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

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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 accretion orogenic belts and extensional basins, both of which can be explained by rollback 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 result from subduction-related processes. Thus, they can be considered as ‘subduction-related’ magmas. Intraplate alkali basalts are also found in the region and generally postdated the ‘subduction-related’ volcanism. These mantle-derived magmas have not (or only slightly) been influenced by subduction-related enrichment. This paper summarizes the geodynamic setting of the Tertiary–Quaternary ‘subduction-related’ magmatism in the various 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 ⁸⁷Sr/⁸⁶Sr and ²⁰⁶Pb/²⁰⁴Pb 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 deflection nearby mantle plumes as a result of slab-rollback 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 research 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 isotopic geochemistry (see summary papers of Doglioni et al. 1989; Royden 1993; 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 (rereating subduction; e.g. Betic–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, that is steep angle of subduction, slab rollback, 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 (Housen & 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 dependent 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 2006), 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 the various 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 ka (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 as a result of 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) 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 to...
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 $^{87}\text{Sr}/^{86}\text{Sr}$, low $^{143}\text{Nd}/^{144}\text{Nd}$ and relatively high $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ isotope ratios compared with mid-ocean ridge basalts (MORB), 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 signatures 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 as a result of decompression in a thinning lithosphere during extension (Fig. 2b) or owing 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 settings. A particular case is the generation of a slab-free region beneath a continental margin as a result of detachment of subducted oceanic lithosphere (‘slab break-off’; Fig. 2c). This can occur when continental lithosphere enters the subduction zone (Davies & von Blanckenburg 1995; von Blanckenburg & Davies 1995). Magmatism related to slab break-off is usually localized and instantaneous following the detachment. Melt generation occurs as a consequence of upwelling of hot
systems (Fig. 1), as follows. Within Southern Europe, three main orogenic systems can be distinguished north–south convergence of Africa relative to Europe. Because the Apenninic arc migrated eastward faster than the northeastern corner of the subduction 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), as follows.

(I) Western–Central Mediterranean:
(1.1) Betic–Alboran–Rif province (Western Mediterranean);
(1.2) 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 initiated in the Alpine region during the Early Cretaceous, when closure of the Tethyan oceanic basins took place by eastward to 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 Meso-Cenozoic to Early Palaeogene (Karamata & Krstić 1996; Karamata et al. 2000). Further east, north-dipping subduction formed the Pontide volcanic arc in Western Anatolia from the Late Cretaceous to the Palaeogene (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 allowed eastward lateral extrusion of the crustal block from the compressive Alpine regime (Ratschbacher et al. 1991). The advancing subduction style changed to a 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 NE, followed by back-arc extension during the Middle Miocene (Hörváth 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 (c. 13 Ma; Jiríček 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 (c. 13 Ma). Post-collisional slab detachment is considered to have occurred gradually from west to ESE 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 detached near-vertical subducted slab causes intermediate depth seismicity (Oncescu et al. 1984; Oncescu & Bonjer 1997; Sperner et al. 2001). Chalot-Prat & Gibracea (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
The mechanism of this process is highly debated. The competing geodynamic models involve: (1) 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 (Rouyden 1993; Lonergan & White 1997; Gelabert et al. 2002; Gill et al. 2004); (2) detachment of the subducted slab (Spakman 1990; Blanco & Spakman 1993; Carminati et al. 1998; Zeck 1999; Calvert et al. 2000); (3) delamination of the lithospheric mantle (Garcia-Dueñas et al. 1992; Docherty & Banda 1995); (4) convective removal of the lower part of the thickened lithosphere (Platt & Vissers 1989; Turner et al. 1999). To the east, the presence of a Tethyan oceanic basin allowed 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 suggested that the subducting slab was split into two main fragments (Apennines and Kabylid slabs) retreating east and SE, respectively. Slab roll-back is explained by the sinking of dense Mesozoic oceanic lithosphere as a result of gravitational instabilities (Elssasser 1971; Malinverno & Ryan 1986; Rouyden 1993), by global eastward asthenospheric mantle flow (Doglioni 1992) or by lateral expulsion of asthenospheric material that 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 Miocene (c. 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 that slab detachment beneath the Apennines involved both lithospheric tomography 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 (Yardar) oceanic branches occurred during the Late Cretaceous–Palaeocene in the Dinaride region followed by collisional (Ecocene) and post-collisional (Oligno–Calabrian) stages (Cvetković et al. 2004). Subduction of the subducted slab beneath the Aegean–Anatolian region, north-dipping subduction terminated by the Eocene, when. This collision also led to the tectonic escape of the Anatolian block relative to the disrupted Eurasian lithospheres. Extension could be attributed to the faster southeastward 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, in particular the Aegean and Hellenic arcs. 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 (Waiel 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 southeastwards in the Dinarides (Pamčić 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; Bercuvala et al. 1983; Ulmer et al. 1983; Kagami et al. 1991; Müller et al. 1992; von Blankenburg & Davies 1995).
Berger et al. 1996). In addition, calc-alkaline andesites, shoshonites and ultrapotassic rocks (lamproites) also occur in subvolcanic facies (Deutsch 1984; Venturrelli 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 (Venturrelli 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 Paleocene 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 ocean island basalt (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 (Cebria & Lopez-Ruiz 1995; Cebría & Péccerillo 1992; Martí et al. 1992, Seyitoğlu & Scott 1992), Serti et al. (1993), Louni-Hacini et al. (1995), Pamić et al. (1995, 2002), Pickay et al. (1995), Christofides et al. (1998), El Bakkali et al. (1998), Harkovska et al. (1998), Marchev & Marchev (1998), von Blanckenburg et al. (1998), Wilson & Bianchini (1999), Aldanmaz et al. (2000), Reza et al. (2001), Coulon et al. (2002), Czerkovic et al. (2004), Duggen et al. (2004), and further references therein. 


Fig. 7. Normal-MORB (N-MORB; Pearce & Parkinson, 1993) normalized multi-element diagrams for representative samples of the various segments of the Alpine–Mediterranean region. (For data sources see Fig. 6.) Carp., Carpathians; UP, ultrapotassic.
to shoshonitic and ultrapotassic volcanism occurred on the SE coast of Spain and in Northern Africa from the Early Miocene to Oligocene (Zeck 1970, 1989; Duggen 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 volcanicism 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 as a result of gravitational collapse; (4) convective melting in the overlying lithosphere (particularly in the lower crust). The close relationship between the distribution of volcanism and the sinking slab was used by Zeck (1996) to support this model. The models can be regarded as post-collisional. The volcanic rocks of the Eastern Rif (Morocco) have 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 Hylbean 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 hawaiite-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 Mid-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 million years quiescence, the volcanism rejuvenated in the Tyrrhenian basin, the Tuscan region and in southeastern Sicily (Hylbean Mts) at about 7–8 Ma. On the west coast of Italy a gradual younging of the volcanism can be observed towards the SE, with still active volcanoes in Campania (Campi Flegrei, Vesuvius; Santacroce et al. 2003). The Tertiary to Quaternary volcanic rocks of Mt. Vulture were formed at 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 enriched (E)-MORB type mafic rocks (Vavilov basin, Tyrrhenian basin), calc-alkaline to shoshonitic (Vulcano, Etna) and the Sicily Channel (Pantelleria).

Although most workers 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 Asis 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 (PecceI 1985, 1999) and the detection of high-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 continuing 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 in the region. The active volcanoes are located along strike-slip tectonic lines (Beccaluva et al. 1982; Gasparini et al. 1982). Thus, an alternative hypothesis for the Aeolian volcanism is a relation 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 and radiogenic isotope ratios; Fig. 8) of the potassic rocks of Stromboli are similar to those 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; PecceI 2001).

The post-collisional volcanism in Italy has been interpreted by Wortel & Spakman (1992, 2000) as being due to gradual slab detachment, based on the absence of high-velocity structure considered to represent subducted slab beneath the Apennines, whereas 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 towards 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 this model, the high-velocity body above the 670 km depth (Piromallo et al. 2001) was interpreted as reflection of compositional difference rather than 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 H₂O–CO₂-rich fluids. However, Goes et al. (2000) proposed that the velocity variation in the mantle could be attributed mostly to changes in temperature, whereas the effect of mantle composition could be negligible (<1%). Further integrated geochemical, 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 riftogenic magmas followed by contemporaneous calc-alkaline, silicic and sporadic ultrapotassic volcanism in the Mid- 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) riftogenic volcanism resulted in extensive ignimbrite sheets. The rhyodacitic to rhyolitic pumices have their petrogenesis inferring mantle-derived mafic magmas mixed withbasaltic andesite and andesite lithic clasts, which are considered mantle and crustal origin. The pyroclastic deposits also contain ‘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 & Konečný 1998; Harangi 2001a) or delamination of the lowermost lithosphere beneath the Pannonian Basin (Downes 1996; Seghedi et al. 1998). The decreasing age-corrected ⁸⁷Sr/⁸⁶Sr 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 Mid-Miocene to the Quaternary and the last volcanic eruption occurred in 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 (Figs 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 & Konečný 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 workers (Némecok et al. 1998; von Blankenburg 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 led Girbacea & Frisch (1998) and Chalot-Prat & Girbacea (2000) to suggest partial delamination of the lower lithosphere beneath this area. In contrast to these models, Balá (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. Mid-Miocene enclaves 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 southeastern 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 eastern Carpathians. In the southeastern 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 eastern 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; Čvetković et al. 2004). Subduction of part of the Tethyan Vardar Ocean occurred during the Late Messozoic to Early Palaeogene, followed by Eocene collision and Oligocene to Pliocene post-collisional collapse (Karamata & Krsitić 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 syn-collisional 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 eastern Serbia often contain ultramafic xenoliths (Čvetković 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; Čvetković 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 plagioclase-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 or collapse stage (Cvetkovic et al. 2004). The scattered ultrapotassic rocks (minettes, lamproites, leuconites, analcimines) show the most extreme enrichment of incompatible elements of all the Tertiary volcanic rocks in this region (Prelevic et al. 2001). They have fairly similar trace element patterns in the mantle-normalized diagrams to 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 (Pamici et al. 2002) or to delamination of the lithospheric root (Cvetkovic et al. 2004).

Seismic tomographic images indicate a high-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-NE-dipping subduction was proposed with the opposite polarity to that inferred beneath the Alps (Pamici 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 volcanic rocks 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 Mid-Miocene calc-alkaline to shoshonitic magmas followed by eruption of alkaline and calc-alkaline magmas during Pliocene to Recent times (Pe-Piper & Piper 1989; Seyitoglu & Scott 1992; Pe-Piper et al. 1995; 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 and high-K intermediate to silicic volcanic rocks characterized by eruption of various magmas (alkaline mafic, calc-alkaline and high-K intermediate to silicic volcanic rocks) along major fault systems at Afyon, Konya and Cappadocia (Figs 5 and 6; Innocenti et al. 1975; Aydar et al. 1995; Alici et al. 1998). In Cappadocia extensive dacitic to rhyolitic ignimbrite sheets were deposited from the Late Miocene to Quaternary, associated with large andesitic stratovolcanoes and alkalai basaltic scoria cones and maars (Pasquare et al. 1988; Le Pennec et al. 1994; Aydar & Gourgou 1998; Kürkçüoğlu et al. 1998; Temel et al. 1998b).

Tertiary to Quaternary volcanism in the Aegean and Western to Central Anatolian region occurred mostly in a post-collisional setting and partly behind active subduction zones (Hellenic and Cyprian). 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 & Bingoel 2000). In general, the ‘oreogenic’ volcanic rocks are potassic (high-K calc-alkaline to shoshonitic), whereas those that 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 (Figs 7 and 8; Keller 1982; Briqueu et al. 1986; Mitropoulos et al. 1987; Hujmans et al. 1988; Güleç 1991; Robert et al. 1992; Pe-Piper et al. 1995; Seyitoglu et al. 1997; Aldanmaz et al. 2000). On the other hand, the younger alkaline mafic volcanic rocks show an intraplate OIB nature (Seyitoglu & Scott 1992; Seyitoglu et al. 1997; Alici et al. 2002). Nevertheless, most workers consider that melt generation of both volcanic suites was mostly due to decompression melting because the melts were generated in the 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 as a result of lithospheric thinning to delamination of the lower thermal boundary layer allowing direct contact with upwelling hot asthenosphere (Seyitoglu & Scott 1996; Aldanmaz et al. 2000). In contrast, a closer relationship with subduction was invoked by Innocenti et al. (1975), Temel et al. (1998a,b) 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 northeastward 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 below 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 representing...
asthenosphere-derived magmas. These could originate either in places where lithospheric extension progressed further allowing partial melting of the upwelling asthenosphere (Seyyidoglu 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 sections showed that a wide variety of mafic rocks can be found in all of the different subprovinces of the Alpine–Mediterranean region. Most of them show a 'subduction-related' composition as reflected by the elevated potassium content (Fig. 6) along with the enrichment of LILE and depletion of HFSE (Fig. 7). However, the large geochemical variability as shown in the SiO₂ v. K₂O 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 occurrence 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 & Downs 1991, 2006) 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' mafic rocks in the Mediterranean region is more difficult, because of the lack of mafic undifferentiated rocks in many areas.

In multi-element diagrams that are normalized 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 could also precede the volcanic activity. However, this geochemical feature can also be interpreted as contamination by crustal material at shallow level. Radiogenic isotope ratios (e.g. ⁸⁷Sr/⁸⁶Sr, ¹⁴³Nd/¹⁴⁴Nd 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 arcs. In the 1980s 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 k (³⁸U/³⁹Sr) mantle (HIMU) and enriched mantle end-members (EMI and EMI). 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 be 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 (Hofmann & White 1982; Weaver 1991; Chauvel et al. 1992; Hart et al. 1992; Hofmann 1997). Alternatively, this geochemical feature can reflect deep recycling of mantle 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 Rh/Sr, low Sm/Nd) and therefore can develop high ⁸⁷Sr/⁸⁶Sr and low ¹⁴⁴Nd/¹⁴⁴Nd 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 Figure 8, Tertiary to Quaternary orogenic volcanic rock suites from the Alpine–Mediterranean region show similar curvilinear trends in the ⁸⁷Sr/⁸⁶Sr v. ¹⁴³Nd/¹⁴⁴Nd 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 Periadiabatic 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 ⁸⁷Sr/⁸⁶Sr isotope ratios can be explained only 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).

To detect the processes of crustal involvement in magmatic evolution, ⁸⁷Sr/⁸⁶Sr isotope ratios are often combined with oxygen isotope data (¹⁸O/¹⁶O or δ¹⁸O, where ¹⁸O/¹⁶O is expressed relative to Standard Mean Ocean Water (SMOW); Fig. 9). The upper mantle is inferred to have relatively homogeneous δ¹⁸O values (±5.5 ± 0.8; Mattey et al. 1994), whereas continental and oceanic crust generally display higher δ¹⁸O values as a result of weathering processes and interaction with marine or meteoric 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 characterized by elevated ³⁸Sr/³⁹Sr, but relatively low δ¹⁸O 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 ³⁸Sr/³⁹Sr ratios are accompanied by high δ¹⁸O values (Fig. 9).

The mechanism by which the continental crust is involved in orogenic magmatism can be constrained by combining ³⁸Sr/³⁹Sr isotope ratios with the δ¹⁸O values either of phenocrysts from the volcanic rocks or of bulk rocks. The δ¹⁸O values of bulk rocks are usually higher than those of phenocrysts, because post-eruptive alteration and low-temperature weathering can increase the δ¹⁸O contents (Taylor 1968; Davidson & Harmon
1989; Ellam & Harmon 1990; Dobosi et al. 1998; Downes et al. 1995, 2001). Therefore, δ18O values of phenocrysts reflect better the isotope composition of the host magma. Unfortunately, only sporadic oxygen isotope data are available for mineral separates from the volcanic rocks of the region. In the 87Sr/86Sr vs. δ18O 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 of the Pannonian Basin (Mason et al. 1996; Harangi et al. 2001; Seghedi et al. 2001) show only minor elevation of δ18O with increasing 87Sr/86Sr. 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 by von Blanckenburg et al. (1998), for the genesis of the Alpine Peri-Adriatic igneous rocks. For the remaining volcanic fields the higher δ18O values at a given 87Sr/86Sr 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 (Briquèu 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 87Sr/86Sr and δ18O values suggests that large amounts of crustal material of various types 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 mafic volcanic rocks (Fig. 1). Coeval eruption of alkali basalts and calc-alkaline or shoshonitic magmas occurs at present in the Aeolian archipelago and Sicily. A similar process took place at the southeastern part of the Carpathian chain at 0.5–1.5 Ma (Mason et al. 1996, 1998; Seghedi et al. 2004). In the Central Mediterranean, the ‘orogenic’ volcanic rocks define a curvilinear trend in the 87Sr/86Sr vs. 206Pb/204Pb diagram (Fig. 10; Peccei et al. 2003). One of the members of this trend has high 87Sr/86Sr and medium 206Pb/204Pb values and is related to continental crust. The other end-member has low 87Sr/86Sr and high 206Pb/204Pb ratios and could be an enriched mantle component which 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 mafic rocks from Sardinia and the Sicily Channel also show isotopic variation trending towards this mantle component, having a mixing trend between DMM and FOZO or HIMU. Mixing of OIB-like intraplate and subducted slab-derived components was also suggested by Peccei et al. (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 relationship between the ‘anorogenic’ alkaline mafic and the ‘orogenic’ volcanic suites. However, the most peculiar feature of these rocks is the very low 206Pb/204Pb 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. Central Mediterranean. Variation of these data indicates different types of contamination (‘source contamination’ and ‘crustal contamination’). Data sources are as for Figure 6. Additional data are from Taylor et al. (1979) and Holm & Munksgaard (1982).
radiogenic Sr isotopic component (lower crust?) and an enriched mantle component with low $^{87}\text{Sr}/^{86}\text{Sr}$ and high $^{206}\text{Pb}/^{204}\text{Pb}$ ratios similar to that inferred for the Central Mediterranean magmas. In contrast, calc-alkaline volcanic rocks from the eastern Carpathians trend toward a mantle component with lower $^{206}\text{Pb}/^{204}\text{Pb}$ 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 $^{206}\text{Pb}/^{204}\text{Pb}$ ratios, possibly implying involvement of an EMI mantle component in their genesis. Alkaline basalts of the Pannonian Basin (Embery-Istzin 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 geo-dynamic 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 and in the compositional variation of the ‘orogenic’ volcanic suites. In some places (e.g. Aeolian Islands–Sicily and southernmost eastern 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 workers 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; Wortel & Spakman 1992, 2000; Blanco & Spakman 1993; Faccena et al. 2003; Piromallo & Morelli 2003). In addition, these models revealed an extensive coherent mass between 450 and 650 km depth 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 on 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 magmatogenesis (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.

![Fig. 10. $^{87}\text{Sr}/^{86}\text{Sr}$ v. $^{206}\text{Pb}/^{204}\text{Pb}$ diagrams for the Tertiary–Quaternary volcanic rocks of the Carpathian–Pannonian region and the Western and Central Mediterranean. Data sources are as for Figure 6. Additional data are from Vollmer (1976).](image-url)
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 workers (e.g. Zeck 1996; Benito et al. 1999; Turner et al. 1999) have emphasized the post-collisional origin of these rocks. Indeed, formation of most of the ‘orogenic’ volcanic rocks in the Mediterranean regions post-dates the active subduction process and appear to be related to slab break-off, lithospheric mantle delamination or lithospheric extension (e.g. Mason et al. 1998; Seyitoglu et al. 1999; Turner et al. 1999; Aldanmaz et al. 2000; Chalot-Prat & Girbacea 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 million 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; Seyitoglu 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; that is, 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; Wilson et al. 1998; Wilson & Bianchini 1999; Harangi 2001a; Gasperini et al. 2002; Peccerillo 2003; Bell et al. 2004) also led some researchers 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, Tyrhenian Basin and Aegean Basin, and the discrepancy between temperature inferred from P and S waves also indicates the presence of partial melt (Goess 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 workers 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 Tyrrenhian area, the coexistence of OIB and ‘orogenic’ magmas was interpreted as the result of 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), which could supply enriched mantle material beneath Campania and the southern Tyrhenian 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 in 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 eastern Carpathians could initiate upwelling of depleted MORB-type mantle material. Deflection of the assumed mantle plume finger beneath the Massif Central towards the SE was also detected by seismic anisotropy pattern (Barroul & Granet 2002). The southeastward asthenospheric flow was explained by combined effects 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 led many researchers 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 magmatogenesis and also influenced the tectonic evolution of the areas (Lavicevich 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, Cvetkovic´ & Cvetkovic 2004; Carpathian–Pannonian region, Harangi 1994; Harangi et al. 2003), which may imply its long-lasting (at least from the Early Cretaceous) presence beneath Europe. Oyarzun et al. (1996) and Wilson (1997) suggested that this enriched mantle component could be derived from the Mesozoic Central Atlantic plume being deflected as a result of either the suction of the European thin-spots or the northeastward 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 2004) could be an alternative model for the wide variation of the Tertiary to Quaternary volcanic rocks of the Mediterranean region.

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