TERTIARY-QUATERNARY INTRA-PLATE MAGMATISM IN EUROPE AND ITS RELATIONSHIP TO MANTLE DYNAMICS

Marjorie Wilson[1*] & Hilary Downes[2]

[1] Institute of Geophysics & Tectonics

School of Earth & Environment, Leeds University, LEEDS LS2 9JT, UK

[2] School of Earth Sciences, Birkbeck College, LONDON WC1E 7HX, UK

Words: 17,500

FIGURES: 11

Tables: 1

Running Title: ***Tertiary-Quaternary magmatism in Europe***

***Corresponding Author**

E-mail: M.Wilson@earth.leeds.ac.uk

Phone/Fax: +44 113 343 5236

Final Revision: 8th April 2005

Abstract

Anorogenic intra-plate magmatism was widespread in Europe from early Tertiary to Recent times, extending west to east from Spain to Bulgaria, and south to north from Sicily to northern Germany. Magmatism is spatially and temporally associated with Alpine-Pyrenean collisional tectonics, the development of an extensive lithospheric rift system in the northern foreland of the Alps, and, locally, with uplift of Variscan basement massifs (Massif Central, Rhenish Massif, Bohemian Massif). The volcanic regions vary in volume from large central volcanoes (e.g. Cantal, Massif Central;Vogelsberg, northern Germany), to small isolated plugs (e.g. Urach and Hegau provinces in southern Germany). Within the Mediterranean region, the Dinarides, the Pannonian Basin and Bulgaria, anorogenic volcanism locally post-dates an earlier phase of subduction-related magmatism.

The major and trace element and Sr-Nd-Pb isotope characteristics of the most primitive mafic magmatic rocks (MgO > 6 wt %) provide important constraints on the nature of the mantle source and the conditions of partial melting.. These are predominantly sodic (melilitites, nephelinites, basanites and alkali olivine basalts); however, locally, potassic magma types (olivine leucitites, leucite nephelinites) also occur. In several localities (e.g., Sicily; Vogelsberg and the Rhine Graben, Germany; Calatrava, central Spain) olivine- and quartz-tholeiites form a significant component of the magmatism. The sodic magmas were derived by variable degrees of partial melting (~ 0.5 - 5 %) within a transitional zone between garnet-peridotite and spinel-peridotite mantle facies, close to the base of the lithosphere; the potassic magma types are interpreted as partial melts of enriched domains within the lithospheric mantle. Mantle partial melting was induced by adiabatic decompression of the asthenosphere, locally in small-scale, plume-like, diapirs which appear to upwell from ~ 400 km depth.

Tertiary and Quaternary volcanic activity within Europe occurs in two principal geotectonic settings: referred to as *orogenic* and *anorogenic* by Wilson & Bianchini (1999). Occurrences of calc-alkaline volcanism (*orogenic*) in the Alpine chain, the Carpathians and the Mediterranean region (Harangi et al., *this volume*) can be explained geodynamically in terms of contemporaneous subduction, and will not be considered further in this review. Here emphasis is placed on the extensive *anorogenic*, dominantly alkaline, volcanic province to the north of the Alpine collision zone, including the Massif Central of France, the Rhenish Massif of northern Germany, the Rhine Graben, and the Eger Graben within the northern part of the Bohemian Massif in the Czech Republic **(Figs. 1 & 2)**. Further to the east mafic alkaline volcanism (*anorogenic*) post-dates a major phase of subduction-related volcanism in the Pannonian Basin, the Dinarides (Serbia, Slovenia, Croatia, N. Bosnia), Bulgaria and western Turkey. Further south,within the Mediterranean region, anorogenic volcanism occurs in Sicily, Sardinia, Monte Vulture and the Veneto area of Italy, in the Alboran Sea and along the northern coast of Africa, locally post-dating earlier phases of subduction-related magmatism. Anorogenic magmatism also occurs in the Iberian peninsula, mainly in the Caltrava province of south central Spain, and within the south-eastern Pyrenees near Olot.

Although magmatism initiated locally in the latest Cretaceous-Paleocene, the major phase of activity in western and central Europe occurred in the Neogene (20-5 Ma), with a subsidiary peak in the Pliocene (4-2 Ma), **Figs. 3 & 4**; eruptions continued locally to a few thousand years BP. Magmatic activity within the European foreland of the Alpine orogen (**Fig.2**) is typically mafic and occurs as small volume monogenetic centres (e.g. Eifel, Urach and Hegau provinces of northern Germany), scattered necks and plugs (e.g. North Hessian Depression, Germany) and fissure-controlled plateau basalts (e.g. Cézallier, Aubrac and Coirons in the French Massif Central. Rarer central volcanic complexes (e.g. Cantal and Mont Dore in the Massif Central; Vogelsberg in northern Germany) include significant volumes of more differentiated magmas which can be related to processes of magmatic differentiation in sub-volcanic magma chambers (e.g. Wilson et al., 1995a).

The volcanic fields are generally concentrated in lithospheric basement teranes which have experienced tectono-thermal events within the last 300-400 Myr (e.g. the Variscan belt of Europe); these typically have higher heat flow and thinner lithosphere than the surrounding cratons (e.g. Baltic Shield) (Prodehl et al, 1992). A number are located on uplifted basement massifs (e.g. Massif Central; Rhenish Massif; Bohemian Massif) which appear to be dynamically supported by hot upwelling asthenospheric mantle diapirs (e.g. Granet et al., 1995; Ritter et al., 2001; Wilson & Patterson, 2001). Magmatic activity was broadly synchronous with the evolution of an extensive intra-continental rift system in western and central Europe, subsequently referred to as ECRIS (East and Central European rift system), the origins of which are intimately linked to the collision of Africa with Eurasia (Wilson & Downes, 1992; Ziegler, 1992; Dèzes et al, 2004).

The most common primitive mafic magma types are sodic basanites and alkali basalts; highly silica-undersaturated, small melt fraction, nephelinites and melilitites occur much less frequently, although they are the dominant magma type in some areas (e.g. Urach province of Germany). Potassic alkaline mafic magmatism (e.g. leucitites, leucite nephelinites) occurs at scattered localities throughout the province (e.g. Calatrava, Spain; Cantal and the Sillon Houiller in the Massif Central; the West Eifel, Germany; Doupovské Hory and Ceské Stredohori in the Bohemian Massif); however, only in the West Eifel do potassic magmas predominate over sodic magma types. More exotic magma types, such as carbonatite, occur very rarely (e.g. Kaiserstuhl in the Rhine Graben, Germany; Monte Vulture, Italy). Felsic magmatic rocks occur in most of the volcanic fields, sometimes in a bimodal association with the basalts; complete differentiation series are, however, rare, and occur only in the central volcanic complexes (e.g. Cantal).

THE GEODYNAMIC SETTING OF THE MAGMATISM

The Late Cretaceous-Cenozoic convergence of Africa-Arabia with Eurasia resulted in the progressive closure of oceanic basins in the Mediterranean region and the collision of the Alpine orogen with the southern passive margin of Europe. Compressional deformation of the lithosphere within western and central Europe occurred as a response to the collisional coupling of the Alpine and Pyrenean orogens with their forelands (Ziegler et al., 1995; Dèzes et al., 2004). Throughout the Tertiary there was a gradual shift of compressional tectonic activity away from the foreland of the Carpathians and Eastern Alps to the foreland of the Central and Western Alps, partly as a consequence of dextral translation between the converging blocks during the late Eocene to Pliocene. Stresses related to the collision of Iberia and Europe interfered with stresses transmitted from the Alpine collision front (Dèzes et al., 2004); these stresses played an important role in the Eocene reactivation of Permo-Carboniferous fracture systems and the localisation of the Cenozoic rifts (e.g. Rhine Graben).

Convergence rates between Africa and Europe decreased rapidly during the late Cretaceous and Paleocene (67-55 Ma) as the African and European plates became mechanically coupled (Rosenbaum et al, 2002). During the late Paleocene (61-55 Ma) a pulse of intense intra-plate compression affected western and central Europe, the East European Craton and North Africa (Dèzes et al., 2004; **Fig. 3**). Compressional stresses exerted by the evolving Alpine and Pyrenean orogenic belts caused lithospheric buckling and basin inversion up to 1700 km north of the orogenic fronts. This deformation was accompanied by local intrusion of small-degree partial melts (e.g. melilitites and nephelinites) in the Massif Central, Vosges, Black Forest, Rhenish Massif and Bohemian Massif.

During the early Eocene (~ 52 Ma) the convergence rate between Africa and Europe gradually increased, followed by a decrease in the early Miocene (~ 19 Ma), Rosenbaum et al (2002). Scattered volcanic activity occurred during the early and middle Eocene in the Massif Central (Michon & Merle, 2001), the Rhenish Massif (Lippolt, 1982) and the Bohemian Massif (Ulrych & Pivec, 1997). During the late Eocene extension initiated along the Massif Central, Bresse and Rhine grabens by transtensional reactivation of older Permo-Carboniferous fracture systems in a northerly directed compressional stress field (Dèzes et al., 2004). At the Eocene-Oligocene boundary, convergence of the West-Alpine orogenic wedge with the European foreland changed to a NW direction (Ceriani et al., 2001), coincident with the detachment of a southerly subducted lithospheric slab beneath the Central and Eastern Alps and associated isostatic rebound of the European foreland lithosphere. (von Blanckenburg and Davies, 1995)

North-directed compressional stresses from the Pyrenees combined with the forces exerted by collisional tectonics in the Central Alps, induced the main Oligocene extensional stage of ECRIS. The Pyrenean component of compressive stress relaxed during the late Oligocene (Dèzes et al., 2004) During the Oligocene the Rhine graben propagated northwards, bifurcating into the Ruhr and Leine grabens (**Fig. 2**); rift propagation was associated with an intensification of volcanic activity in the Rhenish Massif. In the northern parts of the Massif Central rifting was accompanied from the late Oligocene by scattered volcanic activity (Michon & Merle, 2001). In contrast subsidence of the Eger graben within the northern part of the Bohemian Massif commenced only towards the end of its Oligocene magmatic phase.

During the Miocene extension continued in the Rhine, Ruhr and Leine grabens (Schumacher, 2002); their triple junction (**Fig. 2**) was gradually uplifted and became the focus of increased volcanic activity (Sissingh, 2003). Uplift of the Vosges-Black Forest dome commenced between 19-20 Ma; this has been attributed to lithospheric flexuring in the Alpine foreland (Schumacher, 2002; Dèzes et al., 2004). Minor volcanic activity within the Upper Rhine graben, including its rifted flanks, was associated with this phase of uplift from 18-7 Ma (Jung, 1999). Uplift and northward tilting of the Massif Central also commenced during the early Miocene, followed by a rapid increase in volcanic activity during the middle and late Miocene (**Fig. 3**; Michon & Merle, 2001).

Minor compressional deformation of the European lithosphere also occurred during the late Miocene- early Pliocene and in Pliocene-Quaternary times (**Fig. 3**; Dèzes et al., 2004). Extension continues to the present day along the Rhine and Ruhr grabens, whereas subsidence of the Massif Central grabens ceased during the Miocene. Within the Rhenish Massif, volcanic activity shifted to the Eifel region during the Pliocene and Quaternary, coinciding with an acceleration of uplift (Garcia-Castelanos et al., 2000). Uplift of the northern Bohemian Massif, which initiated during the early Miocene, continued throughout Plio-Quaternary times accompanied by renwed volcanic activity (Ulrych et al, 1999; Michon & Merle, 2001). This uplift has been attributed to lithospheric flexuring (Ziegler & Dèzes, this volume) In the northern Massif Central volcanic activity resumed at the beginning of the Pliocene (peaking between 4 and 1 Ma), whereas in the south a second peak of activity occured between 3.5 and 0.5 Ma (Michon & Merle, 2001); volcanism was accompanied by renewed uplift.

On a regional scale there appears to be a broad correlation between the timing of magmatic activity within the northern foreland of the Alps and changes in the regional stress field (**Fig. 3**). A detailed compilation of the available geochronological data for the Massif Central suggests that the main volcanic phases may be associated with periods of compressional stress relaxation in the foreland of the Alpine orogenic belt (Wilson & Patterson, 2001). Magmas must rise through the crust and upper part of the lithospheric mantle through fracture systems; consequently, it is possible that the distribution of Cenozoic magmatism within Europe could be related to reactivation of pre-existing lithospheric discontinuities (e.g. Permo-Carboniferous sutures and fault systems) in response to changes in the regional stress field. The maximum horizontal stress direction within western and central Europe rotated from NNE-SSW to NNW-SSE during the Late Eocene/Early Oligocene to NW-SE in the Late Oligocene (Schreiber & Rotsch, 1998). The orientations of linear chains of volcanic necks and scoria cones commonly reflect the orientation of the contemporary stress field. In most areas Cenozoic rifting initiated earlier than the main phase of magmatic activity and is frequently offset spatially from both magmatism and areas of basement uplift. In a number of areas (e.g. Rhine Graben; Massif Central), however, there is evidence for minor early Tertiary magmatic activity which pre-dates the onset of rifting (**Fig.3**).

The largest Cenozoic rift within central Europe, the Rhine Graben, is about 300 km long and 35-40 km wide. It trends NNE-SSW oblique to the NE trending structural grain of the Variscan crystalline basement of Europe (Moldanubian and Saxothuringian terranes; **Fig. 2**). The northern end of the rift is located to the SE of the Rhenish Massif at the boundary between the Saxothuringian and Rhenohercynian Variscan basement terranes. Extension and subsidence occurred mainly between Oligocene (~ 35 Ma) and Miocene times. Subsidence in the southern part of the rift was interrupted by basement uplift and the magmatic activity of the Kaiserstuhl volcano (Keller *et al*., 1990). It is notable that whilst the Rhine Graben is the most highly extended part of the European rift system, it is largely non-magmatic for much of its length, suggesting that lithospheric extension and decompression-induced partial melting of the upper mantle is not necessarily the main cause of magma generation within the European volcanic province. The Miocene volcanic complex of the Vogelsberg is located at the northern end of the Rhine Graben where it splits into two branches at the boundary between the Saxothuringian and Moldanubian Variscan basement terranes (**Fig. 2**).

AGE AND CHARACTERISTICS OF THE VOLCANIC FIELDS

Rhenish Massif

Cenozoic volcanism in northern Germanyis concentrated in a 350 km long, E-W trending zone extending from the Eifel in the west to the Rhön-Heldberg area in the east (**Fig. 2**; Wedepohl & Baumann, 1999). Volcanic activity started during the Eocene and Oligocene in both the eastern and western extremities of the belt. The climax of volcanic activity occurred between 16 and 18 Ma in the Vogelsberg volcano in the central part of the belt. Volcanism ceased about 5 Myr ago followed by a Quaternary resurgence of activity in the East and West Eifel. Most of the volcanic rocks are relatively primitive alkali olivine basalts, nepheline basanites and olivine nephelinites; quartz tholeiites, however, occur in the Vogelsberg and North Hessian Depression. Locally (e.g. Eifel, Siebengebirge, Westerwald and Rhön) extreme differentiation of the parental mafic magmas produced phonolites and trachytes. In the Eifel district predominantly potassic magmas, including leucitites, were erupted.

The Miocene Vogelsberg is a shield volcano (Bogaard & Wörner, 2003) which erupted basanites, alkali basalts, quartz tholeiites and limited volumes of highly evolved magmas ranging from hawaiite to trachyte. It has an eruptive volume of ~ 600 km^3, probably making it the largest volcanic centre within the European volcanic province (Jung & Masberg, 1998). The volcano is located to the east of the Rhenish Massif, close to the triple junction of the Rhine, Ruhr and Leine Grabens (**Fig. 2**). Volcanism commenced in the Early Miocene (~ 22-23 Ma), however, the main phase of activity began ~ 18 Myr ago and peaked between 16 and 17 Ma. The Rhön and Northern Hessian Depression volcanic fields are closely related, both spatially and temporally, to the Vogelsberg and erupted a similar range of magma types (Wedepohl et al., 1994; Jung & Hoernes, 2000).

In the East and West Eifel volcanic fields about 300, typically small-volume, eruptions occurred from monogenetic centres between 700,000 and 10,800 BP (Schmincke et al., 1983; Wörner et al., 1986), associated with about 250 m of uplift. The volume of magma erupted is quite small (about 15 km^3), but the actual volume of magma generated at mantle depths must have been significantly greater (70-100 km^3; G. Wörner, personal communication, 2004). Two geochemically, spatially and temporally distinct groups of sodic-potassic alkaline volcanics were erupted in the East Eifel; in the NW these include nephelinites, leucitites and their differentiates (erupted ≥ 400 ka), whereas in the SE basanites and their differentiates predominate (erupted between 400 and10 ka; Lippolt et al., 1990). The West Eifel volcanic field covers an area of ~ 600 km^2 and comprises about 240 volcanic centres; these erupted predominantly leucitites and nephelinites with subordinate basanites. About 12,900 years ago there was a major Plinian eruption of the Laacher See volcano which produced ~ 6.3 km^3 of phonolitic tephra, causing a major environmental impact (Litt et al, 2003).

Volcanic activity in the Westerwald started in the Oligocene with the eruption of basalts and trachytes (Schreiber & Rotsch, 1998); the main phase of activity had ended by 20 Ma, although there were short periods of reactivation, with the eruption of basalts, in the Miocene and Pleistocene (Fuhrmann & Lippolt, 1990). Volcanic activity appears to have been synchronous with minor uplift of the Rhenish Massif, which commenced at the end of the Oligocene, strengthened during the Quaternary and continues to the present-day (Meyer et al., 1983).

On the basis of palaeomagnetic data, Schreiber & Rotsch (1998) proposed that the north-eastern part of the Rhenish Massif has rotated clockwise by 10-16˚ since the late Oligocene, associated with a system of dextral strike-slip faults. The Quaternary West and East Eifel volcanic fields are located in the non-rotated western Rhenish Massif block. Block rotation is considered to have initiated in the Late Oligocene due to small changes in the direction of the maximum horizontal compressive stress from NNW to NW.

Southern Germany

Volcanism in southern Germany is confined to a few small regions including the Urach and Hegau provinces to the east of the Rhine Graben, the rift flanks of the Rhine Graben and the Kaiserstuhl volcano which is axially located within the graben where it bisects the Vosges-Black Forest dome (Keller et al., 1990; Glahn et al., 1992; **Fig. 2**). On the basis of K-Ar dating and stratigraphic constraints it is likely that the main phase of volcanic activity ranges from about 45 to 15 Ma (Keller et al., 2002). However, Keller et al. (2002) have recently dated amphibole phenocrysts from an olivine melilitite dyke (Trois Epis) in the Vosges at 60.9 ±0.6 Ma; this suggests that magmatism began some 15 Myr before the onset of graben formation, contemporaneous with the onset of major horizontal crustal shortening in the Western Alps (Gebauer, 1999) and a major phase of foreland compression (Ziegler *et al*., 1995).

Magmatism occurs as a series of dykes, plugs/necks and diatreme pipes, concentrated in two sectors: (1) the Vosges-Black Forest Dome, which is the location of the maximum updoming of the Rhine Graben rift flanks, and the only axially located volcano in the graben (Kaiserstuhl); (2) in the north between Heidelberg and Frankfurt, mostly in the crystalline basement of the Odenwald. Scattered volcanic centres also occur along the flanks of the rift (e.g. Mahlberg). The primary magmas are highly undersaturated mafic alkaline types, predominantly olivine nephelinites and olivine melilitites with high Mg -numbers, Ni and Cr contents. The Miocene Kaiserstuhl complex (15-18 Ma) is an alkaline carbonatite complex which also includes potassic magmas (Schleicher et al. 1990).

The Urach province is an olivine melilitite diatreme field with more than 350 individual volcanic necks for which K-Ar ages range from 11-16 Ma (Lippolt et al., 1973). Most of the diatremes are composed of tuffs of olivine melilitite and olivine melilite nephelinite. The main period of activity is in the middle Miocene, from 16-17 Ma. There does not appear to be any correlation between fault tectonics and the location of the diatremes, although the majority are located in a synclinal structure, the “Urach Trough", in which subsidence has occurred since mid-Triassic times. The Hegau volcanic field, some 100km further south, has a greater variety of magmatic rock types including olivine melilitite, olivine-nepheline melilitite and phonolite, diatreme facies pyroclastics and carbonatites. K-Ar ages range from 7-15 Ma, with emplacement of olivine melilitites between 8.5 and 12 Ma.

Massif Central

Most of the alkaline magmatic activity in France has occurred within the uplifted Variscan basement of the Massif Central, with subordinate amounts further south in the Languedoc (Wilson and Patterson, 2001). The Massif is divided by a NNE-SSW trending late-Variscan strike slip fault, the Sillon Houiller, which represents a major discontinuity between two distinct lithospheric domains (**Fig. 2**; Alard et al., 1996). The eastern Vosges-Auvergne domain is distinguished from the western Limousin domain by thinner crust (<29 km) overlying upper mantle with low seismic velocity (Nicolas et al., 1987; Granet et al., 1995; Zeyen et al., 1997). The characteristics of the Vosges-Auvergne domain have been ascribed to lithospheric thinning above an upwelling asthenospheric mantle diapir.

Cenozoic volcanic activity is concentrated in two main areas (Wilson & Patterson, 2001). A chain of volcanoes extends in an approximately N-S direction along the western edge of the Limagne graben. From north to south these are the Chaîne des Puys, the large stratovolcano of Mont Dore, the basaltic plateau of Cézallier, the central volcano of Cantal and the Aubrac mountains. Southeast of the Limagne graben, surrounding the Le Puy basin, the volcanic areas of Velay, Devès and Vivarais comprise some of the youngest activity. Many of the volcanic fields show pronounced NW-SE trending alignments of eruptive centres (e.g. Aubrac, Coirons, Velay, Devès), sub-parallel with a diffuse system of normal faults and graben segments which may represent the continuation of the N-S trending Limagne graben to the SE. In contrast, the volcanic fields of the Chaine des Puys, in the northern part of the Massif, and Escandorgue, in the extreme south, consist of a large number of volcanic cones aligned in a N-S direction. The changing orientations of these volcanic lineaments reflect the changing orientation of the regional stress field within Europe throughout the Tertiary.

Magmatism peaked between the Upper Miocene and the Pliocene (10-5Ma) with widespread eruption of plateau basalts (alkali basalts and basanites) across the province (Devès, Cézallier, Coirons, Aubrac and Escandorgue) and the formation of the Cantal central volcano (400 km^3; Downes, 1983). Significant volumes of alkali basalt were associated with this phase of activity and the volume of differentiated lavas increased substantially. A second peak of volcanic activity, between 4-2 Ma resulted in the formation of the Mont Dore volcano (200 km^3; Briot et al., 1991), and of the Chaîne de la Sioule, Devès and Escandorgue provinces oriented along NE-SW, NW-SE and N-S fractures respectively. Important uplift along the southeast border of the Massif coincided with this magmatic peak (Derruau, 1971).

Czech Republic-Southwest Poland

Paralleling the Alpine tectonic front, although located much farther north, lies the Eger Graben in the Czech Republic **(Fig. 2).** Its location, parallel to the Saxothuringian-Moldanubian Variscan suture zone, and indeed utilising the suture as its southern margin, may be a response to lithospheric doming of the Bohemian Massif. Ulrych & Pivec (1997) have recognised three magmatic phases on the basis of K-Ar data:

(i) pre-rift melilitite-nephelinite magmatism (79-49 Ma) on the rift flanks.
(ii) syn-rift (42-16 Ma) bimodal basanite-trachyte and nephelinite-phonolite magmatism, followed by a second phase of activity from 13-4 Ma.
(iii) late-stage melilitite-olivine nephelinite activity (2-0.26 Ma) in the westernmost part of the rift near Cheb.

Cenozoic volcanism extends from the German-Czech border eastwards to Upper Silesia in Poland and northern Moravia **(Fig. 2).** The magmatic rocks range in composition from melilitites, basanites, alkali basalts and carbonatites to trachytes (Blusztajn and Hart 1989; Kopecky 1966). Local occurrences of bimodal alkaline magmatism extend for ~ 40km both north and south of the main rift faults; melilite nephelinite magmas are characteristic of the SE border fault. The two main volcanic centres within the graben are the Doupovské Hory and Ceské Stredohori complexes. Doupovské Hory, in the west, is a stratovolcano approximately 30km in diameter, containing a mixture of sodic and potassic mafic magmas and their differentiates (Kopecky 1966). The volcano-sedimentary complex of Ceské Stredohori, further to the east, is the most significant region of intra-plate alkaline volcanism, characterised by lava flows, tuffs, plugs, small sub-volcanic intrusions and dykes of basanite-trachyte with minor nephelinite-phonolite series magmas (Ulrych & Pivec, 1997; Ulrych et al., 2001). On the basis of available K-Ar data (Shrbeny, 1995; Wilson & Rosenbaum, unpublished data), the main phase of volcanism in the Ceské Stredohori was from Late Eocene to Middle Miocene (42-15 Ma); much smaller volumes (< 1 %) of magmatism occurred from 13-9 Ma (mid-Late Miocene), and there was a resurgence of activity in Pliocene-Quaternary times.

Pannonian Basin

The geodynamic evolution of the Pannonian Basin and its relationship to the Alpine-Carpathian orogenic belt has been the focus of a number of recent studies (e.g. Cloetingh & Lankreijer, 2001 and references therein). The development of the Carpathian foldbelt and associated back-arc extensional basins is linked to the Mesozoic-Cenozoic collision of Eurasia with a number of continental microplates including the Italo-Dinaride block. Southward subduction of the European plate under the northern margin of the Pannonian Basin during Paleocene-Eocene times is evidenced by a chain of calc-alkaline volcanoes. Calc-alkaline magmatic activity started in the Eocene and culminated in the Miocene (Downes et al., 1995a). Extension ended in late Miocene times and was followed by a phase of Plio-Pleistocene alkali basaltic volcanism.

The Neogene alkaline volcanism of the Carpathian-Pannonian region (**Fig. 1**) has been extensively studied (e.g. Szabó et al., 1992; Embey-Isztin et al., 1993; Embey-Isztin & Dobosi, 1995; Vaselli et al., 1995; Downes et al. 1995b). Pécskay et al. (1995) present a comprehensive review of the timing of magmatic activity. Alkaline magmatism (including both alkali basalts and rare potassic/ultrapotassic lavas) occurred sporadically from 17 - 0.5 Ma, partly contemporaneously with subduction-related magmatism in some areas (20-0.2 Ma). Within the Inner Carpathians calc-alkaline magmatism migrated eastwards in time (Eocene-Miocene in the Northern Carpathians/Pliocene-Quaternary in the Eastern Carpathians of Romania; Pécskay et al., 1995). The alkaline volcanism is also oldest in the western part of the Pannonian Basin but youngest in the central regions (Embey-Isztin et al., 1993). In the eastern Transylvanian Basin late Tertiary-Quaternary volcanism associated with both extension and subduction occurred simultaneously (Downes et al., 1995b). The alkaline volcanic rocks exhibit two age groups; an older phase at 17-7 Ma and a younger phase from 6-0.5 Ma. Potassic lavas (shoshonites) range in age from 15-1 Ma. Episodic Quaternary volcanism has occurred in the West Carpathians, East Carpathians, Persani Mountains and Apuseni Mountains.

Dinarides

Much less attention has been focused on the southern part of the Pannonian Basin and its links with the Dinaride tectonic zone to the south (**Fig. 1**). This province extends from eastern Slovenia, through northern Croatia, and northern Bosnia into Serbia. Lateral movements of several hundred km along the Periadriatic Lineament in the Alps, Oligocene and Micocene magmatism, and Neogene block rotations provide evidence for substantial mobility in this transitional region (Sachsenhofer et al., 2001).

The northern Dinarides were created by the collision of the northeastern parts of the Apulian plate and the southern margin of the Eurasian plate, which commenced in the Late Jurassic-Early Cretaceous (Tari & Pamic, 1998); during this stage ophiolites were obducted onto the Apulian plate. Uplift of the Dinarides occurred during the Late Eocene-Early Oligocene associated with andesitic-dacitic volcanism and pyroclastic activity (32-22 Ma). Extension started in the Early Miocene but terminated by the end of the Middle Miocene. High levels of volcanic activity from 16-12 Ma resulted in a suite of basalts, andesites, dacites and rhyolites. Eruption of alkali basalts occurred from 10-8.5 Ma (Pamic et al., 1995).

In Serbia there was a distinct phase of alkaline mafic magmatism (mainly basanites) during the Paleocene-Eocene (62-40Ma; Jovanovic et al., 2001; Cvetkovic et al., 2004). Magmatism occurred after the termination of Upper Cretaceous subduction and cessation of calc-alkaline volcanic activity, and mainly occurs in the former arc and fore-arc regions. The alkaline mafic magmas, however, display no subduction-related fingerprint in their geochemistry. It is possible that the magmatism was related to slab-break-off of eastward-subducted oceanic lithosphere.

Bulgaria

In Bulgaria there is a 250 km long, N-S trending magmatic province, ranging in composition from potassic basanite to alkaline lamprophyre (camptonite), which is closely associated with extensional tectonics. In the north (Moesian platform) the magmatism is of Lower Miocene age, whereas in the south (Rhodope Zone) it is Eocene to Oligocene in age. Monogenetic volcanoes and domes dominate the northern part, whereas sills and dyke swarms are more common in the central and southern areas (Vaselli et al., 1997). As in Serbia, the alkaline magmatism post-dates an earlier (Lower Oligcene) phase of calc-alkaline magmatism (Marchev et al., 1998).

Italy, Sicily and Sardinia

Intra-plate alkaline magmatism, which is geochemically distinct from the orogenic magmatism of the Roman Volcanic Province (Wilson & Bianchini, 1999), occurs mainly in Sicily (the Iblean Plateau and Mt. Etna), the Veneto province in the Po Plain region of northern Italy, in central Italy at Monte Vulture, and in Sardinia, **Fig. 1**.

The extension-related, anorogenic, magmatism (5-0.1 Ma) in Sardinia, post-dates an earlier phase of subduction-related magmatism (32-13 Ma), and is characterised by the eruption of both subalkaline and alkaline lavas (including primitive and more differentiated magma types; Beccaluva et al., 1977; 1987; Rutter, 1987). Whilst there is no clear temporal trend, the eruption of subalkaline lavas appears to have occurred preferentially during a short period with a climax at about 3.5-3 Ma (Montanini and Villa, 1993), followed by more widespread eruptions of alkaline magmas. The Plio-Pleistocene subalkaline basic-acid magmatism of Mt. Arci (Cioni et al., 1982; Dostal et al., 1982) appears to be transitional in chemistry between that of the earlier Oligo-Miocene subduction-related cycle and the younger alkaline magmas. This may reflect the presence of an inherited "subduction-related" component in the mantle source of the magmas. Gasperini et al. (2000) have suggested, on the basis of the Sr-Nd-Hf isotope systematics of Pleistocene basalts from Logudoro, that their mantle source may contain a recycled crustal component from a subducted oceanic plateau.

Several phases of Cenozoic volcanic activity have been recognised in the Iblean area of southern Sicily. Miocene and Plio-Pleistocene volcanics occur in the northern part of the Iblean platform, toward the Apennine-Maghrebian compressional front (Beccaluva et al., 1998). The Miocene magmatic phase is predominantly alkaline in composition, characterised by a low melt production rate. After a period of low-level activity from about 6.5 to 4 Ma, a new cycle, with a higher melt production rate, initiated in the Lower-Middle Pliocene, lasting until the Lower Pleistocene. This cycle is characterised by an abrupt compositional change to magmas of predominantly tholeiitic affinity. The melt production rate gradually decreased after the climax of volcanic activity and magmas of various geochemical affinities were erupted simultaneously. Sporadic eruptions of highly undersaturated alkaline lavas occurred in the northernmost part of the plateau, towards Mount Etna, during the Lower Pleistocene. It is difficult, however, to study the migration of volcanism from the Iblean area to the Etna area, as the transition zone is obscured by recent sediments.

Mount Etna is the largest active volcano in Europe with an estimated volume of 500-600 km^3. It is polygenetic, with several distinct stages to its evolution. The oldest volcanic products (ca 600,000 years BP; Gillot et al., 1994) are of tholeiitic affinity and outcrop sporadically at considerable distances from the present volcanic focus. Alkaline mafic magmatism commenced around 220,000 years BP (Condomines et al., 1982; Gillot et al., 1994), and for a short period tholeiitic and alkaline magmas erupted simultaneously. More recent magmatism has been entirely alkaline and the erupted lavas have become progressively more differentiated with time, consistent with the development of a high-level magma chamber system beneath the volcano (Clocchiatti et al., 1988; Tanguy et al, 1997; Corsaro & Pompillio, 2004). The volcanic activity of Etna has been attributed to differential roll-back of a slab of subducted oceanic lithosphere and the formation of a slab window through which upwelling of deeper upper mantle material has occurred (Armienti et al, 2004). In contrast, Montelli et al. (2004) have proposed the existence of a deep mantle plume beneath Etna based upon a new seismic tomographic model.

During the past 10 Myr there has also been extensive magmatism offshore in the Sicily Channel, including the islands of Pantelleria and Linosa. The eruptive products range in composition from nepheline basanite to tholeiitic basalt and their differentiates (Beccaluva et al., 1981; Calanchi et al., 1989).

The Late Pleistocene Mt. Vulture stratovolcano has an unusual geodynamic setting at the intersection of NE-SW and NW-SE trending fault systems at the easternmost border of the Appenine thrust front (Beccaluva et al., 2002). Its eruptive products include pyroclastic deposits and basanitic and melilititic lavas; carbonatites have also been reported.

Localised occurrences of late Paleocene- late Oligocene extension-related (anorogenic) alkali basalts, basanites and subordinate transitional basalts occur in the Veneto region of northern Italy (Siena and Coltorti, 1989; De Vecchi and Sedea, 1995; Milani, 1996). The age of the magmatism is based primarily upon stratigraphical constraints and may extend into the Miocene.

Spain

During the Late Miocene-Quaternary extension-related (anorogenic) alkaline magmatism occurred in central Spain in the Calatrava province (López-Ruiz et al. 1993; Cebria and López-Ruiz, 1995), in northeastern Spain near Olot, just south of the Pyrenees (Cebria et al., 2000), to the NW of Cartagena (Tallante) within the Betic Cordillera and at Cofrentes and Columbretes Island (Wilson & Bianchini, 1999; **Fig. 2**). Extension post-dated the main phase of Alpine compression, giving rise to a series of basins, some of which were magmatically active (Doblas & Oyarzun, 1989). In the Olot area Miocene-Quaternary volcanic vents are associated with NW-SE and NE-SW trending fault systems. The oldest magmatism follows the trend of the NE-SW orientated Cenozoic European rift system, whereas the youngest (Garrotxa) magmatism follows NW-SE fault trends related to Alpine convergence in the Pyrenees.

North African Margin-Alboran Sea

Tertiary-Quaternary magmatic activity also occurs along the whole western Mediterranean margin of North Africa **(Fig. 1**) from Morocco to Tunisia. This may be divided into two stages: Late Cretaceous-Mid-Eocene (ca 42Ma) and Early Miocene-Recent (Wilson & Guiraud, 1998; Wilson & Bianchini 1999). The bulk of the magmatism appears to postdate a major phase of Aquitainian-Burdigalian (ca 20 Ma) compression induced by the Alpine collision, and has many similarities to that of the Betic Cordillera of southern Spain (Hernandez et al., 1987; Lonergan & White, 1997). The earliest magmatic rocks have calc-alkaline affinities becoming progressively more alkaline with time. Given the complex geodynamic setting of the western Mediterranean, and the limited amount of geochemical and geochronological data on the magmatic rocks in both the Betic-Rif and Maghrebide belts, it is difficult to constrain the precise tectonic setting in which the magmas were generated. Some authors consider that the Miocene calc-alkaline volcanic episode post-dated active subduction (e.g. Hernandez & Lepvrier, 1979), whilst others link it directly to subduction (Tricart et al., 1994; Lonergan & White, 1997) or to slab detachment in the Tertiary (Zeck et al., 1992; Monié et al, 1992).

Duggen et al. (2003) have demonstrated that between 6.3 and 4.8 Myr ago there was a marked change in the geochemistry of the magmatism in the western Mediterranean from subduction-related to intra-plate which was synchronous with the Messinian salinity cricis. They relate this to westward roll-back of an eastward dipping slab of Tethyan oceanic lithosphere, delamination of a block of continental lithosphere beneath the Alboran Sea, and associated asthenospheric upwelling. The younger (6.3-0.65 Ma) volcanic rocks are alkali basalts and basanites plus differentiates. The change over from calc-alkaline and shoshonitic magmatism to intra-plate alkaline magmatism was transitional; the youngest shoshonites are dated at 4.8 Ma. The alkaline mafic rocks are similar to oceanic island alkali basalts from the Canary Islands (OIB), and to those from elsewhere in the European Volcanic Province.

Western Turkey

The Western Anatolian volcanic province of Turkey (**Fig. 1**) is located at the eastern end of the Aegean arc, which results from the northward subduction of the African plate beneath the Aegean. Calc-alkaline volcanic activity commenced in the Late Oligocene-Early Miocene, followed by alkali basaltic volcanism from Late Miocene to Recent times. This change in the style of the volcanism has been attributed by some authors to a change in the regional stress field from N-S compression to N-S extension (Yilmaz 1990; Güleç, 1991). Seyitoglu & Scott

(1992), however, consider that the transition to N-S extensional tectonics actually commenced much earlier in the latest Oligocene-Early Miocene. Seyitoglu et al. (1997) have demonstrated that within the youngest volcanic sequence there is a change from potassic magmatism in the Miocene to more sodic (anorogenic) alkaline magmatism in the Quaternary. The geochemical characteristics of the potassic magmas are inferred to reflect the presence of an inherited subduction-modified component in their mantle source.

Large volumes of trachyandesitic-dacitic lava flows and pyroclastic deposits of Miocene age are associated with small volumes of alkali basalt lava flows in the Galatia volcanic province of northwest Central Anatolia (Wilson et al., 1997). The volcanism postdates continental collision, occurring in a trans-tensional tectonic setting associated with movement along the North Anatolian Fault zone. Alkali basalts were erupted during two distinct time periods in the Early Miocene (17-19 Ma) and Late Miocene (<10 Ma); the Early Miocene basalts have geochemical characteristics which suggest the involvement of a subduction-modified mantle source component in their petrogenesis, whereas the late Miocene basalts are identical in their geochemical characteristics to anorogenic alkali basalts erupted throughout western and central Europe and the Mediterranean domain.

TEMPORAL DISTRIBUTION OF THE VOLCANISM

From the Late Eocene (ca 40 Ma) to the present day, anorogenic magmatic activity occurred throughout the European and African margins of the Tethyan collision zone and within the Mediterranean region (Wilson & Bianchini, 1999). Major phases of volcanism occur in the Early Miocene and in the Late Miocene-Pliocene, though activity was not widespread until the Late Miocene (**Figs. 3, 4**). Magmatism locally continues to a few thousand years BP (e.g Chaine des Puys, Massif Central; Laacher See, Eifel province of the Rhenish Massif). This major regional volcanic flare up may reflect a fundamental reorganisation of the convection system within the upper mantle intimately associated with the Alpine collision.

In a number of areas there is also evidence for an earlier phase of Paleocene-Eocene volcanism, for example: the Massif Central and the Bohemian Massif (Downes, 1987; Malkovsky, 1987; Baranyi *et al*., 1976; Horn *et al*., 1972), eastern Serbia and southern Romania (Downes et al., 1995b; Jovanovic *et al*., 2001), the Rhine Graben (Keller *et al*., 2002), the Pannonian Basin (Pecskay *et al*., 1995), and the Veneto province (De Vecci & Sedea, 1995). A number of authors (e.g. Lippolt *et al*, 1973) have suggested that magmatic activity actually started in the Late Cretaceous; these older ages are, however, suspect as they are based on K-Ar age determinations on altered whole rocks. Keller et al. (2002) have recently demonstrated that supposed ~ 85 Ma nephelinites from the Rhine Graben (dated originally by K-Ar) are actually Paleocene in age (~ 61 Ma) when re-dated by Ar-Ar geochronology on amphibole phenocryst mineral separates.

By the Lower Eocene, volcanic activity had extended into the northern Rhine Graben region and in the upper Eocene commenced in the Rhenish Massif (Lippolt, 1982). However, the volume of volcanic rocks at 40Ma was still small compared to the volume subsequently emplaced in Neogene-Recent times. In the French Massif Central magmatism continued in the Bourgogne region and initiated in the Forez graben in the NE part of the massif (Patterson, 1996). The Veneto district of northern Italy also became magmatically active at this time (De Vecchi and Sedea, 1995). Dykes were intruded along the flanks of the Rhine Graben (Lippolt, 1982; Wilson & Keller, unpublished. data).

The onset of major volcanism occurred in the Oligocene in the Bohemian Massif (Doupovské Hory and Ceské Stredohori; Ulrych & Pivec, 1997), the Massif Central (Cantal; Patterson, 1996), the Rhenish Massif (Siebengebirge, Westerwald and Rhön sub-provinces; Lippolt, 1982; Wedepohl *et al*., 1994; Jung & Hoernes, 2000), the Odenwald in the Rhine Graben region (Lippolt, 1982), and in southern Bulgaria (Marchev et al., 1998). Magmatic activity was intimately associated with regional rifting (Ziegler, 1992). Magmatic activity continued in the Veneto district throughout the Oligocene (De Vecci & Sedea, 1995).

The Neogene (Miocene-Pliocene) sub-period was characterised by a peak in volcanic activity throughout Europe. Magmatism occurred in southern and central Germany (Urach, Hegau, North Hessia, Upper Palatinate, Vogelsberg; Lippolt et al., 1973; Jung & Masberg, 1998; Bogaard & Wörner, 2003), Spain (Calatrava, Olot; Lopez-Ruiz *et al*., 1993; Cebria *et al*., 1995; Cebria *et al*., 2000), the French Massif Central (Patterson, 1996; Wilson & Patterson, 2001), southern Italy (Sicily Channel, Iblean plateau in Sicily; Wilson & Bianchini, 1999), Burgenland (eastern Austria), central Slovakia and northern Bulgaria. Some of the largest volcanic edifices in the province (e.g. Cantal, Massif Central) were formed at this time. Concurrently, activity in the Siebengebirge, Westerwald and Rhön regions of northern Germany abated, and the focus of volcanic activity moved eastwards with the eruption of quartz tholeiites in the North Hessian Depression. Soon afterwards, eruptions began to construct the Vogelsberg and Kaiserstuhl volcanic complexes (Lippolt, 1982; Schleicher et al, 1990; Jung & Masberg, 1998). Magmatic activity continued, and became more widespread, in the Bohemian Massif throughout the Miocene (Kopecky, 1966; Ulrych & Pivec, 1997). During the Pliocene the Massif Central, the Calatrava province of central Spain and the Bohemian Massif remained volcanically active, whereas in the Rhenish Massif and south German fields magmatic activity diminished considerably (Patterson, 1996; Lopez-Ruiz *et al*., 1993; Wedepohl *et al*., 1994; Ulrych & Pivec, 1997).

Alkali basaltic volcanism continued throughout the Pliocene and into the Quaternary in the Massif Central (e.g., Chaine des Puys, Vivarais), Italy (Etna), Sardinia, northern Germany (Eifel), Spain (Tallente, Olot, Calatrava), Hungary (Balaton Highlands, Little Hungarian Plain), Romania (Banat and Persani Mountains), eastern Austria (Graz Basin), central and southern Slovakia, southwest Poland and the Czech Republic (Eger Graben). Quaternary magmatism is not known in Calatrava or the south German volcanic fields (Wedepohl et al., 1994; Cebria & López-Ruiz 1995). Important Pleistocene activity in the Bohemian Massif occurs in west Bohemia and northern Moravia (Wimmenauer, 1974). Quaternary eruptions in the Rhenish Massif are concentrated in the Eifel volcanic field on the western margin of the massif, and are characterised by a high proportion of potassic magmatic rocks (Mertes & Schmincke, 1985). In the Massif Central, the most northerly volcanic fields (Chaîne des Puys and Mont-Dore) were active alongside those in the extreme east (Vivarais) and extreme south (Escandorgue and Languedoc), Patterson (1996). In all cases, the volume of magmatism is subordinate to the Neogene phase of activity, suggesting a general decline in the amount of melt being produced. Volcanic activity contined to ~ 4000y BP in the Chaîne des Puys.

There does not appear to be any evidence of a geographical progression in the main locus of magmatism with time (**Fig. 4**). This suggests that magmatic activity is not occurring in response to a single process, such as lithospheric extension, but rather to a combination of processes in this complex geodynamic setting.

RELATIONSHIP BETWEEN MAGMATISM AND BASEMENT UPLIFT

The geology of western and central Europe is characterised by a series of domal uplifts (Massif Central, Rhenish Massif, Bohemian Massif, Armorican Massif, Vosges-Black Forest dome) of Variscan basement, up to 500-600 km in diameter, surrounded and on-lapped by younger sedimentary sequences (**Fig.2**). Basement uplift is generally considered to have initiated during the Neogene, extending over a period of some 15-20 Myr (Ziegler, 1990, 1992). In detail, however, the timing of uplift is not well constrained; preliminary results from a programme of fission track studies to characterise the uplift history from east to west across Europe (A. Hurford, personal communication) suggest that parts of the Variscan basement were already exhumed by the Early Cretaceous. Additionally, there is stratigraphic evidence to suggest that both the Rhenish Massif and the Massif Central were close to sea-level during the Oligicene (Dèzes et al., 2004).

The Rhenish Massif has probably been a permanent high since the end Carboniferous Variscan orogeny (ca 300 Ma; Garcia- Castellanos et al., 2000). Tertiary uplift started with large-scale tilting during the Palaeocene following a long period of tectonic stability during the Mesozoic. Doming initiated during the Eocene, with the major phase of uplift during the Late Oligocene. Uplift continued during the Neogene and Quaternary, accelerating during the Middle Pleistocene. The locus of maximum uplift during the last 800,000 years (250 m) is broadly coincident with the location of a slow velocity anomaly in the upper 400 km of the mantle, identified by Ritter et al. (2001) as a mantle plume on the basis of a local seismic tomography experiment.

A number of the Tertiary-Quaternary volcanic fields within Europe are located on uplifted basement massifs (e.g. Massif Central, Eifel, Bohemian Massif), some of which appear to be dynamically supported by convective upwellings within the upper mantle (eg. Granet *et al*., 1995; Wilson & Patterson, 2001; Ritter et al, 2001). Elsewhere, however, areas of uplifted basement (e.g. the Ardennes within the Rhemish Massif; Armorican Massif; Fig. 2) are devoid of Tertiary-Quaternary magmatic activity. Equally, not all of the volcanically active areas are located on uplifted basement (e.g. Pannonian Basin). Consequently, it seems clear that there is not a simple correlation beween basement uplift, diapiric upwelling of the asthenosphere and magma generation processes.

The presence of a regional erosional hiatus at the Mesozoic-Cenozoic boundary throughout western and central Europe may mark the initiation of basement uplift in the Massif Central, Vosges-Black Forest region, North Hessian Depression, Rhenish Shield, Bohemian Massif, Armorican Massif and the Ardennes (Ziegler, 1990); no European rifting or Alpine collision events are known this early. 'Laramide' basin inversion in the central and west Netherlands Basin (Van Wijhe, 1987), Lower Saxony basin (Betz *et al*., 1987) and on the west margin of the Bohemian Massif (Schröder, 1987) attest to continued uplift into the Mid- and Upper Palaeocene. Further inversion between the upper Eocene and the Lower Oligocene coincides with the first substantial magmatic episode in the Odenwald, south of the Rhenish Massif.

Following a period of Mid-Oligocene subsidence (shown by periodic transgressions onto the Rhenish Massif; Meyer *et al*., 1983), uplift of the Vosges-Black Forest Massif dome and the Massif Central resumed in the Upper Oligocene (Illies, 1977). Uplift was initially restricted to rift shoulders, but quickly increased in intensity and extended throughout western and central Europe (including the Massif Central, eastern Paris Basin, Vosges and Black Forest mountains, Rhenish Massif, Hessian Depression, Harz Mountains and the Bohemian

Massif (Ziegler, 1990). Strong uplift throughout the Lower Miocene to Lower Pliocene coincided with inversion of the Leine, south Ruhr valley and French grabens (Meyer et al., 1983; Ziegler, 1992), a sharp rise in volcanic activity (Lippolt, 1982) and strong uplift in the Alps and Alpine fore-deep (Lemcke, 1974; Malkovsky, 1987). Uplift continued throughout the Pliocene and Pleistocene to the present day in the Massif Central, Rhenish Massif and Bohemian Massif (Becker, 1993). Rhenish shield uplift is currently 0.4 - 0.6mm/yr, with a maximum of 1mm/yr coinciding spatially with the distribution of recent magmatism in the Eifel (Fuchs *et al.,* 1983; Garcia-Castellanos et al, 2000).

The regional onset of basement uplift at the Mesozoic-Cenozoic boundary across Europe, associated with early dyke intrusions (e.g. Rhine Graben), occurred at least 20Myr before the main onset of rifting. This suggests that the main trigger for the Tertiary magmatism within Europe is the diapiric upwelling of mantle beneath the base of the lithosphere. No contemporaneous collisional events are known from the Alps at this time, although extension along the Reykjanes, Aegir and Mohns ridges in the North Atlantic may have induced compressional stresses within the European lithosphere at this time(Becker, 1993).

In a number of areas within the European volcanic province (e.g. Massif Central, Rhenish Massif, northern Bohemian Massif) crustal uplift and surface magmatism during the Cenozoic are strongly linked, both spatially and temporally (Patterson, 1996). The most recent volcanic eruptions from the Rhenish Massif, for example, coincide with highest measured uplift rates (Garcia- Castellanos et al., 2000). Uplift in these three areas correlates spatially with the locus of low velocity anomalies in the upper mantle which have been interpreted as small-scale mantle plumes (e.g. Granet at al, 1995; Wilson & Patterson, 2001). The Vosges-Black Forest dome is, however, distinct from the other uplifted areas. It is somewhat smaller (~300km wide), appears to originate by lithopheric flexuring and is not currently rising.

GEOPHYSICAL STUDIES OF THE UPPER MANTLE

Babuska & Plomerova (1992) have shown that the thickness of the lithosphere beneath western and central Europe is typically 100-120 km; this is a regional characteristic of the Variscan basement. In the northern part of the Massif Central the lithospheric thickness increases to 140 km, whilst thinning to 70-80 km occurs beneath the main grabens (e.g. Limagne Graben). The western Alps have a deep lithospheric root (> 170 km). The asthenosphere-lithosphere boundary below the SE part of the Rhenish Massif is elevated to ~ 60 km depth (Babuska & Plomerova, 1992), and to ~70 km below the Vogelsberg (Braun & Berckhemer, 1993). The lower crust beneath the Vogelsberg is characterised by a strongly reflective zone at ~20 km depth and a Moho depth of ~ 28km, suggesting the presence of a lower crust underplated and intruded by basaltic magma.

Babuska et al. (2002) have produced a more detailed lithospheric model for the Massif Central showing that the lithosphere is thick (100-140 km) in the northern and western parts but thinner (70-80 km) in the south beneath the main volcanic regions of Cantal and Mont Dore to the east of the Sillon Houiller fault (a late Variscan sinistral transfer fault; **Fig. 2**). Additionally, there are significant differences in the orientation of seismic anisotropy within the mantle lithosphere of the western and eastern Massif Central. The eastern Massif Central appears to consist of two domains separated by an E-W trending boundary**.** Based on studies of spinel peridotite mantle xenoliths exhumed by the Cenozoic basalts, this boundary corresponds to a terrane boundary between a northern cratonic and a younger southern domain (Lenoir et al., 2000), each characterised by differently orientated tectonic structures (Michon & Merle, 2001). Babuska et al. (2002) have suggested that the magmas feeding the Cenozoic magmatism of the Massif Central migrated to the surface mainly along such reactivated basement sutures, which are probably trans-lithospheric fault systems. Other areas in which such basement control on the locus of magma migration may be important include the Eger Graben and the volcanic fields of northern Germany (Eifel, Vogelsberg, North Hessian Depression).

Both regional and local seismic tomography studies have imaged anomalously low seismic velocities in the upper mantle beneath western and central Europe (e.g. Spakman et al., 1993; Zielhuis & Nolet, 1994; Hoernle et al., 1995; Granet et al., 1995; Goes et al., 2000; Ritter et al. 2001), consistent with a model of discrete upper mantle diapirs beneath each of the major volcanic fields. None of these studies resolved structure below the 660 km discontinuity. A recent European tomographic model (Bijwaard & Spakman, 1999; Goes et al., 1999), however, has provided some evidence that the upper mantle velocity anomalies may be rooted in the lower mantle. Between 900-1200 km depth there appears to be a semi-circular low velocity structure which links the Iceland plume, a Central European velocity anomaly and a plume-like structure beneath the Canary Islands which may continue to the core-mantle boundary. Low seismic velocities in the upper mantle are considered by Goes et al. (1999) to reflect the presence of mantle some 100-200 ºC hotter than its surroundings. They attribute the geometry of the velocity anomaly to deflection of a lower mantle plume by relatively flat lying subducted slabs on the 660 km discontinuity at the base of the upper mantle (Piromallo et al., 2001).

Ritter et al. (2001) have demonstrated the existence of a 100 km wide, finger-like P-wave velocity anomaly in the upper mantle beneath the Eifel volcanic field which extends to a depth of at least 400 km; this could be about 150-200 ^{o}C hotter than the surrounding mantle if the entire velocity anomaly is translated into a temperature contrast. This is similar to the structure reported by Granet et al. (1995) beneath the Massif Central. Receiver function analysis indicates a depression of the 410 km seismic discontinuity beneath the Eifel consistent with a thermal anomaly of this magnitude (Grunewald et al., 2001). In the lower mantle beneath Europe, Goes et al. (1999) discovered a 500 km x 500 km anomaly at 660-2000 km depth which might be the lower mantle source of this upper mantle thermal anomaly. However a connection between this lower mantle structure and the upper mantle diapir has not been demonstrated. Keyser et al. (2002) have demonstrated that there is a "hole" in the low velocity channel beneath the Eifel at about 200 km depth consistent with an increase in the shear modulus; this might correspond to the depth of onset of partial melting. These authors also located a low velocity region further east beneath the Vogelsberg at about 170-240 km depth. Since there has been no volcanic activity in the Vogelsberg since the mid-Miocene, this anomaly is difficult to interpret; it could reflect a waning Miocene thermal anomaly, or a new diapric upwelling which has not yet reached the base of the lithosphere. It is important to recognise that variations in seismic velocity within the mantle can represent anomalies in composition, temperature and anisotropy. Kyser et al (2002) indicate that the –5% (negative) perturbation in S wave velocity (v_S) between 31-170 km depth below the Eifel is consistent with an excess tempeature of 100K plus ~ 1% partial melt. In the lower part of the asthenosphere the v_S anomaly is at least –1 %, consistent with a temperature anomaly of > 70 K combined with the presence of water in the upwelling mantle.

Piromallo et al. (2001) have used a high-resolution seismic tomographic model to study the structure of the upper mantle beneath Europe. They show that between 400 and 600 km depth there is an ellipsoidal region, 2000 km x 4000 km in area and ~ 100-150 km thick, of faster seismic velocities which might locally inhibit the vigour of upper mantle convection **(Fig. 1).** Wortel & Spakman (2000) also identified the presence of a layer of fast material under the Mediterranean region. If this layer represents a region of cold subducted oceanic lithosphere, its presence would cause a temperature inversion in the upper mantle below 500 km which might greatly modulate the style of mantle convection, locally slowing down the circulation. Such a scenario might invalidate the commonly used assumption of an adiabatic temperature gradient in the upper mantle, as transient convection might not be sufficiently vigorous to create an adiabatic condition (Matyska & Yuen, 2001). The presence of a regional "cool spot" in the Transition Zone (i.e. the region of fast seismic velocities) might explain why the major volcanic regions within Europe (**Fig. 1**) appear to be located peripherally to the fast velocity anomaly in the Transition Zone.

On the basis of a detailed seismic tomographic study of the Massif Central, France, Granet et al. (1995) proposed that all of the major Tertiary-Quaternary volcanic fields of western and central Europe (Fig. 1) are underlain by finger-like thermal anomalies in the asthenosphere, sourced from a laterally extensive layer close to the base of the upper mantle. Wilson & Guiraud (1998) subsequently suggested that similar features may underlie other Tertiary-Quaternary volcanic fields in northern (Hoggar and Tibesti massifs) and central (Darfur Dome) Africa, and in the Canary Islands. The location of these volcanic fields to the north and south of the Alpine collisional tectonic front suggests that the generation of diapiric instabilities in the upper mantle might be linked to subduction processes, including slab break-off, during continental collision of Africa with Eurasia. The scale-length of the diapirs (100-500 km diameter) is much smaller than that typically associated with mantle plumes (1000-2000km diameter) which have been inferred to trigger the flood basalt volcanism of the so-called Large Igneous Provinces or LIPs (White and McKenzie, 1989). Additionally, unlike LIPs, the characteristic volcanism is of alkali basalts, basanites and nephelinites and their differentiates, although locally eruptions of subalkaline (tholeiitic) basalts do occur. In this respect the volcanism shows strong similarities to that of many Atlantic oceanic islands (e.g. Canary Islands, Azores, Cape Verdes) and to island chains within the southwestern Pacific which are inferred to be plume-related. It has been suggested that individual volcanic island chains within the Pacific Ocean represent the locus of hotspots rising from the upper boundary of a much larger wavelength upwelling or "super-swell" within the mantle (McNutt, 1998). Such a model may also be applicable to the convective instabilities which have been inferred to underlie the European volcanic province. On the basis of seismic tomographic images, Goes et al. (1999) have suggested that a low velocity structure between 660 and 2000 km depth represents a lower mantle plume upwelling beneath central Europe which may feed smaller-scale upper mantle plumes beneath each of the volcanic fields.

RELATIONSHIP BETWEEN THE LOCATION OF MAGMATISM AND BASEMENT STRUCTURE

Within the Variscan basement of Europe, a series of elongate, east-west trending terranes (Rhenohercynian, Saxothuringian and Moldanubian) have been identified (Franke, 1989), separated by deep, laterally persistent fault zones, interpreted as tectonic sutures (**Fig. 2**). These major structural units of the European lithosphere resulted from the collision, during the Devonian and Carboniferous, of Laurasia with Gondwana and a number of intervening microplates. The terrane boundaries may be regions of anomalously thin, irregular or weak lithosphere and appear to have exerted a significant control on the location of subsequent Cenozoic magmatism within Europe, possibly acting as pathways for magma ascent through the lithosphere.

Huismans (1999) has demonstrated that asthenospheric diapirism can be generated by rifting processes. Extension of heterogeneous lithosphere could create differential topography at the base of the lithosphere, which might induce further upwelling of low density asthenosphere, resulting in magma generation and surface uplift. Thus, it is possible that the Variscan structural fabric of Europe may have pre-conditioned the subsequent locations of Tertiary-Quaternary volcanism.

THE GEOCHEMICAL CHARACTERISTICS OF THE MAGMATIC ROCKS

How do we classify magmatic rocks as anorogenic?

Magmas of *orogenic* and *anorogenic* affinity can be distinguished based on their major and trace element and Sr-Nd-Pb isotope geochemical characteristics (Wilson & Bianchini, 1999). The variation of K_2O/Na_2O (weight ratio) as a function of SiO_2 (wt %) content can sometimes be quite an effective tool for discrimination; magmas of orogenic affinity frequently have a K_2O/Na_2O ratio >1.5, whereas anorogenic magmas always have a K_2O/Na_2O ratio <1. Caution must be exercised, however, as there are also examples of low-K subduction-related volcanic suites. Much more effective discriminants are trace element ratio plots such as Th/Yb versus Ta/Yb as proposed by Wilson & Bianchini (1999).

The range of magma types observed

Within the European volcanic province the *anorogenic* suites include both alkaline and sub-alkaline magma series, ranging from basalts to more silica-rich compositions. In general, only the most primitive mafic magmas (basalts *sensu lato;* SiO_2 < 55 wt %, MgO > 6 wt %) can provide information about the nature of their mantle source, and, consequently, we focus on the geochemical characteristics of such rock types in subsequent discussions. Table 1 lists the literature sources of the major and trace element and Sr-Nd-Pb isotope data which we have used to characterise the different European volcanic provinces. A total-alkalis (Na_2O + K_2O) versus silica (SiO_2) variation diagram, **Fig. 5**, indicates a wide spectrum of magma compositions ranging from silica-poor nephelinites and melilitites (foidites), through alkali basalts and basanites to transitional and subalkaline basalts (tholeiites).

The geochemical characteristics of the most primitive alkaline mafic magmas erupted throughout the region are, in general, remarkably similar to those of oceanic island basalts (OIB) inferred to be related to the activity of mantle plumes, and of other regions of Cenozoic continental intra-plate volcanism (e.g. Wilson & Downes, 1991). Locally where the alkaline magmatism post-dates a recent episode of subduction-related magmatism (e.g. Sardinia, Pannonian Basin, Dinarides, Bulgaria, Western Turkey), the earliest magmatic rocks may preserve the fingerprint of earlier fluxing of the upper mantle by subduction- zone fluids. Localised oceanic spreading centres within the Mediterranean domain preferentially sample a depleted mantle source component, similar to the source of mid-ocean ridge basalts (MORB), although in the Tyrrhenian Sea this is clearly modified by a subduction-related fluid flux (Wilson & Bianchini, 1999).

Sr-Nd-Pb isotope and trace element chemistry of the most primitive mafic magmas

In Sr-Nd isotope space (**Fig. 6**) the European basalts define a linear array trending from $^{143}Nd/^{144}Nd$ ratios of around 0.5130 towards Bulk Earth values (0.51264); this array may reflect mixing of partial melts derived from different mantle source components (e.g. Wilson & Downes, 1991; Wilson & Bianchini, 1999; Wilson & Patteson, 2001). An isotopically distinct group of quartz tholeiites from northern Germany fall below the array, which may be attributable to crustal contamination of the magmas. A series of broadly linear arrays are also evident in Nd-Pb and Pb-Pb isotope space (**Fig. 7**), fanning away from a common focal point, although there is considerable dispersion of the data. These Sr-Nd-Pb isotope signatures have been attributed to the mixing of partial melts derived from a common, possibly plume-related, asthenospheric mantle source component known as the Low Velocity Conmponent (LVC; Hoernle et al., 1995) or European Asthenospheric Reservoir (EAR; Cebriá & Wilson, 1995) and a number of regionally heterogeneous sub-continental lthospheric mantle components (Cebriá & Wilson, 1995; Granet et al., 1995; Hoernle et al., 1995).

It is generally accepted that the increasing degree of undersaturation in SiO_2 within the sequence olivine tholeiite-alkali olivine basalt-basanite-nephelinite-melilitite principally results from decreasing degrees of partial melting at increasing depth in the mantle (e.g. Wilson, 1989). Constraints on both the depth and degree of partial melting can be provided by the concentration of highly incompatible trace elements in the most primitive mafic magmas, the enrichment of light Rare Earth Elements (LREE) over heavy Rare Earth Elements (HREE) and the CaO/Al_2O_3 ratio. Trace element ratios (e.g. La/Yb or La/Sm) where the numerator has a greater degree of incompatibility than the denominator exhibit a regular decrease from nephelinite and basanite to olivine tholeiite, consistent with increasing degrees of partial melting. High CaO/Al_2O_3, La/Yb and Nb/Y ratios suggest that the alkali basaltic (*sensu lato*) magmas were derived from a garnet-bearing mantle source. Enrichment of highly incompatible trace elements and LREE, and strong fractionation of LREE over HREE, can, however, be explained either by moderate degrees of partial melting of an enriched source or smaller degrees of melting of a more depleted source.

Fig. 8 illustrates the variation of Nb/Y versus Zr/Nb compared to model melting curves for 0.5-5 % partial melting of spinel- and garnet-peridotite facies mantle from Harangi (2001). This clearly indicates that, in most of the volcanic provinces, the mantle partial melting column spans the transition from garnet- to spinel-peridotite facies mantle, probably close to the base of the continental lithosphere (cf Bogaard & Wörner, 2003). Degrees of partial melting are typically less than 1%. Only in those regions in which sub-alkaline tholeiitic basalts occur (e.g. northern Germany, Pannonian Basin and the Iblean Plateau, Sicily) does the degree of partial melting approach 5%; these tholeiitic basalts clearly equilibrated at somewhat shallower depths in spinel-peridotite facies mantle and may include a significant lithospheric mantle source component in their petrogenesis. The insets in **Fig. 8** show the variation of Nb/Y versus K_2O/Na_2O. There is generally a poor correlation between these two parameters. However, it is clear that the most sodic basalts (lowest K_2O/Na_2O) are the subalkaline tholeiites. The distinctive melilitites from the Urach and Hegau volcanic fields to the east of the Rhine Graben have the highest Nb/Y ratios consistent with an extremely low degree of partial melting (<0.5%) within the garnet stability field.

A Rare Earth Element (REE) ratio plot of La/Yb versus Gd/Yb (**Fig. 9**), also supports a model of mixing of partial melts from garnet- and spinel-peridotite facies mantle in the petrogenesis of the magmas. Magmas derived in equilibrium with a mantle source in which garnet is a residual phase have high La/Yb and Gd/Yb ratios because Yb is a compatible trace element in garnet (i.e. it preferentially partitions into garnet rather than the co-existing melt), but is incompatible in spinel.

The ratio of CaO/Al_2O_3 shows a strong negative correlation with wt % SiO_2 (**Fig. 10**) consistent with increasing degrees of partial melting from the melilitites (Urach-Hegau) to the subalkaline tholeiites of northern Germany and the Iblean Plateau (Sicily). A significant proportion of the more silica-rich alkaline mafic magmas also have distinctly low CaO/Al_2O_3 ratios. Many of these samples also have variably elevated K_2O/Na_2O ratios, consistent with their derivation from enriched, probably lithospheric, mantle sources which had been fluxed by subduction-related fluids either during Variscan orogenesis or Alpine collision.

In primitive mantle normalised trace element variation diagrams (**Fig. 11**) the alkali basalts, basanites and nephelinites are typically characterised by marked depletions of K and Rb relative to Ba and Nb, consistent with the presence of residual amphibole or phlogopite in their mantle source. The negative K anomaly disappears in the highest degree partial melts (tholeiitic basalts) consistent with the complete melting of the K-bearing phase in the mantle source. The potassic magma types inferred to be partial melts of enriched lithospheric mantle sources (leucite nephelinites and leucite basanites) have relatively flat trace element patterns and no K anomaly. The absence of a K anomaly suggests that any K-bearing phase in their mantle source (i.e. phlogopite or amphibole) must have completely melted.

DISCUSSION

One of the major problems in petrogenetic studies of intra-continental plate alkaline magmatism is the identification of the source of the primary magmas, in particular whether this is located in the mantle part of the lithosphere, the underlying convecting asthenosphere, or both. It has often been argued that since the basalts have Sr-Nd-Pb isotopic characteristics similar to those of oceanic basalts then they must originate in the asthenosphere (e.g. Wilson & Downes, 1991). A number of workers have argued that mantle plumes must be involved in the generation of the Central and Eastern European province volcanic rocks (e.g. Wedepohl et al., 1994; Wedepohl & Baumann, 1999; Wedepohl, 2000). This remains, however, a subject for debate.

Wilson & Downes (1991, 1992) suggested that the most primitive mafic alkaline volcanic rocks within the Tertiary-Quaternary extension-related magmatic province of western and central Europe (**Fig.2**) have major and trace element and Nd-Sr-Pb-O isotopic characteristics which suggest the involvement of both lithospheric and asthenospheric source components in their petrogenesis. The model developed here to explain regional variations in the geochemistry of the most primitive mafic magmas proposes that the sodic magma types (melilitites, nephelinites, basanites, alkali olivine basalts) are derived from a common asthenospheric mantle source, which we term the European Asthenospheric Reservoir (EAR; Cebria & Wilson, 1995). The EAR is synonymous with the Low Velocity Component (LVC) of Hoernle et al. (1995). The potassic lavas (leucitites, leucite basanites) are envisaged to originate from locally enriched enriched portions of the mantle lithosphere which have been fluxed by subduction-related fluids during Variscan or younger collisional events.

The geochemical characteristics of the lithospheric end-member are in part constrained by those of spinel lherzolite mantle xenoliths entrained within the magmas. Available Sr-Nd-Pb isotopic data (e.g. Downes & Dupuy, 1987; Hartmann & Wedepohl, 1990; Rosenbaum *et al*. 1997; Zangana et al., 1997; Downes, 2001; Wilson & Rosenbaum, unpublished data) suggest that there are widespread but systematic isotopic heterogeneities within the different structural domains within the European lithosphere which may become imprinted upon any asthenosphere-derived magmas passing through them. Phlogopite-amphibole bearing lithospheric mantle, probably metasomatised during or after the Variscan orogeny, appears be the predominant source of potassic mafic magmas within the province (Wilson & Downes, 1992). Amphibole is relatively common within the European mantle xenolith suites (Downes, 2001), whereas phlogopite typically only occurs in those regions in which potassic magma types are erupted. Detailed studies of mantle xenoliths from the Eifel province of northern Germany (Witt-Eickschen *et al*., 1998) have revealed the presence of at least two metasomatic enrichment events; one related to modification by subduction-related fluids during the Variscan orogeny and a more recent vein-type infiltration of presumed Tertiary-Quaternary age.

In the context of the petrogenesis of the primary magma spectrum within the European volcanic province, an important question is whether we can identify specific magma compositions which appear to be derived directly from the asthenosphere (or the thermal boundary layer at the base of the lithosphere) which do not appear to have experienced significant degrees of interaction with enriched lithospheric mantle domains *en route* to the surface. Melilite nephelinites and melilitites are, in general, rather rare highly silica-undersaturated mafic magmas which occur at scattered localitites throughout the European Tertiary-Quaternary volcanic province (**Fig.2**). The best known occurrences are Ciudad Real in Spain, Marcoux in the French Massif Central, Essey-la-Cote and Grand Valtin in the Vosges, the Ohre rift of the Czech Republic, Kaiserstuhl in the Rhinegraben, the Eifel province of the Rhenish Massif and the Urach and Hegau provinces to the east of the Rhine Graben (Wilson et al., 1995b). Locally, however (e.g. Urach and Hegau provinces of Germany, Eger Graben of the Czech Republic) they are a volumetrically significant component of the spectrum of mafic magmas erupted. Melilitites may, therefore, be the most likely candidates for primary partial melts of the thermal boundary layer at the base of the lithosphere, representing the incipient melting of the most fusible parts of the upper mantle (Wilson et al., 1995b; Hegner et al., 1995). In some cases their Sr-Nd-Pb isotope characteristics appear to represent the primary asthenospheric end-member of the European mafic-ultramafic magma spectrum (e.g.Wilson & Downes, 1991, 1992); however, in many cases the melilitites appear to have a hybrid lithosphere-asthenosphere signature.

Bogaard & Wörner (2003) have proposed that High-Ti basanites forming the earliest eruptives in the Vogelsberg area of northern Germany are partial melts of lithospheric mantle which had been metasomatised during the initial stages of uplift of the Rhenish Massif at ca 70 Ma. Subsequent eruptions of tholeiitic basalts are considered to represent higher degrees of partial melting of a much more depleted mantle source component, located either in the lower lithosphere or uppermost asthenosphere. The depleted mantle source component is geochemically similar to MORB-source mantle. With time the influence of an EAR-like source component in the petrogenesis of the Vogelsberg magmas appears to increase as the degree of melting decreases. The sequence is similar to that predicted by Gallagher & Hawkesworth (1992) and Hawkesworth & Gallagher (1993) for the sequential evolution of basaltic volcanism in a region extending above a thermal anomaly in the mantle.

Magma generation within the European upper mantle during the Cenozoic was most probably triggered by adiabatic decompression partial melting of the asthenophere, the solidus of which was locally lowered by the infiltration of slab-derived fluids above contemporaneous subduction zones. Decompression melting may have been triggered locally by lithospheric flexuring in the fore-bulge of the Alps (e.g. Urach province of Germany; Vosges-Black Forest dome), by lithospheric extension (e.g. Limagne Graben; Pannonian Basin; Eger Graben) or by upwelling of asthenospheric mantle diapers (e.g. Massif Central; Eifel). If such diapirs are hotter than the ambient mantle, the rising mantle will intersect the solidus at greater depths; thus much less lithospheric thinning is required to produce relatively large volumes of melt. The amount of melting, and hence the composition of the magmas, is strongly influenced by the local thickness of the lithosphere (e.g. Ellam, 1992). For the generally small amounts of lithospheric extension observed within the European volcanic province (e.g. Merle et al., 1998), it is clear that partial melting requires either an anomalously hot or a volatile-rich mantle source.

The convective instabilities (mantle diapirs) which have been inferred to provide the dominant control on magmatism in a number of areas have been imaged by high-resolution seismic tomography (e.g. Granet et al., 1995; Ritter et al., 2001). Their scale-length suggests that they most probably originate as instabilities within the upper mantle. Their velocity contrast with the surrounding mantle is consistent with a temperature anomaly of up to 100-150 ^{o}C hotter than the ambient mantle. Convective de-stabilisation of the upper mantle may have been initiated by the Alpine collision and the consequent global reorganisation of plate motions. Small-degree, CO_2-H_2O enriched partial melts from the ascending mantle diapirs may have frozen at the base of the lithosphere creating a heterogeneous carbonated phlogopite-lherzolite layer (Wilson et al., 1995b). Partial melting of this layer, during subsequent lithospheric extension or thermal thinning, could produce melilitite-like magmas.

Enrichment of the base of the lithosphere by infiltration of small-degree partial melts could have taken place in several stages, related to Neogene diapiric upwelling of the asthenosphere. It is possible, however, that widespread pollution of the shallow mantle beneath Europe with a plume-like component could have occurred in the Late Cretaceous-Early Tertiary associated with outflow from the Iceland plume system in the North Atlantic, from the Canary Islands plume, or perhaps even earlier during the Mesozoic when there was widespread plume-related magmatism globally (Wilson, 1992). Clearly the simplest model would be to relate the enrichment of the base of the lithosphere to Tertiary mantle upwelling.

SUMMARY

The distribution of the major volcanic provinces within Europe is broadly anti-correlated with the location of a zone of high-velocity, presumed subducted slab material, in the base of the upper mantle (500-600 km depth). Many of the major volcanic fields are located around the periphery of this velocity anomaly (Fig.1), coincident with the distribution of small-scale convective instabilities (mantle diapirs) in the upper mantle imaged by the local seismic tomography experiments (e.g. Granet et al., 1995; Ritter et al., 2001). Triggering of these upwellings may partially be a response to plate subduction and slab detachment during the Alpine collision. Alternatively it is possible that there is a more complex relationship between extensional tectonics within the Alpine foreland and the presence of discontinuities in lithospheric thickness between adjacent terrane blocks (e.g. Massif Central, Rhenish Massif); extension of heterogeneous lithosphere, consisting of a collage of accreted Variscan teranes, might have induced localised convective instabilities in the upper mantle.

Based on the above scenario, melt generation in the asthenosphere and the base of the lithosphere is inferred to be the consequence of decompression partial melting, triggered by mantle upwelling. Locally, melt generation is enhanced by the presence of hydrous fluids from contemporaneous or earlier subduction zones e.g. Pannonian Basin, Sicily, W. Turkey. Whilst the mantle part of the lithosphere may locally contribute to the magmatism, the main magma source region is sub-lithospheric. Lithospheric architecture, however, clearly plays an important role in the location of the volcanic fields.

Plate-scale stresses have controlled the development of the Cenozoic rift system within Europe, often reactivating older Carboniferous fault systems and terrane boundaries. Most of the major rifts (e.g Rhine graben, Limagne Graben) are, however, only weakly magmatic. This demonstrates that passive lithospheric exension alone cannot be the main trigger for magma generation. Changes in the orientation of the regional stress field may play an important role in controlling the migration of mantle-derived magmas through the crust and, thus, the periodicity of the magmatism.

ACKNOWLEDEGEMENTS

During the past decade we have discussed our ideas on the petrogenesis of magmas within the European volcanic province with numerous workers, all of whom are thanked for their insightful comments. Jeff Rosenbaum contributed a significant volume of Sr-Nd-Pb isotope data which we report in the figures, some of which has still to be published. Rob Patterson provided important insights on the uplift history of Europe during the Cenozoic and its relationship to rifting and magmatism. Jaromir Ulrych inspired our work on the Eger Graben in the Czech Republic and provided invaluable support in the field. Discussions with Peter Ziegler over many years have clarified our ideas about the geodynamic setting of the magmatism. Jose-Maria Cebria helped to constrain the isotopic characteristics of the EAR and focussed our ideas about the contribution of enriched lithospheric mantle sources to the petrogenesis of potassic magmas. Collaboration with Uli Achauer and Michel Granet demonstrated the value of seismic tomography in understanding the pattern of upper mantle convection beneath Europe. Michele Lustrino is acknowledged for helpful discussions on the geodynamic setting of Cenozoic magmatism in Europe.

REFERENCES

ALARD, O., DAUTRIA, J. M. & BODINIER, J. L. 1996. Nature of the upper mantle and metasomatic processes on either side of the Sillon Houiller, Central Massif. *Comptes Rendus de l'Academie des Sciences, Serie II. Sciences de la Terre et des Planetes*, **323**, 763-770.

ARMIENTI P., TONARINI S., D'ORAZIO M., INNOCENTI F., 2004. Genesis and evolution of Mt. Etna alkaline lavas: petrological and Sr-Nd-B isotope constraints. In: Conticelli S. and Melluso L. (Eds) A showcase of the Italian research in petrology: magmatism in Italy. *Periodico di Mineralogica*, **73**, Special Issue, 29-52

BABUSKA, V. & PLOMEROVA, J. 1992. The lithosphere in Central-Europe – seismological and petrological aspects. *Tectonophysics*, **207**, 101-163.

BABUSKA, V., PLOMEROVA, J. & VECSEY, L. 2002. Seismic anisotropy of the French Massif Central and predisposition of Cenozoic rifting and volcanism by Variscan suture hidden in the mantle lithosphere. *Tectonics,* **21**, 1-20.

BARANYI, I., LIPPOLT, H. J. & TODT, W. 1976. Kalium-Argon-Altersbestimmungen an tertiären Vulkaniten des Oberrheingraben-Gebietes: II. -Die Alterstraverse vom Hegau nach Lothringen. *Oberrhein geologische Abh.* **25**, 41-62.

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., COLANTONI, P., DI GIROLAMO, P. & SAVELLI. C. 1981. Upper-Miocene submarine volcanism in the Strait of Sicily (Banco senza nome). *Bulletin Volcanol*ogique **44**, 573-581.

BECCALUVA, L., COLTORTI, M., DI GIROLAMO, P., MELLUSO, L., MILANI, L., MORRA, V. & SIENA, F. 2002. Petrogenesis and evolution of Mt. Vulture alkaline volcanism (Southern Italy). *Mineralogy and Petrology*, **74**, 277-297.

BECCALUVA, L., DERIU, M., MACCIOTTA, G., SAVELLI. C. & VENTURELLI G. 1977. Geochronology and magmatic character of the Pliocene-Pleistocene volcanism in Sardinia (Italy). *Bulletin Volcanol*ogique, **40-3**, 1-16.

BECCALUVA, L., SIENA, F., COLTORTI, M., DI GRANDE, A., LO GIUDICE, A., MACCIOTTA, G., TASSINARI, R. & VACCARO, C. 1998. Nephelinitic to tholeiitic magma generation from metasomatized lithospheric mantle in a transcurrent tectonic setting: an integrated petrogenetic model for the Iblean volcanism (Sicily). *Journal of Petrology,* **39**, 1547-1576).

BECKER, A. 1993. An attempt to define a "neotectonic period" for central and northern Europe. *Geologische Rundschau*, **82**, 67-83.

BETZ, D., FÜHRER, F., GREINER, G. & PLEIN, E. 1987. Evolution of the Lower Saxony Basin. *Tectonophysics*, **137**, 127-170.

BIJWAARD, H. & SPAKMAN, W. 1999. Tomographic evidence for a narrow whole mantle plume below Iceland. *Earth and Planetary Science Letters*, **166**, 121-126.

BLUSZTAJN, J. & S. R. HART 1989. Sr, Nd and Pb isotopic character of Tertiary basalts from southwest Poland. *Geochimica et Cosmochimica Acta,* **53**, 2689-2696.

BOGAARD, P.J.F. & WÖRNER, G. 2003. Petrogenesis of basanitic to tholeiitic volcanic rocks from the Miocene Vogelsberg, Central Germany. *Journal of Petrology,* **44**, 569-602.

BRAUN, T. & BERCHEMER, H. 1993. Investigation of the lithosphere beneath the Vogelsberg volcanic complex with P-wave travel time residuals. *Geologische Rundschau* **82**, 20-29.

BRIOT, D., CANTAGREL, J.M., DUPUY, C. & HARMON, R.S. 1991. Geochemical evolution in crustal magma reservoirs: trace element and Sr-Nd-O isotopic variations in two continental intraplate series at Monts Dore, Massif Central, France. *Chemical Geology* **89**, 281-303.

CALANCHI, N., COLANTONI, P., ROSSI, P.L., SAITTA, M. & SERRI, G. 1989. The Strait of Sicily continental rift system: physiography and petrochemistry of the submarine volcanic centres. *Marine Geology,* **87,** 55-83.

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.

CEBRIÁ, J.M. & LÓPEZ-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.

CEBRIÁ, J.M., LÓPEZ-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 Geothermal Research,* **102**, 217-235.

CEBRIÁ, J.M. & WILSON, M. 1995. Cenozoic mafic magmatism in Western/Central Europe: a common European asthenospheric reservoir, *Terra Nova Abstract Supplement* **7**, 162.

CERIANI, S., FÜGENSCHUH, B., & SCHMID, S.M. 2001. Late-stage thrusting at the "Penninic Front" in the Western Alps between Mont Blanc and Plevoux massifs. *International Journal of Earth Science,* **90**, 685-702.

CIONI, R., CLOCCHIATTI, R., DI PAOLA, G.M., SANTACROCE, R. & TONARINI, M. 1982. Miocene calc-alkaline heritage in the Pliocene volcanism of Monte Arci (Sardinia Italy). *Journal of Volcanology and Geothermal Research,* **14,** 133-167.

CLOCCHIATTI, R., JORON, J. & TREUIL, M. 1988. The role of selective alkali contamination in the evolution of recent historic lavas of Mount Etna. *Journal of Volcanology and Geothermal Research***, 34,** 241-249.

CLOETINGH, S. & LANKREIJER, A. 2001. Lithospheric memory and stress field controls on polyphase deformation of the Pannonian Basin-Carpathian system. *Marine & Petroleum Geology*, **18**, 3-11.

CONDOMINES, M., TANGUY, J.C., KIEFFER, G. & ALLEGRE, C.J. 1982. Magmatic evolution of a volcano studied by ^{230}Th-^{238}U disequilibrium and trace elements systematics: the Etna case. *Geochimica Cosmochimica Acta,* **46,** 1397-1416.

CORSARO R.A. & POMPILIO M., 2004. Dynamics of magmas at Mount Etna In: Mt. Etna: volcano laboratory. Geophysical Monograph, **143**, 91-110

CVETKOVIC, V., PRELEVIC, D., DOWNES, H., JOVANOVIC, M., VASELLI, O. & PÉCSKAY, Z. 2004. Origin and geodynamic significance of Tertiary postcollisional basaltic magmatism in Serbia (central Balkan Peninsula). *Lithos* **73**, 161-186.

DERRUAU, M. 1971. *Sur la morphologie du Massif Central*. Géologie, Géomorphologie et Structure Profonde du Massif Central Français, Clermont-Ferrand, Plein Air Service.

DÈZES, P., SCHMID, S.M. & ZIEGLER, P.A. 2004. Evolution of the European Cenozoic Rift System: interaction of the Alpine and Pyrenean orogens with their foreland lithosphere. *Tectonophysics* **389**. 1-33.

DE VECCHI, G. & SEDEA, R. 1995. The Paleogene basalts of the Veneto Region. *Mem. Soc. Geol. It*alia **47,** 253-274.

DOBLAS, M. & OYARZUN, R. 1989. Neogene extensional collapse in the Western Mediterranean (Betic-Rif orogenic belt): Implications for the generation of the Gibraltar arc and magmatic activity. *Geology,* **17,** 430-433.

DOBOSI, G., FODOR, R.V. & GOLDBERG, S.A. 1995. Late Cenozoic alkalic basalt magmatism in northern Hundary and Slovakia; petrology, source compositions and relationship to tectonics. *Acta Vulcanologica* **7**, 199-207.

D'ORAZIO, M., TONARINI, S., INNOCENTI, F. & POMPILIO, M. 1997. Northern Valle del Bove volcanic sucession (Mt. Etna, Sicily): petrography, geochemistry and Sr-Nd isotope data. *Acta Vulcanologica* **9**, 73-86.

DOSTAL, J., DUPUY, C., & VENTURELLI, G. 1982. Geochemistry of volcanic rocks from the Monte Arci (West Sardinia, Italy). *Chemical Geol*ogy, **35,** 247-264.

DOWNES, H. 1983. The petrogenesis of coexisting saturated and understurated continental alkaline magma series. Unpublished PhD thesis, Leeds University, UK.

DOWNES, H. 1987. Tertiary and Quaternary volcanism in the Massif Central, France. In: *Alkaline Igneous Rocks.* J. G. Fitton and B. G. J. Upton (editors), Geological Society Special Publication **30,** pp 517-530.

DOWNES, H. 1993. The nature of the lower continental crust of Europe; petrological and geochemical evidence from xenoliths. *Physics of the Earth and Planetary Interiors*, **79**, 195-218.

DOWNES, H. 2001. Formation and modification of the shallow sub-continental lithospheric mantle; a review of geochemical evidence from ultramafic xenolith suites and tectonically emplaced ultramafic massifs of Western and Central Europe. *Journal of Petrology*, **42**, 233-250.

DOWNES, H. & C. DUPUY 1987. "Textural, isotopic and REE variations in spinel peridotite xenoliths, Massif Central, France." *Earth and Planetary Science Letters,* **82**, 121-135.

DOWNES, H., PANTÓ, GY., PÓKA, T., MATTEY, D.P. & GREENWOOD, P.B. 1995a. Calc-alkaline volcanics of the Inner Carpathian arc, Northern Hungary; new geochemical and oxygen isotopic results. *Acta Vulcanologica,* **7**, 29-41.

DOWNES, H., SEGHEDI,I., SZAKÁCS,A., DOBOSI, G., JAMES, D.E., VASELLI, O., RIGBY, I.J., INGRAM, G.A., REX, D. & PÉCSKAY, Z. 1995b. Petrology and geochemistry of late Tertiary-Quaternary alkaline volcanism in Romania. *Lithos*, **35**, 65-81.

DUGGEN, S., HOERNLE, K., VAN DEN BOGAARD, P., RÜPKE, L. & MORGAN, J.P. 2003. Deep roots of the Messininian salinity crisis. *Nature,* **422**, 602-605.

ELLAM, R.M. 1992. Lithospheric thickness as a control on basalt geochemistry. *Geology*, **20**, 153-156.

EMBEY-ISZTIN, A. & DOBOSI, G. 1995. Mantle source characteristics for Miocene-Pleistocene alkali basalts, Carpathian-Pannonian Region: a review of trace elements and isotopic composition. *Acta Vulcanologica,* **7**, 155-166.

EMBEY-ISZTIN, A., DOWNES, H., JAMES, D.E., UPTON, B.G.J., DOBOSI, G., INGRAM. G.A., HARMON, R.S. & SCHARBERT, H. 1993. The petrogenesis of Piocene alkaline volcanic rocks of the Pannonian Basin, eastern central Europe. *Journal of Petrology,* **34**, 317-343.

FRANKE, W. 1989. Tectonostratigraphic units in the Variscan belt of central Europe. *Geological Society of America Special Paper* **230**, pp 67-90.

FUCHS, K., K. GEHLEN, H. MÄLZER, H. MURAWSKI AND A. SEMMEL 1983. *Plateau Uplift: The Rhenish Shield - a Case History*. Springer, Heidelberg.

FUHRMANN, U. & LIPPOLT, H.J. 1990. Tertiärer Vulkanismus: In: Requadt., H. (ed.) *Erläuterungen zur Geologischen Karte Blatt 5613, Schaumberg.* Geologisches Landesamt Rheinland-Pflaz, Mainz, Germany, pp 84-94.

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

GARCIA-CASTELLANOS, D., CLOETINGH, S. & VAN BALEN, R. 2000. Modelling the Middle Pleistocene uplift in the Ardennes-Rhenish Massif: thermo-mechanical weakening under the Eifel? *Global and Planetary Change,* **27**, 39-52.

GASPERINI, D., BLICHERT-TOFT, J., BOSCH, D., DEL MORO, A., MACERA, P., TÉLOUK, P. & ALBARÈDE, F. 2000. Evidence from Sardinian basalt geochemistry for recycling of plume heads into the Earth’s mantle. *Nature,* **408**, 701-704.

GEBAUER, D. 1999. Alpine geochronology of the Central and Western Alps: new constraints for a complex geodynamic evolution. *Schweizerische Mineralogische und Petrographische Mitteilungen,* **79**, 191-208.

GILLOT, P.Y., KIEFFER, G. & ROMANO, R. 1994. The evolution of Mount Etna in the light of potassium-argon dating. *Acta Volcanologica,* **5,** 81-87.

GLAHN, A., SACHS, P.M. & ACHAUER, U. 1992. A teleseismic and petrological study of the crust and upper mantle beneath the geothermal anomaly of Urach, SW Germany. *Physics of the Earth & Planetary Interiors,* **69**, 176-206.

GOES, S., GOVERS, R. & VACHER, P. 2000. Shallow mantle temperatures under Europe from P and S wave tomography. *Journal of Geophysical Research*, **105,** 11153-11169.

GOES, S., SPAKMAN, W. & BIJWAARD, H. 1999. A lower mantle source for Central European volcanism. *Science,* **286**, 1928-1931.

GRANET, M., WILSON, M. & ACHAUER, U. 1995. Imaging a mantle plume beneath the French Massif Central, *Earth and Planetary Science Letters*, **136,** 281-296

GRUNEWALD, S., KIND, R. & WEBER, M. 2001. The upper mantle under Central Europe – indications for the Eifel plume. *Geophysical Journal International*, **147**, 590-601.

GULEÇ, N. 1991. Crust-mantle interaction in western Turkey: implications from Sr and Nd isotope geochemistry of Tertiary and Quaternary volcanics. *Geological Magazine,* **128,** 417-435.

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. & SEGHEDI, I. (this volume) Tertiary-Quaternary subduction processes and related magmatism in Europe.

HARANGI, S., VASELLI, O., TONARINI, S., SZABO, C., HARANGI, R., & CORADOSSI, N. 1995. Petrogenesis of Neogene extension-related alkaline volcanic rocks of the Little Hungarian Plain volcanic field (West Hungary). *Acta Vulcanologica* **7**, 173-187.

HARTMANN, G. & WEDEPOHL, K. H. 1990. Metasomatically altered peridotite xenoliths from the Hessian Depression (northwest Germany). *Geochimica et Cosmochimica Acta,* **54**, 71-86.

HAWKESWORTH, C.J. & GALLAGHER, K. 1993. Mantle hotspots, plumes and regional tectonics as causes of intra-plate magmatism. *Terra Nova,* **5**, 552-559.

HEGNER, E., WALTER, H.J. & SATIR, M. 1995. Pb-Sr-Nd isotopic compositions and trace element geochemistry of megacrysts and melilitites from the Tertiary Urach volcanic field: source composition of small volume melts under SW Germany. *Contributions to Mineralogy and Petrology,* **122**, 322-335.

HERNANDEZ, J. & LEPVRIER, C. 1979. Le volcanisme calco-alkalin miocène de la région D'Alger (Algérie): pétrologie et signification géodynamique. Bulletin de la Société Géologique de France, **XXI**, 73-86.

HERNANDEZ, J., LAROUZIERE DE, F.D., BOLZE, J. & BORDET, P. 1987. Le magmatisme néogène bético-rifain et le couloir de décrochement trans-Alboran. *Bulletin de la Société Géologique de France,* **III**, 2, 257-267.

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.

HORN, P., LIPPOLT, H.J. & TODT, W. 1972. Kalium-Argon-Altersbestimmung an tertiären Vulkaniten des Oberrheingrabens. I. Gesamtgesteinsalter. *Eclogae Geologicae Helvetiae,* **65**, 131-156.

HUISMANS, R.S. 1999. *Dynamic modelling of the transition from passive to active rifting, application to the Pannonian Basin.* Vrije University, Amsterdam, Netherlands. Published PhD thesis, 196 pp.

ILLIES, H. 1977. Ancient and recent rifting in the Rhine Graben. *Geologie en Mijnbouw***, 56**, 329-350.

JOVANOVIC, M., DOWNES, H., VASELLI, O., CVETKOVIC, V., PRELEVIC, D. & PECSKAY, Z. 2001. Paleogene mafic alkaline volcanic rocks of East Serbia. *Acta Vulcanologica,* **13**, 159-173.

JUNG, S. 1999. The role of crustal contamination during evolution of continental rift-related basalts, a case study from the Vogelsberg area, Central Germany. *Geolines,* **9**, 48-58.

JUNG, S. & HOERNES, S. 2000. The major- and trace-element and isotope (Sr, Nd, O) geochemistry of Cenozoic alkaline rift-type volcanic rocks from the Rhön area (central Germany): petrology, mantle source characteristics and implications for asthenosphere-lithosphere interactions. *Journal of Volcanology and Geothermal Research* , **99**, 27-53.

JUNG. S. & MASBERG, P. 1998. Major- and trace-element systematics and isotope geochemistry of Cenozoic mafic volcanic rocks from the Vogelsberg (central Germany). Constraints on the origin of continental alkaline and tholeiitic basalts and their mantle sources. *Journal of Volcanology and Geothermal Research,* **86**, 151-177.

KELLER, J., BREY, G., LORENZ, V. & SACHS, P. 1990. IAVCEI 1990 Pre-Conference Excursion 2A: Volcanism and Petrology of the Upper Rhinegraben (Urach-Hegau-Kaiserstuhl).

KELLER, J., KRAML. M. & HENJES-KUNST, F. 2002. $^{40}Ar/^{39}Ar$ single crystal laser dating of early volcanism in the Upper Rhine Graben and tectonic implications. *Schweizerische Mineralogische und Petrographische Mitteilungen*, **82**, 121-130.

KEYSER, M., RITTER, J.R.R. & JORDAN, M. 2002. 3D shear-wave velocity structure of the Eifel plume, Germany. *Earth and Planetary Science Letters,* **203**, 59-82.

KOPECKY, L. 1966. Tertiary volcanics. *Regional Geology of Czechoslovakia*. Prague, Publishing House of the Czechoslovak Academy of Science, **1,** 554-81.

LE BAS, M.J., LE MAITRE, R.W., STRECKEISEN, A. & ZANETTIN, B. 1986. A chemical classification of volcanic rocks based on the total alkali-silica diagram. *Journal of Petrology,* **27**, 745-750.

LEMCKE, K. 1974. Vertikalbewegungen des vormesozoischen Sockels im nördlichen Alpenvorland vom Perm bis zur Gegenwart. *Eclogae Geologicae Helvetiae*, **67**, 121-133.

LENOIR, X., GARRIDO, C.J., BODINIER, J.-L. & DAUTRIA, J.-M. 2000. Contrasting lithospheric mantle domains beneath the Massif Central (France) revealed by geochemistry of peridotite xenoliths. *Earth & Planetary Science Letters,* **181**, 359-375.

LIPPOLT, H. J. 1982. K/Ar determinations and the correlation of Tertiary volcanic activity in central Europe. *Geologisches Jahrbuch. Reihe D: Mineralogie, Petrographie, Geochemie, Lagerstaettenkunde*, **D52**, 113-135.

LIPPOLT, H.J., TODT, W., & BARANYI, I. 1973. K-Ar ages of basaltic rocks from the Urach volcanic district, SW Germany. *Fortschritte der Mineralogie,* **50**, 101-102.

LIPPOLT, H. J., TODT, W. & HORN, P. 1974. Apparent potassium-argon ages of lower Tertiary Rhine graben volcanics. In: J. H. Illies and K. Fuchs. *Approaches to Taphrogenesis*, Stuttgart**,** pp 213-221.

LIPPOLT, H.J., TROESCH, M. AND HESS, J.C. 1990. Excess argon and dating of Quaternary Eifel volcanism, IV. Common argon with high and lower-than-atmospheric $^{40}Ar/^{36}Ar$ ratios in phonolitic rocks, East Eifel F.R.G. *Earth and Planetary Science Letters,* **101**, 19-33.

LITT, T., SCHMINCKE, H.-U. & KROMER, B. 2003. Environmental response to climatic and volcanic events in central Europe during the Weichselian Lateglacial. *Quaternary Science Reviews,* **22**, 7-32.

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

LÓPEZ-RUIZ, J., CEBRIÁ, J.M., DOBLAS, M., OYARZUN, R., HOYOS, M. & MARTIN, C. 1993. The late Cenozoic alkaline volcanism of the Central Iberian Peninsula (Calatrava Volcanic Province, Spain): Intra-plate volcanism related to extensional tectonics. *Journal of the Geological Society, London,* **150,** 915-922.

MALKOVSKY, M. 1987. The Mesozoic and Tertiary basins of the Bohemian Massif and their evolution. *Tectonophysics,* **137**, 31-42.

MARCHEV, P., VASELLI, O., DOWNES, H., PINARELLI, L., INGRAM, G., ROGERS, G. & RAICHEVA, R. 1998. Petrology and geochemistry of alkaline basalts and lamprophyres: implications for the chemical composition of the upper mantle beneath the Eastern Rhodopes (Bulgaria). *Acta Vulcanologica,* **10**, 233-242.

MATYSKA, C. & YUEN, D.A. 2001. Are mantle plumes adiabatic? *Earth and Planetary Science Letters*, **189**, 165-176.

MCDONOUGH, W.F. AND SUN, S.-S 1995. Composition of the Earth. *Chemical Geology*, **120,** 223-253.

MCNUTT, M. K. 1998. Superswells. *Reviews of Geophysics*, **36**, 211-244.

MERTES, H. & SCHMINCKE, H.-U. 1985. Mafic potassic lavas of the Quaternary West Eifel volcanic field. *Contributions to Mineralogy and Petrology,* **89**, 330-345.

MEYER, W., ALBERS, H.J., BERNERS, H.P., VON GEHLEN, K., GLATTHAAR, D., LÖHNERTZ, W., PFEFFER, K.H., SCHNÜTGEN, A., WIENEKE, K. & ZAKOSEK, H. 1983. Pre-Quaternary uplift in the central part of the Rhenish Massif. In Fuchs, K., von Gehlen, K., Mälzer, H., Muawski, H. & Semmel, A. (eds.) *Plateau Uplift*. Springer-Verlag, Berlin, pp 9-38.

MICHON, L. & MERLE, O. 2001. The evolution of the Massif Central rift: Spatio-temporal distribution of the volcanism. *Bulletin de la Societe Geologique de France,* **172**, 201-211.

MILANI, X. 1996. Petrogenesis and metallogenic aspects of Tertiary volcanics of the Euganean Hills magmatic complex (Venetian Province). *Plinius - E.J.M. Italian Supplement*, **15**, 129-132.

MONIÉ, P., MONTIGNY, R. & MALUSKI, H. 1992. Age burdigalien de la tectonique ductile extensive dans le massif de l'Edough (Kabylie, Algérie). Données radiométriques ^{39}Ar-^{40}Ar. *Bulletin Société géologique de France* , **163**, 571-584.

MONTANINI, A. & VILLA, I.M. 1993. ^{39}Ar-^{40}Ar chronostratigraphy of Monte Arci volcanic complex (Western Sardinia, Italy). Acta Vulcanologica, **3**, 229-233.

MONTELLI R., NOLET G., DAHLEN F.A., MASTERS G., ENGDAHL E.R., HUNG S.H. 2004. Finite-frequency tomography reveals a variety of plumes in the mantle. *Science*, **303**, 338-343.

NICHOLAS, A., LUCAZEAU, F. & BAYER, R. 1987. Peridotite xenoliths in Massif Central basalts, France: textural and geophysical evidence for asthenospheric diapirism. In: *Mantle Xenoliths*. P. H. Nixon (ed.). New York, John Wiley and Sons Ltd., pp 563-574.

PAMIC, J., MCKEE, E.H., BULLEN, T. & LANPHERE, M. 1995. Tertiary volcanic rocks from the southern Pannonian Basin. *International Geology Review,* **37**, 259-283.

PATTERSON, R. 1996. *Geochemical characteristics and geodynamic setting of Cenozoic mafic magmatism in western and central Europe*. Unpublished PhD thesis, University of Leeds, UK.

PECSKAY, Z., LEXA, J., SZAKÁCS, A., BALOGH, K., SHEGEDI, I., KONECNY, V., KOVÁCS, M., MÁRTON, E., KALICIAK, M., SZÉKI-FUX, V., PÓKA, T., GYARMATI, P., EDELSTEIN, O., ROSU, E. & ZEC, B. 1995. Space and time distribution of Neogene-Quaternary volcanism in the Carpatho-Pannonian region. In: Downes, H. & Vaselli, O. (Eds.) *Neogene and related volcanism in the Carpatho-Pannonian Region*. Acta Volcanologica Special Issue 7, 15-28.

PIROMALLO, C., VINCENT, A.P., YUEN, D.A. & MORELLI, A. 2001. Dynamics of the transition zone under Europe inferred from wavelet cross-spectra of seismic tomography. *Physics of the Earth and Planetary Interiors,* **125**, 125-139.

PRODEHL, C., MUELLER, S., GLAHN, A., GUTSCHER, M. & HAAK, V. 1992. Lithospheric cross sections of the European Cenozoic rift system. *Tectonophysics,* **208**, 113-138.

RITTER, J.R.R., JORDAN, M., CHRISTENSEN, U.R. & ACHAUER, U.R. 2001. A mantle plume beneath the Eifel volcanic fields, Germany. *Earth & Planetary Science Letters,* **186**, 7-14.

ROMANO, R. 1983. Succession of the volcanic activity in the Etnean area. *Mem. Soc. Geol. Italia*, **23**, 27-28.

ROSENBAUM, G., LISTER, G.S., & DUBOZ, C. 2002. Relative motion of Africa, Iberia and Europe during the Alpine orogeny. *Tectonophysics* **359**, 117-129.

ROSENBAUM, J.M., WILSON, M. & DOWNES, H. 1997. Enrichment of the Pannonian-Carpathian mantle: Pb isotope constraints. *Journal of Geophysical Research,* 102, 14947-14961.

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

SACHSENHOFER, R.F., JELEN, B., HAENHÜTTL, C., DUNKL, I. & RAINER, T. 2001. Thermal history of Tertiary basins in Slovenia (Alpine-Dinaride-Pannonian junction). *Tectonophysics*, **334**, 77-99.

SALTERS, V.J.M., HART, S.R. & PANTO, G.1988. Origin of late Cenozoic volcanic rocks of the Carpathian Arc, Hungary. In: Royden, L.H. & Horvath, F. (eds) *The Pannonian Basin: A study in basin evolution*. AAPG Memoir **45**, 279-292.

SCHLEICHER, H., BAUMANN, A. & KELLER, J. 1991. Pb isotopic systematics of alkaline volcanic rocks and carbonatites from the Kaiserstuhl, upper Rhine rift valley, F.R.G. *Chemical Geology*, **93**, 231-243.

SCHLEICHER, H., KELLER, J. & KRAMM, U. 1990. Isotope studies on alkaline volcanics and carbonatites from the Kaiserstuhl, Federal Republic of Germany. *Lithos*, **26,** 21-35.

SCHMINCKE, H.-U., LORENZ, V. & SECK, H.A. 1983. The Quaternary Eifel volcanic fields. In: Fuchs, K., von Gehlen, K., Maelzer, H., Murawski, H., & Semmel, A. (eds) *Plateau Uplift*, Springer, Berlin, pp 139-151.

SCHREIBER, U. & ROTSCH. S. 1998. Cenozoic block rotation according to a conjugate shear system in central Europe – indications from paleomagnetic measurements. *Tectonophysics* **299**, 111-142.

SCHRÖDER, B. 1987. Inversion tectonics along the western margin of the Bohemian Massif. *Tectonophysics* **137**, 93-100.

SCHUMACHER, M.E. 2002. Upper Rhine Graben: the role of pre-existing structures during rift evolution. *Tectonics* , **21**, no 1, 17pp.

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

SEYITOLU, G., ANDERSON, D., NOWELL, G. & SCOTT, B. 1997. The evolution from Miocene Potassic to Quaternary sodic magmatism in western Turkey: implication for enrichment processes in the lithospheric mantle. *Journal of Volcanology and Geothermal Research,* **79,** 127-148.

SHRBENY, O. 1995. Chemical composition of young volcanites of the Czech Republic. *Czech Geological Survey Special Paper 4,* pp 53.

SIENA, F. & COLTORTI, M. 1989. Lithospheric mantle evolution: Evidences from ultramafic xenoliths in the Lessinian volcanics (northern Italy). Chemical Geology, **77**, 47-364.

SISSINGH, W. 2003. Tertiary paleogeographic and tectonostratigraphic evolution of the Rhenish triple junction. *Palaeogeography Palaeoclimatology Palaeoecology*, **196**, 229-263.

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.

SZABÓ, CS., HARANGI, SZ., & 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

TARI, V. & PAMIC, J. 1998. Geodynamic evolution of the northern Dinarides and the southern part of the Pannonian Basin. *Tectonophysics* , **297**, 269-281.

TRICART, P., TORELLI, L., ARGNANI, A., REKHISS, F. & ZITELLINI, N. 1994. Extensional collapse related to compressional uplift in the Alpine Chain off northern Tunisia (Central Mediterranean). *Tectonophysics,* **238**, 317-329.

ULRYCH, J. & PIVEC, E. 1997. Age-related contrasting alkaline volcanic series in North Bohemia. *Chem. Erde.* **5**, 311-336.

ULRYCH, J., CAJZ, V., BALOGH, K. & ERBAN, V. 2001. Geochemistry of the stratified volcanosedimentary complex in the central part of the Ceske Stredohori Mts., north Bohemia. *Krystalinikum,* **27**, 27-49.

VAN WIJHE, D. H. 1987. Structural evolution of inverted basins in the Dutch offshore. *Tectonophysics,* **137**, 171-219.

VASELLI, O., DOWNES, H., THIRLWALL, M.F., DOBOSI, G., CORADOSSI, N., SEGHEDI, I., SZAKÁCS, A. & VANNUCCI, R. 1995. Ultramafic xenoliths in Plio-Pleistocene alkali basalts from the eastern Transylvanian Basin: Depleted mantle enriched by vein metasomatism. *Journal of Petrology*, **36**, 23-54.

VASELLI, O., MARCHEV, P., DOWNES, H., CORADOSSI, N. & INGRAM, G. 1997. Ultramafic xenoliths from Chatala and Kamuka volcanoes (Northern Bulgaria). *Comptes rendus de l'Académie bulgare des Sciences,* **50**, 73-76.

VON BLANCKENBURG, F. & DAVIES, J.H. 1995. Slab break-off: a model for syncollisional magmatism and tectonics in the Alps. *Tectonics*, **14**, 120-131.

WEDEPOHL, K.H. 2000. The composition and formation of Miocene tholeiites in the Central European Cenozoic plume volcanism (CECV). *Contributions to Mineralogy and Petrology,* **140**, 180-189.

WEDEPOHL, K.H. & BAUMANN, A. 1999. Central European Cenozoic plume volcanism with OIB characteristics and indications of a lower mantle source. *Contributions to Mineralogy & Petrology*, **136**, 225-239.

WEDEPOHL, K.H., GOHN, E. & HARTMANN, G. 1994. Cenozoic alkali basaltic magmas of western Germany and their products of differentiation. *Contributions to Mineralogy & Petrology,* **115**, 253-278.

WHITE, R. & MCKENZIE, D. 1989. Magmatism at rift zones: the generation of volcanic continental margins and flood basalts. *Journal of Geophysical Research,* **94**: 7685-7729.

WILSON, M. 1989. *Igneous Petrogenesis*. Kluwer, Netherlands, 450 pp.

WILSON, M. 1992. Magmatism and continental rifting during the opening of the South Atlantic Ocean- a consequence of Lower Cretaceous super-plume activity? In: Storey, B.C., Alabaster, T. & Pankhurst, R. J., *Magmatism and Continental Break-up*. Special Publication of the Geological Society No 68, pp 241-255, London, Geological Society of London.

WILSON, M. & BIANCHINI, G 1999. Tertiary-Quaternary magmatism within the Mediterranean and surrounding regions. In: Durand, B., Jolivet, L., Horvath, F & Seranne, M. (eds) *The Mediterranean Basins: Tertiary Extension within the Alpine Orogen.* Geological Society, London, Special Publication 156, pp 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. & DOWNES, H. 1992. Mafic alkaline magmatism in the European Cenozoic rift system. *Tectonophysics*, **208,** 173-182.

WILSON, M. & GUIRAUD, R. 1998. Late Permian to Recent magmatic activity on the African-Arabian margin of Tethys. In: Macgregor, D.S., Moody, R.T.J. & Clark-Lowes, D.D. (eds) *Petroleum Geology of North Africa.* Special Publication of the Geological Society of London No 132, 231-263.

WILSON, M. & PATTERSON, R. 2001. Intra-plate magmatism related to hot fingers in the upper mantle: Evidence from the Tertiary-Quaternary volcanic province of western and central Europe. In: R. Ernst & K. Buchan (Editors) *Mantle Plumes: Their identification through time*. Geological Society of America Special Paper 352, pp37-58

WILSON, M., DOWNES, H. & CEBRIA, J.-M. 1995a. Contrasting fractionation trends in coexisting continental alkaline magma series; Cantal, Massif Central, France. J*ournal of Petrology,* **36,** 1729-53

WILSON, M., ROSENBAUM, J.M. & DUNWORTH, E.A. 1995b. Melilitites: partial melts of the thermal boundary layer? *Contributions to Mineralogy & Petrology*, **119**, 181-196.

WILSON, M., TANKUT, A. & GÜLEÇ, N. 1997. Tertiary volcanism of the Galatia Province, Central Anatolia, Turkey. *Lithos*, **42**, 105-121.

WIMMENAUER, W., 1974. The alkaline province of Central Europe and France. In: *The Alkaline Rocks* (Ed: Sørensen ,H.), pp 238-270.

WITT-EICKSHEN, G., KAMINSKY, W., KRAMM, U. & HARTE, B. 1998. The nature of young vein metasomatism in the lithosphere of the West Eifel (Germany); geochemical and isotopic constraints from composite mantle xenoliths from the Meerfelder Maar. *Journal of Petrology,* **39**, 155-185.

WÖRNER, G., ZINDLER, A., STAUDIGEL, H. & SCHMINCKE, H.-U. 1986. Sr, Nd, and Pb isotope geochemistry of Tertiary and Quaternary alkaline volcanics from West Germant. *Earth and Planetary Science Letters,* **79**, 107-119.

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

YILMAZ, Y. 1990. Comparison of young volcanic associations of western and eastern Anatolia formed under a compressional regime: a review. *Journal of Volcanoogy and Geothermal Res*earch, **44**, 69-87.

ZANGANA, N., DOWNES, H., THIRLWALL, M.F. & HEGNER, E. 1997. Relationship between deformation, equilibration temperatures, REE and ragiogenic isotopes in mantle xenoliths (Ray Pic, Massif Central, France): an example of plume-lithosphere interaction? *Contributions to Mineralogy and Petrology*, **127**, 187-203.

ZECK, H.P., MONIE, P., VILLA, I.M. & HANSEN, B.T. 1992. Very high rates of cooling and uplift in the Alpine belt of the Betic Cordilleras, southern Spain. *Geology,* **20**, 79-82.

ZEYEN, H., NOVAK, O., LANDES, M., PRODEHL, C., DRIARD, L. & HIRN, A. 1997. Refraction seismic investigations of the northern Massif Central (France). *Tectonophysics*, **275**, 99-117.

ZIEGLER, P. A. 1990. *Geological Atlas of western and central Europe* (2nd edition), Shell Internationale Petroleum Maatschappij B.V. Amsterdam, Geological Society, London, Elsevier.

ZIEGLER, P.A. 1992 European Cenozoic rift system. In: P.A. Ziegler (Editor), Geodynamics of Rifting, Volume I. Case History Studies on Rifts: Europe and Asia. *Tectonophysics*, **208**, 91-111.

ZIEGLER, P.A. & DÈZES, P. (THIS VOLUME) Crustal evolution of Western and Central Europe. In: Gee, D. & Stephenson, R. (eds) *European Lithosphere Dynamics*. Memoir Geological Society of London.

ZIEGLER, P.A., CLOETINGH, S. & VAN WEES, J.-D. 1995. Dynamics of intra-plate compressional deformation: the Alpine foreland and other examples. *Tectonophysics,* **252,** 7-59.

ZIELHUIS, A. & NOLET, G. 1994. Shear-wave velocity variations in the upper mantle beneath Central Europe. *Geophysical Journal International*, **117**, 695-715.

FIGURE CAPTIONS

Fig. 1: False coloured topographic map of Europe and the Mediterranean region indicating the locations of the main Tertiary-Quaternary volcanic fields discussed in this review. Also shown is the location of a zone of high velocity mantle within the mantle Transition Zone (500-600 km) beneath Europe (from Piromallo et al., 2001) which may be a region of subducted slabs at the base of the upper mantle. The ages of such slabs cannot be constrained; however, they most probably represents remnant of subducted Tethyan oceanic lithosphere. The variable size of the red asterisks, marking the location of individual volcanic fields, indicates, schematically, the relative volume of magmatism.
Abbreviations: TTZ- Tornquist-Tesseyre Zone

Fig. 2: Relationship of the main Tertiary-Quaternary volcanic fields in western and central Europe to zones of uplifted basement, major rift systems and the Variscan basement terranes of central Europe. After Wilson & Patterson (2001) and Wilson & Downes (1991).
Abbreviations: PBF – Pas de Bray Fault; SHF – Sillon Houiller Fault; V/BF – Voges-Black Forest dome; RG- Rhine Graben; RH – Rhenohercynian terrane; S- Saxothuringian terrane; M- Moldanubian terrane; NHD- North Hessian Depression.

Fig. 3: Chronology of Tertiary-Quaternary volcanism within Europe and the Mediterranean region in relation to major periods of lithospheric extension, basement uplift and phases of Alpine compression. For data sources see text. Note that the time scale from 65 to 25 Ma is compressed.
Abbreviations: CS -Ceské Stredohori; DH- Doupovsky Hory; TS- Tyrhennian Sea

Fig. 4: Summary of the changing distribution and intensity of Tertiary-Quaternary magmatism throughout Europe and the Mediterranean region. See text for details.

Fig. 5: Total alkali-silica variation diagrams for the most primitive mafic magmatic rocks The classification boundaries are from Le Bas et al. (1986). The dashed grey line in (c) marks the subdivision between alkaline and subalkaline magma series.
Sources of data: see Table 1

Fig. 6: Variation of $^{143}Nd/^{144}Nd$ versus $^{87}Sr/^{86}Sr$ for the most primitive mafic volcanic rocks. EAR – isotopic composition of the European asthenospheric Reservoir from Cebria & Wilson (1995). BE - Bulk Earth. Sources of data: see Table 1.

Fig. 7

- **(a)** Variation of $^{143}Nd/^{144}Nd$ versus $^{206}Pb/^{204}Pb$ for the most primitive mafic volcanic rocks.
- **(b)** Variation of $^{207}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ for the most primitive mafic volcanic rocks.

EAR – isotopic composition of the European asthenospheric Reservoir (EAR) from Cebria & Wilson (1995). Sources of data: see Table 1

Fig. 8: Variation of Nb/Y versus Zr/Nb for the most primitive mafic volcanic rocks. Curves are model melting curves from Harangi (2001) for 0.5 -5% partial melting of spinel- and garnet-peridotite facies mantle. Sources of data: see Table 1
Model parameters (from Harangi, 2001)**:**
Source composition: Zr 11.3 ppm, Nb 0.72 ppm, Y 2.7 ppm
Source mineralogy:
Spinel lherzolite: ol58 – opx30 – cpx10-sp2 (%)

Garnet lherzolite: ol59.9 – opx25.5 – cpx8.8 – gt5.8 (%)

Melting modes:

ol1.2 – opx8.1 – cpx76.4 – sp14.3 (%)

ol1.2 – opx8.1 – cpx36.4 – gt54.3 (%)

Fig. 9: Variation of La/Yb versus Gd/Yb for the most primitive mafic volcanic rocks.

Sources of data: see Table 1

Fig. 10: Variation of CaO/Al_2O_3 versus SiO_2 for the most primitive mafic volcanic rocks.

Sources of data: see Table 1

Fig. 11: Primitive mantle normalised trace element variation diagrams for representative primitive mafic volcanic rocks. Normalisation constants from McDonough & Sun (1995). Sources of data: see Table 1