions of intraplate magmas such as HIMU-OIBs.

## Hyblean Mts.

The Hyblean Plateau is located in SE Sicily and represents the northern portion of the subducting African foreland. The Hyblean Mts. are bounded eastwards by the Malta escarpment and westwards by the Strait of Sicily; the Gela Nappe bounds its northern margin. The suture line between African (i.e. Hyblean Plateau) and European (i.e. northern Sicily) plates passes between Mt. Etna (in an interland position) and the Hyblean Mts.

Unlike all other circum-Mediterranean volcanic provinces, the Hyblean Mts. represent a long-lived magmatic system, whose early products (known only from drill cores) are Late Triassic basaltic rocks. The earliest outcropping products are dated Late Cretaceous and are represented by relatively mafic rocks with transitional affinity and basaltic composition. Other peaks of volcanic activity occur in the Middle-Late Miocene (mainly Tortonian; explosive products emplaced in a subaqueous environment with mainly alkaline affinity and basanitic to basaltic compositions) and Middle to Late Pliocene (thick subaerial lava flows; hyaloclastites and pillow lavas with a wide range of mafic compositions from Qz-tholeiite to strongly undersaturated alkaline lavas (ankaratrite); both subalkaline and alkaline rocks have sodic rather than potassic character (Trua et al., 1997, 1998; Beccaluva et al., 1998; Bianchini et al., 1999). Alkaline mafic magmas of the Miocene-Pleistocene volcanic cycles frequently contain peridotite mantle xenoliths. The origin of the most recent volcanic activity in the Hyblean Mts. has not been related to a mantle plume but to the lithospheric faulting of the Hyblean Plateau and the development of pull-apart basins with subsequent adiabatic decompressive melting (Trua et al., 1997; Beccaluva et al., 1998). On the basis of major, trace element and isotopic constraints, the Miocene-Pliocene volcanism of the Hyblean area has been linked to depleted mantle sources, variably modified by asthenospheric metasomatizing melts or fluids, with both alkali-silicate and carbonatitic composition, capable of stabilizing metasomatic phases (e.g. amphibole, phlogopite, apatite and carbonate) partly replacing the original paragenesis (Beccaluva et al., 1998). Trace element (e.g. relatively high Nb-Ta contents) and isotopic constraints ($^{87}Sr/^{86}Sr$ = 0.7027-0.7033; $^{143}Nd/^{144}Nd$ = 0.5129-0.5133; $^{206}Pb/^{204}Pb$ = 19.2-20; $^{207}Pb/^{204}Pb$ = 15.57-15.65) show analogies with HIMU- and, to a lesser extent, EMII-like end-member compositions.

## Pantelleria and Linosa

The islands of Pantelleria and Linosa lie in a transtensive zone of post-Miocene NW-trending horsts and grabens located between Sicily and Tunisia (Strait of Sicily). Unlike the Aeolian archipelago, the Pantelleria products (~118-4 ka; Civetta et al., 1998, and references therein) show sodic rather than potassic affinity and are represented only by alkaline to peralkaline volcanic rocks. Basalt and hawaiite flows are volumetrically scarce with respect to more evolved compositions such as trachyte and rhyolite. The latter are quartz-saturated and of peralkaline affinity (pantellerite), approaching the compositions of some Atlantic islands such as the Azores and Ascension (Esperança and Crisci, 1995).

Differentiation processes in shallow magma chambers are responsible for the lack of primitive melt compositions. Strong contrasts exist regarding the evolution of magma through AFC-type processes (e.g. Esperança and Crisci, 1995) or in a closed system (Civetta et al., 1998). Variable trace element ratios and elevated $^{207}Pb/^{204}Pb$ are believed to be indicators of the addition of ancient components (which resemble the enriched lithosphere sampled by circum-Tyrrhenian potassic magmas) to DMM-HIMU (± EMI) mantle sources (Esperança and Crisci, 1995; Civetta et al., 1998).

The total ranges of $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ are 0.7030-0.7042 and 0.51289-0.51302, respectively. Whereas Nd isotopic compositions of mafic and evolved rocks show no substantial differences, basalt and hawaiite generally have less radiogenic Sr ($^{87}Sr/^{86}Sr$ = 0.7030-0.7032) than trachyte and pantellerite. With respect to Sr and Nd, the Pb isotopic ratios of mafic products show wider ranges (e.g. $^{206}Pb/^{204}Pb$ = 19.09-19.94); trachyte and pantellerite display smaller variations and cluster in the mafic product range ($^{206}Pb/^{204}Pb$ = 19.48-19.69).

Major and trace elements plus isotopic constraints (Sr, Nd, Pb, He) allowed Civetta et al. (1998) to propose for Pantelleria, as well as for Mt. Etna, a mantle plume-related origin, consistently with the giant plume model of Hoernle et al. (1995).

The Pleistocene volcanic activity of Linosa (1.06-0.53 Ma; Rossi et al., 1996) started with hydromagmatic products (tuff rings, tuff cones, spatter cones) and, once elevated above sea level, continued with emission of lava flows. Volcanic products are mainly of sodic alkaline to slightly transitional serial character and are mainly represented by basalt and hawaiite; more evolved lithologies (mugearite, benmoreite, trachyte) have also been found. This aspect contrasts with the composition of the volcanic products of Pantelleria where evolved types (trachyte, peralkaline rhyolite) volumetrically prevail over scarce alkali basalt.

Trace element abundances (Rossi et al., 1996) and Sr, Nd and Pb isotopic ratios (Civetta et al., 1998) suggest a within-plate tectonic setting of formation, with bell-shaped patterns in multi-element diagrams, peaking at Nb with relatively low LILE, and with $^{87}Sr/^{86}Sr$ (0.7030-0.7031) $^{143}Nd/^{144}Nd$ (0.51294-0.51298) $^{206}Pb/^{204}Pb$ (19.11-19.43) within the HIMU-OIB compositional field.

## Ustica

The Island of Ustica is located NE of Sicily, in the southern Tyrrhenian, and is made up of Quaternary volcanic rocks with Na-alkaline affinity and a composition ranging from alkali basalt to rarer trachyte. Multi-elemental primitive mantle-normalized diagrams show Ba enrichment over HFSE, typical of subduction-related settings, although the general patterns are bell-shaped. Trace element compositions allowed Cinque et al. (1988) to support the hypothesis that the source of the Ustica alkali basalt was slightly contaminated by a component of slab origin. The transitional character between within-plate (e.g. Na-rich composition, overall "bell-shaped patterns" in primitive mantle-normalized diagrams) and orogenic settings (low Ta, Nb, Hf, Zr, Ti; high Ba, La) of the most primitive volcanic rocks of Ustica share some similarities with the products of Mt. Vulture. These features are thought to reflect the tectonic setting of emplacement of the two localities: close to the foreland for Mt. Vulture (thus escaping major contamination by subducted material) and far from the front arc for Ustica (where the subducted slab lost its metasomatic capacity in favor of volcanic rocks closer to the front arc, i.e., the Aeolian Islands). At the moment, only Sr isotopic data are available for Ustica ($^{87}Sr/^{86}Sr$ = 0.70306-0.70342; Cinque et al., 1988), and indicate depleted mantle sources not contaminated by radiogenic crustal material.

## Plio-Pleistocene volcanism of Sardinia

In the western sector of the extending Tyrrhenian Sea, extensional movements resulted in the development of a rift system (Campidano graben in SW Sardinia, N-S oriented fault system of Sarrabus area in SW sector) and in within-plate magmatism. This magmatic activity developed in Sardinia about 10 Ma after the end of the "orogenic" Oligo-Miocene cycle, from ~5.3 Ma (Capo Ferrato; southwest Sardinia) to ~0.1 Ma (Logudoro, northern Sardinia), thus roughly contemporaneously with the orogenetic magmatic activity in central and southeastern Tyrrhenian area. The products are mainly mafic to slightly evolved rocks, although differentiated products occur as well (Di Battistini et al., 1990; Montanini et al., 1994; Lustrino et al., 1996; Lustrino et al., 2000a; 2000b). Both alkaline (basanite, alkali basalt, basanite, hawaiite, mugearite, benmoreite to trachyte and phonolite) and subalkaline types (tholeiitic basalt to rhyolite through basaltic andesite, andesite and dacite) are present. The alkaline rocks are mildly to strongly alkaline rocks mainly with sodic affinity, although some slightly potassic types are also found (Lustrino et al., 1996). The subalkaline rocks are less primitive than their alkaline counterparts and show a tholeiitic character (Lustrino, 1999). Some of the most evolved subalkaline volcanic rocks (e.g., rhyolites from Mt. Arci, central Sardinia) appear to be the product of fractionation of tholeiitic magmas plus assimilation of crustal components via AFC or pure anatectic partial melts with strongly radiogenic compositions ($^{87}Sr/^{86}Sr$ = 0.7053 to 0.7155; Cioni et al., 1982; Montanini et al., 1994); processes of magma mixing between basaltic l.s. and rhyolitic melts produced intermediate dacitic compositions (Montanini et al., 1994). The peculiarity of these rocks is their "transitional" character between classical within-plate anorogenic products (e.g., "bell-shaped" incompatible trace element patterns) and subduction-modified compositions (e.g., relatively low HFSE content and high LILE/HFSE ratios; Di Battistini et al., 1990; Lustrino et al., 1996, 2000b). Abundant mantle xenoliths (e.g., Lustrino et al., 1999) are often found associated with alkaline products at different stages of evolution, testifying to the rapid ascent of magma and the existence of magma chambers at subcrustal depths (Lustrino et al., 1996). $^{87}Sr/^{86}Sr$ isotopic ratios of the less evolved types range from 0.7031 to 0.7054, but most samples cluster near 0.7044 ± 2; $\varepsilon_{Nd}$ show almost exclusively negative values clustering close to –5; only a few samples reach more radiogenic values of +5 (Cioni et al, 1982; Lustrino, 1999; Lustrino et al., 2000a). The Plio-Pleistocene volcanic rocks of Sardinia reach the least radiogenic Pb isotopic composition of the entire Cenozoic European Volcanic Province ($^{206}Pb/^{204}Pb$ down to 17.5; Lustrino, 2000a). This aspect, coupled with trace element anomalies, has been related to ancient (Panafrican/Hercynian) modification of their mantle sources (Lustrino et al., 2000a).

The Cenozoic-Quaternary magmatic evolution of Sardinia (Oligo-Miocene orogenic volcanic cycle followed by Plio-Quaternary anorogenic volcanism) finds its counterparts in the Cenozoic evolution of the Valencia trough (western Mediterranean) and northern Morocco. Here, two volcanic cycles have been recognized (Early–Middle Miocene calc-alkaline volcanic rocks, followed by Middle Miocene to Recent alkaline ones) have been recognized (Martì et al., 1992; El Bakkali et al., 1998).

## DISCUSSION AND CONCLUSIONS

The Neogene to Present volcanic rocks emplaced around and within the western Mediterranean may be roughly divided into three groups (Wilson and Bianchini, 1999). *Group 1* has within-plate geochemical features and is mainly represented by tholeiitic and sodic alkaline products with OIB-like characters; the mantle sources of this group avoided the chemical perturbations induced by the subduction systems related to the Alpine orogeny. *Group 2* has compositions generally related to subduction-related settings (i.e., tholeiitic to calc-alkaline and high-K calc-alkaline and potassic to ultrapotassic alkaline compositions). *Group 3* comprises the oceanic floor of the Mediterranean, which shows compositions variable from N-MORB to E-MORB and calc-alkaline basalt. Major attention is now devoted to the first two groups.

Their trace element compositions are extremely variable, mainly because of fractionation processes. Generally, within-plate products show bell-shaped patterns in primitive mantle-normalized diagrams, peaking at Nb-Ta, whereas subduction-modified volcanic rocks show stronger fractionation between LILE and HFSE (e.g., Ba/Nb), LREE/HFSE (e.g., La/Nb) and also among HFSE (e.g. Ti/Nb and Zr/Hf) and negative peaks at Nb-Ta.

The similarity of the *Group 1* volcanic rocks with Ocean Island Basalts (OIBs), in terms of major and trace elements as well as Sr-Nd-Pb isotopic compositions, has allowed many authors to propose for them asthenospheric rather than lithospheric mantle sources (e.g., Wilson and Downes, 1991; Wedepohl and Baumann, 1999). Moreover, seismic tomography underneath Europe has traced plume channels down to a depth of 250 km (Hoernle et al., 1995; Granet et al., 1995) reinforcing the possibility of derivation from asthenospheric mantle, excluding major contributions from the lithosphere (Wedepohl and Baumann, 1999). In terms of mantle end-members (Zindler and Hart, 1986), this groups show variable amounts of sources with HIMU- and DM-like isotopic character, plus a little EMI involvement.

Instead, major and trace element and Sr-Nd-Pb isotopic ratios of *Group 2* rocks suggest derivation from more heterogeneous mantle sources identified in the lithospheric mantle (D'Antonio et al., 1999; Turner et al., 1999). This groups show isotopic compositions more shifted towards the EMII mantle end-member. It is important to recall that the "subduction" signature of some volcanic rocks belonging to this group has been explained either as contamination of continental crust or as derived by metasomatic modification of mantle sources by very low degree asthenospheric partial melts, without invoking any subduction component in their petrogenesis (e.g., Ayuso et al., 1998; Conticelli et al., 1998; Di Battistini et al., 1998; Turner et al., 1999).

Within this context, the Plio-Pleistocene volcanic rocks of Sardinia play a key role. From the geotectonic and major element points of view, these rocks belong to *Group 1*, but some trace element features make them transitional with the products of *Group 2*. In particular, the *Group 1* and *Group 2* volcanic rocks may be quite well discriminated using LILE/HFSE ratios such as Ba/Nb. In Fig. 2 this ratio is shown versus MgO: volcanic rocks with within-plate geochemical features (and geotectonically unrelated to active or recent subduction plate systems) display values of Ba/Nb (~5-20) overlapping with MORB and HIMU-OIB values, but definitely lower than the volcanic rocks from the same area related to active or recent subduction systems (Ba/Nb ~20-200). The great majority of the Plio-Pleistocene volcanic rocks of Sardinia (with the exception of only three samples: Capo Ferrato trachyte, Guspini hawaiite, Rio Girone basanite) show intermediate Ba/Nb values ranging from ~18 to ~38 (Lustrino, 1999; Lustrino et al., 2000a).

Moreover, the Plio-Pleistocene volcanic rocks of Sardinia show a unique Sr-Nd-Pb isotopic composition among all the Cenozoic European volcanic rocks. Fig. 3 shows the Sr-Nd-Pb isotopic composition of the Neogene to Present volcanic rocks of the western Mediterranean. Clearly, *Group 1* plots in the depleted quadrant, with $\varepsilon_{Sr}$ <0 and $\varepsilon_{Nd}$ >0, whereas *Group 2* plots towardw more enriched compositions with $\varepsilon_{Sr}$ >0 and $\varepsilon_{Nd}$ <0. Most of the Plio-Pleistocene volcanic rocks of Sardinia deviate from the array defined by the Neogene to Present volcanic rocks of the western Mediterranean, clustering to lower $\varepsilon_{Sr}$ for a given $\varepsilon_{Nd}$. The differences among *Group 1*, *Group 2* and Sardinian samples are highlighted by the Pb isotopic ratios. With few exceptions, the volcanic rocks of Sardinia show the least radiogenic $^{206}Pb/^{204}Pb$ isotopic composition ever recorded in the Cenozoic European Volcanic Province, as revealed by the $^{206}Pb/^{204}Pb$ vs $^{207}Pb/^{204}Pb$ and $^{206}Pb/^{204}Pb$ vs $^{208}Pb/^{204}Pb$ plots (Fig. 3). Considering Sr, Nd and Pb isotopic ratios, these Plio-Pleistocene volcanic rocks define a field overlapping the classical EMI compositions (e.g., Walvis Ridge, South-West Indian Ridge, Afanasy-Nikitin rise, Pitcairn seamounts; Richardson et al., 1982; Mahoney et al., 1992, 1996; Woodhead and Devey, 1993).

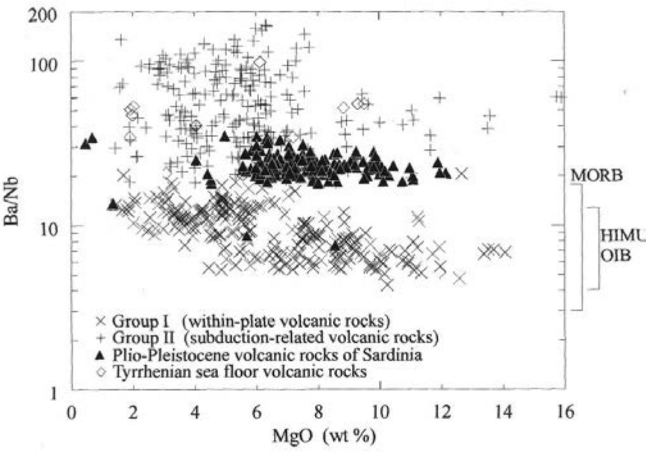

Fig. 2 - MgO vs. Ba/Nb diagram for Neogene to Present volcanic rocks of western Mediterranean area. References in text and in Lustrino (1999).

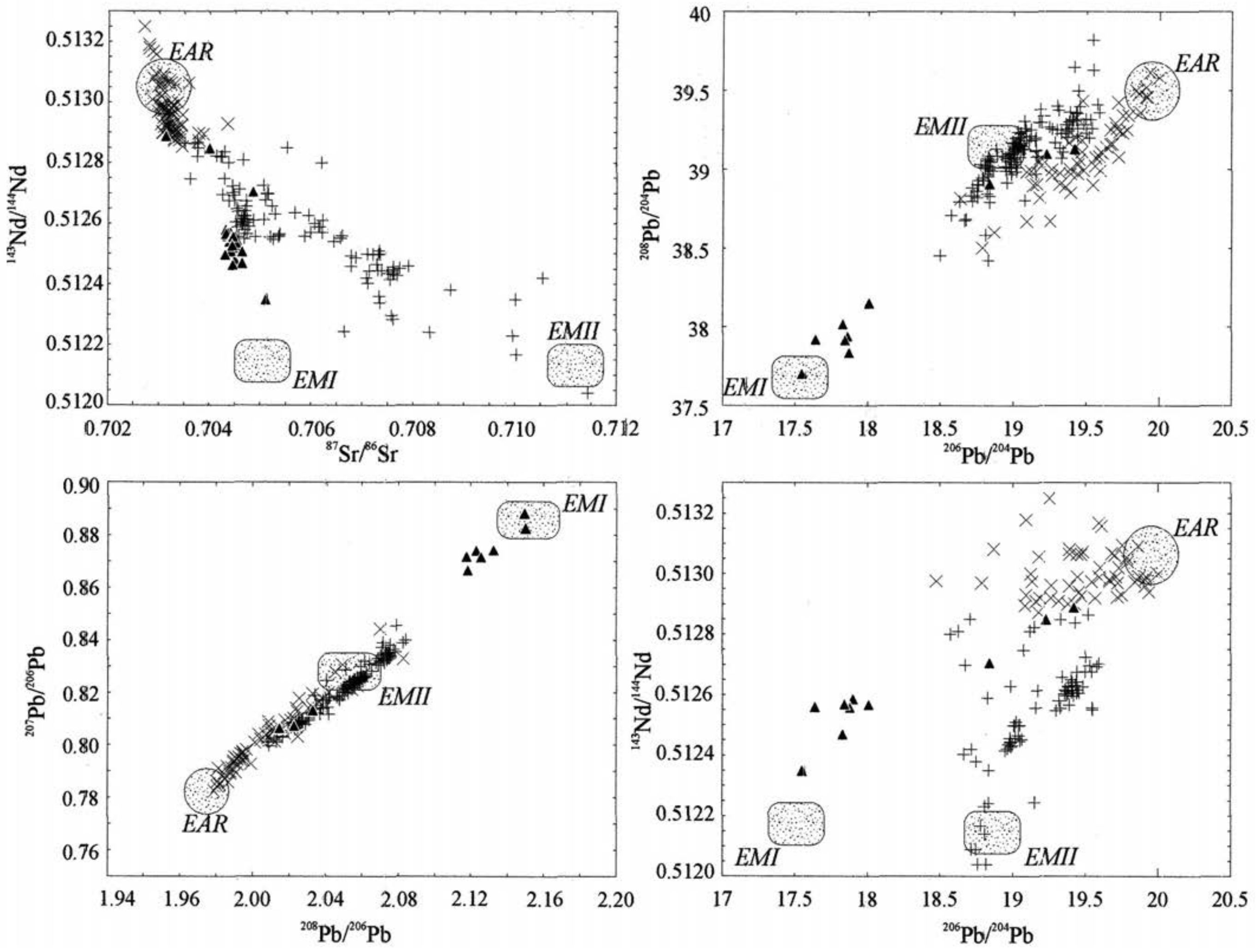

Fig. 3 - Sr-Nd-Pb isotopic ratios of Neogene to Present volcanic rocks of western Mediterranean area. X: Within-plate volcanic rocks (Group I in text); crosses: subduction-related volcanic rocks (Group II in text); filled triangles: Plio-Pleistocene volcanic rocks of Sardinia. EAR: (European Asthenospheric Reservoir; Granet et al., 1995); EMI and EMII (Enriched Mantle I and II; Zindler and Hart, 1986). See text for further explanations and references.

The EMI-like composition of the vast majority of Plio-Pleistocene volcanic rocks from Sardinia has been related to lithospheric sources modified during the previous orogenesis (Panafrican and Hercynian) with digestion of lower crustal lithologies (Lustrino, 1999; Lustrino et al., 2000a).

At the beginning of the Mesozoic, the European subcontinental mantle already presented geochemical and rheological heterogeneities due to its geodynamic evolution. Its heterogeneity is linked (Lustrino, 2000) to: 1) formation and destruction of oceanic crust; 2) crustal stacking during continent-continent collision which forced at least the lower portions of the crust to melt partially; 3) delamination and detachment processes which put asthenosphere and lithosphere (lower crust and uppermost mantle) into contact; 4) upwelling of the asthenospheric mantle during post-collisional phases (Late Carboniferous-Permian); 5) large-scale faults which put different mantle domains into contact and led to the ascent of deep fluids.

Interaction of the lithospheric mantle with lower crustal lithologies may have taken place according to two not mutually exclusive scenarios (Lustrino, 2000):

1) *Pre- to syn-collisional stage subduction*. Before the Hercynian continent-continent collision, huge volumes of Archean-Proterozoic oceanic crust were consumed in subduction processes. There is, indeed, much evidence for Hercynian ultrapotassic and shoshonitic magmatism in Europe, related to the subduction of this oceanic crust (e.g., Shaw et al., 1993). During the digestion of the oceanic crust, gravitative sinking of the cold, dense slab may have occurred and, later, during continent-continent collision, lithospheric delamination processes near the Conrad discontinuity. Decoupling of the brittle upper crust from the ductile lower crust may have detached the latter and caused it to subduct, together with the continental lithospheric mantle. Conversely, the upper crust may have been obducted, thrust and imbricated along the accretional front, as is now widely recognizable along the European Hercynian belt, thus avoiding contamination of mantle sources (Lustrino, 2000) (Fig. 4).
2) *Post-collisional sinking of dense mafic lower crust*. Continent-continent collision caused crustal shortening up to 600 km (Matte, 1991), with crustal stacking which forced the lower crust down to mantle depths, with a consequent rise in the temperature gradient. In the new P-T conditions, melting of the lower crust may have started to melt partially, to generate (mixed with various portions of mantle material) the backbone of the European Hercynides, leaving mafic granulitic residua. As commonly observed in many worldwide orogens (e.g., Smithies and Champion, 1999), the compressive phase was followed

by isostasy-related uplift and the formation of intermontane troughs. Thermal inputs from the upwelling asthenospheric mantle caused high-T/low-P regional metamorphism (Lustrino, 2000 and references therein). During this stage, sinking of the dense cumulate and mafic-restitic lower crust may have occurred (Meissner and Mooney, 1998), with the return of the lowermost mafic keel to the mantle. In this way, material with low Rb/Sr, Sm/Nd and U/Pb (Gao et al., 1998) returned to the mantle, modifying the original ratios and hence lowering time-integrated isotopic ratios.

Delamination and detachment of the lithosphere (including significant amounts of the lower crust) is possible only for a thickened and weakened lithosphere. The Sardinian lithosphere in the Paleozoic shares these two assumptions: thickening after crustal stacking following continent-continent collision, and weakening by consumption of water-rich altered oceanic crust before the closure of the Rheic and Massif Central-Moldanubian Oceans.

Delamination may develop at both lithospheric mantle level (i.e. lithospheric mantle sinks into the asthenosphere) and crustal level (i.e., sinking of the lowermost part of the crust coupled with the lithosphere mantle), depending on the thermomechanical and rheological proprieties of these realms. In particular, delamination and detachment may only occur if the total crustal thickness exceeds ~50 Km. In this case, i.e., in tectonically piled crustal materials along the continent-continent collisional margin, the lowermost crust is metamorphosed to the granulite/eclogite-facies. This high-grade metamorphism may deplete rocks with large ion incompatible elements such as Rb and U, thus lowering Rb/Sr and U/Pb ratios and leaving REE interelemental ratios almost unaltered (Farmer, 1992). Granulite/eclogite is characterized, with respect to the original lower crust, by higher density (up to 3.3 g/cm$^3$), which promotes delamination and detachment.

Thus, processes such as crustal and lithospheric delamination and detachment, together with thermal and chemical perturbations induced by subduction dynamics and the presence of active and passive ascent of asthenospheric mantle, largely overlapped within the western Mediterranean area. Volcanic products emplaced during the last 30 Ma bear all the signs of a strongly heterogeneous upper mantle below the area from Spain to Italy and from France to Morocco. Both asthenospheric and lithospheric sources were mobilized, with interactions which chemically modified their geochemical signature.

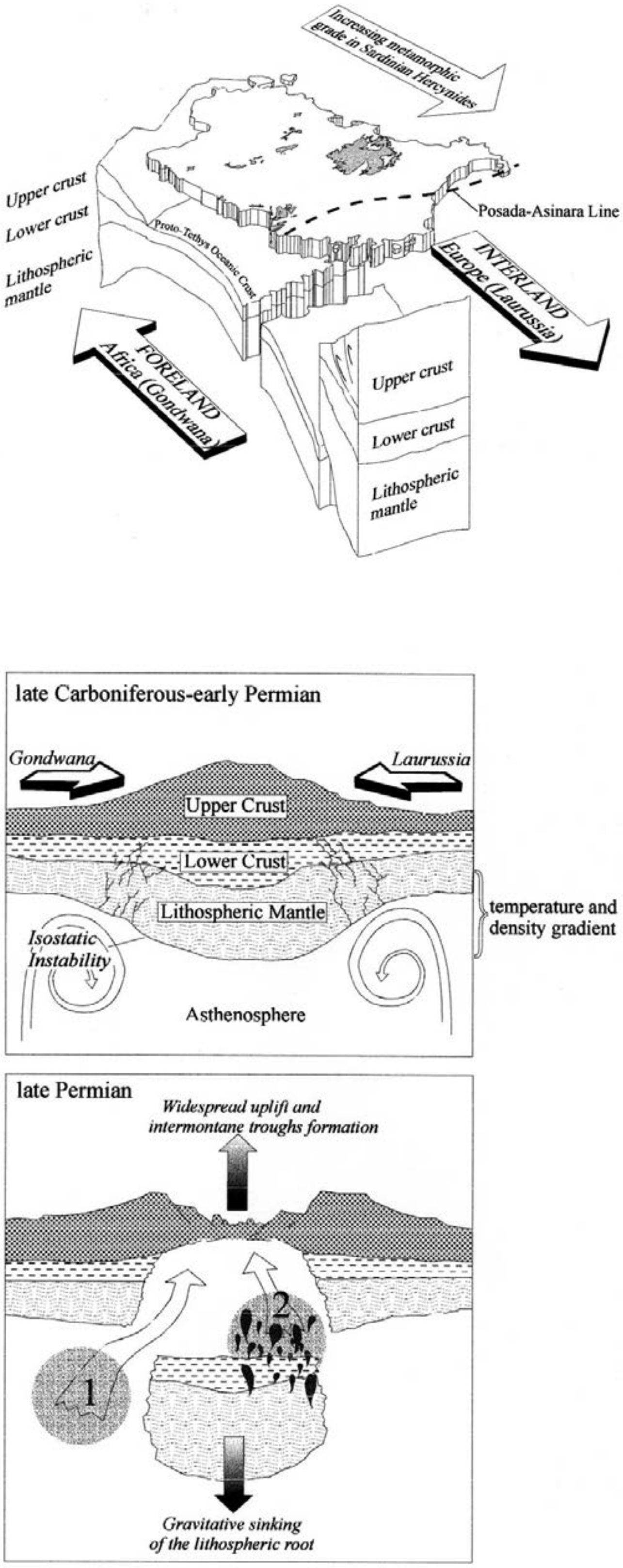

Fig. 4 - a. Pre-Carboniferous subduction of proto-Tethys oceanic crust before Hercynian orogeny s.s. (i.e., before continent-continent collision).
b. Delamination, detachment and sinking of overthickened lithospheric root during end of Hercynian orogeny. 1 = Future source of Cenozoic European Volcanic Province products, with within-plate geochemical features and strong asthenospheric signature; 2 = Future source of majority of Plio-Pleistocene volcanic rocks of Sardinia (UPG group of Lustrino et al., 2000a), with strong lower crustal and lithospheric signature.

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## REFERENCES

Argnani A. and Savelli C., 1999. Cenozoic volcanism and tectonics in the southern Tyrrhenian Sea: space-time distribution and geodynamic significance. J. Geodyn., 27: 409-432.

Ayuso R.A., De Vivo B., Rolandi G., Seal II R.R. and Paone A., 1998. Geochemical and isotopic (Nd-Pb-Sr-O) variations bearing on the genesis of volcanic rocks from Vesuvius, Italy. J. Volcanol. Geotherm. Res., 82: 53-78.

Beccaluva L., Di Girolamo P. and Serri G., 1991. Petrogenesis and tectonic setting of the Roman Volcanic Province, Italy. Lithos, 26: 191-221.

Beccaluva L., Siena F., Coltorti M., Di Grande A., Lo Giudice A., Macciotta G., Tassinari R. and Vaccaro C., 1998. Nephelinitic to tholeiitic magma generation in a transtensional tectonic setting: an integrated model for the Iblean volcanism, Sicily. J. Petrol., 39: 1547-1576.

Benito R., Lopez-Ruiz J., Cebria J.M., Hertogen J., Doblas M., Oyarzun R. and Demaiffe D., 1999. Sr and O isotope constraints on source and crustal contamination in the high-K calc-alkaline and shoshonitic Neogene volcanic rocks of SE Spain. Lithos, 46: 773-802.

Bianchini G., Bell K. and Vaccaro C., 1999. Mantle sources of the Cenozoic Iblean volcanism (SE Sicily, Italy): Sr-Nd-Pb isotopic constraints. Mineral. Petrol., 67: 213-221.

Bindi L., Cellai D., Melluso L., Conticelli S., Morra V. and Menchetti S., 1999. Crystal chemistry of clinopyroxene from alkaline undersaturated rocks of the Monte Vulture volcano, Italy. Lithos, 46: 259-274.

Boccaletti M., Nicolich R. and Tortorici L., 1990. New data and hypothesis on the development of the Tyrrhenian basin. Palaeo. Palaeo. Palaeo., 77: 15-40.

Briot D., Cantagrel J.M., Dupuy C. and Harmon R.S., 1991. Geochemical evolution in crustal magma reservoirs: trace-element and Sr-Nd-O isotopic variations in two continental intraplate series at Monts Dore, Massif Central, France. Chem. Geol., 89: 281-303.

Brotzu P. (Ed.), 1997. The Tertiary calcalkaline volcanism of Sardinia. Per. Mineral., Spec. Iss., 66.

Brotzu P., Lonis R., Melluso L., Morbidelli L., Traversa G. and Franciosi L., 1997. Petrology and evolution of calcalkaline magmas from the Arcuentu volcanic complex (SW Sardinia, Italy). Per. Mineral., 66: 151-164.

Busà T, Clocchiatti R. and Cristofolini R., 1999. “Low P” and “High P” alkaline magmas from Mt. Etna: their origin and evolution from the study of mineralogy and chemistry of lavas and of olivine-trapped inclusions. Per. Mineral., 68: 163-183.

Carmignani L., Decandia F.A., Disperati L., Fantozzi P.L., Lazzarotto A., Liotta D. and Oggiano G., 1995. Relationships between the Tertiary structural evolution of the Sardinia-Corsica-Provençal domain and the Northern Apennines. Terra Nova, 7: 128-137.

Carminati E., Wortel M.J.R., Meijer P.Th. and Sabadini R., 1998. The two-stage opening of the western-central Mediterranean basins: a forward modeling test to a new evolutionary model. Earth Planet. Sci. Lett., 160: 667-679.

Castorina F., Stoppa F., Cundari A. and Barbieri M., 2000. An enriched mantle source for Italy’s melilitite-carbonatite association as inferred by its Nd-Sr isotopic signature. Mineral. Mag., 64: 625-639.

Cebria J.M. and Lopez-Ruiz J., 1995. Alkali basalts and leucitites in an extensional intracontinental plate setting: the late Cenozoic Calatrava volcanic province (central Spain). Lithos, 35: 27-46.

Cebria J.M., Lopez-Ruiz J., Doblas M., Oyarzun R., Hertogen J. and Benito R., 2000. Geochemistry of the Quaternary alkali basalts of Garrotxa (NE volcanic province, Spain): a case of double enrichment of the mantle lithosphere. J. Volc. Geotherm. Res., 102: 217-235.

Cella F., Fedi M., Florio G. and Rapolla A., 1998. Gravity modelling of the litho-asthenosphere system in the Central Mediterranean. Tectonophysics, 287: 117-138.

Chauvel C. and Jahn B.M., 1984. Nd-Sr isotope and REE geochemistry of alkali basalts from the Massif Central, France. Geochim. Cosmochim. Acta, 48: 93-110.

Cinque A., Civetta L., Orsi G. and Peccerillo A., 1988. Geology and geochemistry of the island of Ustica (southern Tyrrhenian Sea). Rend. S.I.M.P., 43: 987-1002.

Cioni R., Clocchiatti R., Di Paola G.M., Santacroce R. and Tonarini S., 1982. Miocene calc-alkaline heritage in the Pliocene post-collisional volcanism of Monte Arci (Sardinia, Italy). J. Volc. Geotherm. Res., 14: 133-167.

Civetta L., D’Antonio M., Orsi G. and Tilton G.R., 1998. The geochemistry of volcanic rocks from Pantelleria island, Sicily channel: petrogenesis and characteristics of the mantle source region. J. Petrol., 39: 1453-1491.

Conticelli S., 1998. The effect of crustal contamination on ultrapotassic magmas with lamproitic affinity: mineralogical, geochemical and isotope data from the Torre Alfina lavas and xenoliths, central Italy. Chem. Geol., 149: 51-81

Conticelli S. and Peccerillo A., 1992. Petrology and geochemistry of potassic and ultrapotassic volcanism in central Italy: petrogenesis and inferences on the evolution of the mantle sources. Lithos, 28: 221-240.

Cundari A., 1994. Role of subduction in the genesis of potassic basaltic rocks: a discussion paper on the unfashionable side of the role. Miner. Petrogr. Acta, 37: 81-90.

D’Antonio M., Civetta L. and Di Girolamo P., 1999. Mantle source heterogeneity in the Campanian region (south Italy) as inferred from geochemical and isotopic features of mafic volcanic rocks with shoshonitic affinity. Mineral. Petrol., 67: 163-192.

Dautria J.M. and Liotard J.M., 1990. Les basaltes d’affinité tholéiitique de la marge méditerranéenne française. C. R. Acad. Sci. Paris, 311: 821-827.

Davies G.E. and Lloyd F.E., 1989. Pb-Sr-Nd isotope and trace element data bearing on the origin of the potassic subcontinental lithosphere beneath south-west Uganda. In: Ross J. (Ed.), Proc. 4th Int. Kimb. Conf. Perth, Geol. Soc. Australia Spec. Publ., 14: 785-794.

De Astis G., La Volpe L., Peccerillo A. and Civetta L., 1997. Volcanological and petrological evolution of Vulcano Island (Aeolian arc, southern Tyrrhenian sea). J. Geophys. Res., 102: 8021-8050.

Del Moro A., Gioncada A., Pinarelli L., Sbrana A. and Joron J.L., 1998. Sr, Nd and Pb isotope evidence for open system evolution at Vulcano, Aeolian arc, Italy. Lithos, 43: 81-106.

Di Battistini G., Montanini A., Vernia L., Bargossi G.M. and Castorina F., 1998. Petrology and geochemistry of ultrapotassic rocks from the Montefiascone volcanic complex (Central Italy): magmatic evolution and petrogenesis. Lithos, 43: 169-195.

Di Battistini G., Montanini A. and Zerbi M., 1990. Geochemistry of volcanic rocks from southeastern Montiferro. N. Jahrb. Miner. Abh., 162: 35-67.

Di Girolamo P, Morra V. and Perrone V., 1992. Ophiolitic olistoliths in Middle Miocene turbidites (Cilento group) at Mt. Centaurino (southern Appennines, Italy). Ofioliti, 17: 199-217.

Docherty C. and Banda E., 1995. Evidence for eastward migration of the Alboran Sea based on regional subsidence analysis: a case for basin formation by delamination of the subcrustal lithosphere? Tectonics, 14: 804-818.

Doglioni C. Gueguen E., Sàbat F. and Fernandez M., 1997. The Western Mediterranean extensional basins and the Alpine orogen. Terra Nova, 9: 109-112.

Doglioni C., Harabaglia P., Merlini S., Mongelli F., Peccerillo A. and Piromallo C., 1999. Orogens and slabs vs. their direction of subduction. Earth Sci. Rev., 45: 167-208.

D’Orazio M., Tonarini S., Innocenti F. and Pompilio M., 1997. Northern Valle del Bove volcanic succession (Mt. Etna, Sicily): petrography, geochemistry and Sr-Nd isotope data. Acta Vulcanol., 9: 73-86.

Dostal J., Coulon C. and Dupuy C., 1982. Cainozoic andesitic rocks of Sardinia (Italy). In: A. Thorpe (Ed.), Andesites. p. 353-370.

Downes H., 1987. Tertiary and Quaternary volcanism in the Massif Central, France. In: J.C. Fitton and B.G. Upton (Eds.), Alkaline igneous rocks. Geol. Soc. Londo Spec. Publ. 30: 517-530.

Duermeijer C.E., van Vugt N., Langereis C.G. and Muelenkamp J.E., 1998. A major late Tortonian rotation phase in the Crotone basin using AMS as tectonic tilt and timing of the Tyrrhenian basin. Tectonophysics, 287: 233-249.

El Bakkali S., Gourgaud A., Bourdier J.L., Bellon H. and Gundogdu N., 1998. Post-collision Neogene volcanism of the eastern Rif (Morocco): magmatic evolution through time. Lithos, 45: 523-543.

Esperança S. and Crisci G.M., 1995. The Island of Pantelleria: a case for the development of DMM-HIMU isotopic compositions in a long-lived extensional setting. Earth Planet. Sci. Lett. 136: 167-182.

Faccenna C., Mattei M., Funiciello R. and Jolivet L., 1997. Styles of back-arc extension in the central Mediterranean. Terra Nova, 9: 126-130.

Farmer G.L., 1992. Magmas as tracers of lower crustal composition: an isotopic approach. In: D.M. Fountain, R. Arculus and R.W Kay (Eds.), Continental lower crust, Elsevier, p. 363-390.

Francalanci L., Taylor S.R., McCulloch M.T. and Woodhead J.D., 1993. Geochemical and isotopic variations in the calc-alkaline rocks of Aeolian arc, southern Tyrrhenian Sea, Italy: constraints on magma genesis. Contrib. Mineral. Petrol., 113: 300-313.

Gao S., Luo T.C., Zhang B.R., Hang H.F., Han Y.W., Zhao Z.D. and Hu Y.K., 1998. Chemical composition of the continental crust as revealed by studies in east China. Geochim. Cosmochim. Acta, 62: 1959-1975.

Gertisser R. and Keller J., 2000. From basalt to dacite: origin and evolution of the calc-alkaline series of Salina, Aeolian arc, Italy. Contrib. Mineral. Petrol., 139: 607-626.

Granet M., Wilson M. and Achauer U., 1995. Imaging a mantle plume beneath the French Massif Central. Earth Planet. Sci. Lett., 136: 281-296.

Gualteri L. and Zappone A., 1998. Hypothesis of ensialic subduction in the Northern Apennines: a petrophysical contribution. Mem. Soc. Geol. It., 52: 205-214.

Gueguen E., Doglioni C. and Fernandez M., 1998. On the post-25 Ma geodynamic evolution of the western Mediterranean. Tectonophysics, 298: 259-269.

Guerrera F., Martin-Algarra A. and Perrone V., 1993. Late Oligocene-Miocene syn/late-orogenic successions in Western and Central Mediterranean chains from the Betic Cordillera to the southern Apennines. Terra Nova, 5: 525-544.

Hoernle K., Zhang Y.S. and Graham D., 1995. Seismic and geochemical evidence for large-scale mantle upwelling beneath the eastern Atlantic and western and central Europe. Nature, 374: 34-39.

Jones A.P., Kostoula T., Stoppa F. and Woolley A.R., 2000. Petrography and mineral chemistry of mantle xenoliths in a carbonate-rich melilititic tuff from Mt. Vulture volcano, southern Italy. Mineral. Mag., 64: 593-613.

Lecca L., Lonis R., Luxoro S., Melis E., Secchi F. and Brotzu P., 1997. Oligo-Miocene volcanic sequences and rifting stages in Sardinia: a review. Per Mineral., 66: 7-61.

Liotard J.M., Briqueu L., Dautria J.M. and Jakui B., 1999. Basanites et néphélinites du Bas-Languedoc (France): contamination crustale et hétérogénéité de la source mantellique. Bull. Soc. Géol. France, 170: 423-433.

Lloyd F.E., Edgar A.D. and Ragnarsdottir K.V., 1996. LREE distribution in perovskite, apatite and titanite from south west Ugandan xenoliths and kamafugite lavas. Mineral. Petrol., 57: 205-228.

Lonergan L. and White N., 1997. Origin of the Betic-Rif mountain belt. Tectonics, 16: 504-522.

Lustrino M., 1999. Petrogenesis of Plio-Quaternary volcanic rocks from Sardinia: possible implications on the evolution of the European subcontinental mantle. Unpublished PhD thesis, Univ. Napoli Federico II, 188 pp.

Lustrino M., 2000. Phanerozoic geodynamic evolution of circum-Italian realm. Int. Geol. Rev., 42: 724-757.

Lustrino M., Melluso L. and Morra V., 1999. Origin of glass and its relationships with phlogopite in mantle xenoliths from central Sardinia (Italy). Per. Mineral., 68: 13-42.

Lustrino M., Melluso L. and Morra V., 2000a. The role of lower continental crust and lithospheric mantle in the genesis of Plio-Pleistocene volcanic rocks from Sardinia (Italy). Earth Planet. Sci. Lett., 180: 159-170.

Lustrino M., Melluso L. and Morra V., 2000b. Petrogenesis of Pliocene volcanic rocks from Orosei-Dorgali (Sardinia, Italy). AGU Fall Meeting, San Francisco.

Lustrino M., Melluso L., Morra V. and Secchi F., 1996. Petrology of Plio-Quaternary volcanic rocks from central Sardinia. Per. Mineral., 65: 275-287.

Mahoney J.J., le Roex A.P., Peng Z., Fisher R.L. and Natland J.H., 1992. Southwestern limits of Indian ocean ridge mantle and the origin of low $^{206}$Pb/$^{204}$Pb mid-ocean ridge basalt: isotope systematics of the central southwest Indian ridge (17°-50°e). J. Geophys. Res., 97: 19771-19790.

Mahoney J.J., White W.M., Upton B.G.J., Neal C.R. and Scrutton R.A., 1996. Beyond EM-1: lavas from Afanasy-Nikitin rise and the Crozet archipelago, Indian Ocean. Geology, 24: 615-618.

Mantovani E., Albarello D., Tamburelli C., Babbucci D. and Viti M., 1997. Plate convergence, crustal delamination, extrusion tectonics and minimization of shortening work as main controlling factors of the recent Mediterranean deformation pattern. Ann. Geof., 40: 611-643.

Martì J., Mitjavila J., Roca E. and Aparicio A., 1992. Cenozoic magmatism of the Valencia trough (Western Mediterranean): relationship between structural evolution and volcanism. Tectonophysics, 203: 145-165.

Matte Ph., 1991. Accretionary history and crustal evolution of the Variscan belt in Western Europe. Tectonophysics, 196: 309-377.

Mayer G., Mai P.M., Plenefisch T., Echtler H. Luschen E., Wehrle V., Muller B., Bonjer K.P., Prodehl C. and Fuchs K., 1997. The deep crust of the southern Rhine graben: reflectivity and seismicity as images of dynamic processes. Tectonophysics, 275: 15-40.

Meissner R. and Mooney W., 1998. Weakness of the lower continental crust: a condition for delamination, uplift and escape. Tectonophysics, 296: 47-60.

Melluso L., Morra V. and Di Girolamo P., 1996. The Mt. Vulture volcanic complex (Italy): evidence for distinct parental magmas and for residual melts with melilite. Mineral Petrol., 56: 225-250.

Montanini A., Barbieri M. and Castorina F., 1994. The role of fractional crystallization, crustal melting and magma mixing in the petrogenesis of rhyolites and mafic inclusion-bearing dacites from the Monte Arci volcanic complex (Sardinia, Italy). J. Volc. Geotherm. Res., 61: 95-120.

Morelli C., 1998. Lithospheric structure and geodynamics of the Italian Peninsula derived from geophysical data: a review. Mem. Soc. Geol. It., 52: 113-122.

Morra V., Secchi F.A. and Assorgia A., 1994. Petrogenetic significance of peralkaline rocks from Cenozoic calcalkaline volcanism from SW Sardinia, Italy. Chem. Geol., 118: 109-142.

Morra V., Secchi F.A.G., Melluso L. and Franciosi L., 1997. High-Mg subduction-related Tertiary basalts in Sardinia, Italy. Lithos, 40: 69-91.

Muttoni G., Argnani A., Dent D.V., Abrahamsen N. and Cibin U., 1998. Paleomagnetic evidence for Neogene tectonic rotations in the northern Apennines, Italy. Earth Planet. Sci. Lett., 154: 25-40.

Neumann E.R., Martì J, Mitjavila J. and Wulff-Pedersen E., 1999. Origin and implications of mafic xenoliths associated with Cenozoic extension-related volcanism in the Valéncia trough, NE Spain. Mineral. Petrol., 65: 113-139.

Peccerillo A., 1990. On the origin of the Italian potassic magmas - comments. Chem. Geol. 85: 183-191.

Peccerillo A., 1998. Relationships between ultrapotassic and carbonate-rich volcanic rocks in central Italy: petrogenetic and geodynamic implications. Lithos, 43: 267-279.

Peccerillo A., 1999. Multiple mantle metasomatism in Central-

Southern Italy: geochemical effects, timing and geodynamic implications. Geology, 27: 315-318.

Peccerillo A., Conticelli S. and Manetti P., 1987. Petrological characteristics and the genesis of the recent magmatism of southern Tuscany and northern Latium. Per. Mineral., 56: 157-172.

Platt J.P. and Vissers R.L.M., 1989. Extensional collapse of thickened continental lithosphere: a working hypothesis for the Alboran Sea and Gibraltar Arc. Geology, 17: 540-543.

Rampone E., Hofmann A.W. and Raczed I., 1998. Isotopic contrasts within the Internal Liguride ophiolite (N. Italy): the lack of a genetic mantle-crust link. Eart Planet. Sci. Lett., 163: 175-189.

Richardson S.H., Erlank A.J., Duncan A.R. and Reid D.L., 1982. Correlated Nd, Sr and Pb isotope variation in Walvis Ridge basalts and implications for the evolution of their mantle source. Earth Planet. Sci. Lett., 59: 327-342.

Rogers N.W., 1992. Potassic magmatism as a key to trace-element enrichment processes in the upper mantle. J. Volc. Geotherm. Res., 50: 85-99.

Rogers N.W., James D., Kelley S.P. and De Mulder M., 1998. The generation of potassic lavas from the eastern Virunga province, Rwanda. J. Petrol., 39: 1223-1247.

Rossi P.L., Tranne C.A., Calanchi N. and Lanti E., 1996. Geology, stratigraphy and volcanological evolution of the Island of Linosa (Sicily channel). Acta Vulcanol., 8: 73-90.

Royden L.H., 1993. Evolution of retreating subduction boundaries formed during continental collision. Tectonics, 12: 629-638.

Santo A.P., 2000. Volcanological and geochemical evolution of Filicudi (Aeolian Islands, south Tyrrhenian Sea, Italy). J. Volcanol. Geotherm. Res., 96: 79-101.

Savelli C. and Gasparotto G., 1994. Calc-alkaline magmatism and rifting of the deep-water volcano of Marsili (Aeolian back-arc, Tyrrhenian Sea). Marine Geol., 119: 137-157.

Sborshchikov I.M. and Al'mukhamedov A.I., 1992. Submarine volcanoes of the Tyrrhenian Sea - testaments to the opening of a backarc basin. Int. Geol. Rev., 34: 166-177.

Séranne M., 1999. The gulf of Lion continental margin (NW Mediterranean) revisited by IBS: an overview. In: B. Durand, L. Jolivet, F. Horvath and M. Seranne (Eds.), The Mediterranean basins: Tertiary extension within the Alpine orogen. Geol. Soc. London, 156: 15-36.

Serri G., Innocenti F. and Manetti P., 1993. Geochemical and petrological evidence of the subduction of delaminated Adriatic continental lithosphere in the genesis of the Neogene-Quaternary magmatism of central Italy. Tectonophysics, 223: 117-147.

Shaw A., Downes H. and Thirlwall M.F., 1993. The quartz-diorites of Limousin: elemental and isotopic evidence for Devono-Carboniferous subduction in the Hercynian belt of the French Massif Central. Chem. Geol., 107: 1-18.

Smithies R.H. and Champion D.C., 1999. Late Archaean felsic alkaline igneous rocks in the eastern goldfields, Ylgarn craton, western Australia: a result of lower crustal delamination? J. Geol. Soc. London, 156: 561-576.

Stoppa F. and Cundari A., 1995. A new Italian carbonatite occurrence at Cupaello (Rieti) and its genetic significance. Contrib. Mineral. Petrol., 122: 275-288.

Stoppa F. and Lavecchia G., 1992. Late Pleistocene ultra-alkaline magmatic activity in the Umbria-Latium region (Italy): an overview. J. Volcanol. Geotherm. Res., 52: 277-293.

Tedesco D., 1997. Systematic variations in the $^3$He/$^4$He ratio and carbon of fumarolic fluids from active volcanic areas in Italy: evidence for radiogenic $^4$He and crustal carbon addition by the subducting African Plate? Earth Planet. Sci. Lett., 151: 255-269.

Torres-Roldàn R.L., Poli G. and Peccerillo A., 1986. An Early Miocene arc-tholeiitic dike event from the Alboran Sea - evidence for precollisional subduction and back-arc crustal extension in the westernmost Mediterranean. Geol. Rundsh., 75: 219-234.

Trua T., Esperança S. and Mazzuoli R., 1998. The evolution of the lithospheric mantle along the N. African Plate: geochemical and isotopic evidence from the tholeiitic and alkaline volcanic rocks of the Hyblean plateau, Italy. Contrib. Mineral. Petrol., 131: 307-322.

Trua T., Laurenzi M.A. and Oddone M., 1997. Geochronology of the Plio-Pleistocene Hyblean volcanism (SE Sicily): new $^{40}$Ar/$^{39}$Ar data. Acta Vulcanol., 9: 167-176.

Turi B. and Taylor H.P., 1976. Oxygen isotope studies of potassic volcanic rocks of the Roman Province, central Italy. Contrib. Mineral. Petrol., 55: 1-31.

Turner S.P., Platt J.P., George R.M.M., Kelley S.P., Pearson D.G. and Nowell G.M., 1999. Magmatism associated with orogenic collapse of the Betic-Alboran domain, SE Spain. J. Petrol., 40: 1011-1036.

van Der Meulen J.M., Meulenkamp J.E. and Wortel M.J.R., 1998. Lateral shifts of Apenninic foredeep depocentres reflecting detachment of subducted lithosphere. Earth Planet. Sci. Lett., 154: 203-219.

Vigliotti L. and Langenheim V.E., 1995. When did Sardinia stop rotating? Terra Nova, 7: 424-435.

Vissers R.L.M., Platt J.P. and van der Wal D., 1995. Late orogenic extension of the Betic Cordillera and the Alboran domain: a lithospheric view. Tectonics, 14: 786-803.

Vollmer R., 1976. Rb-Sr and U-Pb systematics of alkaline rocks: the alkaline rocks from Italy. Geochim. Cosmochim. Acta, 40: 283-295.

Vollmer R., 1990. On the origin of the Italian potassic magmas - reply. Chem. Geol., 85: 191-196.

Vollmer R. and Hawkesworth C.J., 1980. Lead isotopic composition of the potassic rocks from Roccamonfina (South Italy). Earth Planet. Sci. Lett., 47: 91-101.

Wang W. and Takahashi E., 2000. Subsolidus and melting experiments of K-doped peridotite KLB-1 to 27 GPa: its geophysical and geochemical implications. J. Geophys. Res., 105: 2855-2878.

Wedepohl K.H. and Baumann A., 1999. Central European Cenozoic plume volcanism with OIB characteristics and indications of a lower mantle source. Contrib. Mineral. Petrol., 136: 225-239.

Wilson M. and Bianchini G., 1999. Tertiary-Quaternary magmatism within the Mediterranean and surrounding regions. In: B. Durand, L. Jolivet, F. Horvath and M. Séranne (Eds.), The Mediterranean basins: Tertiary extension within the Alpine orogen. Geol. Soc. London Spec. Pap., 156: 141-168.

Wilson M. and Downes H., 1991. Tertiary-Quaternary extension-related alkaline magmatism in western and central Europe. J. Petrol., 32: 811-849.

Wilson M., Downes H. and Cebria J.M., 1995. Contrasting fractionation trends in coexisting continental alkaline magma series; Cantal, Massif Central, France. J. Petrol., 36: 1729-1753.

Woodhead J.D. and Devey C.W., 1993. Geochemistry of the Pitcairn seamounts, I: source character and temporal trends. Earth Planet. Sci. Lett., 116: 81-99.

Zangana N.A., Downes H., Thirlwall M.F., Marriner G.F. and Bea F., 1999. Geochemical variations in peridotite xenoliths and their constituent clinopyroxenes from Ray Pic (French Massif Central): implications for the composition of the shallow lithospheric mantle. Chem. Geol., 153: 11-35.

Zeck H.P., 1997. Mantle peridotites outlining the Gibraltar arc - centrifugal extensional allochthons derived from the earlier Alpine, westward subducted nappe pile. Tectonophysics, 281: 195-207.

Zeyen H., Novak O., Landes M., Prodehl C., Driad L. and Hirm A., 1997. Refraction-seismic investigations of the northern Massif Central (France). Tectonophysics, 275: 99-117.

Ziegler P.A., 1992. European Cenozoic rift system. Tectonophysics, 208: 91-111.

Zindler A. and Hart S., 1986. Chemical geodynamics. Ann. Rev. Earth Planet. Sci., 14: 493-571.

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