Tertiary-Quaternary subduction processes and related magmatism in the Alpine-Mediterranean region

Szabolcs Harangi[1,*], Hilary Downes[2] and Ioan Seghedi[3]

[1] Department of Petrology and Geochemistry, Eötvös University, H-1117 Budapest, Pázmány Péter sétány 1/C, Hungary; e-mail: szabolcs.harangi@geology.elte.hu

[2] Birkbeck/UCL Research School of Earth Sciences, Birkbeck University of London, Malet St., London WC1E 7HX, UK

[3] Institute of Geodynamics, 19-21, str. Jean-Luis Calderon, Bucharest 70201, Romania

* corresponding author

number of word of abstract: 396
number of word of text: 12097
number of word of references: 9030
number of word of figure captions: 875

Abstract

During Tertiary to Quaternary times, convergence between Eurasia and Africa resulted in a variety of collisional orogens and different styles of subduction in the Alpine-Mediterranean region. Characteristic features of this area include arcuate orogenic belts and extensional basins, both of which can be explained by roll-back of subducted slabs and retreating subduction zones. After cessation of active subduction, slab detachment and post-collisional gravitational collapse of the overthickened lithosphere took place. This complex tectonic history was accompanied by the generation of a wide variety of magmas. Most of these magmas (e.g. low-K tholeiitic, calc-alkaline, shoshonitic and ultrapotassic types) have trace element and isotopic fingerprints that are commonly interpreted to reflect enrichment of their source regions by subduction-related fluids. Thus, they can be considered as 'subduction-related' magmas irrespective of their geodynamic relationships. Intraplate alkali basalts are also found in the region generally postdated the 'subduction-related' volcanism. These mantle-derived magmas have not been, or only slightly, influenced by subduction-related enrichment.

This paper summarises the geodynamic setting of the Tertiary-Quaternary "subduction-related" magmatism in the different segments of the Alpine-Mediterranean region (Betic-Alboran-Rif province, Central Mediterranean, the Alps, Carpathian-Pannonian region, Dinarides and Hellenides, Aegean and Western Anatolia), and discusses the main characteristics and compositional variation of the magmatic rocks. Radiogenic and stable isotope data indicate the importance of continental crustal material in the genesis of these magmas. Interaction with crustal material probably occurred both in the upper mantle during subduction ('source contamination') and in the continental crust during ascent of mantle-derived magmas (either by mixing with crustal melts or by crustal contamination). The $^{87}Sr/^{86}Sr$ and $^{206}Pb/^{204}Pb$ isotope ratios indicate that an enriched mantle component, akin to the source of intraplate alkali mafic magmas along the Alpine foreland, played a key role in the petrogenesis of the 'subduction-related' magmas of the Alpine-Mediterranean region. This enriched mantle component could be related to mantle plumes or to long-term pollution (deflection of the central Atlantic plume and recycling of crustal material during subduction) of the shallow mantle beneath Europe since the late Mesozoic. In the first case, subduction processes could have had an influence in generating asthenospheric flow by deflecting nearby mantle plumes due to slab roll-back or slab break-off. In the second case, the variation in the chemical composition of the volcanic rocks in the Mediterranean region can be explained by "statistical sampling" of the strongly inhomogeneous mantle followed by variable degrees of crustal contamination.

The Alpine-Mediterranean region is one of the most complex geodynamic settings on Earth. Subduction of oceanic plates, collision of continents, opening of extensional basins and possible upwelling of mantle plumes have all occurred associated with the formation of a wide variety of igneous rocks during the Tertiary and Quaternary. These processes are still active in some parts of this region. The geodynamic processes and volcanic activity have been the focus of researches for a long time. During the last decade a number of papers have been published using the results of new techniques such as seismic tomography and isotope geochemistry (see summary papers of Wilson & Bianchini 1999; Doglioni *et al.* 1999; Lustrino 2000; Wortel & Spakman 2000).

Convergent margins are the sites where subduction of oceanic lithosphere occurs beneath oceanic or continental plates. The style of subduction depends upon various parameters, including the rate of convergence, the rate of subduction, the nature of the subducted lithosphere and the polarity of subduction (Jarrard 1986; Royden & Burchfiel 1989; Doglioni 1993). Tertiary-Quaternary subduction in the Alpine-Mediterranean region was governed by the convergence between Eurasia and Africa in an area where continental and oceanic microplates were trapped between the converging continental plates. This resulted in various styles of subduction and collision (Royden & Burchfiel 1989; Royden 1993; Doglioni *et al.* 1999). Royden & Burchfiel (1989) proposed that orogenic belts with high topographic elevation were formed where the rate of convergence exceeded the rate of subduction (advancing subduction; e.g., Alps). In contrast, low topographic relief and regional extension in the upper plate are considered to characterize subduction boundaries where the rate of subduction exceeded the rate of overall plate convergence (retreating subduction; e.g., Betics–Alboran-Rif, Apennines, Hellenic and Carpathian thrust belts). Doglioni (1991; 1993) and Doglioni *et al.* (1999) emphasized the importance of subduction polarity. Westward-directed subduction zones oppose mantle flow and have similar features to retreating subduction boundaries, i.e. steep angle of subduction, slab roll-back, opening of extensional basins and termination of subduction when the buoyant continental lithosphere enters the trench. Eastward-directed subduction zones are reinforced by mantle flow and show a lower angle of subduction, together with a lack of extension in the overlying plate. Following subduction of oceanic lithosphere, continent-continent collision occurs resulting in thickening of the continental crust and lithosphere. Detachment of the dense oceanic slab (Davies & von Blanckenburg 1995), delamination of the thick lithospheric mantle (Bird 1979), sometimes with the dense mafic lower crust (Lustrino *et al.* 2000) or convective removal of the lower lithosphere (Housman *et al.* 1981; Platt & Vissers 1989; Turner *et al.* 1999) could be responsible for post-collisional extension and related magmatism. The geochemistry of the magmas is dependant on the rheology of the continental plates involved in the collision, the extent of collision and the velocity of plate convergence (Wang *et al.* 2004).

The complex tectonic evolution of the Alpine-Mediterranean region has been associated with formation of a wide range of Tertiary to Quaternary and even recent igneous rocks (Fig. 1). Wilson & Bianchini (1999) divided the magmatic activity of this area into "orogenic" and "anorogenic" types. Alkali basaltic magmas of anorogenic type erupted mainly along the foreland of the Alps (see Wilson & Downes, this volume), but can be found also throughout the Mediterranean region. Orogenic calc-alkaline, potassic to ultrapotassic and silicic magmas erupted in the convergent margins of the Alpine-Mediterranean region. These volcanic rocks show indeed a subduction-related geochemical composition. In this paper, we highlight the results of the most recent publications on the Tertiary to Quaternary volcanism and show that geodynamic and petrogenetic models are still highly controversial in spite of the emerging data. One of the aims of this paper is to present the competing tectonic and petrogenetic models, the volcanic histories of different areas of this region and finally to search for the origin of the magmas and the reason for melt generation processes in this complex tectonic setting.

Generation of magmas with 'subduction-related' geochemistry

Subduction of oceanic lithosphere often results in a linear chain of volcanoes along an island arc or active continental margin (Fig. 2A; Gill 1981; Thorpe 1982; Wilson 1989). Most of the volcanic rocks, which build up these volcanoes, are calc-alkaline in composition. In addition, low-K tholeiitic and potassic magmas can also be associated with active subduction. The primary magmas are considered to form by melting of hydrous peridotite either in the asthenospheric mantle wedge or in the subcontinental lithospheric mantle (Gill 1981). The complex processes beneath active volcanic arcs seem to develop fairly quickly (Gill & Williams 1990; Gill *et al.* 1993; Reagan *et al.* 1994; Elliott *et al.* 1997). Dehydration of the descending slab, metasomatism of the mantle wedge by aqueous fluids, partial melting and eruption of magmas can take place in < 30 kyr (Elliott *et al.* 1997; Turner *et al.* 2000). Therefore, the presence of calc-alkaline magmatism is widely considered as evidence for the existence of an active subduction zone (e.g., Pearce & Cann 1973; Wood 1980). Most calc-alkaline magmas are intermediate in composition (andesite to dacite) and true basalts are rare in most suites due to the differentiation processes in shallow level magma chambers.

Subduction-related magmas worldwide have trace element and isotopic fingerprints that are usually interpreted as reflecting fluid involvement in their genesis. Such fluids are either aqueous solutions or silicate melts released from the subducted oceanic lithosphere and its overlying sediments. Their effects are seen in high ratios of large ion lithophile elements (LILE; such as Cs, Rb, Ba, K, Sr) and Pb to high field strength elements (HFSE; e.g., Nb, Ta, Zr, Hf and Ti, Fig. 3). The LILE are soluble in aqueous fluids (Tatsumi *et al.* 1986), therefore they are enriched relative to the immobile HFSE and rare earth elements (REE; Gill 1981; Pearce 1982; Ellam & Hawkesworth 1988; Hawkesworth *et al.* 1994; Pearce & Peate 1995). This is reflected by negative anomalies in HFSE and the relative enrichment of LILE in trace element patterns in mantle-normalized multi-element diagrams (Fig. 3). Addition of pelagic or terrestrial sediment to the mantle has a fairly similar geochemical effect as aqueous fluid metasomatism (increase of LILE), however, it usually also results in a marked enrichment of Th relative to Nb (Elliott *et al.* 1997) and it strongly influences the radiogenic and stable isotope ratios. Subduction-related magmas often have relatively high ^{87}Sr/^{86}Sr, low ^{143}Nd/^{144}Nd and relatively high ^{207}Pb/^{204}Pb and ^{208}Pb/^{204}Pb isotope ratios compared with mid-ocean ridge basalts, consistent with interaction with a continental crustal component. This component could be introduced to the mantle via subduction of sediment, or could enter the mantle-derived magmas as they pass through the continental crust.

Such 'subduction-related' geochemical fingerprints characterize, however, not only the calc-alkaline and low-K tholeiitic magmas in active subduction zones, but also the potassic and ultrapotassic rocks as well as silicic igneous rocks, which are formed in anorogenic or post-collisional settings. In this case, these trace element and isotopic signature were inherited from the mantle source region modified previously by fluids released from subducted slab (Johnson *et al.* 1978; Hawkesworth *et al.* 1995). Reactivation, i.e. partial melting of such metasomatized mantle, could occur due to decompression in a thinning lithosphere during extension (Fig. 2B) or due to the heat flux of upwelling hot asthenospheric mantle material.

Magmas with 'subduction-related' geochemical signatures can also be generated in syn- and post-collisional tectonic setting. A particular case is the generation of a slab-free region beneath a continental margin due to detachment of subducted oceanic lithosphere ("slab break-off"; Fig.2C). This can occur when continental lithosphere enters the subduction zone (Davies & von Blanckenburg 1995; Wong *et al.* 1997). It result from the tensional force between the buoyant continental lithosphere and the denser oceanic slab, and can cause the formation of calc-alkaline and ultrapotassic magmas and crustal-derived silicic melts (Davies & von Blanckenburg, 1995; von Blanckenburg & Davies, 1995). Magmatism related to slab break-off is usually localised and instantaneous following the detachment. Melt generation occurs as a consequence of upwelling of hot asthenosphere into the void left between the separating lithospheres. The lithosphere of the overriding plate is conductively heated by the asthenospheric mantle flow and this can result in various degrees of melting within the metasomatized lithospheric mantle. Intrusion of mantle-derived mafic magmas into the thick continental crust could initiate crustal anatexis and formation of silicic magmas ("anatectic rhyolites or granites").

Delamination or convective removal of the lithospheric mantle could also lead to generation of magmas with 'subduction-related' geochemical features (e.g., Turner *et al.* 1996; 1999; Chalot-Prat & Gîrbacea 2000; Fig. 2D). Removal of lower lithosphere results in upwelling of hot asthenosphere, which heats up the overlying cooler continental lithosphere. Partial melting could occur first in the volatile-rich portions of the lithospheric mantle producing LILE-enriched magmas.

In summary, magmas with 'subduction-related' geochemical signatures could be formed in different tectonic settings. The common feature of these magmas is explained by the similar nature of their mantle source regions. Fluid-related metasomatism could take place just before the melt generation or be associated with an older subduction event.

Cenozoic subduction zones in the Alpine-Mediterranean region

Figure 4 shows the main Tertiary-Quaternary subduction systems in southern Europe. In general, their development can be explained in the context of convergence of the European and African plates, whereas at the easternmost part of the region, continental collision between Arabia and Eurasia could have played an important role in the evolution of the Anatolian-Aegean system (Jolivet *et al.* 1999). However, Gueguen *et al.* (1998) and Doglioni *et al.* (1999) argued that this relative convergence between Africa and Europe could not be the main mechanism resulting in subduction in the western-central Mediterranean, because the Apenninic arc migrated eastward faster than the postulated north-south convergence of Africa relative to Europe. Within southern Europe, three main orogenic systems can be distinguished that can be divided into further local subduction systems (Fig. 1):

I. Western-Central Mediterranean
    I.1. Betic-Alboran-Rif province (Western Mediterranean)
    I.2. Apennines-Maghrebides subduction zone (Central Mediterranean)
II. Alps-Carpathian-Pannonian (ALCAPA) system
    II.1. Alpine zone (Periadriatic-Insubric Line)
    II.2. Carpathian-Pannonian region
III. Dinarides-Eastern Mediterranean system
    III.1. Dinarides-Hellenides
    III.2. Aegean-Anatolian region (Eastern Mediterranean)

The most characteristic features of this area are the arcuate orogenic belts and the opening of extensional basins within the overall compressional regime. This region is characterized by mobile subduction zones, where migration of the arcs could be up to 800 km (Gueguen *et al.* 1998; Fig. 4). At the present day, active subduction occurs only beneath

Calabria and the Aegean arc; in the other regions subduction has ceased and in most cases the current geodynamic setting is post-collisional. Magmatic activities occurred at various stages during the evolution of these subduction systems, but much of it appears to belong to the post-collisional stages.

Subduction started in the Alpine region during the Early Cretaceous, when closure of the Tethyan oceanic basins took place by eastward-southeastward subduction beneath the Austroalpine-Apulian plate (Dercourt *et al.* 1986). In the Dinarides, eastward subduction of part of the Tethyan Vardar ocean occurred during the Late Mesozoic to Early Palaeogene (Karamata & Krstič 1996; Karamata *et al.* 2000). Further east, north-dipping subduction formed the Pontide volcanic arc in western Anatolia from the Late Cretaceous to the Palaeocene (Şengör & Yilmaz 1981). These subduction processes were followed by continental collision stage during the Eocene in each region.

In the eastern part of the Alpine region, roughly south-dipping subduction was still active (Carpathian subduction zone), where an oceanic embayment was present (Csontos *et al.* 1992; Fodor *et al.* 1999). This weak lateral boundary could have enabled eastward lateral extrusion of the crustal block from the compressive Alpine regime (Ratschbacher *et al.* 1991). The advancing subduction style changed to retreating one during the Early Miocene (Royden 1993). Retreat of the subduction zone beneath the Carpathians enhanced the lateral movement of the North-Pannonian block towards the northeast, followed by back-arc extension during the Middle Miocene (Horváth 1993). Core-complex-type and back-arc extension resulted in the formation of the Pannonian basin underlain by thin (50-80 km) continental lithosphere (Tari *et al.* 1999). 'Soft' collision (Sperner *et al.* 2002) of the North-Pannonian block with the European continent occurred during the Late Badenian (≈13 Ma; Jiřiček 1979), whereas subduction was still active along the Eastern Carpathians. Roll-back of the subducted slab resulted in further east-west extension in the back-arc area (Royden *et al.* 1982). Subduction ceased beneath the Eastern Carpathians during the Late Miocene (≈13 Ma). Post-collisional slab detachment is considered to have occurred gradually from west to east-southeast as a zipper-like process (Tomek & Hall 1993; Mason *et al.* 1998; Seghedi *et al.* 1998; Wortel & Spakman 2000; Sperner *et al.* 2002). The slab break-off is now in the final stage beneath the southern part of the Eastern Carpathians (Vrancea zone), where the detaching near vertical subducted slab causes intermediate depth seismicity (Oncescu *et al.* 1984; Oncescu & Benjer 1997; Sperner *et al.* 2001). Chalot-Prat & Gîrbacea (2000) suggested partial delamination of the lithospheric mantle beneath this region.

Formation of the western-central Mediterranean subduction system started during the Late Oligocene, when the Alpine subduction terminated. The Apennines-Maghrebides west-directed subduction formed along the back-thrust belt of the pre-existing Alps-Betics orogen (Doglioni *et al.* 1999). At this time, the Betics reached a collisional stage and, as a result, the orogenic crust thickened considerably (> 50 km; Vissers *et al.* 1995). During the Early Miocene, rapid post-collisional extension took place forming the Alboran basin underlain by thin continental lithosphere. However, the mechanism of this process is highly debated. The competing geodynamic models involve (a) back-arc extension behind the westward retreat of an east-directed subduction zone along the present Gibraltar arc or the Horseshoe seamounts in the eastern Atlantic (Royden 1993; Lonergan & White 1997; Gelabert *et al.* 2002; Gill *et al.* 2004); (b) detachment of the subducted slab (Spakman 1990; Blanco & Spakman 1993; Carminati *et al.* 1998; Zeck 1999; Calvert *et al.* 2000); (c) delamination of the lithospheric mantle (Garcia-Dueňas *et al.* 1992; Docherty & Banda 1995) and (d) convective removal of the lower part of the overthickened lithosphere (Platt & Vissers 1989; Turner *et al.*, 1999). To the east, the presence of a Tethyan oceanic basin enabled the retreat of the Apennines-Maghrebides subduction zone (Carminati *et al.* 1998; Gueguen *et al.* 1998). Gelabert *et al.* (2002) argued that longitudinal shortening controlled the development of this arcuate subduction belt. They suggest that the subducting slab was split into two main fragments (Apennines and Kabylian slabs) retreating east and southeast, respectively. Slab roll-back is explained by the sinking of dense Mesozoic oceanic lithosphere due to gravitational instability (Elsasser 1971; Malinverno & Ryan 1986; Royden 1993), by global eastward asthenospheric mantle flow (Doglioni 1992) or by lateral expulsion of asthenospheric material which was shortened and squeezed by plate convergence (Gelabert *et al.* 2002). Lithospheric extension behind the retreating subduction zone resulted in the formation of the Liguro-Provençal, Algerian and Tyrrhenian basins underlain by newly formed oceanic crust, whereas the Valencia trough is underlain by thin continental lithosphere. Continental collision is thought to be associated with slab detachment along the north African margin during the Middle Miocene (≈ 16 Ma; Carminati *et al.* 1998; Coulon *et al.* 2002). Removal of the southward component of roll-back induced the eastward migration of the Apenninic arc accompanied by eastward migration of extension behind the subduction zone. Wortel & Spakman (1992) and van der Muelen *et al.* (1998) suggested Late Miocene-Pleistocene slab detachment beneath the Apennines based on seismic tomographic models and the lateral shifts of Apenninic depocentres. In contrast, Doglioni *et al.* (1994) emphasized the different roll-back rates along the arc, splitting it at least two 'sub-arc' portions. The subducting slab of the Ionian ocean still continues beneath Calabria. Behind it, new oceanic crust has been formed beneath the Vavilov and Marsili basins. Seismic tomographic models show positive seismic anomalies above the 670 km discontinuity beneath the entire Mediterranean region including the Pannonian and Aegean areas (Wortel & Spakman 2000; Piromallo *et al.* 2001; Piromallo & Morelli 2003). This is interpreted as accumulation of subducted residual material. In contrast to the widely accepted subduction-related models, a sharply different geodynamic scenario, i.e. a relationship with continental extension and/or upwelling mantle plume, has also been suggested to explain the evolution of the Central Mediterranean (Vollmer 1989; Lavecchia & Stoppa 1996; Ayuso *et al.* 1998; Lavecchia *et al.* 2003; Bell *et al.* 2004). Lavecchia *et al.* (2003) argued that the deformation style of the central Apennine fold-and-thrust belt, the absence of an accretionary wedge above the assumed subduction plane and the occurrence of ultra-alkaline and carbonatitic magmas within the Apennine mountain chain are evidence against the classic subduction-related models. They proposed that plume-induced lithospheric stretching and local-scale rift push-induced crustal shortening form a viable alternative model for the evolution of the Central Mediterranean region (Lavecchia *et al.* 2003; Bell *et al.* 2004).

Closure of the Tethyan (Vardar) oceanic branches occurred during the Late Cretaceous-Palaeocene in the Dinaride region followed by collisional (Eocene) and post-collisional (Oligocene/Early Miocene) stages (Cvetkovič *et al.* 2004). In the Aegean-Anatolian region, north-dipping subduction terminated by the Eocene, when continental collision occurred along the Vardar-Izmir-Ankara suture zone (Şengör & Yilmaz 1981). The subduction zone has migrated south-westward and its present position is found along the Hellenic-Cyprus arc (Doglioni *et al.* 2002). A continuous descending lithospheric slab was detected beneath the Hellenic arc by seismic tomography (Wortel & Spakman 1992; 2000). The subducted slab appears to cross the 670 km discontinuity and penetrates the lower mantle. Further east, collision between the Arabian and Anatolian plates took place during the Eocene (Şengör & Kidd 1979; Pearce *et al.* 1990). This collision also led to the tectonic escape of the Anatolian plate by right-lateral strike-slip movement along the North Anatolian Fault and left-lateral strike-slip along the East-Anatolian Fault during the Middle Miocene (McKenzie 1972; Dewey & Şengör 1979). It was accompanied by widespread crustal extension and lithospheric thinning in Western Anatolia and the Aegean. The reason for the extension is, however, highly controversial. Dewey (1988) suggested gravitational collapse of the overthickened lithosphere. The orogenic collapse model was also accepted by Seyitoğlu

& Scott (1996) and Gautier *et al.* (1999), but they suggested that it occurred earlier, i.e. during the latest Oligocene to Early Miocene (24-20 Ma) time and therefore it could not be associated with the tectonic escape of the Anatolian block. Other authors have emphasized the back-arc type extension of the Aegean region behind the retreating subduction along the Hellenic arc (McKenzie 1978; Le Pichon & Angelier 1979; Meulenkamp *et al.* 1988; Pe-Piper & Piper 1989). In Western Anatolia, Aldanmaz *et al.* (2000) invoked delamination of the lower lithosphere to explain the extension and related magmatism. Doglioni *et al.* (2002) ruled out the influence of both the westward extrusion of the Anatolian block and the collapse of overthickened lithosphere and suggested an alternative geodynamic scenario for the Eastern Mediterranean. They interpreted the extension in the Aegean-Western Anatolian region as a result of the differential convergence rates between the north-eastward-dipping subduction of Africa relative to the disrupted Eurasian lithospheres. Extension could be attributed to the faster south-eastward motion of Greece relative to Anatolia. Thus, Doglioni *et al.* (2002) argued that the Aegean region cannot be considered as a classic back-arc basin.

The next sections will outline the main characteristics of the Tertiary to Quaternary subduction systems in southern Europe, the geochemical features of the magmatism, and the possible geodynamic relationships between magmatism, subduction and post-collisional processes. Figure 5 summarizes the age distribution of magmatism in this region, separated into orogenic and anorogenic types.

Alpine subduction system

Subduction of Tethyan oceanic slabs occurred beneath the Alps during the Late Cretaceous to Palaeogene; however, no prominent subduction-related volcanism appears to have taken place during this period. The only evidence for subduction-related volcanic eruptions comes from Early Eocene andesitic clasts found in flysch sediments (Waibel 1993; Rahn *et al.* 1995). A characteristic feature of the Alpine collisional orogen is the occurrence of a chain of Oligocene to Early Miocene intrusions and dykes along the Periadriatic and Insubric lines. They continue eastward in the Pannonian Basin along the Balaton line (Downes *et al.* 1995; Benedek 2002) and south-eastwards in the Dinarides (Pamić *et al.* 2002). These igneous rocks have a bimodal character (granodioritic-tonalitic intrusions and basaltic dykes; Exner 1976; Cortecci *et al.* 1979; Bellieni *et al.* 1981; Dupuy *et al.* 1982; Beccaluva *et al.* 1983; Ulmer *et al.* 1983; Kagami *et al.* 1991; Müller *et al.* 1992; von Blanckenburg & Davies 1995; Berger *et al.* 1996). In addition, calc-alkaline andesites, shoshonites and ultrapotassic rocks (lamproites) also occur in subvolcanic facies (Deutsch 1984; Venturelli *et al.* 1984b, Altherr *et al.* 1995). All of these igneous rocks are characterized by ‘subduction-related’ geochemical features. Suggested models for the origin of these igneous rocks include subduction (e.g. Tollmann 1987; Kagami *et al.* 1991; Waibel 1993), extension (e.g. Laubscher 1983), and gradual slab detachment (von Blanckenburg & Davies 1995; von Blanckenburg *et al.* 1998). The source regions of the primary magmas of the Periadriatic line are inferred to be in the lithospheric mantle (Venturelli *et al.* 1984b; Kagami *et al.* 1991; von Blanckenburg 1992). Mafic melts could have subsequently mixed with silicic magmas generated in the lower crust.

Alkaline mafic rocks (‘anorogenic’ type) crop out only south of the Eastern Alps, in the Veneto region (De Vecchi & Sedea 1995; Milani *et al.* 1999; Macera *et al.* 2003; Fig. 1). The volcanism occurred in two stages, from the Late Palaeocene to Early Oligocene (30-35 Ma) and during the Early Miocene. It resulted in alkaline and tholeiitic basalts and basanites with subordinate trachytes and rhyolites (De Vecchi & Sedea 1995). The mafic volcanic rocks show an OIB-like composition without any sign of subduction-related component. De

Vecchi & Sedea (1995) and Milani *et al.* (1999) interpreted this volcanism as related to lithospheric extension in the Southern Alps (Zampieri 1995). In contrast, Macera *et al.* (2003) invoked slab detachment and the ensuing rise of a deep mantle plume into the lithospheric gap.

Betic-Alboran-Rif province (western Mediterranean)

Tertiary to Quaternary volcanic rocks in the western Mediterranean are found in central Spain (Calatrava province), the Olot region, the Valencia trough, SE-Spain (Betics), the Alboran basin and along the coast of Northern Africa (Morocco to Algeria; Fig. 1). The Calatrava and Olot regions are characterized by Late Miocene to Quaternary alkaline basaltic and leucititic rocks (Cebriá & Lopez-Ruiz 1995; Cebriá *et al.* 2000), similar to those occurring in the European Rift Zone (Wilson & Downes 1991). In the other areas calc-alkaline, high-K calc-alkaline, shoshonite and lamproites can be found in addition to late-stage alkali basalts. Duggen *et al.* (2003) pointed out that the transition of calc-alkaline ('orogenic') to alkaline ('anorogenic') magmatism (6.3-4.8 Ma) was coeval with the Messinian salinity crisis (5.96-5.33 Ma), i.e. the desiccation of the Mediterranean sea due to closure of the marine gateway.

The 'orogenic' volcanism started around Malaga with intrusion of tholeiitic (basalts to andesite; Fig. 6) dikes into the Alboran block during the early Oligocene. In addition, high-K dacites also occur in this area. It was followed by volcanism in the Valencia trough during the Late Oligocene that continued during the Miocene up to Present. Calc-alkaline volcanism forming mostly dacitic to rhyolitic pyroclastic deposits characterized the first stage of volcanic activity, whereas alkaline basaltic magmas erupted during the later volcanic stage (Martì *et al.* 1992). The alkaline basalts have intraplate (OIB) geochemical affinity and often contain ultramafic xenoliths. This scenario could be explained by progressive extension of the continental lithosphere and a change of the source region from lithospheric to asthenospheric one.

The Alboran basin is also underlain by thin continental crust similar to the Valencia trough. Volcanic rocks on Alboran island and the sea floor have been dated between 11 and 7 Ma (Duggen *et al.* 2004). They are mostly low-K tholeiitic rocks with clear 'subduction-related' geochemical features (Duggen *et al.* 2004; Gill *et al.* 2004; Fig. 7). More widespread calc-alkaline to shoshonitic and ultrapotassic volcanism occurred on the southeast coast of Spain and in Northern Africa from the Early Miocene to Pliocene (Zeck 1970; 1992; 1998; Nixon *et al.* 1984; Venturelli *et al.* 1984a; 1988; Hertogen *et al.* 1985; Di Battistini *et al.* 1987; Louni-Hacini *et al.* 1995, El Bakkali *et al.* 1998; Benito *et al.* 1999; Turner *et al.* 1999; Coulon *et al.* 2002; Duggen *et al.* 2004; Gill *et al.* 2004; Fig. 6). Calc-alkaline volcanism was associated with intrusion of granitoid magmas in Northern Africa (Fourcade *et al.* 2001) and southern Spain (Zeck *et al.* 1989; Duggen *et al.* 2004). The calc-alkaline volcanism resulted in andesites and dacites with subordinate rhyolites and shoshonites (Fig. 6). Sporadic cordierite- and garnet-bearing dacites were interpreted as anatectic magmas (Zeck 1970; 1992). Late Miocene ultrapotassic lamproites are found in the central and northern part of the calc-alkaline volcanic belt of SE Spain (Nixon *et al.* 1984; Venturelli *et al.* 1984a; 1988; Hertogen *et al.* 1985). Throughout the region, sporadic eruptions of alkaline mafic magmas followed the calc-alkaline magmatism (El Bakkali *et al.* 1998; Coulon *et al.* 2002; Duggen *et al.* 2004).

The geodynamic setting of the western Mediterranean calc-alkaline volcanic activity is ambiguous. The models can be divided into the following groups: (1) subduction-related; (2) subduction break-off; (3) delamination of lithospheric mantle due to gravitational collapse; (4) convective removal of the lower lithosphere. Torres-Roldán *et al.* (1986), Royden (1993), Lonergan & White (1997), Duggen *et al.* (2003; 2004) and Gill *et al.* (2004) assumed that contemporaneous subduction occurred with the calc-alkaline volcanism. Geophysical data indicate an east-dipping subducted slab (Gutscher *et al.* 2002) beneath the Alboran region. Duggen *et al.* (2004) and Gill *et al.* (2004) emphasized that the 'subduction-related' nature and particularly the strong depletion in the light REE and HFSE of the Alboran tholeiites (Fig. 7) could only be explained by formation in a metasomatized mantle wedge above a subducted slab. Furthermore, they assumed that all the other calc-alkaline volcanic rocks in the Betic-Rif province could be generated in the same geodynamic setting. Blanco & Spakman (1992) and Calvert *et al.* (2000) argued, however, that the seismic tomography models show a detached near-vertical lithospheric slab from about 180-200 km down to the 670 km discontinuity beneath the Alboran region. Zeck (1996) considered that slab break-off could have had a major role in melt generation. Influx of hot asthenospheric mantle into the widening gap above the sinking slab induced partial melting in the overlying lithosphere (particularly in the lower crust). The close relationship between the distribution of volcanism in the Alboran volcanic province and the surface projection of the sinking slab was used by Zeck (1996) to support this model. Fourcade *et al.* (2001) and Coulon *et al.* (2002) also invoked slab break-off to explain the calc-alkaline to alkaline magmatism in Northern Algeria. Other authors (Venturelli *et al.* 1984a; Platt & Vissers 1989; Zeck 1996; Benito *et al.* 1999; Turner *et al.* 1999) argued that the Betic-Alboran volcanism was post-collisional, following Late Cretaceous to Oligocene subduction and Late Oligocene to Early Miocene continental collision. Benito *et al.* (1999), Turner *et al.* (1999) and Coulon *et al.* (2002) suggested that the primary melts were generated in the lithospheric mantle, which had been metasomatised previously by fluids derived from subducted pelagic sediments. These mantle-derived magmas subsequently mixed with crustal melts. Zeck (1970; 1992; 1998) argued for a crustal anatectic origin for the calc-alkaline magmas of southern Spain. Platt & Vissers (1989), Benito *et al.* (1999) and Turner *et al.* (1999) emphasized that melt generation occurred by decompression melting due to extensional collapse of the overthickened orogenic wedge or convective removal of the lithospheric root. In North Africa, El Bakkali *et al.* (1998) also suggested an extension-related origin for the calc-alkaline to potassic magmas of the Eastern Rif (Morocco).

Central Mediterranean (Italy)

Tertiary-Quaternary volcanism in the Central Mediterranean resulted in extremely variable magmatic rocks from tholeiites (Vavilov basin, Tyrrhenian basin), calc-alkaline to shoshonitic (Sardinia, Aeolian Islands, Roman Province), ultrapotassic (Corsica, Central Italy) and anatectic rhyolites (Tuscany; Serri 1990; Peccerillo 1999; 2003; Fig. 1 and 6). Alkali basaltic rocks with OIB chemistry also occur sporadically in Sardinia (Rutter 1987; Lustrino *et al.* 2000), the southern Tyrrhenian Basin (Serri 1990; Trua *et al.* 2003), eastern Sicily (Etna and Hyblean plateau; Carter & Civetta 1977; Tonarini *et al.* 1995; D'Orazio *et al.* 1997; Tanguy *et al.* 1997; Trua *et al.* 1998) and in the Pantelleria rift (Esperanca & Crisci 1995; Civetta *et al.* 1998). In addition, minor occurrences of carbonatites and melilitites have been described in the central Apennines east of the Roman Province (Stoppa & Lavecchia 1992; Stoppa & Cundari 1995; Stoppa & Woolley 1996). The carbonatitic nature of these rocks has been questioned, however, by Peccerillo (1998) who suggested that they could represent a mixture of silicate magmas and carbonate material and could be classified as ultrapotassic rocks of kamafugitic affinity. The strongly undersaturated hauyne-bearing alkaline volcanic rocks of Mt. Vulture (De Fino *et al.* 1986; Serri 1990; Melluso *et al.* 1996) also have an exotic position (Fig. 1) and distinct magma source region compared with the Roman Province rocks.

Volcanism started in the Early to Middle Miocene in Sardinia with the eruption of tholeiitic and calc-alkaline magmas (Dostal *et al.* 1982; Morra *et al.* 1997; Downes *et al.* 2001; Fig. 5). The 14 Ma Sisco lamproite in northern Corsica represents the oldest ultrapotassic rock in the Central Mediterranean. After a few Myr long quiescence, the volcanism was rejuvenated in the Tyrrhenian basin, the Tuscan region and in southeastern Sicily (Hyblean Mts.) at about 7-8 Ma. On the west coast of Italy a gradual younging of the volcanism can be observed towards the southeast with still active volcanoes in Campania (Campi Flegrei, Vesuvius; Santacroce *et al.* 2003). The distinct alkaline volcanic rocks of Mt. Vulture were formed 0.7-0.1 Ma (Melluso *et al.* 1996). Volcanic activity in Sardinia rejuvenated with eruption of alkaline mafic magmas from 5.5 to 0.1 Ma (Di Battistini *et al.* 1990; Lustrino *et al.* 2000). A southeastward shift of volcanism has been pointed out by Argnani & Savelli (1999). Opening of the southern Tyrrhenian basin was accompanied by formation of seamounts consisting of E-MORB to OIB type mafic rocks (Vavilov, Marsili; Serri, 1990; Trua *et al.* 2003). Active volcanism is taking place in the Aeolian islands (Stromboli, Vulcano), in Etna and the Sicily channel (Pantelleria).

Although most authors suggest that subduction has played an important role in the evolution of the Central Mediterranean (e.g., Keller 1982; Doglioni 1991; Serri *et al.* 1993), calc-alkaline volcanic rocks are volumetrically subordinate within the magmatic suites. Instead, the characteristic rocks are potassic to ultrapotassic (Fig. 6). Furthermore, the Tertiary to Quaternary volcanic rocks of this region show an extremely variable trace element and isotope chemistry (Peccerillo, 2003). The close temporal and spatial relationship of this wide range of magmas indicates a heterogeneous mantle source metasomatized during several distinct events (Peccerillo 1985; 1999; Serri *et al.* 1993). The strongly potassic character of many of the magmas has been explained either by source contamination by subducted continental crustal material (Peccerillo 1985; Ellam *et al.* 1989; Conticelli & Peccerillo 1992; Serri *et al.* 1993; De Astis *et al.* 2000) or by metasomatism of deep mantle-derived melts (Vollmer 1989; Stoppa & Lavecchia 1992; Ayuso *et al.* 1998). West-dipping subduction of oceanic lithosphere and possibly thinned continental lithosphere is considered to have terminated in the Late Miocene (≈ 13 Ma), thus most of the volcanism in the Central Mediterranean can be regarded as post-collisional.

Evidence for subduction includes the introduction of continental crustal material into the mantle sources of the magmas (Peccerillo 1985, 1999) and the detection of fast velocity material either continuously extending from the surface (beneath Calabria) and accumulating in the transition zone (e.g., Spakman *et al.* 1993; Piromallo *et al.* 2001; Piromallo & Morelli 2003). Serri *et al.* (2003) proposed that delamination and subduction of the Adriatic continental lithosphere related to the still ongoing collision in the northern Apennines could be a viable mechanism to explain the incorporation of crustal material in the mantle source and the eastward migration of magmatism in central Italy. Active subduction in the region occurs in Calabria. Keller (1982) directly related the recent volcanism in the Aeolian Islands to active subduction process. However, the Aeolian Islands lie 200 to 300 km above the Benioff zone (Anderson & Jackson 1987) on thinned continental basement (Schutte 1978). Furthermore, they form rather a ring-shaped structure considering also the submarine seamounts at the southern margin of the Marsili basin, which is characterised by oceanic crust. The active volcanoes are located along strike-slip tectonic lines (Gasparini *et al.* 1982; Beccaluva *et al.* 1982). Thus, an alternative hypothesis for the Aeolian volcanism is a relationship with a back-arc environment, where magma generation is attributed to asthenospheric domal uplift developing along a NW-SE trending extensional tectonic zone (Crisci *et al.* 1991; Mazzuoli *et al.* 1995). Nevertheless, subduction could have had a major –

probably indirect – influence on the genesis of the magmas (release of aqueous fluids from the downgoing slab and metasomatism of the upper mantle, injection of subducted sedimentary component into the upper mantle; Ellam *et al.* 1989; Francalanci *et al.* 1993). Compositional features (ratios of incompatible trace elements, radiogenic isotope ratios; Fig. 8) of the potassic rocks of Stromboli are similar to that of the alkaline volcanic rocks of Campania (Vesuvius and Phlegrean Fields), indicating common mantle source regions consisting of a mixture of intraplate and subducted slab-derived (continental sediment) components (De Astis *et al.* 2000; Peccerillo 2001).

The post-collisional volcanism in Italy has been interpreted as being due to gradual slab detachment by Wortel & Spakman (1992; 2000) based on the absence of high velocity structure considered to represent subducted slab beneath the Apennines, while a continuous slab was identified beneath southern Italy. However, Piromallo & Morelli (2003) argued that their better resolved model showed more vertical continuity of the fast structure in the top 200 km beneath the northern part of the Apennines.

In contrast to the most popular subduction-related models, the presence of a mantle plume and related continental rifting was put forward by Lavecchia *et al.* (2003) and Bell *et al.* (2004). Gasperini *et al.* (2002) also invoked upwelling of deep mantle material beneath southern Italy, but they combined it with the subduction scenario, suggesting a broad window in the Adria plate where deep mantle layers are channelled toward the surface. Lavecchia *et al.* (2003) and Bell *et al.* (2004) proposed that a plume arising from the core-mantle boundary could be trapped within the transition zone beneath the Ligurian-Tyrrhenian region. Asymmetric growth of the plume head within the transition zone as modelled by Brunet & Yuen (2000) could lead to a volume excess within the asthenosphere and an eastward mantle flow. This is thought to result in an eastward migrating thinning of the overlying lithosphere. The rift push forces generated on the eastern side of the extending system could be responsible for the fold-and-thrust belt structure beneath the Apennines. In their model, the high velocity body above the 670 km depth (Piromallo *et al.* 2001) was interpreted as reflection of compositional difference rather then abrupt change in the mantle temperature. Lavecchia *et al.* (2003) suggested that the fast zones in the transition zone could be a highly depleted and dehydrated plume head, whereas the overlying asthenosphere was enriched by H_2O-CO_2 rich fluids. However, Goes *et al.* (2000) proposed that the velocity variation in the mantle could be attributed mostly to changes in temperature, while the effect of mantle composition could be negligible (<1%). Further integrated geophysical, structural and geophysical studies are needed to test the contrasting models for the evolution of the Central Mediterranean.

Carpathian-Pannonian Region

The Carpathian-Pannonian region (Fig. 1) shows many features that are similar to those of the Mediterranean subduction systems, such as arcuate and retreating subduction zones, formation of back-arc extensional basins and a wide range of magma-types (e.g., Horváth & Berckhemer 1982; Csontos *et al.* 1992; Szabó *et al.* 1992; Seghedi *et al.* 1998; Fodor *et al.* 1999; Tari *et al.* 1999; Bada & Horváth 2001; Harangi 2001a). Volcanic activity in this region started with eruption of Early Miocene rhyolitic magmas followed by contemporaneous calc-alkaline, silicic and sporadic ultrapotassic volcanism in the Middle and Late Miocene (Fig. 5). Coeval calc-alkaline and alkaline mafic magmas were erupted during the Late Miocene to Quaternary (Szabó *et al.* 1992; Pécskay *et al.* 1995; Seghedi *et al.* 1998; 2004; Harangi 2001b).

The Miocene (21-13 Ma) rhyolitic volcanism resulted in extensive ignimbrite sheets. The rhyodacitic to rhyolitic pumices have 'subduction-related' geochemical features consistent with both mantle and crustal origin. The pyroclastic deposits also contain basaltic andesite and andesite lithic clasts, which are considered as cogenetic with the rhyolites. Harangi *et al.* (2005) interpreted their petrogenesis inferring mantle-derived mafic magmas mixed with variable amount of crustal melts. The silicic volcanism could represent the initiation of back-arc lithosphere extension (Lexa & Konečny 1998; Harangi 2001a) or delamination of the lowermost lithosphere beneath the Pannonian Basin (Downes 1996; Seghedi *et al.* 1998). The decreasing age-corrected $^{87}Sr/^{86}Sr$ ratios of the pumices indicate a gradually decreasing crustal component in their genesis.

A major feature of the region is the Carpathian arc, an arcuate belt of calc-alkaline volcanic complexes composed mostly of andesites and dacites (Fig. 6) along the northern and eastern margin of the Pannonian Basin. They were formed from the Middle Miocene to the Quaternary and the last volcanic eruption occurred at the southernmost part of the East Carpathians only 10-40 ka ago (Fig. 5; Pécskay *et al.* 1995). The major and trace element compositions of these rocks show fairly similar character compared with the large variability of the Western and Central Mediterranean volcanic suites (Fig. 6 and 7). However, there are major differences in spatial and temporal evolution and underlying lithospheric structure between the western and eastern segments of the Carpathian volcanic arc. These differences also appear in the geochemistry of the volcanic products, leading Harangi & Downes (2000) and Harangi (2001a) to suggest contrasting origins for the calc-alkaline magmas in the different segments. Calc-alkaline volcanism in the western Carpathian arc could be related directly to the main extensional phase of the Pannonian Basin (Lexa & Konečny 1998; Harangi 2001a; Harangi *et al.* 2001), whereas calc-alkaline magmas in the eastern Carpathian arc could have a closer relationship with subduction, particularly with gradual slab break-off (Mason *et al.*, 1998; Seghedi *et al.*, 1998; 2004). Gradual slab detachment was also proposed in the evolution of the Carpathian arc by other authors (von Blanckenburg *et al.* 1998; Nemčok *et al.* 1998; Wortel & Spakman 2000; Sperner *et al.* 2002). Coexisting eruptions of alkaline basaltic and shoshonitic magmas in the southernmost part of the East Carpathians lead Gîrbacea & Frisch (1998) and Chalot-Prat & Gîrbacea (2000) to suggest partial delamination of the lower lithosphere beneath this area. In contrast to these models, Balla (1981), Szabó *et al.* (1992) and Downes *et al.* (1995a) considered that melt generation in the whole calc-alkaline suite was a direct consequence of subduction of the European plate and occurred in the metasomatized mantle wedge above the downgoing slab. Calc-alkaline volcanic rocks also occur far from the Carpathian arc, in the inner part of the Pannonian Basin. Middle Miocene andesites of the Apuseni Mountains are found about 200 km behind the volcanic front. Roşu *et al.* (2001) and Seghedi *et al.* (2004) suggested that the location and compositions of these rocks is inconsistent with a typical subduction model and can be explained rather by decompression melting of the lower crust and/or of the enriched lithospheric mantle in an extensional regime.

Seismic tomographic images indicate a low velocity anomaly beneath the Carpathian-Pannonian region (except at the south-eastern margin of the Carpathians) at shallow depth (Spakman 1990; Wortel & Spakman 2000; Piromallo & Morelli 2003). A fast anomaly was detected beneath the Eastern Carpathians in a depth range of 100-300 km, but it cannot be followed beneath the Western Carpathian chain (Piromallo & Morelli 2003). Thus, no evidence is present for a detached subducted slab under the latter area, although Tomek & Hall (1993) interpreted the deep seismic-reflection data as evidence for subducted European continental crust beneath the Western Carpathians. In the south-eastern part of the Carpathians, beneath the Vrancea zone, a weak fast anomaly is present becoming more pronounced with increasing depth. The localized Vrancea slab is considered to represent the final stage of slab break-off (Wenzel *et al.* 1998; Sperner *et al.* 2001) beneath the east Carpathians. The oceanic slab is considered as either already detached from the surface (Wortel & Spakman 2000) or still attached to the continental lithosphere (Fan *et al.* 1998; Sperner *et al.* 2001). An approximately 150-200 km thick positive anomaly occurs between 400 and 600 km beneath the entire Carpathian-Pannonian region that is interpreted as accumulation of Mesozoic subducted slab material (Wortel & Spakman 2000).

Dinarides and Hellenides

A continuous belt of Tertiary igneous activity is present from the eastern Alps to the north Aegean crossing the southern Pannonian Basin (Slovenia and Croatia), the Dinarides (Serbia, Macedonia) and the Rhodope-Thrace region (Bulgaria and Greece; Fig. 1; Pamić *et al.* 1995; 2002; Christofides *et al.* 1998; 2001; Harkovska *et al.* 1998; Marchev *et al.* 1998; Yilmaz & Polat 1998; Jovanović *et al.* 2001; Prelević *et al.* 2001; Cvetković *et al.* 2004). Subduction of part of the Tethyan Vardar Ocean occurred during the Late Mesozoic to Early Palaeogene, followed by Eocene collision and Oligocene to Pliocene post-collisional collapse (Karamata & Krstić 1996; Karamata *et al.* 1999). This igneous belt comprises Eocene to Oligocene granitoid bodies and basanites, Oligocene to Miocene shoshonites, high-K calc-alkaline volcanic rocks and ultrapotassic rocks (lamproites and leucitites).

Most of the Palaeogene granitoids have been interpreted as syncollisional magmas that underwent various degrees of crustal contamination (Christofides *et al.* 1998; Marchev *et al.* 1998; Pamić *et al.* 2002). The Palaeocene-Eocene basanites in East Serbia often contain ultramafic xenoliths (Cvetković *et al.* 2001) and have major and trace element composition akin to OIB (Jovanović *et al.* 2001). Similar xenolith-bearing alkaline mafic rocks also occur in the Rhodopes (Marchev *et al.* 1998). The primary magmas are inferred to originate in an enriched asthenospheric mantle source. Melt generation could have been triggered either by detachment of the subducted slab resulting in a slab window or by a short extensional event during the collisional phase (Jovanović *et al.* 2001; Cvetković *et al.* 2004). The Oligocene to Early Miocene high-K calc-alkaline and shoshonitic series comprises basalts, basaltic andesites and trachyandesites (Fig. 6). They have relatively high mg-values and high concentration of Ni and Cr, indicative of near primary magmas. The presence of phlogopite-bearing ultramafic xenoliths clearly indicates a mantle-origin for these melts, which have typical ‘subduction-related’ compositions (Fig. 7). This signature could be inherited from the lithospheric mantle source metasomatized possibly during the post-collisional/collapse stage (Cvetković *et al.* 2004). The scattered ultrapotassic rocks (minettes, lamproites, leucitites, analcimites) show the most extreme enrichment of incompatible elements of all the Tertiary volcanic rocks in this region (Prelević *et al.* 2001). They have fairly similar trace element patterns in the mantle normalised diagrams as the high-K volcanic rocks, but with more pronounced anomalies. Thus, they could also represent magmas derived from metasomatized lithospheric mantle. Melt generation could be related either to slab break-off (Pamić *et al.* 2002) or to delamination of the lithospheric root (Cvetković *et al.* 2004).

Seismic tomographic images indicate a positive velocity anomaly from about 100 km to 600 km beneath the Southern Dinarides and Hellenides region, whereas a low-velocity anomaly was detected beneath the Northern Dinarides (Spakman *et al.* 1993; Goes *et al.* 1999; Wortel & Spakman 2000). This feature has been interpreted as detachment of a subducted slab in the north, whereas it is still unbroken in the south and continues towards the south Aegean area (Wortel & Spakman 2000). Beneath the Dinarides a north to northeast dipping subduction was proposed with the opposite polarity to that inferred beneath the Alps (Pamić *et al.* 2002). Stampfli *et al.* (2001) suggested that the Vardar Ocean (the Tethyan oceanic branch in the Dinaride-Hellenide region) and the Piedmont-Penninic Ocean (Alpine Tethyan oceanic branch) were not connected during the Mesozoic. Therefore, the two linear Palaeogene igneous belts along the Periadriatic line and along the Dinarides could not belong to the same subduction system.

Eastern Mediterranean (Greece and Turkey)

Tertiary-Quaternary volcanic activity in this region was characterized by eruption of various magmas (alkaline mafic, calc-alkaline and high-K intermediate to silicic volcanics and sporadic ultrapotassic rocks) in the Aegean and Western to Central Anatolia (Fig. 1; Fytikas *et al.* 1984; Doglioni *et al.* 2002). Volcanism occurred in two main phases: eruption of Oligocene to Middle Miocene calc-alkaline to shoshonitic magmas followed by eruption of alkaline and calc-alkaline magmas during Pliocene to Recent times (Pe-Piper & Piper 1989; Pe-Piper *et al.* 1995; Seyitoğlu & Scott, 1992; Aldanmaz *et al.*, 2000; Doglioni *et al.*, 2002). In the Aegean-Western Anatolian region, volcanism started in the Oligocene following the Tethyan collision (Yilmaz *et al.* 2001). The calc-alkaline volcanism resulted mostly in andesitic to dacitic rocks, and was associated with emplacement of granitic plutons in NW Anatolia. Most of the volcanism occurred, however, during the Early to Middle Miocene (20-14 Ma), when high-K andesitic to rhyolitic effusive and explosive volcanism with cogenetic plutons characterized the northern Aegean and the Western Anatolia (Fig. 5 and 6; Fytikas *et al.* 1984; Pe-Piper & Piper 1989; Seyitoğlu & Scott, 1992; Wilson *et al.* 1997; Altunkayak & Yilmaz, 1998; Aldanmaz *et al.* 2000; Yilmaz *et al.* 2001). In Western Anatolia, these igenous rocks are distributed mostly along the Izmir-Ankara suture zone. A Middle Miocene (14-15 Ma) lamproite was reported by Savasçin *et al.* (2000). During the Middle to Late Miocene, granitic plutonism took place in the Cycladic and Menderes massifs (Altherr *et al.* 1982; Innocenti *et al.* 1982; Delaloye & Bingöl 2000). Following about 4 Myr quiescence, the volcanism resumed in the Late Miocene (10 Ma) when alkaline mafic magmas with OIB-like composition erupted mostly in the eastern Aegean and the western margin of Anatolia (Güleç, 1991; Seyitoğlu *et al.* 1997; Aldanmaz *et al.* 2000; Alici *et al.* 2002). The last eruption of basanitic to phonotephritic magmas occurred in the Kula region at 1.1-0.02 Ma (Güleç 1991). In the Aegean region Pe-Piper *et al.* (1995) found a southward migration of volcanism. Calc-alkaline volcanism has characterized the Aegean volcanic arc from the Pliocene up to Recent times (Mann 1983; Barton & Huijsmans 1986; Briqueu *et al.* 1986; Mitropoulos *et al.* 1987; Huijsmans *et al.* 1988; Francalanci *et al.* 1998).

Central Anatolia shows roughly the same volcanic history. Middle Miocene to Pliocene high-K calc-alkaline andesitic to rhyolitic magmas erupted along major fault systems at Afyon, Konya and Cappadocia (Fig. 5 and 6; Innocenti *et al.* 1975; Aydar *et al.* 1995; Alici *et al.* 1998; Temel *et al.* 1998a; 1998b). In Cappadocia extensive dacitic to rhyolitic ignimbrite sheets were deposited from the Late Miocene to Quaternary, associated with large andesitic stratovolcanoes and alkali basaltic scoria cones and maars (Pasquare *et al.* 1988; Le Pennec *et al.* 1994; Aydar & Gourgaud 1998; Kürkçüoglu *et al.* 1998; Temel *et al.* 1998b).

Tertiary to Quaternary volcanism in the Aegean-Western to Central Anatolian region occurred mostly in a post-collisional setting and partly behind active subduction zones (Hellenic and Cyprean). The origin of the Miocene plutonic igneous rocks was interpreted as crustal anatexis related to high T/medium P metamorphism (Altherr *et al.* 1982; Innocenti *et al.* 1982; Bröcker *et al.* 1993; Delaloye & Bingöl 2000). In general, the 'orogenic' volcanic rocks are potassic (high-K calc-alkaline to shoshonitic); whereas those occur along the Aegean island arc are calc-alkaline (Fig. 6). Their trace element and isotopic compositions are consistent with involvement of a subduction component (Fig. 7 and 8; Keller, 1982; Briqueu *et al.* 1986; Mitropoulos *et al.* 1987; Huijmans *et al.* 1988; Güleç 1991; Robert *et al.* 1992; Pe-Piper *et al.* 1995; Seyitoğlu *et al.* 1997; Aldanmaz *et al.* 2000). On the other hand, the younger alkaline mafic volcanic rocks show an intraplate OIB nature (Seyitoğlu & Scott 1992; Seyitoğlu *et al.* 1997; Alici *et al.* 2002). Nevertheless, most authors consider that melt generation of both volcanic suites was mostly due to decompression melting because of extension of continental lithosphere. Initially, magmas with 'subduction-related' geochemical signature were generated in the lithospheric mantle regions metasomatized by fluids and melts during an earlier subduction event. Perturbation of these metasomatic portions of the lower lithosphere could take place either due to lithospheric thinning or to delamination of the lower thermal boundary layer allowing direct contact with upwelling hot asthenosphere (Seyitoğlu & Scott, 1996; Aldanmaz *et al.* 2000). In contrast, a closer relationship with subduction was invoked by Innocenti *et al.* (1975), Temel *et al.* (1998a; 1998b) and Doglioni *et al.* (2002) to explain the calc-alkaline volcanism especially in Central Anatolia. They considered that the primary magmas originated in the mantle wedge above the subducting Africa plate and subsequently underwent assimilation and fractional crystallization to produce the intermediate to rhyolitic magmas. The Pliocene to Recent volcanic rocks in the Aegean arc seem to be a clearer candidate to have formed as a consequence of active subduction. Geophysical data clearly indicate a north-eastward to northward dipping slab beneath the Aegean region (Wortel & Spakman 1992; Spakman *et al.* 1993). The present volcanic arc is located 130-140 km above the seismic Benioff zone (Makropoulos & Burton, 1984), 200-250 km behind the subduction front. Lithospheric extension, however, may have played an important role in melt generation along the present arc, indicated by the underlying thin lithosphere and predominance of asthenosphere-derived uncontaminated mafic volcanic rocks in Santorini (Mitropoulos *et al.* 1987). In contrast, Briqueu *et al.* (1986) considered that there is a close relationship between the active volcanic arc and subduction, and assumed a contribution of a small amount of subducted sedimentary component in the genesis of the arc magmas.

The late-stage alkaline basaltic rocks have a composition akin to OIB; therefore, they are interpreted as represent asthenosphere-derived magmas. This could take place either in places where lithospheric extension progressed further allowing partial melting of the uprising asthenosphere (Seyitoğlu *et al.* 1997) or along strike-slip zones, where localized stretching could result in production of alkaline magmas (Aldanmaz *et al.* 2000). Doglioni *et al.* (2002) suggested that the shallow subducted slab beneath Anatolia could be folded by the isostatic rebound of the mantle beneath the extensional area. The stretching between Greece and Anatolia and the differential velocity of convergence with the underlying slab could have generated a sort of window, allowing upward rise and partial melting of the asthenosphere.

Discussion

Petrogenetic features

The previous chapters showed that a wide variety of magmatic rocks can be found in all of the different subprovinces of the Alpine-Mediterranean region. Most of them show typical 'subduction-related' composition as reflected by the elevated potassium content (Fig. 6) along with the enrichment of LIL elements and depletion of HFS elements (Fig. 7). However, the large geochemical variability as shown in the SiO_2 vs. K_2O diagrams (Fig. 6) implies that complex petrogenetic processes have operated, involving different mantle sources, contamination by different crustal material and different degrees of fractional crystallization. Another important feature of the orogenic magmatic suites is the common occurrences of potassic-ultrapotassic rocks in each subprovince. They are the most characteristic of the Central Mediterranean area. OIB-type alkaline sodic mafic magmas akin to those erupted in the European foreland (Wilson & Downes 1991; this volume) overlap spatially and temporally with the 'orogenic' volcanism, although they are most characteristic of the later magmatic phases. The majority of these alkaline mafic rocks clearly indicate a distinct mantle source regions unaffected or only slightly affected by subduction-related fluids. On the other hand, interpretation of the origin of the 'subduction-related' magmatic rocks in the Mediterranean region is more difficult, because of the lack of mafic undifferentiated rocks in many areas.

In multi-element diagrams which are normalised to mid-ocean ridge basalts (N-MORB; Fig. 7), the Mediterranean orogenic rocks all show fairly similar features such as enrichment in LILE and depletion in HFSE (e.g., negative Nb-anomaly). As discussed previously, these characters are signs of a subduction component in the genesis of the magmas. Subduction and subduction-related metasomatism of the mantle wedge can be contemporaneous with the magmatism, but it could precede the volcanic activity, too. However, this geochemical feature can also be interpreted as contamination by crustal material at shallow level. Radiogenic isotope ratios (e.g., $^{87}Sr/^{86}Sr$, $^{143}Nd/^{144}Nd$ and Pb-Pb isotope ratios) are not changed by closed system petrogenetic processes such as partial melting and crystal fractionation; therefore they can be used to characterize the source region of the magmas and to detect possible crustal contamination. Recognition of the nature of the pre-metasomatized mantle source region could be important to constrain the geodynamic evolution of the volcanic areas. In the 1980's four main mantle end-member reservoirs were distinguished based on the radiogenic isotope variation of oceanic basalts (White 1985; Zindler & Hart 1986): depleted MORB-mantle (DMM), high μ ($^{238}U/^{204}Pb$) mantle (HIMU) and enriched mantle end-members (EMI and EMII). In addition to these mantle components a primitive mantle reservoir, called as PREMA (Zindler & Hart 1986) or FOZO (Hart *et al.* 1992) was also suggested to be present in the mantle. These mantle components could represent distinct parts of the mantle, although they could also spatially related (Hart 1988). Among them, the HIMU and FOZO are often interpreted to relate to upwelling mantle plumes coming from the core-mantle boundary (Hofman & White 1982; Weaver 1991; Chauvel *et al.* 1992; Hart *et al.* 1992; Hofmann 1997). Alternatively, this geochemical feature can reflect derivation of magmas from metasomatized lithospheric mantle (Hart 1988; Sun & McDonough 1989; Halliday *et al.* 1995; Niu & O'Hara 2003) and in this case no mantle plume is needed.

In continental and convergent margin magmas, these isotope ratios are masked by the signature of continental crust and therefore it is difficult to discriminate between mantle and crustal sources. Subcontinental lithosphere can preserve long-lived geochemical heterogeneity (e.g., high Rb/Sr, low Sm/Nd) and therefore can develop high $^{87}Sr/^{86}Sr$ and low $^{143}Nd/^{144}Nd$ values with time. Certain lithospheric mantle-derived magmas (e.g., lamproites, kimberlites) show radiogenic isotope ratios akin to those of crustal-derived silicic melts (Nelson *et al.*, 1986).

As shown in Fig. 8, Tertiary to Quaternary orogenic volcanic rock suites from the Alpine-Mediterranean region show similar curvilinear trends in the $^{87}Sr/^{86}Sr$ vs. $^{143}Nd/^{144}Nd$ diagram. An exception is the calc-alkaline volcanic rocks from the Betics, which have large scatter in the isotopic ratios. Most of the volcanic series define a continuous trend suggesting a common origin in terms of two-component mixing between a mantle component and an enriched component. Assimilation of crustal material by mantle-derived magma has been suggested for the Periadriatic magmas (Dupuy *et al.* 1982; Juteau *et al.* 1986; Kagami *et al.* 1991; von Blanckenburg *et al.* 1998) and for the East Carpathians calc-alkaline magmatism

(Mason *et al.* 1996). However, such trends could imply also derivation of magmas from a strongly heterogeneous upper mantle without significant upper crustal assimilation, as has been proposed for the Central Italian magmas (e.g. Peccerillo 1985; 1999) and Sardinia (Downes *et al.* 2001). The high $^{87}Sr/^{86}Sr$ isotope ratios can only be explained by involvement of upper crustal material in the genesis of these magmas, and the most plausible explanation is that upper crustal continental material was subducted into the upper mantle and injected into their mantle source (Peccerillo 1985; 1999).

In order to detect the processes of crustal involvement in magmagenesis, $^{87}Sr/^{86}Sr$ isotope ratios are often combined with oxygen isotope data ($^{18}O/^{16}O$ or $\delta^{18}O$ where $^{18}O/^{16}O$ is expressed relative to SMOW; Fig. 9). The upper mantle is inferred to have relatively homogeneous $\delta^{18}O$ values (+5.5±0.8; Mattey *et al.* 1994), whereas continental and oceanic crust generally display higher $\delta^{18}O$ values due to weathering processes and interaction with marine or meteoritic water (Taylor 1968; Cerling *et al.* 1985). Interaction with crustal material could occur in two end-member processes (Fig. 9). At convergent plate margins, crustal material could be added to the upper mantle either via subduction of continental or pelagic sediments with the oceanic lithosphere or by the entry of crustal lithosphere into the mantle during mature subduction. Dehydration and melting of the subducted crustal material result in metasomatism of the upper mantle, the source region of 'subduction-related' magmas. This process is termed 'source contamination' (James 1981; Tera *et al.* 1986; Wilson 1989; Ellam & Harmon 1990) and is characterised by elevated $^{87}Sr/^{86}Sr$, but relatively low $\delta^{18}O$ values in the resulting magmas. Involvement of a crustal component could also occur within the continental crust when the ascending mantle-derived magmas assimilate fusible continental material (Taylor 1980; DePaolo 1981; Hildreth & Moorbath 1988; Davidson & Harmon 1989). In magmas formed by this process ('crustal contamination'), variable $^{87}Sr/^{86}Sr$ ratios are accompanied by high $\delta^{18}O$ values (Fig. 9).

The mechanism by which the continental crust is involved in orogenic magmatism can be better constrained by combining $^{87}Sr/^{86}Sr$ isotope ratios with the $\delta^{18}O$ values either of phenocrysts from the volcanic rocks or bulk rocks. The $\delta^{18}O$ values of bulk rocks are usually higher than those of phenocrysts, because post-eruptive alteration and low-temperature weathering can increase the ^{18}O contents (Taylor 1968; Davidson & Harmon 1989; Ellam & Harmon 1990; Dobosi *et al.* 1998; Downes *et al.* 1995; 2001). Therefore, $\delta^{18}O$ values of phenocrysts reflect better the isotope composition of the host magma. Unfortunately, only sporadic oxygen isotope data are available in mineral separates from the volcanic rocks of the region. In the $^{87}Sr/^{86}Sr$ vs. $\delta^{18}O$ diagram (Fig. 9), the orogenic volcanic rocks of the Alpine-Mediterranean region show large variations. Calc-alkaline volcanic rocks from Sardinia (Downes *et al.* 2001) and most from the Pannonian Basin (Mason *et al.* 1996; Harangi *et al.* 2001; Seghedi *et al.* 2001) show only minor elevation of $\delta^{18}O$ with increasing $^{87}Sr/^{86}Sr$. These trends can be explained either by source contamination (Downes *et al.* 2001; Seghedi *et al.* 2001) or by mixing of mantle-derived magmas with lower crustal metasedimentary material (Harangi *et al.* 2001). Mixing between lithospheric mantle-derived magmas and lower crustal melts has also been proposed for the genesis of the Alpine Periadriatic igneous rocks by von Blanckenburg *et al.* (1998). For the remaining volcanic fields the higher $\delta^{18}O$ values at a given $^{87}Sr/^{86}Sr$ could indicate upper crustal contamination (Mason *et al.* 1996). Contamination of the mantle source by subducted crustal material has been proposed also for Stromboli, Roccamonfina and for the potassic rocks of Vulsini (Taylor *et al.* 1979; Holm & Munksgaard 1982; Ellam & Harmon 1990). In contrast, contamination by upper crustal material combined with crystal fractionation in mantle-derived magmas is envisaged for the calc-alkaline volcanic rocks of SE Spain (Benito *et al.*, 1999), for most of the volcanic rocks of the Aeolian arc (Ellam & Harmon, 1990) and the Aegean arc (Briqueu *et al.*, 1986).

In summary, continental crustal material has played an important role in the genesis of the 'orogenic' magmas of the Mediterranean region. Variation of $^{87}Sr/^{86}Sr$ and $\delta^{18}O$ values suggests that large amount of various crustal material were recycled into the upper mantle during subduction and the following collision and post-collisional events. In the following, we attempt to characterize the pre-metasomatized mantle sources.

One of the characteristic features of the Tertiary to Quaternary 'subduction-related' volcanic rocks of the Alpine-Mediterranean region is their close spatial and often temporal association with alkaline sodic mafic volcanic rocks (Fig. 1). Coeval eruption of alkali basalts and calc-alkaline/shoshonitic magmas occurs presently in the Aeolian archipelago and Sicily. Similar process took place at the southeastern part of the Carpathian chain about 0.5-1.5 Ma ago (Mason *et al.* 1996; 1998; Seghedi et al 2004). In the Central Mediterranean, the 'orogenic' volcanic rocks define a curvilinear trend in the $^{87}Sr/^{86}Sr$ vs. $^{206}Pb/^{204}Pb$ diagram (Fig. 10; Peccerillo 2003; Bell *et al.* 2004). One of the end-members of this trend has high $^{87}Sr/^{86}Sr$ and medium $^{206}Pb/^{204}Pb$ values and is related to continental crust. The other end-member has low $^{87}Sr/^{86}Sr$ and high $^{206}Pb/^{204}Pb$ ratios and could be an enriched mantle component that evolved with high U/Pb ratio over a long period of time. This mantle component shows similarities to the HIMU mantle end-member or to FOZO and is characteristic of OIB magmas. The alkaline sodic mafic rocks from Sicily and the Sicily channel also show isotopic variation trending towards this mantle component having a mixing trend between DMM and FOZO/HIMU. Mixing of OIB-like intraplate and subducted slab-derived components was also suggested by Peccerillo (2001) for the genesis of potassic rocks from Campania and Stromboli. Pleistocene basalts from Sardinia deviate from all of these volcanic rocks. They show a transitional geochemical character between the 'anorogenic' alkaline sodic mafic rocks and the 'orogenic' volcanic suites. However, the most peculiar feature of these rocks is the very low $^{206}Pb/^{204}Pb$ isotope values (Gasperini *et al.* 2000; Lustrino *et al.* 2000), which are similar to the EMI-type OIB (Fig. 10). Gasperini *et al.* (2000) interpreted their origin as derivation from recycled oceanic plateaux material. In contrast, Lustrino (2000) and Lustrino & Dallai (2003) argued that the EMI-type nature of the Sardinian basalts can be explained by post-collisional delamination of the lithospheric mantle and the lower crust during the Hercynian orogeny, melting of the lower crust and the contamination of the lithospheric mantle by this silicic melt. In the Carpathian-Pannonian region, the Sr-Pb isotope plot suggests a more complex petrogenetic scenario (Fig. 10; Harangi, 2001a). Calc-alkaline volcanic rocks from the Western Carpathians (Northern Pannonian Basin) fall in a curvilinear trend between a strongly radiogenic Sr isotopic component (lower crust?) and an enriched mantle component with low $^{87}Sr/^{86}Sr$ and high $^{206}Pb/^{204}Pb$ ratios similar to that inferred for the Central Mediterranean magmas. In contrast, calc-alkaline volcanic rocks from the East Carpathians trend toward a mantle component with lower $^{206}Pb/^{204}Pb$ ratios, which is more characteristic of depleted MORB-type mantle (DMM). This mantle source was modified by addition of subducted flysch sediments and the primary magmas underwent high-level crustal contamination (Mason *et al.* 1996). The youngest South Harghita shoshonites deviate from this trend having significantly lower $^{206}Pb/^{204}Pb$ ratios, possibly implying involvement of an EMI mantle component in their genesis. Alkali basalts of the Pannonian Basin (Embey-Isztin *et al.* 1993) form a continuous trend between the DMM and FOZO/HIMU mantle end-members. Thus, in the Carpathian-Pannonian region, a multi-component mixing model can be envisaged (Salters *et al.* 1988; Rosenbaum *et al.* 1997; Harangi 2001a), where different mantle sources (DMM and FOZO/HIMU and possibly also EMI) and lower and upper crustal components could have been involved in the genesis of the volcanic rocks.

Petrogenesis of the Tertiary to Quaternary magmas in the Mediterranean region is as complex and controversial as the geodynamic evolution of the area. The mantle source regions are extremely heterogeneous comprising all the identified mantle end-members found in oceanic basalts. This can be observed both in the undifferentiated alkaline mafic rocks, but also in the compositional variation of the ‘orogenic’ volcanic suites. In some places (e.g. Aeolian Islands-Sicily and southernmost East Carpathians) these alkaline sodic and ‘orogenic’ magmas erupted contemporaneously and spatially close to one another implying that heterogeneity in the upper mantle could exist both horizontally and vertically on at least a 10 km scale. Crustal rocks were subducted into the upper mantle and the fluids and melts released from them thoroughly metasomatized the subcontinental mantle, the source of the ‘orogenic’ magmas. In addition, crustal material was also incorporated into the ascending magmas at higher crustal levels.

Geodynamic implications

The low-K to high-K calc-alkaline volcanic rocks, the shoshonites and ultrapotassic formations as well as alkaline volcanic rocks of the Alpine-Mediterranean region were formed in a convergent plate margin setting. The geochemistry of these magmas indicates a strongly heterogeneous mantle beneath this area. Most authors suggest that this can be explained by a lengthy period of subduction and subsequent post-collisional processes. Subduction of remnant Tethyan oceanic plates appears to have played an important role in the evolution of this region and has also had a major influence on the regional upper mantle structure. Seismic tomographic models show the presence of high velocity anomalies beneath the Gibraltar arc, Calabria and the Hellenic arc interpreted as recently subducted slabs (Spakman *et al.* 1988; Blanco & Spakman 1993; Wortel & Spakman 1992; 2000; Faccena *et al.* 2003; Piromallo & Morelli 2003). In addition these models revealed an extensive coherent mass between 450 and 650 km depths that is interpreted as remnants of subducted Mesozoic oceanic slabs (Spakman *et al.* 1993; Piromallo *et al.* 2001; Piromallo & Morelli 2003). Indeed, most of the Tertiary to Quaternary volcanic rocks in the Mediterranean region show ‘subduction-related’ geochemical features. Some of them are found along volcanic arcs (Aeolian arc, Aegean arc) associated with the active subduction zones (Keller 1982). However, as shown in previous sections, there are debates whether they could be considered as classic volcanic arcs. Some features would seem to indicate a back-arc tectonic setting (Mitropoulos *et al.* 1987; Mazzuoli *et al.* 1995). In this case, subduction could have only an indirect influence on the magmagenesis (Ellam *et al.* 1989). The principal reason for magma generation could be passive extension of continental lithosphere resulting in decompression melting of the lithospheric and asthenospheric mantle variably metasomatized by previous subduction processes. Another candidate for volcanism directly related to active subduction is the Late Miocene low-K tholeiitic to calc-alkaline volcanic products of the Alboran basin (Duggen *et al.* 2004; Gill *et al.* 2004). However, other authors (e.g. Zeck 1996; Benito *et al.* 1999; Turner *et al.* 1999) emphasize the post-collisional origin of these rocks. Indeed, formation of most of the ‘orogenic’ volcanic rocks in the Mediterranean regions postdates the active subduction process and appear to be related to slab break-off, lithospheric mantle delamination or lithospheric extension (e.g. Seyitoğlu *et al.* 1999; Mason *et al.* 1998; Turner *et al.* 1999; Aldanmaz *et al.* 2000; Chalot-Prat & Gîrbacea 2000; Wortel & Spakman 2000; Harangi 2001a; Coulon *et al.* 2002; Seghedi *et al.* 2004). The ‘subduction-related’ geochemical character of the volcanic rocks is inherited from the mantle source regions modified previously (a few millions to several tens or even hundreds of million years before) by fluids released from subducted slabs. Post-collisional or back-arc extension of the lithosphere could result in the decompression melting of the hydrous portion of the lithospheric mantle first (Gallagher & Hawkesworth 1992), followed by the melting of the deeper asthenosphere. This could explain the initial 'orogenic' magmatism and the subsequent alkali basaltic volcanism in many areas of the Mediterranean region (e.g. Wilson *et al.* 1997; Seyitoğlu *et al.* 1999; Harangi 2001a).

Alkaline mafic rocks akin to those occurring in central Europe occur sporadically in this region, often very close to the 'orogenic' volcanic formations. Furthermore, rare volcanic rocks types such as carbonatites, melilitites and/or kamafugites in the Apennines are more characteristic of intra-plate rift settings (Lavecchia & Stoppa 1996; Lavecchia *et al.* 2003). This may imply also another mechanism for magmatism of the Mediterranean region, i.e. upwelling of hot mantle plume. The role of a mantle plume in the genesis of the volcanic rocks of Central Italy was first suggested by Vollmer (1976; 1989). Recognition of an enriched component (FOZO/HIMU) in both the 'anorogenic' and 'orogenic' volcanic rocks in many subprovinces (Hoernle *et al.* 1995; Ayuso *et al.* 1998; Wilson & Bianchini 1999; Harangi 2001a; Gasperini *et al.* 2002; Peccerillo 2003; Bell *et al.* 2004) also lead some authors to propose mantle plume activity. This could be supported by the extensive low-velocity anomaly beneath most of this area (Hoernle *et al.* 1995; Wortel & Spakman 2000; Piromallo & Morelli 2003) that could be interpreted as presence of anomalously hot mantle material. The estimated temperature from the P and S velocity anomalies approaches the dry solidus under the Pannonian Basin, western Mediterranean, Tyrrhenian and Aegean Basin, and the discrepancy between temperature inferred from P and S waves also indicates the presence of partial melt (Goes *et al.* 2000). Harangi (2001b) supposed also a relatively hot mantle beneath the Pannonian Basin based on the composition of the Late Miocene-Pliocene alkali basalts. As an extreme case, Lavecchia *et al.* (2003) and Bell *et al.* (2004) argued that the geodynamic evolution of the Central Mediterranean has been controlled by an upwelling plume and subduction had no role whatsoever. Other authors combined the subduction-related models with the existence of OIB-like mantle (Fig. 11). Gasperini *et al.* (2002) assumed that the HIMU signature of many of the volcanic rocks in the Central Mediterranean could be related typically to an upwelling plume. They invoked a plate window beneath the central Apennines, where deep mantle plume material could be channelled toward the shallow mantle zones (Fig. 11A). Decompression melting of this hot plume material could result in the enriched mantle component of many of the volcanic rocks in Central Italy. In the southern Tyrrhenian area, the coexistence of OIB and 'orogenic' magmas was interpreted by lateral flow of African enriched mantle along a tear at the edge of the Ionian plate (Fig. 11B; Trua *et al.* 2003). Mantle anisotropy studies in this area also indicate a toroidal mantle flow around the Calabrian slab (Civello & Margheriti 2004) that could supply enriched mantle material beneath Campania and the southern Tyrrhenian area from behind the Calabrian subduction zone. In the Carpathian-Pannonian region the compositional variation of Miocene to Quaternary calc-alkaline volcanic rocks implies contrasting genesis. Isotopic values of andesitic to dacitic rocks at the western segment of the Carpathian arc show a mixing trend between an enriched (FOZO/HIMU-type) mantle and a crustal component (Fig. 10; Harangi 2001a) similar to other volcanic suites in the Mediterranean region, whereas the calc-alkaline volcanic rocks in the eastern segment of the Carpathian arc show a mixing trend between a depleted mantle and a crustal component. A possible explanation for the contrasting mantle source regions is that enriched mantle could flow from the assumed plume finger beneath the Bohemian Massif to the thinned Pannonian Basin through the gap left behind the detached slab under the western Carpathians (Fig. 11C). In the east, no enriched mantle material could penetrate beneath the thick Ukrainian Shield, therefore slab break-off beneath the East Carpathians could initiate upwelling of depleted MORB-type mantle material. Deflection of the assumed mantle plume finger beneath the Massif Central towards the southeast was also detected by seismic anisotropy pattern (Barroul & Granet 2002). The reason of the south-eastward asthenospheric flow was explained by combined effect of Apenninic slab roll-back and the opening of the extensional basins behind it (Barroul & Granet 2002; Barroul *et al.* 2004). In summary, the FOZO/HIMU mantle component recognized in the compositional variation of many Mediterranean volcanic suites lead many authors to propose the influence of localized mantle plume(s) in the genesis of the magmas. Whether upwelling of hot mantle material was the ultimate cause of the magmagenesis and also influenced the tectonic evolution of the areas (Lavecchia *et al.* 2003) or subduction and post-collision processes (slab roll-back, slab break-off, delamination of the lower lithosphere) initiated deflection of nearby mantle plumes, requires further combined geochemical, geophysical and tectonic research.

Nevertheless, the HIMU signature of the mantle source could also be interpreted as due to metasomatic processes without assuming mantle plumes (Sun & McDonough 1989; Anderson 1994; Halliday *et al.* 1995; Niu *et al.* 1999). It is remarkable that the enriched, HIMU-like mantle component was detected also in earlier, pre-Neogene volcanic rocks of this region (Veneto region, Macera *et al.* 2003; Dinarides, Cvetković *et al.* 2004; Carpathian-Pannonian region, Harangi 1994; Harangi *et al.* 2003) that may imply its long-lasting (at least from the Early Cretaceous) presence beneath Europe. Oyarzun *et al.* (1997) and Wilson (1997) suggested that this enriched mantle component could be derived from the Mesozoic Central Atlantic plume deflected either due to the suction of the European thin-spots or due to the north-eastward motion of the African plate. In any case, portions of the deflected plume material could have polluted the shallow upper mantle beneath Europe since the Early Cretaceous. In addition, subduction of crustal material could also contribute to the inhomogeneity of the shallow mantle. Statistical sampling of this heterogeneous mantle (SUMA model, Meibom & Anderson 2003) could be an alternative model for the wide variation of the Tertiary to Quaternary volcanic rocks of the Mediterranean region.

Discussions with the PANCARDI Igneous Team for the last decade have helped us to develop our ideas on the Tertiary to Quaternary magmatism and its geodynamic relationships in the Alpine, Pannonian, Carpathian and Dinarides regions. Part of this study belongs to the research project supported by the Hungarian Science Foundation (OTKA # T 037974) to SzH. The critical reviews of C. Doglioni and F. Chalot-Prat helped to improve the paper and are gratefully acknowledged. We thank also for patient editorial help of R. Stephenson and D. Gee. R. Lukács is thanked for the careful work on producing the reference list.

Aldanmaz, E., Pearce, J.A., Thirlwall, M.F. & Mitchell, J.G. 2000. Petrogenetic evolution of late Cenozoic, post-collision volcanism in western Anatolia, Turkey. Journal of Volcanology and Geothermal Research, 102, 67-95.

Alici, P., Temel, A. & Gourgaud, A. 2002. Pb-Nd-Sr isotope and trace element geochemistry of Quaternary extension-related alkaline volcanism: a case study of Kula region (western Anatolia, Turkey). Journal of Volcanology and Geothermal Research, 115, 487-510.

Alici, P., Temel, A., Gourgaud, A., Kieffer, G. & Gundogdu, M.N. 1998. Petrology and geochemistry of potassic rocks in the Golcuk area (Isparta, SW Turkey): genesis of enriched alkaline magmas. Journal of Volcanology and Geothermal Research, 85, 423-446.

Altherr, R., Keuzer, H., Wendt, I., Lenz, H., Wagner, G.A., Keller, J., Harre, W. & Hohndorf, A. 1982. A Late Oligocene/Early Miocene high temperature belt in the Attic-Cycladic cristalline complex (SE Pelagonian, Greece). Geologisches Jahrbuch, 23, 97-164.

Altherr, R., Lugovic, B., Meyer, H.P. & Majer, V. 1995. Early Miocene post-collosional calc-alkaline magmatism along the easternmost segment of the Periadriatic fault system (Slovenia and Croatia). Mineralogy and Petrology, 54, 225-247.

Anderson, D.L. 1994. The sublithospheric mantle as the sourc of continental flodd basalts. Earth and Planetary Science Letters, 123, 269-280.

Anderson, H. & Jackson, J. 1987. The deep seismicity of the Tyrrhenian Sea. Geophysical Journal of the Royal Astronomical Society, 91, 631-637.

Aparico, A., Mitjavila, J.M., Arana, V. & Vila, I.M. 1991. La edad del volcanism de las islas Columbrete Grande Alboran (Mediterraneo Occidentale). Boletim Geologica y Minero, 102, 562-570.

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

Aydar, E. & Gourgaud, A. 1998. The geology of Mount Hasan stratovolcano, central Anatolia, Turkey. Journal of Volcanology and Geothermal Research, 85, 129-152.

Aydar, E., Gourgaud, A., Deniel, C., Lyberis, N. & Gundogdu, N. 1995. Le volcanisme quarternaire de l'Anatolie centrale (Turquie): association de magmatism caco-alcalin en domaine de convergence. Canadian Journal of Earth Sciences, 32, 1085-1069.

Ayuso, R.A., De Vivo, B., Rolandi, G., Seal II, R.R. & Paone, A. 1998. Geochemical and isotopic (Nd-Pb-Sr-O) variations bearing on the genesis of volcanic rocks from Vesuvius, Italy. Journal of Volcanology and Geothermal Research, 82, 53-78.

Bada, G. & Horváth, F. 2001. On the structure and tectonic of the Pannonian Basin and surrounding orogens. Acta Geologica Hungarica, 44, 301-327.

Balla, Z. 1981. Neogene Volcanism of the Carpatho-Pannonian Region. Earth Evol. Sci., 3-4, 240-248.

Barroul, G., Deschamps, A. & Coutant, O. 2004. Mapping upper mantle anisotrophy beneath SE France by SKS splitting indicates Neogene asthenospheric flow induced by Apenninic slab roll-back and deflected by the deep Alpine roots. Tectonophysics, 394, 125-138.

Barroul, G. & Granet, M. 2002. A Tertiary asthenospheric flow beneath the southern French Massif Central related to the west Mediterranean extension evidenced by upper mantle seismic anisotropy. Earth and Planetary Science Letters, 202, 30-47.

Barton, M. & Huijsmans, J.P.P. 1986. Post-caldera dacites from the Santorini volcanic complex, Aegean Sea, Greece: an example of eruption of lavas of near-constant composition over a 2,200 year period. Contributions to Mineralogy and Petrology, 94, 472-475.

Beccaluva, L., Bigioggero, B., Chiesa, S., Colombo, A., Fanti, G., Gatto, G.O., Gregnanin, A., Montrasio, A., Piccirillo, E.M. & Tunesi, A. 1983. Post collisional orogenic dyke magmatism in the Alps. Mem. Soc. Geol. Ital., 26, 341-359.

Beccaluva, L., Brotzu, P., Macciotta, G., Morbidelli, L., Serri, G. & Traversa, G. 1987. Cainozoic tectonomagmatic evolution and inferred mantle in the Sardo-Tyrrhenian area. The lithosphere in Italy. Advances in Earth Science Research. Accademia Nazionale Lincei, 80, 229-248.

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

Beccaluva, L., Gabbianelli, G., Lucchini, F., Rossi, P.L. & Savelli, C. 1985. Petrology and K/Ar ages of volcanics dredged from the Eolian seamounts: implication for geodynamic evolution of the southern Tyrrhenian basin. Earth and Planetary Science Letters, 74, 187-208.

Beccaluva, L., Rossi, P.L. & Serri, G. 1982. Neogene to recent volcanism of the Southern Tyrrhenian-Sicilian Area: Implication for the geodynamic evolution of the Calabrian arc. Earth Evol. Science, 3, 222-238.

Bell, K., Castorina, F., Lavecchia, G., Rosatelli, G. & Stoppa, F. 2004. Is there a mantle plume below Italy? EOS, Transactions, Americal Geophysical Union, 85, 541-547.

Bellieni, G., Peccerillo, A. & Poli, G. 1981. The Vedrette di Ries (Riesenferner) plutonic complex: petrological and geochemical data bearing on its genesis. Contributions to Mineralogy and Petrology, 78, 145-156.

Bellon, H., Bordet, P. & Montenat, C. 1983. Chronologie du magmatisme neogene des Cordilleres Betiques, Espagne meridionale. Bull. Soc. Geol. (France), 25, 205-217.

Benedek, K. 2002. Paleogene igneous activity along the easternmost segment of the Periadriatic-Balaton Lineament. Acta Geologica Hungarica, 54., 359-371.

Benito, R., Lopez-Ruiz, J., Cebria, J.M., Hertogen, J., Doblas, M., Oyarzun, R. & 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.

Berger, A., Rosenberg, C. & Schmid, S.M. 1996. Ascent, emplacement and exhumation of the Bergell pluton within the Southern Steep Belt of the Central Alps. Schweiz. Miner. Petrol. Mitt., 76, 357-382.

Bird, P. 1979. Continental delamination and the Colorado Plateau. Journal of Geophysical Research, 84, 7561-7571.

Blanco, M.J. & Spakman, W. 1993. The P-wave velocity structure of the mantle below the Iberian Peninsula: evidence for subducted lithosphere below southern Spain. Tectonophysics, 221, 13-34.

Bradshaw, T.K., Hawkesworth, C.J. & Gallagher, K. 1993. Basaltic volcanism in the Southern Basin and Range: No role for a mantle plume. Earth and Planetary Science Letters, 116, 45-62.

Briqueu, L., Javoy, M., Lancelot, J.R. & Tatsumoto, M. 1986. Isotope geochemistry, of recent magmatism in the Aegean arc: Sr, Nd, Hf, and O isotopic ratios in the lavas of Milos and Santorini-geodynamic implications. Earth and Planetary Science Letters, 80, 41-54.

Bröcker, M., Kreuzer, H., Mattheus, A. & Okrusch, M. 1993. 40Ar/39Ar and oxygen isotope studies of polymetamorphism from Tinos island, Cycladic blueschist belt, Greece. Journal of Metamorphic Geology, 11, 223-240.

Brunet, D. & Yuen, D.A. 2000. Mantle plumes pinched in the transition zone. Earth and Planetary Science Letters, 178, 13-27.

Calvert, A., Sandvol, E., Seber, D., Barazangi, M., Roecker, S., Mourabit, T., Vidal, F., Alguacil, G. & Nacer, J. 2000. Geodynamic evolution of the lithosphere and upper mantle beneath the Alboran region of the western Mediterranean; Constraints from travel time tomography. J.Geophys.Res., 105, 10,871-10,898.

Carminati, E., Wortel, M.J.R., Spakman, W. & Sabadini, R. 1998. The role of slab detachment processes in the opening of the western-central Mediterranean basins: some geological and geophysical evidence. Earth and Planetary Science Letters, 160, 651-665.

Carter, S.R. & Civetta, L. 1977. Genetic implications of the isotope and trace element variations in the Eastern Sicilian volcanics. Earth and Planetary Science Letters, 36, 168-180.

Castorina, F., Stoppa, F., Cundari, A. & Barbieri, M. 2000. An enriched mantle source for Italy's melilitite-carbonatite association as inferred by its Nd-Sr isotope signature. Mineralogical Magazine, 64, 625-639.

Cebriá, J.M., Lopez-Ruiz, J., Doblas, M., Oyarzun, R., Hertogen, J. & Benito, R. 2000. Geochemistry of the Quaternary alkali basalts of Garrotxa (NE volcanic province, Spain): a case of double enrichment of the mantle lithosphere. Journal of Volcanology and Goethermal Research, 102, 217-235.

Cebria, J.-M. & 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.

Cerling, T.E., Brown, F.H. & Bowman, J.R. 1985. Low temperature alteration of volcanic glass: hydration, Na, K, 18O and Ar mobility. Chemical Geology, 52, 281-293.

Chalot-Prat, F. & Gîrbacea , R. 2000. Partial delamination of continental mantle lithosphere, uplift-related crust-mantle decoupling, volcanism and basin formation: a new model for the Pliocene-Quaternary evolution of the southern East-Carpathians, Romania. Tectonophysics, 327, 83-107.

Chauvel, C., Hofmann, A.W. & Vidal, P. 1992. HIMU-EM: The French Polynesian connection. Earth and Planetary Science Letters, 110, 99-119.

Christofides, G., Koroneos, A., Soldatos, T., Eleftheriadis, G. & Kilias, A. 2001. Eocene magmatism (Sithonia and Elatia plutons) in the Internal Hellenides and implications for Eocene-Miocene geological evolution of the Rhodope Massif (Northern Greece). In: Downes, H. & Vaselli, O. (eds) Tertiary magmatism in the Dinarides Balkan Peninsula. - Acta Vulcanologica 13, 73-89.

Christofides, G., Soldatos, T., Eleftheriadis, G. & Koroneos, A. 1998. Chemical and isotopic evidence for source contamination and crustal assimilation in the Hellenic Rhodope plutonic rocks. In: Christofides, G., Marchev, P. & Serri, G. (eds) Tertiary magmatism of the Rhodopian Region. Acta Vulcanologica 10, 305-318.

Civello, S. & Margheriti, L. 2004. Toroidal mantle flow around the Calabrian slab (Italy) from SKS splitting. Geophysical Research Letters, 31, L10601.

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

Conticelli, S. & 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.

Cortecci, G., Del Moro, A., Leone, G. & Pardini, G.C. 1979. Correlation between strontium and oxygen isotopic compositions of rocks from the Adamello Massif (Northern Italy). Contributions to Mineralogy and Petrology, 68, 421-427.

Coulon, C., Megartsi, M.h., Fourcade, S., Maury, R.C., Bellon, H., Louni-Hacini, A., Cotten, J., Coutelle, A. & Hermitte, D. 2002. Post-collisional transition from calc-alkaline to alkaline volcanism during the Neogene in Oranie (Algeria): magmatic expression of a slab breakoff. Lithos, 62, 87-110.

Crisci, G.M., De Rosa, R., Esperanca, S., Mazzuoli, R. & Sonnino, M. 1991. Temporal evolution of a three component system: the island of Lipari (Aeolian Arc, southern Italy). Bulletin of Volcanology, 53, 207-221.

Csontos, L., Nagymarosy, A., Horváth, F. & Kovác, M. 1992. Tertiary evolution of the Intra-Carpatian area: a model. In: Ziegler, P.A. (eds) Geodynamics of rifting, vol. I. Case studies on rifts: Europe and Asia. - Tectonophysics 208, 221-241.

Cvetkovic, V., Prelevic, D., Downes, H., Jovanovic, M., Vaselli, O. & Pecskay, Z. 2004. Origin and geodynamic significance of Tertiary postcollisional basaltic magmatism in Serbia (central Balkan Peninsula). Lithos, 73, 161-186.

Davidson, J.P. & Harmon, R.S. 1989. Oxygen isotope constraints on the petrogenesis of volcanic arc magmas from Martinique, Lesser Antilles. Earth and Planetary Science Letters, 95, 255-270.

Davidson, J.P., McMillan, N.J., Moorbath, S., Worner, G., Harmon, R.S. & Lopez-Escobar, L. 1990. The Nevados de Pavachata volcanic region, 18o S/69oW, N Chile, II. Evidence for widespread crustal involvement in Andean magmatism. Contributions to Mineralogy and Petrology, 105, 412-430.

Davies, J.H. & von Blanckenburg, F. 1995. Slab breakoff: A model of lithospheric detachment and its test in the magmatism and deformation of collisional orogens. Earth and Planetary Science Letters, 129, 85-102.

De Astis, G., Peccerillo, A., Kempton, P.D., La Volpe, L. & Wu, T.W. 2000. Transition from calc-alkaline to potassium-rich magmatism in subduction environments: geochemical and Sr, Nd, Pb isotopic constraints from the island of Vulcano (Aeolian arc). Contributions to Mineralogy and Petrology, 139, 684-703.

De Fino, M., La Volpe, L., Peccerillo, A., Piccaretta, G. & Poli, G. 1986. Petrogenesis of Mt. Vulture volcano (Italy): inferences from mineral chemistry, major and trace element data. Contributions to Mineralogy and Petrology, 92, 161-177.

De Vecchi, G. & Sedea, R. 1995. The Paleogene basalts of the Veneto Region (NE Italy). Mem. Soc. Geol. Ital., 47, 253-274.

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

Delaloye, M. & Bingöl, E. 2000. Granitoids from western and northwestern Anatolia: geochemistry and modelling of geodynamic evolution. International Geology Review, 42, 241-286.

DePaolo, D.J. 1981. Trace element and isotopic effects of combined wallrock assimilation and fractional crystallization. Earth and Planetary Science Letters, 53, 189-202.

Dercourt, J., Zonenshain, L.P., Ricou, L.-E., Kazmin, V.G., Le Pichon, X., Knipper, A.L., Grandjacquet, C., Sbortshikov, I.M., Geyssant, J. & Lepvrier, C. 1986. Geological evolution of the tethys belt from the atlantic to the pamirs since the LIAS. Tectonophysics, 123, 241-315.

Deutsch, A. 1984. Young Alpine dykes south of the Tauern Window (Austria): a K-Ar and Sr isotope study. Contributions to Mineralogy and Petrology, 85, 45-57.

Dewey, J.F. 1988. Extensional collapse of orogens. Tectonics, 7, 1123-1139.

Dewey, J.F. & Sengör, A.M.C. 1979. Aegean and surrounding regions: Complex multiplate and continuum tectonics in a convergent zone. Geological Society of America Bullettin, 90, 84-92.

Di Battistini, G., Montanini, A. & Zerbi, M. 1990. Geochemistry of volcanic rocks from southeastern Montiferro. Neues Jahrbuch Mineralogie Abhandlungen, 162, 35-67.

Di Battistini, G., Toscani, L., Laccarino, S. & Villa, I.M. 1987. K/Ar ages and the geological setting of calc-alkaline volcanic rocks from Sierra de Gata, SE Spain. Neues Jahrb.Mineral.Mh., 8, 369-383.

Dobosi, G., Downes, H., Mattey, D. & Embey-Isztin, A. 1998. Oxygen isotope ratios of phenocrysts from alkali basalts of the Pannonian basin: Evidence for an O-isotopically homogeneous upper mantle beneath a subduction-influenced area. Lithos, 42, 213-223.

Docherty, C. & Banda, E. 1995. Evidence for the 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. 1991. A proposal of kinematic modelling for W-dipping subductions - possible applications to the Tyrrhenian-Apennines system. Terra Nova, 3, 423-434.

Doglioni, C. 1992. Main differences between thrust belts. Terra Nova, 4, 152-164.

Doglioni, C. 1993. Comparison of subduction zones versus the global tectonic pattern: a possible explanation for the Alps-Carpathians system. Geophys. Trans., 37, 253-264.

Doglioni, C., Agostini, S., Crespi, M., Innocenti, F., Manetti, P., Riguzzi, F. & Savasçin, M.Y. 2002. On the extension in western Anatolia and the Aegean sea. Journal of Virtual Explorer, 7, 167-181.

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

Doglioni, C., Mongelli, F. & Pieri, P. 1994. The Puglia uplift (SE Italy): an anomaly in the foreland of the Apenninic subduction due to buckling of a thick continental lithosphere. Tectonics, 13, 1309-1321.

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

Dostal, J., Coulon, C. & Dupuy, C. 1982. Cainozoic andesitic rocks of Sardinia (Italy). In: Thorpe, R.S. (eds) Andesites, Wiley and Sons Ltd, 353-370.

Downes, H. 1996. Neogene magmatism and tectonics in the Carpatho-Pannonian region. In: K., D. (eds) PANCARDI Workshop 1996, Dynamics of the Pannonian-Carpathian-Dinaride System- Mid. Ges. Geol. Bergbaustud. Österr. 41., 104-105.

Downes, H., Pantó, G., Póka, T., Mattey, D. & Greenwood, B. 1995. Calc-alkaline volcanics of the Inner Carpathian arc, Northern Hungary: new geochemical and oxygen isotopic results. In: Downes, H. & Vaselli, O. (eds) Neogene and related magmatism in the Carpatho-Pannonian Region Acta Vulcanologica, 7, 29-41.

Downes, H., Seghedi, I., Szakacs, A., Dobosi, G., James, D.E., Vaselli, O., Rigby, I.J., Ingram, G.A., Rex, D. & Pecskay, Z. 1995. Petrology and geochemistry of late Tertiary/Quaternary mafic alkaline volcanism in Romania. Lithos, 35, 65-81.

Downes, H., Thirlwall, M.F. & Trayhorn, S.C. 2001. Miocene subduction-related magmatism in southern Sardinia: Sr-Nd- and oxygen isotopic evidence for mantle source enrichment. Journal of Volcanology and Geothermal Research, 106, 1-22.

Duggen, S., Hoernle, K., van den Bogaard, P. & Harris, C. 2004. Magmatic evolution of the Alboran region: The role of subduction in forming the western Mediterranean and causing the Messinian Salinity Crisis. Earth and Planetary Science Letters, 218, 91-108.

Duggen, S., Hoernle, K., van den Bogaard, P., Rüpke, L. & Morgan, J.P. 2003. Deep roots of the Messinian salinity crisis. Nature, 422, 602-606.

Dupuy, C., Dostal, J. & Fratta, M. 1982. Geochemistry of the Adamello Massif (Northern Italy). Contrib. Mineral. Petrol., 80, 41-48.

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

Ellam, R.M. & Harmon, R.S. 1990. Oxygen isotope constraints on the crustal contribution to the subduction-related magmatism of the Aeolian Islands, southern Italy. Journal of Volcanology and Geothermal Research, 44, 105-122.

Ellam, R.M. & Hawkesworth, C.J. 1988. Elemental and isotopic variations in subduction related basalts: Evidence for a three component model. Contrib. Mineral. Petrol., 98, 72-80.

Ellam, R.M., Hawkesworth, C.J., Menzies, M.A. & Rogers, N.W. 1989. The volcanism of Southern Italy: Role of subduction and the relationship between potassic and sodic alkaline magmatism. Journal of Geophysical Research, 94, 4589-4601.

Elliott, T., Plank, T., Zindler, A., White, W. & Bourdon, B. 1997. Element transport from slab to volcanic front at the Mariana arc. J. Geophys. Res., 102, 14.991-15.019.

Elsasser, W.M. 1971. Seafloor spreading as thermal convection. Journal of Geophysical Research, 76, 1101-1112.

Embey-Isztin, A., Downes, H., James, D.E., Upton, B.G.J., G., D., Ingram, G.A., Harmon, R.S. & Scharbert, H.G. 1993. The petrogenesis of Pliocene alkaline volcanic rocks from the Pannonian Basin, Eastern Central Europe. Journal of Petrology, 34, 317-343.

Esperanca, S. & 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 and Planetary Science Letters, 136, 167-182.

Exner, C. 1976. Die Geologische Position der Magmatite des periadriatischen Lineamentes. Verh. Geol. B.-A. Wien, 2, 3-64.

Faccenna, C., Jolivet, L., Piromallo, C. & Morelli, A. 2003. Subduction and depth of convection in the Mediterranean mantle. Journal of Geophysical Research, 107, 1-13.

Fan, G., Wallace, T.C. & Zhao, D. 1998. Tomographic imaging of deep velocity structure beneath the Eastern and Southern Carpathians, Romania: implications for continental collision. Journal of Geophysical Research, 103, 2705-2723.

Fodor, L., Csontos, L., Bada, G., Györfi, I. & Benkovics, L. 1999. Tertiary tectonic evolution of the Pannonian basin system and neighbouring orogens: a new synthesis of palaeostress data. In: Durand, B., Jolivet, L., F., H. & Séranne, M. (eds) The Mediterranean Basins: Tertiary Extension within the Alpine Orogen. - Geological Society, London, Special Publications 156, 295-334.

Fourcade, S., Capdevila, R., Ouabadi, A. & Martineau, F. 2001. The origin and geodynamic significance of the Alpine cordierite-bearing granitoids of northern Algeria. A combined petrological, mineralogical, geochemical and isotopic (O, H, Sr, Nd) study. Lithos, 57, 187-216.

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

Francalanci, L., Varekamp, J.C., Vouioukalakis, G., Defant, M.J., Innocenti, F. & Manetti, P. 1998. Crystal retention, fractionation and crustal assimilation in a convecting magma chamber, Nisyros volcano, Greece. Bulletin of Volcanology, 56, 601-620.

Fytikas, M., Innocenti, F., Manetti, P., Mazzuoli, R., Peccerillo, A. & Villari, L. 1984. Tertiary to Quaternary evolution of volcanism in the Aegean region. In: Robertson, A.H.F. & Dixon, J.G. (eds) Geological Evolution of the Eastern Mediterranean. - Geological Society, London, Special Publications 17, 687-699.

Gallagher, K. & Hawkesworth, C.J. 1992. Dehydration melting and the generation of continental flood basalts. Nature, 358, 57-59.

Garcia-Duenas, V., Balanyá, J.C. & Martinez-Martinez, J.M. 1992. Miocene extensional detachments in the outcropping basement of the Northern Alborab Basin (Betics) and their tectonic implications. Geomarine Letters, 12, 88-95.

Gasparini, C., Iannaccone, G., Scandone, P. & Scarpa, R. 1982. Seismotectonics of the Calabrian arc. Tectonophysics, 84, 267-299.

Gasperini, D., Blichert-Toft, J., Bosch, D., Del Moro, A., Macera, P., Telouk, P. & Albarede, F. 2000. Evidence from Sardinian basalt geochemistry for recycling of plume heads into the Earth's mantle. Nature, 408, 701-704.

Gasperini, D., Blichert-Toft, J., Bosch, D., Del Moro, A., Macera, P., Telouk, P. & Albarede, F. 2002. Upwelling of deep mantle material through a plate window: Evidence from th geochemistry of Italian basaltic volcanism. Journal of Geophysical Research, 107, 2367-2371.

Gautier, P., Brun, J.-P., Moriceau, R., Sokoutis, D., Martinod, J. & Jolivet, L. 1999. Timing, kinematics and cause of Aegean extension: a scenario based on a comparison with simple analogue experiments. Tectonophysics, 315, 31-72.

Gelabert, B., Sábat, F. & Rodríguez-Perea, A. 2002. A new proposal for the late Cenozoic geodynamic evolution of the western Mediterranean. Terra Nova, 14, 93-100.

Gertisser, R. & Keller, J. 2000. From basalt to dacite: origin and evolution of the calc-alkaline series of Salina, Aeolian Arc, Italy. Contributions to Mineralogy and Petrology, 139, 607-626.

Gill, J.B. 1981. Orogenic andesites and plate tectonics. Springer, Berlin, 390 pp.

Gill, J.B., Morris, J.D. & Johnson, R.W. 1993. Timescales for producing the geochemical signature of island arc magmas: U-Th-Po and Be-B systematics in recent Papua New Guinea lavas. Geochimica et Cosmochimica Acta, 57, 4269-4283.

Gill, J.B. & Williams, R.W. 1990. Th isotope and U-series studies of subduction-related volcanic rocks. Geochimica et Cosmochimica Acta, 54, 1427-1442.

Gill, R.C.O., Aparicio, A., El Azzouzi, M., Hernandez, J., Thirlwall, M.F., Bourgois, J. & Marriner, G.F. 2004. Depleted arc volcanism in the Alboran Sea and shoshonitic volcanism in Morocco: geochemical and isotopic constraints on Neogene tectonic processes. Lithos, 78, 363-388.

Gîrbacea , R. & Frisch, W. 1998. Slab in the wrong place: Lower lithospheric mantle delamination in the last stage of Eastern Carpathians subduction retreat. Geology, 26, 611-614.

Goes, S., Govers, R. & Vacher, P. 2000. Shallow mantle temperatures under Europe from P and S wave tomography. Journal of Geophysical Research, 105, 11,153-11,169.

Goes, S., Spakman, W. & Bijwaard, H. 1999. A lower mantle source for central European volcanism. Science, 286, 1928-1931.

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

Güleç, N. 1991. Crust-Mantle interaction in Western Turkey: Implications from Sr and Nd geochemistry of Tertiary and Quaternary volcanics. Geological Magazine, 128, 417-435.

Gutscher, M.A., Malod, J., Rehault, J.P., Contrucci, I., Klingelhoefer, F., Mendes-Victor, L. & Spakman, W. 2002. Evidence for active subduction beneath Gibraltar. Geology, 30, 1071-1074.

Halliday, A.N., Lee, D.C., Tommasini, S., Davies, G.R., Paslick, C.R., Fitton, J.G. & James, D.E. 1995. Incompatible trace element in OIB and MORB source enrichment in the sub-oceanic mantle. Earth and Planetary Science Letters, 133, 379-395.

Harangi, S. 1994. Geochemistry and petrogenesis of the Early Cretaceous continental rift-type volcanic rocks of the Mecsek Mountains, South Hungary. Lithos, 33, 303-321.

Harangi, S. 2001. Neogene to Quaternary Volcanism of the Carpathian-Pannonian Region - a review. Acta Geologica Hungarica, 44, 223-258.

Harangi, S. 2001. Neogene magmatism in the Alpine-Pannonian Transition Zone - a model for melt generation in a complex geodynamic setting. Acta Vulcanologica, 13, 25-39.

Harangi, S. & Downes, H. 2000. Contrasting origins of Neogene calc-alkaline volcanic suites in the Carpathian-Pannonian Region, Eastern-Central Europe. Journal of Conference Abstracts, 5, 484.

Harangi, S., Downes, H., Kósa, L., Szabó, C., Thirlwall, M.F., Mason, P.R.D. & Mattey, D. 2001. Almandine garnet in calc-alkaline volcanic rocks of the Northern Pannonian Basin (Eastern-Central Europe): geochemistry, petrogenesis and geodynamic implications. Journal of Petrology, 42, 1813-1843.

Harangi, S., Mason, P.R.D. & Lukács, R. 2005. Correlation and petrogenesis of silicic pyroclastic rocks in the Northern Pannonian Basin, Eastern-Central Europe: in situ trace element data of glass shards and mineral chemical constraints. Journal of Volcanology and Geothermal Research, in press.

Harangi, S., Tonarini, S., Vaselli, O. & Manneti, P. 2003. Geochemistry and petrogenesis of Early Cretaceous alkaline igneous rocks in Central Europe: implications for a long-lived EAR-type mantle component beneath Europe. Acta Geologica Hungarica, 46, 77-94.

Harangi, S., Vaselli, O., Tonarini, S., Szabó, C., Harangi, R. & Coradossi, N. 1995. Petrogenesis of Neogene extension-related alkaline volcanic rocks of the Little Hungarian Plain Volcanic Field (Western Hungary). In: Downes, H. & Vaselli, O. (eds) Neogene and related magmatism in the Carpatho-Pannonian Region. Acta Vulcanologica 7, 173-187.

Harkovska, A., Marchev, P., Machev, P. & Pécskay, Z. 1998. Paleogene magmatism in the Central Rhodope Area, Bulgaria - A review and new data. In: Christofides, G., Marchev, P. & Serri, G. (eds) Tertiary magmatism of the Rhodopian Region. - Acta Vulcanologica 10, 199-216.

Hart, S.R. 1988. Heterogeneous mantle domains: signatures, genesis and mixing chronologies. Earth and Planetary Science Letters, 90, 273-296.

Hart, S.R., Hauri, E.H., Oschmann, L.A. & Whitehead, J.A. 1992. Mantle plumes and entrainment: isotopic evidence. Science, 256, 517-520.

Hawkesworth, C., Turner, S., Gallagher, K., Hunter, A., Bradshaw, T. & Rogers, N. 1995. Calc-alkaline magmatism, lithospheric thinning and extension in the Basin and Range. Journal of Geophysical Research, 100, 10271-20286.

Hawkesworth, C. & Vollmer, R. 1979. Crustal contamination versus enriched mantle: 143Nd/144Nd and 87Sr/86Sr evidence from the Italian volcanics. Contributions to Mineralogy and Petrology, 69, 151-169.

Hawkesworth, C.J., Gallagher, K., Hergt, J.M. & McDermott, F. 1994. Destructive plate margin magmatism: Geochemistry and melt generation. Lithos, 33, 169-188.

Hertogen, J., López-Ruiz, J., Rodríguez Badiola, E., Demaiffe, D. & Weis, D. 1985. Petrogenesis of ultrapotassic volcanic rocks from SE Spain: trace elements and Sr-Pb isotopes. Terra Cognita, 5, 215-216.

Hildreth, W. & Moorbath, S. 1988. Crustal contributions to arc magmatism in the Andes of central Chile. Contrib. Mineral. Petrol., 98, 455-489.

Hoernle, K., Zhang, Y.S. & 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.

Hofmann, A.W. 1997. Mantle geochemistry: the message from oceanic volcanism. Nature, 385, 219-229.

Hofmann, A.W. & White, W.M. 1982. Mantle plumes from ancient oceanic crust. Earth and Planetary Science Letters, 57, 421-436.

Holm, P.M. & Munksgaard, N.C. 1982. Evidence for mantle metasomatism: an oxygen and strontium isotope study of the Vulsinian District, Central Italy. Earth and Planetary Science Letters, 60, 376-388.

Horvath, F. 1993. Towards a mechanical model for the formation of the Pannonian basin. Tectonophysics, 226, 333-357.

Horváth, F. & Berckhemer, H. 1982. Mediterranean back arc basins. In: Berckhemer, H. & Hsü, K. (eds) Alpine-Mediterranean geodynamics. Geodynamic Series 7., American Geophysical Union and Geological Society of America, 141-173.

Houseman, G.A., McKenzie, D.P. & Molnar, P.J. 1981. Convective instability of a thickened boundary layer and its relevance for the thermal evolution of continental convergent belts. Journal of Geophysical Research, 86, 6115-6132.

Huijsmans, J.P.P., Barton, M. & Salters, V.J.M. 1988. Geochemistry and evolution of the calc-alkaline volcanic complex of santorini, Aegean Sea, Greece. Journal of Volcanology and Geothermal Research, 34, 283-306.

Innocenti, F., Kolios, N., Manetti, P., Rita, F. & Villari, L. 1982. Acid and basic late neogene volcanism in central Aegean Sea: its nature and geotectonic significance. Bulletin of Volcanology, 45, 87-97.

Innocenti, F., Mazzuoli, R., Pasquare, G., Radicati di Brozolo, F. & Villari, L. 1975. the Neogene calc-alkaline volcanics of Central Anatolia: geochronological data on Kayseri-Nide area. Geological Magazine, 112, 349-360.

James, D.E. 1981. The combined use of oxygen and radiogenic isotopes as indicators of crustal contamination. Annual Review of Earth and Planetary Sciences, 9, 311-344.

Jarrard, R.D. 1986. Relations among subduction parameters. Rev. Geophys., 24, 217-284.

Jiricek, R. 1979. Tectonic development of the Carpathian arc in the Oligocene and Neogene. In: Mahel, M. (eds) Tectonic profiles through the Western Carpathians., Geol. Inst. Dionyz Stur, Bratislava, 205-214.

Johnson, R.W., Mackenzie, D.E. & Smith, I.E.M. 1978. Delayed partial melting of subduction-modified mantle in papua new guinea. Tectonophysics, 46, 197-216.

Jolivet, L., Frizon de Lamotte, D., Mascale, A. & Séranne, M. 1999. The Mediterranean Basins: Tertiary extension within the Alpine orogen - an introduction. In: Durand, B., Jolivet, L., F., H. & Séranne, M. (eds) The Mediterranean Basins: Tertiary Extension within the Alpine Orogen. - Geological Society, London, Special Publications 156, 1-14.

Jovanovic, M., Downes, H., Vaselli, O., Cvetkovic, V., Prelevic, D. & Pécskay, Z. 2001. Paleogene mafic alkaline volcanic rocks of East Serbia. In: Downes, H. & Vaselli, O. (eds) Tertiary magmatism in the Dinarides Balkan Peninsula. - Acta Vulcanologica 13, 159-173.

Juteau, M., Michard, A. & Albarede, F. 1986. The Pb-Sr-Nd isotope geochemistry of some recent circum-Mediterranean granites. Contrib. Mineral. Petrol., 92, 331-340.

Kagami, H., Ulmer, P., Hansmann, W., Dietrich, V. & Steiger, R.H. 1991. Nd-Sr isotopic and geochemical characteristics of the southern Adamello (northern Italy) intrusives: implications for crustal versus mantle origin. Journal of Geophysical Research, 96, 14331-14346.

Karamata, S., Dimitrijevic, M.N. & Dimitrijevic, M.D. 1999. Oceanic realms in the central part of the Balkan Peninsula during the Mesozoic. Slovak Geological Magazin, 5, 173-177.

Karamata, S. & Krstic, B. 1996. Terranes of Serbia and neighbouring areas. In: Knezevic, V. & Krstic, B. (eds) Terranes of Serbia, Beograd, 25-40.

Karamata, S., Olujic, J., Protic, L., Milovanovic, D., Vujnovic, L., Popevic, A., Memovic, E., Radovanovic, Z. & Resimic-Saric, K. 2000. The western belt of the Vardar Zone - the remnant of a marginal sea. In: Karamata, S. & Jankovic, S. (eds) Geology and metallogeny of the Dinarides and the Vardar Zone, Bajna Luka-Srpsko Sarajevo. Collections and Monographs 1, The Academy of Sciences and Arts of the Republic Srpska.

Keller, J. 1982. Mediterranean island arcs. In: Thorpe, R.S. (eds) Adesites, Wiley, Chichester, 307-325.

Kürkçüoglu, B., Sen, E., Aydar, E., Gourgaud, A. & Gündogdu, N. 1998. Geochemical approach to magmatic evolution of Mt. Ercyies stratovolcano, central Anatolia, Turkey. Journal of Volcanology and Geothermal Research, 85, 473-494.

Laubscher, H.P. 1983. The late Alpine (Periadriatic) intrusions and the Insubric Line. Memorie della Società Geologica Italiana, 26, 21-30.

Lavecchia, G., Boncio, P., Creati, N. & Brozzetti, F. 2003. Some aspects of the Italian geology not fitting with a subduction scenario. Journal of Virtual Explorer, 10, 1-14.

Lavecchia, G. & Stoppa, F. 1996. The tectonic significance of Italian magmatism: an alternative view to the popular interpretation. Terra Nova, 8, 435-446.

Le Pennec, J.-L., Bourdier, J.-L., Froger, J.-L., Temel, A., Camus, G. & Gourgaud, A. 1994. Neogene ignimbrites of the Nevsehir plateau (Central Turkey): stratigraphy, distribution and source constraints. Journal of Volcanology and Geothermal Research, 63, 59-87.

Le Pichon, X. & Angelier, J. 1979. The Hellenic Arc and trench system: a key to the neotectonic evolution of the eastern Mediterranean area. Tectonophysics, 60, 1-42.

Lexa, J. & Konecný, V. 1998. Geodynamic aspects of the Neogene to Quaternary volcanism. In: Rakús, M. (eds) Geodynamic development of the Western Carpathians, Geological Survey of Slovak Republik, Bratislava, 219-240.

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

Louni-Hacini, A., Bellon, H., Maury, R.C., Megartsi, M., Coulon, C., Semroud, B., Cotten, J. & Coutelle, A. 1995. Datation 40K-40Ar de la transition du volcanisme calco-alcalin au volcanisme alcaline en Oranie au Miocène supérieur. Comptes Rendus de l'Académie des Sciences, 321, 975-982.

Lustrino, M. 2000. Volcanic activity from the Neogene to the Present evolution of the Western Mediterranean area. A review. Ofioliti, 25, 87-101.

Lustrino, M. & Dallai, L. 2003. On the origin of EM-I end-member. Neues Jahrbuch Mineralogie Abhandlungen, 179, 85-100.

Lustrino, M., Melluso, L. & Morra, V. 2000. The role of lower continental crust and lithospheric mantle in the genesis of Plio-Pleistocene volcanic rocks from Sardinia (Italy). Earth and Planetary Science Letters, 180, 259-270.

Macera, P., Gasperini, D., Piromallo, C., Blichert-Toft, J., Bosch, D., Del Moro, A. & Martin, S. 2003. Geodynamic implications of deep mantle upwelling in the source of Tertiary volcanics from the Veneto region (South-Eastern Alps). Journal of Geodynamics, 36, 563-590.

Makropoulos, K.C. & Burton, P.W. 1984. Greek tectonics and seismicity. Tectonophysics, 106, 275-304.

Malinverno, A. & Ryan, W.B.F. 1986. Extension of the Tyrrhenian Sea and shortening in the Appennines as result of arc migration driven by sinking lithosphere. Tectonics, 5, 227-245.

Mann, A.C. 1983. Trace element geochemistry of high alumina basalt-andesite-dacite-rhyolite lavas of the main volcanic series of Santorini Volcano, Greece. Contributions to Mineralogy and Petrology, 84, 43-57.

Marchev, P., Rogers, G., Conrey, R., Quick, J., Vaselli, O. & Raicheva, R. 1998. Paleogene orogenic and alkaline basic magmas in the Rhodope zone: relationships, nature of magma sources, and role of crustal contamination. In: Christofides, G., Marchev, P. & Serri, G. (eds) Tertiary magmatism of the Rhodopian Region. - Acta Vulcanologica 10, 217-232.

Martí, J., Mitjavila, J., Roca, E. & Aparicio, A. 1992. Cenozoic magmatism in the Valencia Trough (western Mediterranean): relationship between structural evolution and volcanism. Tectonophysics, 203, 155-166.

Mason, P.R.D., Downes, H., Thirlwall, M., Seghedi, I., Szakács, A., Lowry, D. & Mattey, D. 1996. Crustal assimilation as a major petrogenetic process in east Carpathian Neogene to Quaternary continental margin arc magmas. Journal of Petrology, 37, 927-959.

Mason, P.R.D., Seghedi, I., Szakacs, A. & Downes, H. 1998. Magmatic constraints on geodynamic models of subduction in the East Carpathians, Romania. Tectonophysics, 297, 157-176.

Mattey, D., Lowry, D. & Macpherson, C. 1994. Oxygen isotope composition of mantle peridotite. Earth and Planetary Science Letters, 128, 231-241.

Mazzuoli, R., Tortorici, L. & Ventura, G. 1995. Oblique rifting in Salina, Lipari and Vulcano islands (Aeolian island, southern Italy). Terra Nova, 7, 444-452.

McKenzie, D. 1972. Active tectonics of the Mediterranean region. Geophysical Journal of the Royal Astronomical Society, 30, 109-185.

McKenzie, D. 1978. Active tectonics of the Alpine-Himalayan belt: the Aegean Sea and surrounding regions. Geophysical Journal of the Royal Astronomical Society, 55, 217-254.

Meibom, A. & Anderson, D.L. 2003. The statistical upper mantle assemblage. Earth and Planetary Science Letters, 217, 123-139.

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

Meulenkamp, J.E., Wortel, M.J.R., van Wamel, W.A., Spakman, W. & Hoogerduyn-Starting, E. 1988. On the Hellenic subduction zone and the geodynamic evolution of Crete since the late Middle Miocene. Tectonophysics, 146, 203-216.

Milani, L., Beccaluva, L. & Coltorti, M. 1999. Petrogenesis and evolution of the Euganean magmatic complex, Veneto Region, North-East Italy. European Journal of Mineralogy, 11, 379-399.

Mitropoulos, P., Saunders, A.D. & Marsh, N.G. 1987. Petrogenesis of Cenozoic volcanic rocks from the Aegean Island Arc. Journal of Volcanology and Goethermal Research, 32, 177-193.

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

Müller, D., Stumpfl, E.F. & Taylor, W.R. 1992. Shoshonitic and alkaline lamprophyres with elevated Au and PGE concentrations from the Kreuczek Mountains, Eastern Alps, Austria. Miner. Petrol. Mitt., 46, 23-42.

Nelson, D.R., McCulloch, M.T. & Sun, S.-S. 1986. The origins of ultrapotassic rocks as inferred from Sr, Nd and Pb isotopes. Geochimica et Cosmochimica Acta, 50, 231-245.

Nemcok, M., Pospisil, L., Lexa, J. & Donelick, R.A. 1998. Tertiary subduction and slab break-off model of the Carpathian-Pannonian region. Tectonophysics, 295, 307-340.

Niu, Y., Collerson, K.D., Batiza, R., Wendt, J.I. & Regelous, M. 1999. The origin of E-type MORB at ridges far from mantle plumes: The East Pacific Rise at 11o20'. Journal of Geophysical Research, 104, 7067-7087.

Niu, Y. & O'Hara, M.J. 2003. Origin of ocean island basalts: A new perspective from petrology, geochemistry, and mineral physics considerations. Journal of Geophysical Research, 108, 2209.

Nixon, P.H., Thirlwall, M.F., Buckley, F. & Davies, C.J. 1984. Spanish and Western Australian lamproites: aspects of whole rock geochemistry. In: Kornprobst, J. (eds) Kimberlites I: Kimberlites and Related Rocks., Elsevier, Amsterdam, 285-296.

Oncescu, M.C. & Bonjer, K. 1997. A note on the depth recurrence and strain release of large Vrancea earthquakes. Tectonophysics, 272, 291-302.

Oncescu, M.C., Burlacu, V., Anghel, M. & Smalberger, V. 1984. Three-dimensional P-wave velocity image under the Carpathian arc. Tectonophysics, 106, 305-319.

Oyarzun, R., Doblas, M., López-Ruiz, J. & Cebriá, J.M. 1997. Opening of the central Atlantic and asymmetric mantle upwelling phenomena: Implications for long-lived magmatism in western North Africa and Europe. Geology, 25, 727-730.

Pamic, J., Balen, D. & Herak, M. 2002. Origin and geodynamic evolution of Late Paleogene magmatic associations along the Periadriatic-Sava-Vardar magmatic belt. Geodinamica Acta, 15, 209-231.

Pamic, J., McKee, E.H., Bullen, T.D. & Lanphere, M.A. 1995. Tertiary Volcanic Rocks from the Southern Pannonian Basin, Croatia. International Geology Review, 37, 259-283.

Pasquare, G., Poli, G., Vezzoli, L. & Zanchi, A. 1988. Continental arc volcanism and tectonic setting in Central Anatolia, Turkey. Tectonophysics, 146, 217-230.

Pearce, J.A. 1982. Trace element characteristics of lavas from destructive plate boundaries. In: Thorpe, R.S. (eds) Andesites. Orogenic andesites and related rocks, J. Wiley and Sons, 525-548.

Pearce, J.A., Bender, J.F., De Long, S.E., Kidd, W.S.F., Low, P.J., Guner, Y., Saroglu, F., Yilmaz, Y., Moorbath, S. & Mitchell, J.G. 1990. Genesis of collision volcanism in Eastern Anatolia, Turkey. Journal of Volcanology and Geothermal Research, 44, 189-229.

Pearce, J.A. & Cann, J.R. 1973. Tectonic setting of basic volcanic rocks determined using trace element analyses. Earth and Planetary Science Letters, 19, 290-300.

Pearce, J.A. & Parkinson, I.J. 1993. Trace element models for mantle melting: application to volcanic arc petrogenesis. In: Prichard, H.M., Alabaster, T., Harris, N.B.W. & Neary, C.R. (eds) Magmatic Processes and Plate Tectonics - Geological Society Special Publication 76, 373-403.

Pearce, J.A. & Peate, D.W. 1995. Tectonic implications of the composition of volcanic arc magmas. Annual Review of Earth and Planetary Sciences, 23, 251-285.

Peccerillo, A. 1985. Roman comagmatic province (central Italy): Evidence for subduction-related magma genesis. Geology, 13, 103-106.

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. 2001. Geochemical similarities between th Vesuvius, Phlegrean Field and Stromboli volcanoes: petrogenetic, geodynamic and volcanological implications. Mineralogy and Petrology, 73, 93-105.

Peccerillo, A. 2003. Plio-Quaternary magmatism in Italy. Episodes, 26, 222-226.

Peccerillo, A., Conticelli, S. & Manetti, P. 1987. Petrological characteristics and the genesis of the recent magmatism of South Tuscany and North Latium. Period. Mineral., 56, 167-183.

Peccerillo, A., Kempton, P.D., Harmon, R.S., Wu, T.W., Santo, P., Boyce, A.J. & Tripodo, A. 1993. Petrological and geochemical characteristics of the Alicudi volcano, Aeolian Islands, Italy: implications for magma genesis and evolution. Acta Vulcanologica, 3, 235-249.

Pécskay, Z., Lexa, J., Szakács, A., Balogh, K., Seghedi, I., Konecny, V., Kovács, M., Márton, E., Kaliciak, M., Széky-Fux, V., Póka, T., Gyarmati, P., Edelstein, O., Rosu, E. & Zec, B. 1995. Space and time distribution of Neogene-Quartenary volcanism in the Carpatho-Pannonian Region. In: Downes, H. & Vaselli, O. (eds) Neogene and related volcanism in the Carpatho-Pannonian Region 7, Acta Vulcanologica, 15-28.

Pe-Piper, G. & Piper, D.J.W. 1989. Spatial and temporal variation in Late Cenozoic back-arc volcanic rocks, Aegean Sea region. Tectonophysics, 169, 113-134.

Pe-Piper, G., Piper, D.J.W., Kotopouli, C.N. & Panagos, A.G. 1995. Neogene volcanoes of Chios, Greece: the relative importance of subduction and back-arc extension. In: Smellie, J.L. (eds) Volcanism Associated with Extension at Consuming Plate Margins. - Geological Soc.Spec.Publ. 81, 213-231.

Piromallo, C. & Morelli, A. 2003. P wave tomography of the mantle under the Alpine-Mediterranean area. Journal of Geophysical Research, 108, 2065, doi:10.1029/2002JB001757.

Piromallo, C., Vincent, A.P., Yuen, D.A. & Morelli, A. 2001. Dynamics of the trasition zone under Europe inferred from wavelet cross-spectra of seismic tomography. Physics of the Earth and Planetary Interiors, 125, 125-139.

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

Prelevic, D., Cvetkovic, V., Foley, S.F., Jovanovic, M. & Melzer, S. 2001. Tertiary ultrapotassic-potassic rocks from Serbia, Yugoslavia. In: Downes, H., Vaselli, O. (eds) Tertiary magmatism in the Dinarides Balkan Peninsula. - Acta Vulcanologica 13, 101-115.

Rahn, M., Stern, W.B. & Frey, M. 1995. The origin of the Taveyannaz sandstone: arguments from whole-rock and clinopyroxene composition. Schweitzerische Mineralogische Petrographische Mitteilungen, 75, 213-224.

Ratschbacher, L., Frisch, W., Linzer, H.-G. & Merle, O. 1991. Lateral extrusion in the eastern Alps, 2. Structural analysis. Tectonics, 10, 257-271.

Reagan, M.K., Morris, j.D., Herrstrom, E.A. & Murrell, M.T. 1994. Uranium series and beryllium isotope evidence for an extended history of subduction modification of the mantle below Nicaragua. Geochimica et Cosmochimica Acta, 58, 4199-4212.

Robert, U., Foden, J. & Varne, R. 1992. The Dodecanese Province, SE Aegean: A model for tectonic control on potassic magmatism. Lithos, 28, 241-260.

Rogers, N.W., Hawkesworth, C.J., Parker, R.J. & Marsh, J.R. 1985. The geochemistry of potassic lavas from Vulsini, central Italy and implications for mantle enrichment processes beneath the Roman region. Contributions to Mineralogy and Petrology, 90, 244-257.

Rosu, E., Szakács, A., Downes, H., Seghedi, I., Pécskay, Z. & Panaiotu, C. 2001. The origin of Neogene calc-alkaline and alkaline magmas in the Apuseni Mountains, Romania: the adakite connection. Rom. Journal of Mineral Deposits, 71, suppl.2. ABCD-Geode 2001 workshop, 3-23.

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

Royden, L.H. & Burchfiel, B.C. 1989. Are systematic variations in thrust belt style related to plate boundary process? (The Western Alps versus the Carpathians). Tectonics, 8, 51-61.

Royden, L.H., Horváth, F. & Burchfiel, B.C. 1982. Transform faulting, extension and subduction in the Carpathian-Pannonian region. Geological Society of America Bullettin, 93, 717-725.

Rutter, M.J. 1987. Evidence for crustal assimilation by turbulently convecting, mafic alkaline magmas: geochemistry of mantle-xenolith-bearing lavas from Northern Sardinia. Journal of Volcanology and Geothermal Research, 32, 343-354.

Salters, V.J.M., Hart, S.R. & Gy., P. 1988. Origin of Late Cenozoic volcanic rocks of the Carpathian arc, Hungary. In: Royden, L.H. & F., H. (eds) The Pannonian Basin. A study in basin evolution. Am. Assoc. Pet. Geol. Mem. 45, 279-292.

Santacroce, R., Cristofolini, R., La Volpe, L., Orsi, G. & Rosi, M. 2003. Italian active volcanoes. Episodes, 26, 227-234.

Savasçin, M.Y., Agostini, S., Doglioni, C., Innocenti, F., Kaya, O., Manetti, P. & Tokçaer, M. 2000. Late Cenozoic shoshonitic volcanism in south Western Anatolia. IESCA 2000 Abstracts, T5, 95.

Schutte, K.G. 1978. Crustal structure of southern Italy. In: Closs, H., Roeder, D. & Schmidt, K. (eds) Alps, Apennines, Hellenides. Schweiserbart, Stuttgart, 315-321.

Seghedi, I., Balintoni, I. & Szakacs, A. 1998. Interplay of tectonics and neogene post-collisional magmatism in the intracarpathian region. Lithos, 45, 483-497.

Seghedi, I., Downes, H., Pecskay, Z., Thirlwall, M.F., Szakacs, A., Prychodko, M. & Mattey, D. 2001. Magmagenesis in a subduction-related post-collisional volcanic arc segment: the Ukrainian Carpathians. Lithos, 57, 237-262.

Seghedi, I., Downes, H., Szakacs, A., Mason, P.R.D., Thirlwall, M.F., Rosu, E., Pecskay, Z., Marton, E. & Panaiotu, C. 2004. Neogene-Quaternary magmatism and geodynamics in the Carpathian-Pannonian region: a synthesis. Lithos, 72, 117-146.

Sengör, A.M.C. & Kidd, W.S.F. 1979. Post-collisional tectonics of the Turkish-Iranian plateau and a comparison with Tibet. Tectonophysics, 55, 361-376.

Sengör, A.M.C. & Yilmaz, Y. 1981. Tethyan evolution of Turkey; a plate tectonic approach. Tectonophysics, 75, 181-241.

Serri, G. 1990. Neogene-Quaternary magmatism of the Tyrrhenian region: characterization of the magma sources and geodynamic implications. Memorie della Società Geologica Italiana, 41, 219-242.

Serri, G., Innocenti, F. & 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.

Seyitoglu, G., Anderson, D., Nowell, G. & Scott, B. 1997. The evolution from Miocene potassic to Quaternary sodic magmatism in western Turkey: implications for enrichment processes in the lithospheric mantle. Journal of Volcanology and Geothermal Research, 76, 127-147.

Seyitoglu, G. & Scott, B.C. 1992. Late Cenozoic volcanic evolution of the northeastern Aegean region. Journal of Volcanology and Geothermal Research, 54, 157-176.

Seyitoglu, G. & Scott, B.C. 1996. The cause of N_S extensional tectonics in Western Turkey: tectonic escape vs. back-arc spreading vs. orogenic collapse. Journal of Geodynamics, 22, 145-153.

Spakman, W. 1990. Images of the upper mantle of central Europe and the Mediterranean. Terra Nova, 2, 542-553.

Spakman, W., Van Der Lee, S. & Van Der Hilst, R.D. 1993. Travel-time tomography of the European-Mediterranean mantle down to 1400 km. Physics of the Earth and Planetary Interiors, 79, 3-74.

Spakman, W., Wortel, M.J.R. & Vlaar, N.J. 1988. The Hellenic subduction zone: a tomographic image and its geodynamic implications. Geophys. Res. Lett., 15, 60-63.

Sperner, B., Lorenz, F., Bonjer, K., Hettel, S., Muller, B. & Wenzel, F. 2001. Slab break-off - abrupt cut or gradual detachment? New insights from the Vrancea Region (SE Carpathians, Romania). Terra Nova, 13, 172-179.

Sperner, B., Ratschbacher, L. & Nemcok, M. 2002. Interplay between subduction retreat and lateral extrusion: tectonics of the Western Carpathians. Tectonics, 21, 1051, doi:10.1029/2001TC901028.

Stampfli, G.M., Mosar, J., Favre, F., Pillevuit, A. & Vannay, J.C. 2001. Permo-Mesozoic evolution of the western Tethys realm: the Neo-Tethys East-Mediterranean Basin connection. In: Ziegler, P.A., Cavazza, W., Robertson, A.H.F. & Crasquin-Soleau, S. (eds) Peri-Tethyan rift/wrench basins passive margins. Peri-Tethys Memoir 6, Mem. Mus. Nat. Hist. Nat. 186, 1-20.

Stoppa, F. & Cundari, A. 1995. A new carbonatite occurrence at Cupaello (Rieti) and its genetic significance. Contributions to Mineralogy and Petrology, 122, 275-288.

Stoppa, F. & Lavecchia, G. 1992. Late Pleistocene ultra-alkaline magmatic activity in the Umbria-Latium region (Italy): An overview. Journal of Volcanology and Geothermal Research, 52, 277-293.

Stoppa, F. & Woolley, A.R. 1996. Italian carbonatites: field occurence, petrology and regional significance. Mineralogy and Petrology, 59, 43-67.

Sun, S.-S. & McDonough, W.F. 1989. Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. In: Saunders, A.D. & Norry, M.J. (eds) Magmatism in the Ocean Basins. - Geological Society Special Publication 42, 313-345.

Szabo, C., Harangi, S. & Csontos, L. 1992. Review of Neogene and Quaternary volcanism of the Carpathian-Pannonian region. Tectonophysics, 208, 243-256.

Tanguy, J.-C., Condomines, M. & Kieffer, G. 1997. Evolution of the Mount Etna magma: Constraints on the present feeding system and eruptive mechanism. Journal of Volcanology and Geothermal Research, 75, 221-250.

Tankut, A., Wilson, M. & Yihunie, T. 1998. Geochemistry and tectonic setting of Tertiary volcanism in the Güvem area, Anatolia, Turkey. Journal of Volcanology and Geothermal Research, 85, 285-301.

Tari, G., Dövényi, P., Horváth, F., Dunkl, I., Lenkey, L., Stefanescu, M., Szafián, P. & Tóth, T. 1999. Lithospheric structure of the Pannonian basin derived from seismic, gravity and geothermal data. In: Durand, B., Jolivet, L., Horváth, F. & Séranne, M. (eds) The Mediterranean Basins: Tertiary extension within the Alpine orogen. - Geological Society, London, Special Publication 156, 215-250.

Tatsumi, Y., Hamilton, D.L. & Nesbitt, R.W. 1986. Chemical characteristics of fluid phase released from a subducted lithosphere and the origin of arc magmas: evidence from high pressure experiments and natural rocks. J. Volcanol. Geotherm. Res., 29, 293-309.

Taylor, H.P.J. 1968. The oxygen isotope geochemistry of igneous rocks. Contributions to Mineralogy and Petrology, 19, 1-71.

Taylor, H.P.J. 1980. The effects of assimilation of country rocks by magmas on 18O/16O and 87Sr/86Sr systematics in igneous rocks. Earth and Planetary Science Letters, 47, 243-254.

Taylor, H.P.J., Gianetti, B. & Turi, B. 1979. Oxygen isotope geochemistry of the potassic rocks from the Roccamonfina volcano, Roman comagmatic region, Italy. Earth and Planetary Science Letters, 46, 81-106.

Temel, A., Gundogdu, M.N. & Gourgaud, A. 1998. Petrological and geochemical characteristics of Cenozoic high-K calc-alkaline volcanism in Konya, Central Anatolia, Turkey. Journal of Volcanology and Geothermal Research, 85, 327-354.

Temel, A., Gundogdu, M.N., Gourgaud, A. & Le Pennec, J.-L. 1998. Ignimbrites of Cappadocia (Central Anatolia, Turkey): petrology and geochemistry. Journal of Volcanology and Geothermal Research, 85, 447-471.

Tera, F., Brown, L., Morris, J., Sacks, I.S., Klein, J. & Middleton, R. 1986. Sediment incorporation in island arc magmas: inferences from 10Be. Geochimica et Cosmochimica Acta, 50, 535-550.

Thompson, R.N. 1977. Primary basalts and magma genesis. III. Alban Hills Roman Comagmatic Province, Central Italy. Contributions to Mineralogy and Petrology, 60, 91-108.

Thorpe, R.S. 1982. Andesites, Orogenic andesites and related rocks. Wiley and Sons Ltd.

Tollmann, A. 1987. The Alpidic evolution of the Eastern Alps. In: Flügel, H.W. & Faulp, P. (eds) Geodynamics of the Eastern Alps., Deuticke, Vienna, 361-378.

Tomek, C. & Hall, J. 1993. Subducted continental margin imaged in the Carpathians of Czechoslovakia. Geology, 21, 535-538.

Tonarini, S., Armienti, P., D'Orazio, M. & Innocenti, F. 2001. Subduction-like fluids in the genesis of Mt. Etna magmas: evidence from boron isotopes and fluid mobile elements. Earth and Planetary Science Letters, 192, 471-483.

Tonarini, S., Armienti, P., D'Orazio, M., Innocenti, F., Pompilio, M. & Petrini, R. 1995. Geochemical and isotopic monitoring of Mt. Etna 1989-1993 eruptive activity: bearing on the shallow feeding system. Journal of Volcanology and Geothermal Research, 64, 95-115.

Torres-Roldán, R.L., Poli, G. & Peccerillo, A. 1986. An early Miocene arc-tholeiitic magmatic dyke event from the Alboran Sea: Evidence for pre-collisional subduction and back arc crustal extension in the westernmost Mediterranean. Geologisches Rundschau, 71, 219-234.

Trua, T., Esperanca, S. & Mazzuoli, R. 1998. The evolution of the lithospheric mantle along the North African Plate: geochemical and isotopic evidence from the tholeiitic and alkaline volcanic rocks of the Hyblean plateau, Italy. Contributions to Mineralogy and Petrology, 131, 307-322.

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

Turi, B. & Taylor, H.P. 1976. Oxygen isotope studies of potassic volcanic rocks of the Roman Province, central Italy. Contributions to Mineralogy and Petrology, 55, 1-31.

Turner, S., Arnaud, N., Liu, J., Rogers, N.W., Hawkesworth, C., Harris, N.B.W., Kelley, S.P., van Calsteren, P. & Deng, W. 1996. Post-collisional, shoshonitic volcanism on the Tibetan Plateau: implications for convective thinning of the lithosphere and the source of ocean island basalts. Journal of Petrology, 37, 45-71.

Turner, S., Bourdon, B., Hawkesworth, C. & Evans, P. 2000. 226Ra-230Th evidence for multiple dehydration events, rapid melt ascent and the time scales of differentiation beneath the Tonga-Kermadec island arc. Earth and Planetary Science Letters, 179, 581-593.

Turner, S.P., Platt, J.P., George, R.M.M., Kelley, S.P., Pearson, D.G. & Nowell, G.M. 1999. Magmatism associated with orogenic collapse of the Betic-Alboran Domain, SE Spain. Journal of Petrology, 40, 1011-1036.

Ulmer, P., Callegari, E. & Sonderegger, U.C. 1983. Genesis of the mafic and ultramafic rocks and their genetical relations to the tonalitic-trondhjemitic granitoids of the southern part of the Adamello batholith (Northern Italy). Memorie della Società Geologica Italiana, 26, 171-222.

van der Muelen, M.J., Meulenkamp, J.E. & Wortel, M.J.R. 1998. Lateral shifts of Apenninic foredeep depocentres reflecting detachment of subducted lithosphere. Earth and Planetary Science Letters, 154, 203-219.

Venturelli, G., Capedri, S., Di Battistini, G., Crawford, A., Kogarko, L.N. & Celestini, S. 1984. The ultrapotassic rocks from southeastern Spain. Lithos, 17, 37-54.

Venturelli, G., Salvioli Mariani, E., Foley, S.F., Capedri, S. & Crawford, A.J. 1988. Petrogenesis and conditions of crystallization of Spanish lamproitic rocks. Canadian Mineralogist, 26, 67-79.

Venturelli, G., Thorpe, R.S., Dal Piaz, G.V., Del Moro, A. & Potts, P.J. 1984. Petrogenesis of calc alkaline, shoshonitic and associated ultrapotassic Oligocene volcanic rocks from the Northwestern Alps, Italy. Contributions to Mineralogy and Petrology, 86, 209-220.

Vissers, R.L.M., Platt, J.P. & 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-Th-Pb systematics of alkaline rocks: the alkaline rocks from Italy. Geochimica et Cosmochimica Acta, 40, 283-295.

Vollmer, R. 1989. On the origin of the Italian potassic magmas. 1. A discussion contribution. Chemical Geology, 74, 229-239.

Vollmer, R., Johnston, K., Ghiara, M.R., Lirer, L. & Munno, R. 1981. Sr isotope geochemistry of megacrysts from continental rift and converging plate margin alkaline volcanism in South Italy. Journal of Volcanology and Geothermal Research, 11, 317-327.

Von Blanckenburg, F. 1992. Combined high-precision chronometry and geochemical tracing using accessory minerals: applied to the central-Alpine Bergell intrusion (central Europe). Chemical Geology, 100, 19-40.

Von Blanckenburg, F. & Davis, J.H. 1995. Slab breakoff: a model for syncollisional magmatism and tectonics in the Alps. Tectonics, 14, 120-131.

Von Blanckenburg, F., Kagami, H., Deutsch, A., Oberli, F., Meier, M., Wiedenbeck, M., Barth, S. & Fischer, H. 1998. The origin of Alpine plutons along the Periadriatic lineament. Schweitz. Mineral. Petrogr. Mitt., 78, 55-66.

Waibel, A.F. 1993. Nature and plate-tectonic significance of orogenic magmatism in the European Alps: a review. Schweiz. Mineral. Petrogr. Mitt., 73, 391-405.

Wang, K.-L., Chung, S.-L., O'Reilly, S.Y., Sun, S.-S., Shinjo, R. & Chen, C.-H. 2004. Geochemical constraints for the genesis of post-collisional magmatism and the geodynamic evolution of the Northern Taiwan Region. Journal of Petrology, 45, 975-1011.

Weaver, B.L. 1991. The origin of ocean island basalt end-member compositions: trace element and isotopic constraints. Earth and Planetary Science Letters, 104, 381-397.

Wenzel, F., Lorenz, F., Sperner, B. & Oncescu, M.C. 1998. Seismotectonics of the Romanian Vrancea area. In: Wenzel, F.e.a. (eds) Vrancea Earthquakes, Kluwer, Dordrecht, 15-25.

White, W.M. 1985. Sources of oceanic basalts: radiogenic isotope evidence. Geology, 13, 115-118.

Wilson, M. 1989. Igneous Petrogenesis. Unwin Hyman, London., 466 pp.

Wilson, M. 1997. Thermal evolution of the Central Atlantic passive margins: continental break-up above a Mesozoic super-plume. Journal of the Geological Society, London, 154, 491-495.

Wilson, M. & Bianchini, G. 1999. Tertiary-Quaternary magmatism within the Mediterranean and surrounding regions. In: Durand, B., Jolivet, L., Horváth, F. & Séranne, M. (eds) The Mediterranean Basins: Tertiary extension within the Alpine orogen. - Geological Society London Special Publication 156, 141-168.

Wilson, M. & Downes, H. 1991. Tertiary-Quaternary extension-related alkaline magmatism in Western and Central Europe. Journal of Petrology, 32, 811-849.

Wilson, M., Tankut, A. & Güleç, N. 1997. Tertiary volcanism of the Galatia Province, Central Anatolia, Turkey. Lithos, 42, 105-121.

Wong, S.Y.M., Ton, A. & Wortel, M.J.R.-., , . 1997. Slab detachment in continental collision zones: an analysis of controlling parameters. Geophys. Res. Lett., 24, 2095-2098.

Wood, D.A. 1980. The application of a Th Hf Ta diagram to problems of tectonomagmatic classification and to establishing the nature of crustal contamination of basaltic lavas of the British Tertiary volcanic province. Earth and Planetary Science Letters, 50, 11-30.

Wortel, M.J.R. & Spakman, W. 1992. Structure and dynamics of subducted lithosphere in the Mediterranean. Procedings of the Nederlandse Akadamie voor Wetenschappen, 95, 325-347.

Wortel, M.J.R. & W., S. 2000. Subduction and Slab Detachment in the Mediterranean-Carpathian Region. Science, 290, 1910-1917.

Yilmaz, Y., Genc, S.C., Karacik, Z. & Altunkaynak, S. 2001. Two contrasting magmatic associations of NW Anatolia and their tectonic significance. Journal of Geodynamics, 31, 243-271.

Yilmaz, Y. & Polat, A. 1998. Geology and evolution of the Thrace volcanism, Turkey. In: Christofides, G., Marchev, P. & Serri, G. (eds) Tertiary magmatism of the Rhodopian Region. - Acta Vulcanologica 10, 293-303.

Zampieri, D. 1995. Tertiary extension in the Southern Trento Platform, Southern Alps, Italy. Tectonics, 14, 645-657.

Zeck, H.P. 1970. An erupted migmatite from Cerro del Hoyazo, SE Spain. Contributions to Mineralogy and Petrology, 26, 225-246.

Zeck, H.P. 1992. Restite-melt and mafic-felsic magma mixing and mingling in an S-type dacite, Cerro del Hoyazo, southeastern Spain. Trans. Royal Soc. Edinburgh: Earth Sciences, 83, 139-144.

Zeck, H.P. 1996. Betic-Rif orogeny: subduction of Mesozoic Tethys lithosphere under eastward drifting Iberia, slab detachment shortly before 22 Ma, and subsequent uplift and extension tectonics. Tectonophysics, 254, 1-16.

Zeck, H.P. 1999. Alpine plate kinematics in the western Mediterranean: a westward-directed subduction regime followed by slab roll-back and slab detachment. In: Durand, B., Jolivet, L., Horváth, F. & Séranne, M. (eds) The Mediterranean Basins: Tertiary extension within the Alpine Orogen. - Geological Society, London, Special Publications. 156, 109-120.

Zeck, H.P., Albat, F., Hansen, B.T., Torres-Roldán, R.L. & Garcia-Casco, A. 1989. Alpine tourmaline-bearing muscovite leucogranites, intrusion age and petrogenesis, Betic Cordilleras, SE Spain. Neues Jahrbuch Mineralogie, 11, 513-520.

Zeck, H.P., Kristensen, A.B. & Williams, I.S. 1998. Post-collisional volcanism in a sinking slab setting--crustal anatectic origin of pyroxene-andesite magma, Caldear Volcanic Group, Neogene Alboran volcanic province, southeastern Spain. Lithos, 45, 499-522.

Zindler, A. & Hart, S.R. 1986. Chemical geodynamics. Annual Review of Earth and Planetary Sciences, 14, 493-571.

Figure captions

Figure 1. Simplified map for the distribution of Tertiary to Quaternary volcanic rocks in central and southern Europe. Dark blue areas indicate oceanic crust.

ECRIS= European Cenozoic Rift System, BAR=Betic-Alboran-Rif province (Ab=Alboran, Be=Betic, RTG=Gourougou-Trois Furches-Ras Tarf (Rif), Or=Oranie, Ca=Calatrava, Ol=Olot), CM=Central Mediterranean (Sa=Sardinia, Si=Sisco, Tu=Tuscany, Rp=Roman province, Ca=Campania, Vu=Vulture, Va=Vavilov, Ma=Marsili, Us=Ustica, Ai=Aeolian Islands, Et=Etna, Hy=Hyblei, Pa=Pantelleria), PIL=Periadriatic-Insubric Line (Be=Bergell, Ad=Adamello, Po=Pohorje, Ve=Veneto), CPR=Carpathian-Pannonian region (WC=Western Carpathians, NEC=Northeastern Carpathians, EC=Eastern Carpathians, Ap=Apuseni), DR=Dinarides and Rhodope (Di=Dinarides, RT=Rhodope-Thrace), AA=Aegean-Anatolia (Sa=Santorini, WA=Western Anatolia, Ku=Kula, Af=Afyon, Ko=Konya, Ga=Galatia, CA=Central Anatolia)

Figure 2. Geodynamic settings for generation of calc-alkaline magmas: A. Magmatism at active subduction; B. lithospheric extension-related magmatism following an earlier subduction event; C. slab break-off magmatism; D. post-collisional lithospheric delamination-related magmatism

Figure 3. N-MORB (Pearce & Parkinson 1993) normalized trace element pattern of selected ‘subduction-related’ volcanic rocks. Mariana (volcanic arc): Elliott *et al.* (1997); South Andes (active continental margin): Davidson *et al.* (1990); Columbia River Trough (intracontinental extensional area): Bradshaw *et al.* (1993). The arrows represent the typical depletion and enrichment features in ‘subduction-related’ volcanic rocks.

Figure 4. Migration of subduction zones in the Alpine-Mediterranean region during the Tertiary to Quaternary (after Wortel & Spakman, 2000).

Figure 5. Age distribution of the Tertiary to Quaternary magmatism in the Alpine-Mediterranean region. Data are from Bellon *et al.* (1983), Fytikas *et al.* (1984), Beccaluva *et al.* (1985; 1987; 1991), Di Battistini *et al.* (1987), Peccerillo *et al.* (1987), Aparico *et al.* (1991), Conticelli & Peccerillo (1992), Martí *et al.* (1992), Seyitoglu & Scott (1992), Serri *et al.* (1993), Louni-Hacini *et al.* (1995), Pécskay *et al.* (1995), Christofides *et al.* (1998), El Bakkali *et al.* (1998), Harkovska *et al.* (1998), Marchev *et al.* (1998), von Blanckenburg *et al.* (1998), Wilson & Bianchini (1999), Aldanmaz *et al.* (2000), Roşu *et al.* (2001), Coulon *et al.* (2002), Pamić, *et al.* (1995; 2002), Cvetković *et al.* (2004), Duggen *et al.* (2004) and further references therein. WM=Western Mediterranean, CM=Central Mediterranean, ALCAPA=Alps-Carpathians-Pannonian region, DEM=Dinarides and Eastern Mediterranean.

Figure 6. SiO_2 vs. K_2O diagrams (Gill 1981; Sh=shoshonite series, HKCA=High-K calc-alkaline series, CA=calc-alkaline series, Th=low-K tholeiitic series, B=basalt; BA=basaltic andesite, A=andesite, D=dacite, R=rhyolite) for the 'subduction-related' volcanic rocks at the different segments of the Alpine-Mediterranean region. Note the wide compositional variations!

Western Mediterranean: Nixon *et al.* (1984), Venturelli *et al.* (1984), Zeck *et al.* (1998), Benito *et al.* (1999), Turner *et al.* (1999); Duggen *et al.* (2004), Gill *et al.* (2004); Central Mediterranean (Al-Fi-Sa-Pa: Alicudi, Filicudi, Salina and Panarea): Rogers *et al.* (1985), Ellam *et al.* (1988), Crisci *et al.* (1991), Conticelli & Peccerillo (1992), Francalanci *et al.* (1993), Peccerillo *et al.* (1993), Del Moro *et al.* (1998), Ayuso *et al.* (1998), De Astis *et al.* (2000), Gertisser & Keller (2000), Downes *et al.* (2001); Carpathian-Pannonian Region: Downes *et al.* (1995a), Mason *et al.* (1996), Harangi *et al.* (2001, in prep), Seghedi *et al.* (2001, 2004a); Eastern Mediterranean (WA=Western Anatolia; CA=Central Anatolia): Mitropoulos *et al.* (1987), Huijsmans *et al.* (1988), Pe-Piper & Piper (1989), Seyitoglu & Scott (1992); Wilson *et al.* (1997), Francalanci *et al.* (1998), Kürkçüoglu *et al.* (1998), Tankut *et al.* (1998), Temel *et al.* (1998), Aldanmaz *et al.* (2000), Cvetković *et al.* (2004).

Figure 7. Normal-MORB (N-MORB, Pearce & Parkinson, 1993) normalized multi-element diagrams for representative samples of different segments of the Alpine-Mediterranean region. For data source see Fig. 6. (Carp.=Carpathians; UP=ultrapotassic).

Figure 8. $^{87}Sr/^{86}Sr$ vs. $^{143}Nd/^{144}Nd$ diagram for the Tertiary-Quaternary volcanic and plutonic rocks at the different segments of the Alpine-Mediterranean region. For data source see Fig. 6. Additional data: Western Mediterranean: Cebria *et al.* 2000; Central Mediterranean: Carter & Civetta (1977), Hawkesworth & Vollmer (1979), Ellam & Harmon (1990), Esperanca & Crisci (1995), Tonarini *et al.* (1995; 2001); D'Orazio *et al.* (1997), Trua *et al.* (1998), Castorina *et al.* (2000), Lustrino *et al.* (2000); Alps-Carpathian-Pannonian region: Juteau *et al.* (1986), Kagami *et al.* (1991), von Blanckenburg *et al.* (1992, 1998), Embey-Isztin *et al.* (1993), Harangi *et al.* (1995), Macera *et al.* (2003); Dinarides-Eastern Mediterranean: Briqueu *et al.* (1986), Gülec (1991), Pamić *et al.* (1995). SV-Po-CF-Cu=melilitite-carbonatite association in San Venanzo, Polino, Colle Fabri, Cupaello. CAV=calc-alkaline volcanic rocks. DMM=Depleted MORB mantle, EMI and EMII=Enriched mantle I and II, HIMU= high μ ($^{238}U/^{204}Pb$) mantle components (Zindler & Hart, 1986).

Figure 9. $^{87}Sr/^{86}Sr$ vs. $\delta^{18}O$ diagram for the Tertiary-Quaternary volcanic rocks of the Carpathian-Pannonian Region and the Central Mediterranean. Variation of these data indicates different types of contamination ('source contamination' and 'crustal contamination'). For data source see Fig. 6. Additional data are from Taylor *et al.* (1979) and Holm & Munksgaard (1982).

Figure 10. $^{87}Sr/^{86}Sr$ vs. $^{206}Pb/^{204}Pb$ diagram for the Tertiary-Quaternary volcanic rocks of the Carpathian-Pannonian Region and the Western and Central Mediterranean. For data source see Fig. 6. Additional data are from Vollmer (1976).

Figure 11. Proposed models for the involvement of an enriched mantle component (EAR) of the 'orogenic magmas' in the Carpathian-Pannonian and Mediterranean Region. A. Deep mantle upwelling could occur via a slab window beneath Central Italy as

proposed by Gasperini *et al*. (2002). B. Toroidal mantle flow around the Calabrian slab from the African mantle was proposed by Trua *et al*. (2003) and Civello & Margheriti (2004). C. Carpathian-Pannonian Region: slab detachment could result in the suction of a hot, enriched asthenospheric mantle material possibly from the Bohemian mantle plume finger.