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Petrological and geochemical variations of Plio-Quaternary volcanism in the Tyrrhenian Sea area: regional distribution of magma types, petrogenesis and geodynamic implications

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ABSTRACT. — The Plio-Quaternary magmatism in the Tyrrhenian Sea area shows a strong regionality in the distribution of magma types, which allows distinguishing several magmatic provinces or zones. These are: 1) Tuscany, 2) Latium, 3) Intra-Apennine region, 4) Neapolitan area, 5) Ernici-Roccamonfina, 6) Mt. Vulture, 7) Aeolian Arc, 8) Sicily, 9) Tyrrhenian Sea floor, and 10) Sardinia. The different provinces are sometimes divided by important tectonic lines and show distinct mechanical characteristics of the lithosphere (i.e., Moho depth, lid thickness, occurrence of deep seismicity, etc.).

In Tuscany, mafic calc-alkaline to ultrapotassic magmas coexist with silicic intrusive and extrusive rock of crustal anatectic origin. Magmatism in central Italy ranges from calc-alkaline to ultrapotassic, but each province displays peculiar major and/or trace element and/or isotopic composition. Calc-alkaline to shoshonitic magmatism dominates in the Aeolian Arc. Igneous activity in the Sicily and Sardinia provinces consist of tholeiitic to Na-alkaline products, which show low LILE/HFSE ratios, typical of intraplate volcanics. Intraplate and arc-type rocks coexist on the Tyrrhenian Sea floor.

Radiogenic isotope compositions (Sr, Nd, Pb) of mafic rocks show moderate within-province variations. However, when the whole Plio-Quaternary magmatism in considered, continuous trends are observed, which connect various mantle compositions. Rocks from the Sicily province have HIMU-type signatures composition trending toward DMM-EM1. Rocks from Sardinia and the Tyrrhenian Sea plot between EM1 and HIMU composition. Rocks from the Aeolian Arc to Tuscany define a trend connecting the HIMU-like rocks of Sicily with a Tuscany mafic ultrapotassic end-member characterised by high $^{87}Sr/^{86}Sr$, low $^{143}Nd/^{144}Nd$ and moderately low $^{206}Pb/^{204}Pb$. This end-member is more enriched in radiogenic Sr than EM2 mantle component, and resembles closely the upper crust for both trace element ratios and radiogenic isotope ratios.

The anorogenic trace element signatures of magmatism in Sicily and Sardinia suggest a genesis in a mantle which suffered little or no contamination by subduction processes, at least in recent times. Radiogenic isotopic trends reveal an interaction between various mantle components (HIMU, DMM, EM1). In contrast, the magmatism in the Aeolian Arc and peninsular Italy highlights interaction between HIMU-type and upper crustal reservoirs. Geochemical modelling demonstrates that such an interaction cannot have occurred during magma ascent to the surface (magma contamination), but took place in the upper mantle by addition of upper crustal material (source contamination). Such a conclusion implies a subduction-related origin for the magmatism in the Aeolian Arc and the Italian peninsula. The

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coexistence of anorogenic-type and arc-type rocks in the Tyrrhenian Sea calls for a role of both intraplate and subduction-modified mantle sources.

The hypothesis that best explains the regionality of magma types in Italy and their age, geochemical and isotopic characteristics is that subduction of Ionian-Adria plate affected the Sardinia block during Oligo-Miocene and successively shifted south-eastward towards its present position in the southern Tyrrhenian Sea. This caused a migration of subduction-related magmatism from Sardinia, through the Tyrrhenian Sea to southern Italy and the Aeolian Arc. Contemporaneously, the back-arc opening of the Tyrrhenian Sea basin generated passive asthenospheric upwelling and the formation of anorogenic-type magmas, which coexist with subduction-related rocks. The Apennine chain underwent anticlockwise rotation and segmentation during Tyrrhenian Sea opening, breaking into various arc sectors along which variable types of sedimentary material were subducted. These induced strong heterogeneities in the mantle wedge, which are reflected by regional variations of geochemical and isotopic composition of the magmatism along the Italian peninsula. The hypothesis of the presence of deep mantle plumes in the Tyrrhenian Sea area is unable to explain most of the compositional characteristics of the magmatism. However, the HIMU-like isotopic signatures of rocks in Sicily (e.g. Etna, Ustica, Iblei) resemble closely those of several intraplate volcanics in central and eastern Europe (e.g. Massif Central in France, Eifel region in Germany). This calls for a wide European mantle reservoir, may be well explained by a deep mantle plume, but does not necessarily require one.

RIASSUNTO. — Il magmatismo Plio-Quaternario dell'area circum-tirrenica mostra una forte regionalità nella distribuzione dei tipi di magma. Sulla base delle caratteristiche petrologiche e geochimiche delle rocce più primitive, è possibile distinguere diverse zone o province magmatiche: 1) Provincia Toscana, 2) Provincia Laziale o Provincia Romana s.s., 3) Provincia Intra-Appenninica, 4) Provincia Napoletana, 5) Ernici-Roccamonfina, 6) Monte Vulture, 7) Arco Eoliano, 8) Sicilia, 9) Bacino Tirrenico e 10) Sardegna.

Alcune province sono separate da importanti linee tettoniche e sono caratterizzate da peculiari caratteristiche della litosfera e del tipo di sismicità.

In Toscana, magmi mafici da calc-alcalini a ultrapotassici sono associati con rocce intrusive ed effusive di origine anatettica crostale. Il magmatismo in Italia centrale è prevalentemente alcalino-potassico, ma ogni provincia mostra proprie peculiarità per i tenori in elementi in tracce e per le composizioni isotopiche. L'Arco Eoliano è dominato da magmatismo calc-alcalino e shoshonitico. L'attività ignea in Sicilia e Sardegna è rappresentata da prodotti toleiitici, transizionali e Na-alcalini, i quali mostrano bassi rapporti di LILE/HFSE, tipici del vulcanismo entroplacca. Nel Bacino Tirrenico si rinvengo vulcaniti di arco strettamente associate a rocce di tipo entroplacca.

La composizione degli isotopi radiogenici (Sr, Nd, Pb) delle rocce femiche mostra moderate variazione all'interno delle singole province. Tuttavia, se si considera l'intero magmatismo Plio-Quaternario, si osservano trend continui tra varie composizioni mantelliche. Le rocce siciliane sono caratterizzate da composizione di tipo HIMU con tendenza verso DMM-EMI. Quelle della Sardegna e del Bacino Tirrenico hanno composizione tra EMI e HIMU. Le rocce affioranti nell'Arco Eoliano e lungo la penisola italiana definiscono un trend continuo tra le rocce di tipo HIMU della Sicilia e le rocce ultrapotassiche della Toscana. Queste ultime sono caratterizzate da pattern degli elementi incompatibili simili a quelli della crosta superiore, e hanno valori degli isotopi di Nd e Pb simili al componente mantellico EM2 ma rapporti $^{87}Sr/^{86}Sr$ molto più elevati.

Il carattere geochimico anorogenico del magmatismo siciliano e sardo suggerisce una genesi in un mantello affetto da scarsa o assente contaminazione da processi di subduzione, almeno in tempi recenti; i trend degli isotopi radiogenici rivelano un'interazione tra varie componenti mantelliche (HIMU, DMM, EMI). Al contrario, il magmatismo dell'Arco Eoliano e della penisola italiana mette in evidenza un'interazione tra sorgenti di tipo HIMU e la crosta superiore. I modelli geochimici dimostrano che tale interazione non può essere avvenuta per contaminazione dei magmi all'interno della crosta, ma si è realizzata per aggiunta di materiale crostale al mantello superiore (contaminazione o metasomatismo mantellico). Il magmatismo dell'Arco Eoliano e della penisola italiana è dunque da mettere in relazione a processi di subduzione. La coesistenza di rocce entroplacca e di arco nel Tirreno evidenzia la presenza di sorgenti anorogeniche insieme a quelle modificate da processi di subduzione.

Il modello geodinamico che meglio spiega la distribuzione areale dei tipi di magma in Italia, e le loro variazioni di età, caratteristiche geochimiche e composizioni isotopiche, prevede che la subduzione della placca Ionica-Adriatica al di sotto del blocco Sardo-Corso e dell'arco appennino ha prodotto una intensa e variabile contaminazione del cuneo mantellico. La migrazione della zona di subduzione verso sud-est ha causato una migrazione del magmatismo orogenico dalla Sardegna, attraverso il Tirreno, fino all'Italia meridionale e all'Arco Eoliano. Nello stesso tempo, l'apertura del bacino tirrenico ha prodotto una risalita astenosferica con formazione di magmi di tipo anorogenico coesistenti con quelli di arco. La catena Appenninica ha subito rotazione antioraria e segmentazione durante l'apertura del Tirreno, frammentandosi in vari archi minori, lungo i quali venivano subdotti vari tipi di sedimenti. Tale processo ha generato forti eterogeneità composizionali nel cuneo mantellico, che si riflettono nelle variazioni regionali di composizione geochimica e isotopica del magmatismo lungo la penisola italiana. L'ipotesi di un plume mantellico di origine profonda sotto il Bacino Tirrenico non è in grado di spiegare, da sola, molte delle caratteristiche composizionali del magmatismo. Tuttavia, le composizioni di tipo HIMU delle rocce della Sicilia, simili a quelle di molte vulcaniti entraplacca dell'Europa continentale (es. Massiccio Centrale in Francia, regione Eifel in Germania), possono essere spiegate dalla presenza di una estesa e omogenea sorgente mantellica europea che può essersi originata dall'espansione di un plume.

KEY WORDS: *petrology, geochemistry, geodynamics, magmatism, Tyrrhenian Sea, Apennines, Italy, mantle reservoirs.*

INTRODUCTION

Plio-Quaternary magmatism in Italy (Fig. 1) exhibits an extremely variable composition, ranging from subalkaline (tholeiitic and calc-alkaline), to Na- and K-alkaline and ultra-alkaline, from mafic to felsic, and from oversaturated to strongly undersaturated in silica (Fig. 2). Trace element abundances and ratios are also highly variable, covering both intra-plate and orogenic compositions (Fig. 3). There is a strong regionality in the distribution of magma types. For instance, tholeiitic to Na-alkaline rocks occur in Sardinia, eastern Sicily and Sicily Channel. Calc-alkaline and shoshonitic rocks are concentrated in the Aeolian Arc and some Tyrrhenian seamounts, but are also found in several places in central Italy (e.g. Campania and Tuscany) (Fig. 1). Since most of the Italian volcanic rocks are of mantle origin, this extreme magmatic diversity requires a strongly heterogeneous upper mantle, which has distinct compositions in various volcanic zones.

These complexities are likely a heritage of the geodynamic evolution of the circum-Tyrrhenian area, which has undergone several cycles of distension and convergence, with associated mantle melting, consumption of lithospheric slabs and mantle contamination. In this paper we review the most prominent data on Plio-Quaternary magmatism and discuss their petrogenetic and geodynamic significance, taking into account the tectonic evolution of this complex area.

REGIONAL DISTRIBUTION OF MAGMA TYPES AND IDENTIFICATION OF MAGMATIC PROVINCES

Italian Plio-Quaternary magmatism spans mafic, intermediate and felsic compositions. Mafic rocks (here defined as those having MgO > 4 wt%) are volumetrically subordinate but are widespread, and in most cases show relatively high Mg#, Cr and Ni, close to mantle-equilibrated melts. The study of these rocks is of the highest interest for the aim of defining compositions of mantle sources. Therefore, in the following paragraphs discussion will concentrate on data from mafic rocks.

Extensive major, trace element and isotopic investigations carried out in the last two decades have brought to recognition of several distinct magmatic provinces or zones in the circum-Tyrrhenian area. A «magmatic province» is here defined as a relatively restricted zone within which igneous rocks have been emplaced over a relatively short period of time, of a few Ma or less. As it will be shown later, the rocks of each province show peculiar compositional characteristics (e.g. petrochemical affinity, or geochemical signatures, or even a particular association of magma types), which make them different from other rocks occurring in adjacent areas. However, rocks of a given province are not necessarily comagmatic, i.e. do not necessarily derive from a single source or magma type, although in some cases they do. Therefore, our definition of magmatic province is somewhat

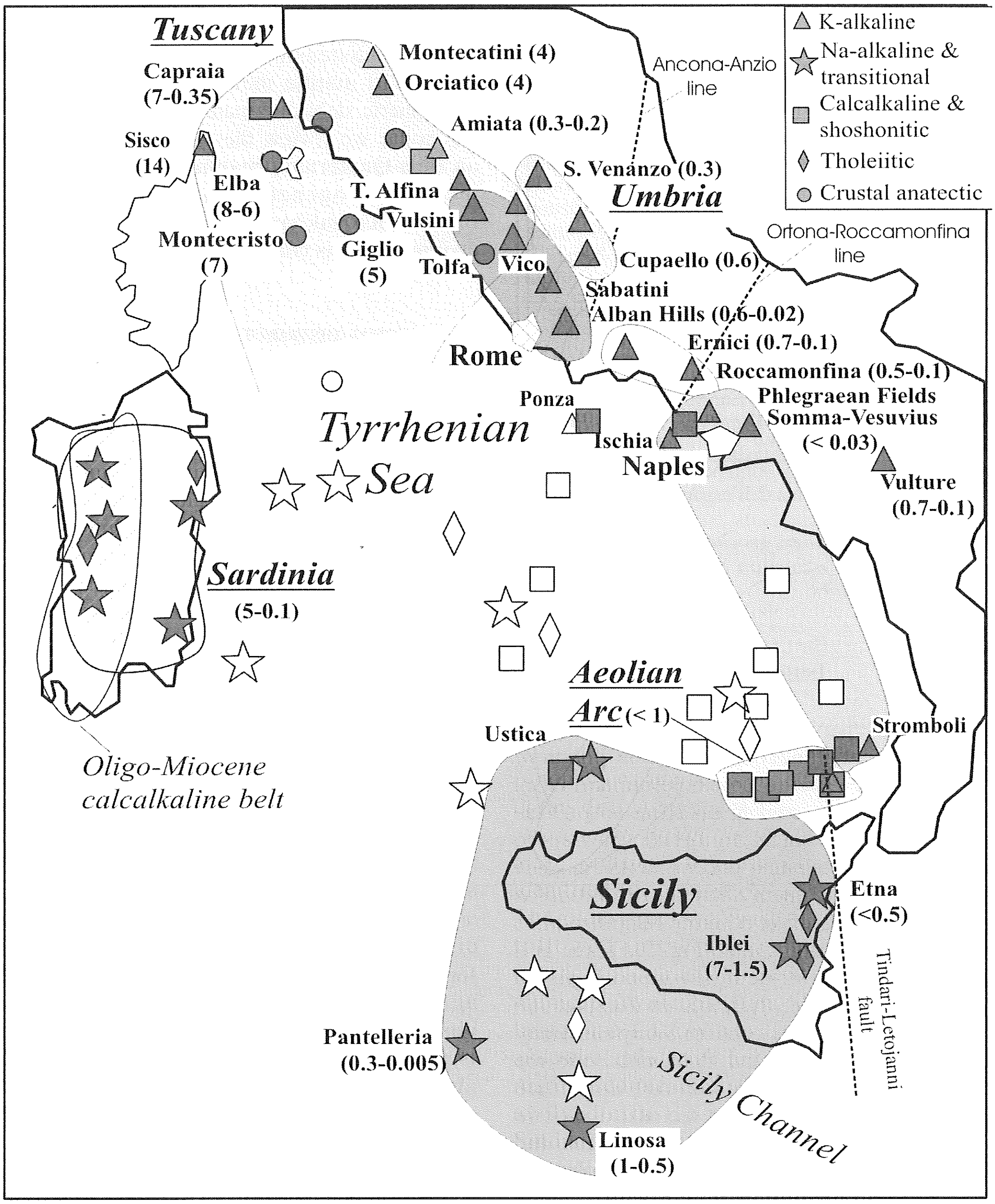

Fig. 1 – Distribution of Recent magmatism in Italy. Open symbols indicate seamounts. Ages (in Ma) are given in parentheses for some centres. Different colours denote various magmatic provinces.

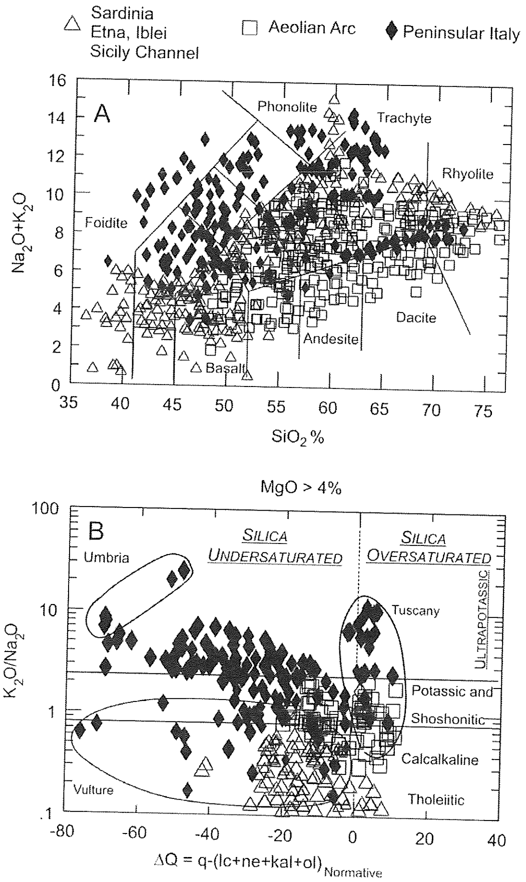

Fig. 2 – **A.** Total alkali vs. silica classification diagram for Italian Plio-Quaternary magmatic rocks (Peccerillo, 2002). **B.** ΔQ vs. K_2O/Na_2O diagram for Italian Plio-Quaternary mafic volcanic rocks (MgO > 4 wt%). ΔQ is the sum of normative quartz minus normative undersaturated minerals (olivine, nepheline, leucite, kalsilite, etc.). Positive ΔQ designate silica oversaturated magmas, whereas silica undersaturated rocks have negative ΔQ.

different from that given by J.W. Judd, A Harker, H.S. Washington and other fathers of igneous petrology at the turn between nineteenth and twentieth century, which also implied a comagmatic origin for the rocks of a given province. The reason for grouping different rock types on the basis of the criteria outlined above, relies on the assumption that magmas closely associated in space and time with specific compositional characteristics are

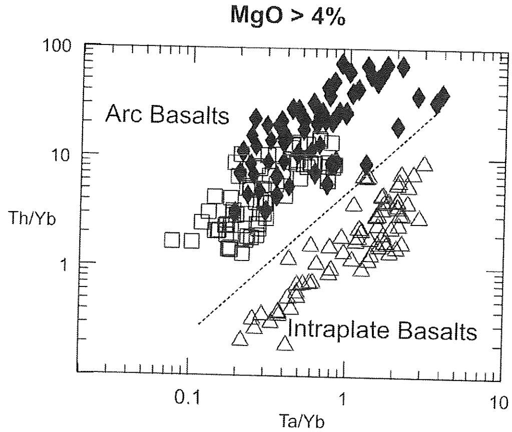

Fig. 3 – Th/Yb vs. Ta/Yb diagram for Plio-Quaternary mafic rocks from Italy, discriminating between intraplate and subduction-related basalts (Pearce, 1982). Symbols as in Fig. 2.

likely related to common geological events, which are somewhat different from those working in other areas. Therefore, the identification of these zones and the study of magma compositions provide important information concerning the petrogenesis and geodynamic evolution of various areas, which is lost if wider magmatic province are considered. Based on our definition, the igneous activity of the circum-Tyrrhenian area can be grouped into the following magmatic provinces:

1) *Tuscany Province* (~8-0.2 Ma) – This province extends from southern Tuscany and the Tuscan archipelago to the Tolfa-Manziana-Ceriti zone and central Tyrrhenian Sea (e.g. Vercelli seamount). A 14 Ma-old ultrapotassic dyke from Sisco (Corsica) is also considered as belonging to this province. The Tuscany magmatism consists of dominant acid rocks with minor amounts of mafic hypoabyssal bodies and lavas. Mafic rocks range from calc-alkaline to ultrapotassic lamproitic composition, displaying large variations of trace element abundances and isotopic ratios (see Conticelli *et al.*, this issue). In spite of the diversity of their petrological affinities and trace element abundances, all the mafic rocks

from Tuscany have similar incompatible element patterns and plot along single trends on trace element variation diagrams (Fig. 4). These are different from other Plio-Quaternary provinces around the Tyrrhenian Sea, suggesting a specific type of mantle source composition. Overall, the Tuscany mafic rocks, although being of mantle origin, have crustal-like geochemical and isotopic signatures (e.g., $^{87}Sr/^{86}Sr$ around 0.709-0.717 and incompatible element patterns which resemble granites and gneiss) (Fig. 5) (Poli *et al.*, 1984; Conticelli and Peccerillo, 1992; Peccerillo *et al.*, 2001). Note that the Tuscany mafic magmatism resembles very closely the Oligocene (30 Ma old) calc-alkaline to ultrapotassic rocks from the Western Alps (Venturelli *et al.*, 1984; Peccerillo, 1999). Acid intrusive and effusive rocks have a crustal anatectic origin and their genesis is likely related to isotherm uprise during mafic magma emplacement into the crust. However, pure crustal melts are rare, and the bulk of the acid magmatism is represented by hybrids between mantle-derived and crustal anatectic magmas (e.g. Peccerillo *et al.*, 1987; Poli, 1992; Poli *et al.*, 2002, this issue).

2) *Latium Province* or Roman Province s.s. (~0.8-0.02 Ma) – This is part of the belt of potassic and ultrapotassic rocks running from northern Latium to the Neapolitan area, which was defined as the Roman Comagmatic Region by Washington (1906) (see Conticelli *et al.*, this issue). The Latium Province includes the large stratovolcanoes and volcanic complexes of Vulsini, Vico, Sabatini, and Alban Hills. These volcanoes erupted mafic to felsic rocks belonging to the potassic series (KS) and to the highly potassic series (HKS). Potassic rocks are nearly saturated in silica and range from potassic trachybasalt to trachyte. HKS rocks are ultrapotassic, strongly undersaturated in silica and range from leucite-tephrite and leucitite to phonolite. The mafic rocks of this province have incompatible element patterns similar to the Tuscany lamproites, but display higher LILE/HFSE and lower Ce/Sr ratios, as well as distinct trace element variation trends (Figs. 4, 5). The Latium KS and HKS mafic rocks have slightly variable isotopic compositions, which are intermediate between mantle and crustal values, although they are less extreme than in Tuscany (e.g. $^{87}Sr/^{86}Sr$ is typically around 0.710 for both KS and HKS; Hawkesworth and Vollmer, 1979; Conticelli and Peccerillo, 1992; Conticelli *et al.*, 2002; Conticelli *et al.*, this issue).

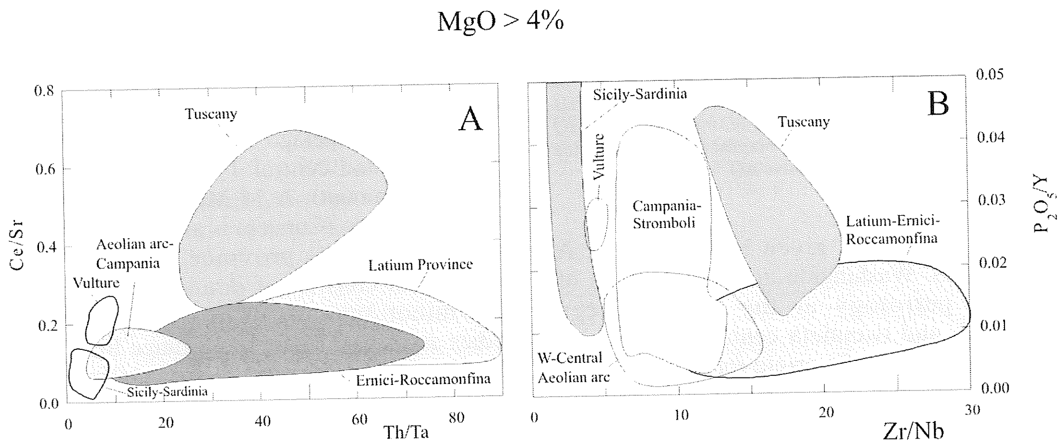

Fig. 4 – Incompatible trace element ratios in mafic Plio-Quaternary volcanic rocks from Italy. Note different trends for various magmatic provinces.

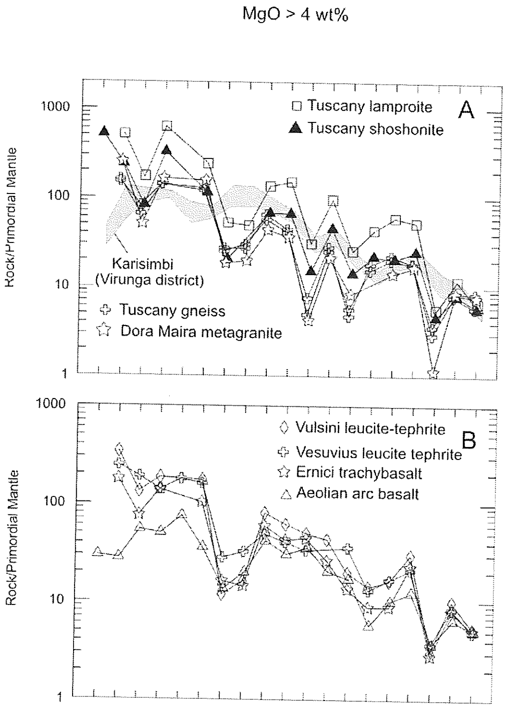

Fig. 5 – Incompatible element patterns of Italian mafic rocks. Compositions of upper crustal rocks (Tuscany gneiss and Dora Maira metagranites) and of east Africa potassic rocks (Virunga District) (data from Cadoppi, 1990; Rogers *et al.*, 1992; Conticelli, 1998) are also shown.

3) *Intra-Apennine Province* (~0.6-0.3 Ma) – This consists of numerous monogenetic mainly explosive centres, showing very peculiar chemical and mineralogical composition. Typical rocks are olivine- and clinopyroxene-melilitites (kamafugites) containing olivine, pyroxene, melilite, leucite, kalsilite, monticellite, and several accessory minerals such as perovskite, zirconian schorlomite, etc. Remarkable characteristics of the most mafic rocks are a strong SiO_2-undersaturation, very high CaO, MgO contents and K_2O/Na_2O ratios, and low Al_2O_3 and Na_2O (e.g. Conticelli and Peccerillo, 1992). Incompatible element patterns, LILE/HFSE and radiogenic isotope signatures ($^{87}Sr/^{86}Sr \sim 0.710$-$0.711$) are similar to the Latium rocks. Intra-Apennine volcanism, however, is here considered as a separate magmatic province on the basis of the kamafugitic affinity of volcanic centres, a characteristics which is not found in other provinces in the Tyrrhenian area, although some kamafugitic-like lavas may be present in the Latium volcanoes (see Federico *et al.*, 1994). Carbonate-rich pyroclastic rocks are also present in the internal zones of Apennines, and are believed to represent carbonatitic magmas (e.g. Stoppa and Woolley, 1997). However, there are several objection to this hypothesis, as discussed elsewhere (Peccerillo, 1998; Peccerillo, this issue).

4) *Neapolitan Province* (~ 0.15 Ma to Present). This is formed by the Somma-Vesuvius, Phlegraean Fields and Ischia-Procida volcanoes. Probably also the eastern Pontine Islands (~ 0.8-0.13 Ma) belong to this province. As in the Latium Province, rock composition have a KS and HKS composition, but calc-alkaline mafic volcanics have been also found by borehole drillings and among xenoliths (Di Girolamo, 1978; Santacroce, 1987; Ayuso *et al.*, 1997; D'Antonio *et al.* 1999; Pappalardo *et al.*, 1999; Somma *et al.*, 2001, and references therein). The mafic volcanic rocks of this province have lower $^{87}Sr/^{86}Sr$, higher $^{143}Nd/^{144}Nd$ and distinct trends of trace element ratios than the Latium Province. Moreover, the Neapolitan mafic rocks have several trace element and isotope ratios that are basically coincident with the rocks of Stromboli in the eastern Aeolian Arc. This led Peccerillo (2001) to suggest that the Neapolitan volcanoes cannot represent the southern end of the Roman Province, as suggested by several authors (e.g. Washington, 1909; Conticelli *et al.*, this issue), but eventually the northern extension of the Aeolian Arc. On the other hand, if the Neapolitan volcanoes are considered as a district of the Roman Province, this should also include Stromboli.

5) *Ernici-Roccamonfina Province* (~ 0.7-0.1 Ma). This zone is characterised by the close association of KS and HKS mafic rocks. Preliminary data from a detailed investigation suggest that rocks with lower K_2O contents,

falling in the range of calc-alkaline and shoshonitic basalts, do also occur at Ernici (author's unpublished data). KS has lower potassium, incompatible element contents and $^{87}Sr/^{86}Sr$ than HKS volcanics (Civetta *et al.*, 1981), and show incompatible element ratios and isotopic signatures resembling those of the Neapolitan volcanoes. In contrast, HKS resembles Latium leucite-tephrites. Therefore, the Ernici-Roccamonfina Province is a zone where Roman-type HKS and Neapolitan-type KS rocks coexist.

6) *Mount Vulture* (~ 0.8-0.1 Ma). This is the easternmost Plio-Quaternary volcano in Italy. Rocks (mostly basanite and trachyphonolite with minor foidite, tephrite, phono-tephrite and melilitite) are less potassic than in the Latium Province, are enriched in Na_2O and the main foid is haüyne rather than leucite. HFSE contents are higher than in the Latium rocks, and $^{87}Sr/^{86}Sr$ is lower. Therefore, this volcano defines a distinct magmatic province, as stated by Washington (1906).

7) *Aeolian Arc* (~1 Ma to Present). The Aeolian Arc is formed by seven islands, which represent the emergent part of larger structure which also includes several seamounts. The main rock types belong to the calc-alkaline, high-K calc-alkaline and shoshonitic series. Slightly undersaturated leucite-bearing tephrites similar to KS rocks occur at Vulcano and Stromboli. Petrological and geochemical data show that the Aeolian islands define three distinct sectors. The western sector mainly contains island-arc type calc-alkaline rocks with relatively unradiogenic Sr isotopic compositions ($^{87}Sr/^{86}Sr$ = 0.7035 to 0.7045) (e.g. Ellam *et al.*, 1989; Francalanci *et al.*, this issue). The central islands of Vulcano and Lipari display similar isotopic signatures as the western arc, but contain abundant shoshonites and some KS rocks. Moreover large amounts of rhyolitic magma have been erupted in this sector over the last 20 ka. The eastern sector is formed by Panarea and Stromboli. Stromboli consists of calc-alkaline, shoshonitic and potassic rocks, which are isotopically and geochemically distinct from the western arc and resemble the Neapolitan volcanoes, as mentioned earlier (De Astis at al., 2000; Peccerillo, 2001). The island of Panarea, which is sited between Stromboli and Lipari-Vulcano has intermediate characteristics between the western-central arc and Stromboli (Calanchi *et al.*, 2002).

8) *Sicily Province* (7.5 Ma to Present). This province includes Mt. Etna, Iblei Mts., Ustica, and the volcanoes of the Sicily Channel (Linosa, Pantelleria and several seamounts). Rocks range from tholeiitic to sodic alkaline in composition. Ratios of LILE/HFSE are low, falling in the field of intraplate rocks (Fig. 3); however, some weak arc signatures have been detected at Etna and Ustica (Beccaluva *et al.*, 1982; Cinque *et al.*, 1988; Schiano *et al.*, 2001; Tonarini *et al.*, 2001).

9) *Tyrrhenian Sea floor* (~3 Ma-Present?). Here two large volcanic structures have been identified: the Vavilov seamount (~3-2 Ma) and the Marsili seamount (~1-Present?), both sitting on oceanic crust. Other volcanic edifices are scattered through the Tyrrhenian Sea. These show compositions ranging from MORB and OIB to arc-type. Calc-alkaline volcanoes apparently become younger going south-eastward (e.g., Locardi, 1993).

10) *Sardinia* (~5-0.1 Ma) – This island is characterized by Pliocene to Quaternary tholeiitic to prevailingly Na-alkaline volcanic activity. Trace element and isotopic signatures are close to intraplate basalts (Gasperini *et al.*, 2000; Lustrino, 2000; Lustrino *et al.*, 2000).

Sr-Nd-Pb ISOTOPE COMPOSITIONS OF MAGMATIC PROVINCES

Radiogenic (Sr, Nd, Pb) isotope compositions show moderate variation within the single magmatic provinces (e.g. Hawkesworth and Vollmer, 1979; Vollmer, 1989; Peccerillo, 2003 and references therein). However, when the entire circum-Tyrrhenian volcanism is considered, radiogenic isotope ratios are observed to cover a very large compositional spectrum. Overall, isotopic compositions of mafic rocks define smooth trends between distinct end-members (Fig. 6). The rock from the southern Tyrrhenian Sea and the Italian peninsula define a trend between a HIMU-like composition (represented by Etna-Iblei) and another end-member represented by the Tuscany rocks. This trend highlights an overall increase of $^{87}Sr/^{86}Sr$ and a decrease of $^{143}Nd/^{144}Nd$, and Pb isotopes from south to the north. Another trend between HIMU and EM1 is defined by Tyrrhenian Sea and Sardinia rocks. Finally, Sicily Channel volcanoes basically plot between HIMU and DMM. The HIMU, DMM and EM1 compositions are found at a global scale in several intra-oceanic islands (Hofmann, 1997). In contrast, the end-member represented by Tuscany mafic rocks is peculiar of the Italian peninsula. It is more enriched in radiogenic Sr than EM2 mantle component, and closely resembles the upper crust. Yet, it is of obvious mantle origin, since Tuscany mafic rocks have high Mg# (up to 75), Ni and Cr (several hundreds of ppm), whose values are close to compositions of primary mantle-derived melts.

GEOPHYSICAL AND STRUCTURAL FEATURES OF MAGMATIC PROVINCES

The magmatic provinces recognised on the basis of petrological and geochemical studies also show different characteristics of the mantle-crust system and are sometimes separated from each other by tectonic lineaments of regional significance (see Peccerillo and Panza, 1999). It is also worth noting that a subdivision of the Apennine system into different tectonic zones made by Meloni *et al.* (1997) on the basis of paleomagnetic data is strikingly similar to the one based on petrological and geochemical grounds and shown in Fig. 1.

The Tuscany Province developed in a zone of thinned continental crust and high heat flow (Mongelli and Zito, 1994). Scarascia *et al.* (1994) reported evidence of a double-Moho in this area, respectively situated at depths of approximately 25 and 60 Km, and separated by a low seismic velocity channel (6.8 km/s). Finetti *et al.* (2001) interpreted the deeper Moho as a relict of Ligure-Piemontese slab, which was subducting beneath this area until the Oligocene (see Doglioni *et al.*, 1999).

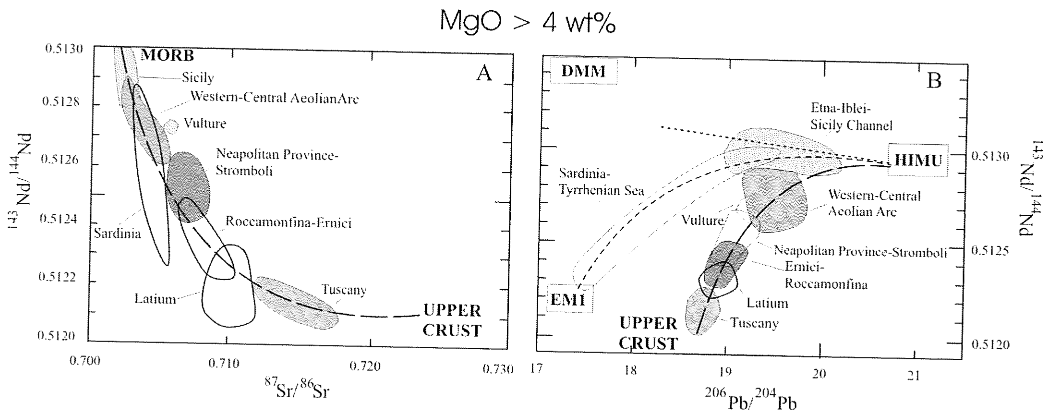

Fig. 6 – $^{87}Sr/^{86}Sr$, $^{143}Nd/^{144}Nd$, $^{206}Pb/^{204}Pb$ variation diagrams for Plio-Quaternary Italian mafic rocks. Central Italy and Aeolian Arc rocks fall along a mixing trend involving HIMU and upper crust. Sicily, Sicily Channel, Sardinia and some Tyrrhenian Sea seamounts (anorogenic magmatism) plot along mantle-mantle mixing trends involving HIMU, EM1, and DMM end-members.

The Latium Province developed in a zone of NW-SE trending normal faults cutting Tuscan and Umbrian tectonic units. It is bounded in the south by the Ancona-Anzio tectonic line. The crustal thickness is less than 25 km, regional heat flow is higher than in Tuscany (e.g. Barberi *et al.*, 1994), and the deeper Moho is absent.

The Intra-Apennine Province is characterised by a thicker crust (Moho at 35-40 km) and lithosphere (e.g. Locardi and Nicolich, 1988; Scarascia *et al.*, 1994) than the Latium Province, by low heat flow (Mongelli and Zito, 1994), and by negative gravimetric anomalies. The degree of extension is less intense and volcanism is much less abundant than in the Latium Province.

A rigid vertical body with high seismic wave velocity cuts the upper mantle beneath the Tuscany, Latium and Intra-Apennine provinces, and has been interpreted to represent the remnants of the Adria slab subducting beneath the northern Apennines (e.g., Panza and Mueller, 1979; Babuska *et al.*, 1985; Peccerillo and Panza 1999, and references therein).

The Ernici-Roccamonfina Province occurs in an area affected by Plio-Quaternary extensional tectonics with NW-SE normal faults and NE-SW transtensional faults. It is bounded by the Ancona-Anzio line in the north and by the Ortona-Roccamonfina line in the south. There is a very thin (about 10 km) low velocity wedge (V_S = 3.95 km/s) beneath the Moho, which overlies a thick rigid layer with S-wave velocity of 4.65 km/s (Panza *et al.*, 2003). Regional heat flow is lower than in the Latium Province.

The Neapolitan Province develops south of the Ortona-Roccamonfina line. It is characterised by Plio-Quaternary NW-SE and NE-SW trending normal and transtensional faults, high heath flow and positive gravity anomalies. There is a low velocity layer (V_S = 3.35 km/s) beneath the Moho in the Vesuvius and Phlegraean Fields, which becomes thicker beneath Ischia.

Vulture is the only recent volcano on the Italian peninsula which is located east of the Apennine compression front. It rises close to the Apulian foredeep along the anti-Apenninic Neapolitan normal fault system, which represents an extension of the 41° parallel line.

The Aeolian Arc occurs on the Calabro-Peloritano basement. The western and central sector are divided by the Tindari-Letojanni fault, which represents the continuation of Malta Escarpment passive margin (Grasso *et al.*, 1990). Although there is no active seismicity beneath the western arc, seismic activity beneath the eastern sector, defines a steep plane with earthquake foci extending up to Campania (Falsaperla *et al.*, 1999).

Sicilian volcanoes developed in different structural contexts. Etna rises at the intersection between the Tindari-Letojanni lineament and the NNE-SSW fault system. The Iblei magmatism took place along NE-SW extensional faults. Pantelleria and Linosa developed in zones of NW-SE trending rifting.

Sardinia Plio-Quaternary volcanism developed along extensional faults generated contemporaneously with the opening of the Tyrrhenian Sea. It overlies calc-alkaline to shoshonitic Oligocene-Miocene volcanism. The crystalline basement in Sardinia is represented by Precambrian and Palaeozoic rocks affected by the Hercynian orogenesis.

Finally, the Tyrrhenian Sea volcanism formed over a thinned continental crust or oceanic crust with a shallow asthenosphere (Panza *et al.*, 2003 and references therein).

DISCUSSION

The variable petrological characteristics of the Italian Plio-Quaternary mafic igneous rocks require a wide variety of mantle compositions and physical-chemical conditions of magma genesis (i.e. different confining pressure, source mineralogy, fluid pressure, degrees of partial melting, etc.; see Wendlandt and Eggler, 1980; Peccerillo, 2002; Conticelli *et al.*, this issue). The Na-alkaline and tholeiitic rocks from Sardinia, Sicily and some Tyrrhenian seamounts display compositions falling

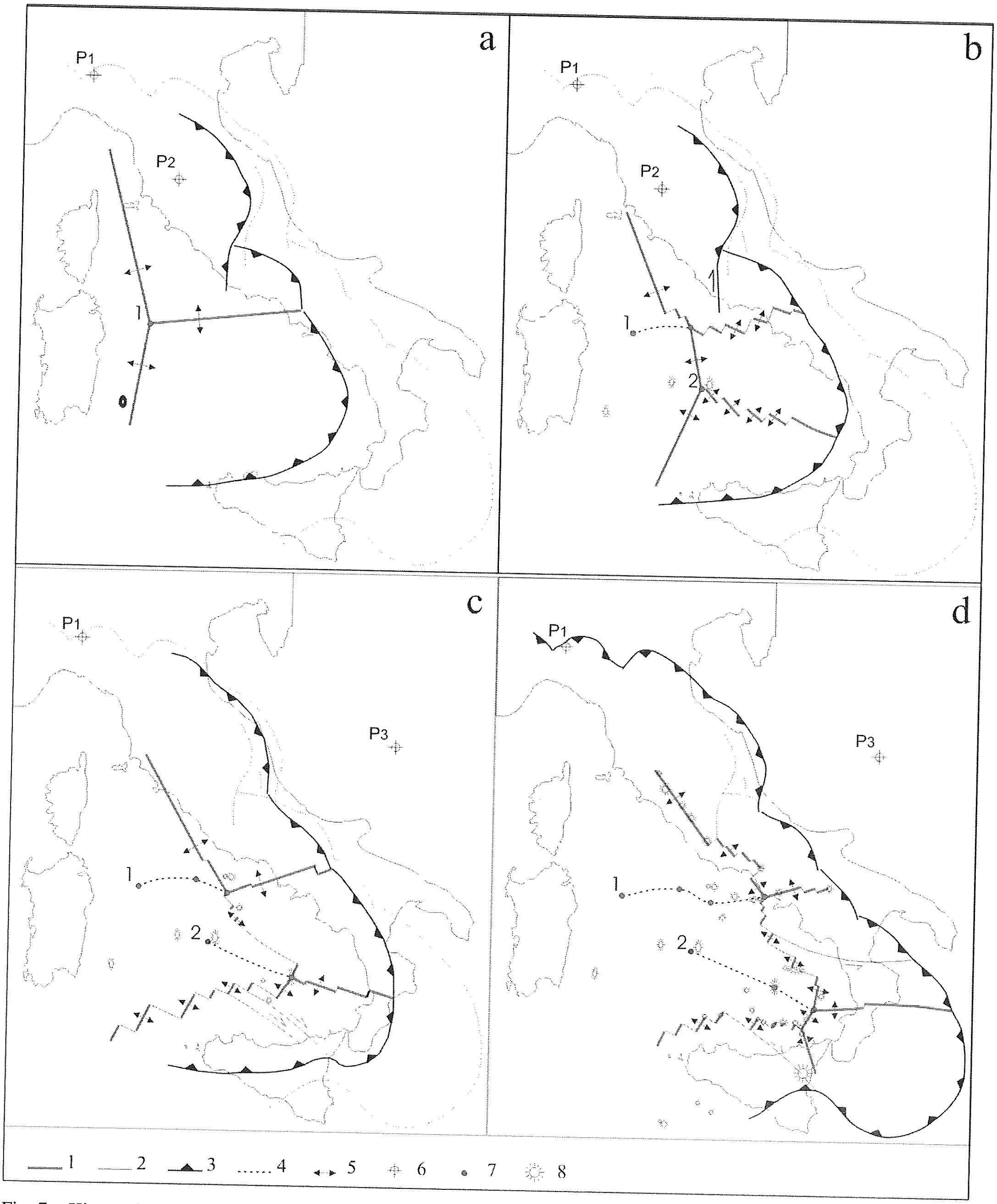

Fig. 7 – Kinematic reconstructions of the Tyrrhenian-Apennines system. (a) Late Tortonian-Early Messinian; (b) Pliocene; (c) Pleistocene; (d) Present time. P1 is the northern and central Apennines rotation pole. P2 is the southern Apennines rotation pole during Late Tortonian-Pliocene. P3 is the southern Apennines rotation pole from Pleistocene to present time. (1) extensional axis, (2) transform fault, (3) foredeep, (4) triple junction migration line, (5) extensional direction, (6) pole of rotation, (7) triple junction, (8) volcano.

between HIMU-DMM-EM1 mantle end-members. This suggests that the magmas from these provinces were generated by melting of both depleted and enriched mantle sources, similar to those of MORB and of oceanic island basalts. Calc-alkaline and shoshonitic rocks from Aeolian Arc and some Tyrrhenian seamounts display typical island arc compositions. There is a general, though not unanimous agreement that these rocks were formed in a mantle wedge modified by subduction processes. Finally, potassic and ultrapotassic rocks from central Italy share many geochemical characteristics with Aeolian volcanoes (e.g. high LILE/HFSE ratios), although they are more enriched in incompatible elements and display Sr-Nd-Pb isotopic compositions that resemble the upper crust rather than the upper mantle. A wealth of studies (e.g. Conticelli and Peccerillo, 1992; Conticelli, 1998; Conticelli *et al.*, this issue) have shown that these crustal signatures cannot be derived from wall rock contamination by uprising magmas (magma contamination), but reflect those of their mantle sources. Therefore, there is a general agreement that the upper mantle beneath central Italy is anomalous and has been heterogeneously enriched by addition of crustal material (mantle contamination). However, the nature and timing of these processes are debated.

In the authors' opinion, the wide range of magma compositions occurring in the circum-Tyrrhenian area results from complex geodynamic processes. These can only be partially understood by geochemical and isotopic evidence alone, and are best interpreted by framing geochemical and petrological data within the geodynamic evolution history of the Tyrrhenian Sea.

Geodynamic evolution of the Tyrrhenian Sea area

Recent studies demonstrated that the Tyrrhenian Sea and western Mediterranean regions have undergone numerous Wilson cycles in the last 300 Ma (e.g., Lustrino, 2000; Rosenbaum *et al.*, 2002). During Hercynian orogenesis, this area was affected by the consumption of a large oceanic basin, which generated extensive magmatism and mantle contamination. According to several authors, there was considerable crustal thickening during Hercynian orogenesis; this provoked lower crustal detachment and sinking into the upper mantle (e.g., Lustrino 2000). After the Hercynian orogenesis, a rifting phase formed the North Atlantic-Tethys Ocean basin. This required extensive mantle melting and extraction of basaltic magmas, to form new oceanic crust of the Ligure-Piemontese ocean. In the early Cretaceous time a new compressive stage started, causing the consumption of the Ligure-Piemontese ocean, and leading to the Alpine-Apennine orogenesis. These processes are responsible for the most important structural features of a large area between Africa and Eurasia, including the Alps and Apennine chains, and are believed to be responsible for generation of the most significant geochemical enrichments in the upper mantle beneath the western and central Mediterranean regions (e.g. Beccaluva *et al.*, 1989; Lustrino, 2000).

There is debate on the geometry of subduction during the consumption of the Ligure-Piemontese ocean. Most authors suggest that subduction was dipping southward until Oligocene; subsequently, after the collision in the Alps, there was an inversion of slab dip, with subduction going north-westward under the Iberia and Europe plates (e.g. Gueguen *et al.*, 1997; Doglioni *et al.*, 1999). Other authors suggest a subduction of the European plate under the Adriatic one for the Alpine sector only, while for the western portion of the Tethys they suggest subduction of Adriatic-African plates under European and Iberian ones (e.g. Treves, 1984; Principi, 1994). This second hypothesis implies the existence of a large transform fault between the two sectors with opposite vergence. Marroni and Treves (1998) suggest a sinistral transpression regime for the evolution of the northern Apennine during the Oligocene.

The Adriatic lithosphere subduction under Corsica probably begins along this lineament as a consequence of the Africa-Europe relative motion and the Corsica-Sardinian block counter-clockwise rotation. Around 18 Ma, Sardinia, Corsica and Kabylides reached their present position. The Ligure-Piemontese oceanic basin was already subducted and collision between Corsica-Sardinia block and the Apennine continental margin occurred, while the marginal Algerian-Povençal basin with the Sardinian volcanic arc were already formed (Dewey *et al.*, 1989; Rosembaum *et al.*, 2002). From this moment the extension jumps to the present Sardinia and the Corsica eastern margin, but significant extension in the Tyrrhenian basin starts from Upper Tortonian. Probably during this period of relative quiescence, continental crust incorporated in the subduction impeded further propagation of the back-arc extension. Thus, relative motion between Africa and Europe become prevalent and provoked crustal shortening in the Apennines until a new lithospheric gravitational instability led to further westward dipping subduction of the Adriatic-Ionic lithospheric plate, and to the Tyrrhenian back-arc extension. The reason for this new subduction is still not clear. The Apennine chain in fact is composed entirely of Mesozoic sedimentary cover. Its basement never crops out and there is no clear evidence of it from subsurface data.

The sedimentary cover of the Adriatic margin shows two rifting events during the Mesozoic, which led to a remarkably crustal thinning. The first rifting took place during the middle Triassic and formed the Lagonegrese basin for which Finetti (1982) and Stampfli and Mosar (1998) suggests an oceanic basement. The second rifting created the Ligure-Piemontese oceanic basin. A Lagonegro coeval deep basin has been also recognized in the Northern Apennine (Punta Bianca). It cannot therefore be excluded that within the Apennines domain there were portions of oceanic basement or continental crust injected with subcrustal basalt/gabbro, which could produce new lithospheric gravitational instability of the Adriatic plate.

There is now a general agreement on the tight connection between evolution of the Apennine chain and the Tyrrhenian back-arc extension (e.g. Beccaluva *et al.*, 1989; Mantovani *et al.*, 1997). Several evolutionary models have been proposed for the Tyrrhenian-Apennine system, but the kinematic approach of Dewey *et al.* (1989) and Turco and Zuppetta (1998) is particularly useful for understanding differential behaviour of various sectors and the development of various magmatic provinces along the Italian peninsula. According to these authors, the Apennine chain has been subdivided into two main arcs and some other minor kinematic blocks. The mutual relative motions between rigid blocks, also evidenced by paleomagnetic data (Meloni *et al.*, 1997), created the present shape of Apennines chain and the Tyrrhenian basin.

In Fig. 7 a kinematic model is shown to explain the evolution of the Tyrrhenian-Apennine system in which the extension of the volcanic areas is considered with particular attention. In order to outline the space/time distribution and the geotectonic setting of the Tyrrhenian volcanics, we have modified and simplified previous kinematic models. Here, we consider the Apennine chain constituted by northern and southern arcs. The former includes the northern and central Apennines; the latter includes the Calabrian Arc, the southern Apennine and the Maghrebide-Sicilian chain. The amount of relative motion between Africa and Europe can be considered negligible in this short period of time (Dewey *et al.*, 1989). Therefore, we postulate a zero relative motion between the Sardinia-Corsica plate and the Adria plate, in order to simplify the model.

The poles of rotation between each single arc and the Sardinian-Corsica block have been redetermined using the main structural elements (bathymetry of the Tyrrhenian basin, main Apennine tectonic lineaments and volcano alignments that we consider important axes of extension) and are shown in Fig. 7.

The arc migration leads to longitudinal stretching of the chain and to late nucleation of minor arcs. The extension axes among the many crustal blocks form triple junctions that we treat, from a kinematic point of view, in a similar way as the oceanic ridges. The strike of the structures derived from such an extensional regime represents an important element for determining velocity ratios among crustal blocks.

The extension axes migrated together with the arcs. During the Late Tortonian-Early Messinian times, the triple junction n. 1, (derived from the relative motion between the two main arcs and the Sardinian-Corsica block), was formed by the northern and southern Tyrrhenian extension axes and by the anti-Apennine lineament related to the different migration direction of the two arcs (Fig. 7a). This formed a minor arc segment, between the northern Apennine front and the anti-Apennine lineament, where the Ernici-Roccanonfina volcanism successively developed. The triple junction n.1 moved eastward along the so-called 41° parallel lineament, which we postulate represents a fracture zone that divides the northern and southern Tyrrhenian basin, characterised by different extension rates. When the southern Tyrrhenian extension axis reached the Magnaghi volcano, the southern Apennine arc underwent splitting into a southern and a northern sector. The former moved round a pole located in southern Tunisia. The latter continued to move around the previous pole. During Pliocene time, these two different migrations led to a new extensional axis between two sectors of the southern arc, generating a new triple junction (triple junction n. 2) (Fig. 7b), which successively migrated along the Vavilov-Marsili lineament. Therefore, two extensional axes intersecting the Apennine chain were created. The northern one is represented by the Pontine Islands-Phlegraean Fields -Vulture lineament; the southern axis occurs along the Vavilov-Marsili-Stromboli-Catanzaro trough lineament.

When the two triple junctions reached respectively the Pontine Islands and the Marsili basin, the eastern portion of the southern arc began to move around a new closer pole (Fig. 7c). This involves a slight variation of migration of the northern triple junction and a greater extension across southern Calabria and the Peloritani mountains. At the present time the extension axes of the Tyrrhenian-Apennine system correspond to recent volcano alignments (Fig. 7d).

The main implication for magmatism of the model discussed above is that it suggest a fragmentation of the Apennine arc into several sectors, divided by lithospheric discontinuities. Each sector had a rather independent behaviour, as also demonstrated by paleomagnetic data (Meloni *et al.*, 1997). We suggest that subduction processes have been going on rather independently along each of these arcs, and probably brought different types of upper crustal material into the mantle. This provides an explanation for the occurrence of distinct compositions of magmatic provinces in the peninsular Italy.

EVOLUTION OF MANTLE SOURCES

There are several petrological, geochemical and structural features, which must be considered by any model for the genesis of the Tyrrhenian magmatism and its relation with geodynamics. These include:

1. The crust, like trace element and isotope signatures of the potassic magmatism along the Italian peninsula.
2. The distinct trends of incompatible element ratios and isotopic signatures for various magmatic provinces in the Italian peninsula.
3. The similar compositions between Tuscany and the Oligocene Western Alps mafic magmatism.
4. The dominance of calc-alkaline, arc-type magmatism in the Aeolian Arc and its association with deep seismicity.
5. The occurrence of various types of OIB-like rocks in Sardinia and Sicily.
6. The coexistence of intraplate- and arc-type volcanoes on the Tyrrhenian Sea floor.

The crust-like compositional features of the mafic magmas along the Italian peninsula clearly require that upper crustal material was added to the mantle, as discussed earlier. Most of these rocks, especially the Tuscany lamproites, show trace element patterns and isotopic signatures which are very similar to granites and gneiss, suggesting a bulk addition of these rocks to the upper mantle, and little or no element fractionation during metasomatism and the following partial melting. This points to a relatively young age (i.e. a maximum of a few million years) for the contamination process. It is unlikely, in fact, that the upper mantle of a very active, continuously evolving area such as the Tyrrhenian Sea, would fully preserve for long times the crustal trace element signatures acquired at the moment of contamination. This is also supported by the flat trends of Rb/Sr vs. $^{87}Sr/^{86}Sr$ variations observed in the single magmatic provinces, which, if interpreted as isochrones, would indicate maximum ages of some 50-60 Ma for metasomatism (see discussion in Peccerillo. 2002).

The distinct trends of trace elements in the various provinces in central-southern Italy suggest that different types of contaminants were added to the upper mantle in the various regions. This is probably an effect of segmentation of the Apennine chain from Miocene to Present, which favored different types of crustal material to be added to the mantle, as discoused earlier. The similar trace element and geochemical characteristics of Latium and Intra-Apennine provinces suggest a common type of metasomatic agent for these two provinces. Rocks with an overall composition resembling marly sediments have been suggested by geochemical modeling (Peccerillo *et al.*, 1988). On the other hand, the different petrochemical affinity of mafic magmas from the two provinces (i.e. kamafugitic vs. KS and HKS) is probably related to different depths of magma genesis and/or to distinct pre-metasomatic compositions (i.e. lherzolitic to harzburgitic) of the mantle rocks (e.g. Peccerillo *et al.*, 1988).

The geochemical characteristics of the Neapolitan volcanoes and Stromboli have been modeled by assuming contamination by a mixture of fluids and sedimentary material released from the Ionian slab (Peccerillo, 2001). The mantle source of the western and central Aeolian Arc was also contaminated by the Ionian slab, but the amount of sediment involved was much less, as indicated by the more primitive isotopic composition in the western islands (Francalanci *et al.*, this issue). Note that the Ionian plate is believed to be oceanic in nature. Consequently, it has been able to provide large amounts of aqueous fluids to the mantle wedge, thus explaining the dominance of calc-alkaline magmatism in the Aeolian Arc. The occurrence of both Latium-type and Neapolitan-type magmas in the Ernici-Roccamonfina zone may indicate a superimposition of two types of mantle contamination events.

The very similar petrological and geochemical characteristics of Tuscany and Western Alps Oligocene magmatism that of require a common metasomatic event. Overall, this magmatism is much older than in the other provinces of central-southern Italy. According to Peccerillo (2002) the contamination of both the Western Alps and Tuscany mantle sources took place during Alpine subduction. Note that there is ample evidence for deep subduction of upper crust during the Alpine collision (i.e. Dora Maira rocks; Chopin, 1984; Cadoppi, 1990). The common nature of the Western Alps and Tuscany magmatism argues against two separate immersion of pre-Oligocene subduction zones (Treves, 1984; Principi, 1994) and favors the hypothesis of a single subduction zone with a south-eastward immersion (e.g. Doglioni et al., 1999).

Finally, the HIMU, DMM and EM1 compositions of Sicily and Sardinia rocks and the lack of subduction-related signatures require generation in mantle sources which were not affected by recent subduction processes. These souces may represent deep mantle plumes and/or mixtures of lithospheric and asthenospheric mantle materials, which have interacted in recent times to form a range of geochemical and isotopic compositions (e.g. Beccaluva *et al.*, 1998; Trua *et al.*, 1998). The coexistence of intraplate- and arc-type volcanoes on the Tyrrhenian Sea floor reveal that both subduction-contaminated and uncontaminated mantle sources have fed the volcanism in this area.

Based on the above evidence, a model for the evolution of the mantle sources of central Italy magmatism has been hypothesized as consisting of the following main stages (Peccerillo, 1999):

Stage 1. East dipping Alpine subduction processes brought upper crustal material into the lithospheric mantle beneath the Africa margin, i.e. beneath the Western Alps and Tuscany. This took place during collision stages and generated a mantle whose incompatible element isotopic signatures were imprinted by upper crustal material (i.e. Dora Maira granites or metapelites).

Stage 2. The post-Oligocene subduction of the Adria plate beneath the European margin and the extensional tectonics behind the west-dipping subduction zone dismembered the lithospheric mantle contaminated during Alpine subduction, and triggered melting with generation of Western Alps and Tuscany mafic magmas. Therefore, the magmatism in these areas is younger than metasomatism, and took place during back-arc extension, when isotherm uprise triggered partial melting.

Stage 3. The continued subduction of the Adria plate beneath the northern-central Apennine area brought new type of crustal material (marls?) into the mantle, providing metasomatism for the Latium and Intra-Apennine provinces. Accordingly, these magmas would be related to a different and younger contamination event than in Tuscany. The continental nature of the Adria plate explains both the crustal-like signatures of volcanism in central Italy and the lack or scarcity of calc-alkaline products.

Stage 4. Subduction of the Ionian plate beneath the southern Apennines produced the magmatism in the Aeolian Arc and the Neapolitan volcanoes. The subduction zone shifted from Sardinia to the present position beneath the Aeolian Arc, contemporaneously with the opening of the Tyrrhenian Sea from Miocene to Present. The Ionian Sea is probably oceanic in nature, which explains the relatively unradiogenic Sr and radiogenic Nd isotopic compositions of Aeolian Arc and Neapolitan volcanoes as well as the large amounts of calc-alkaline rocks in the Aeolian Arc.

According to this model, the coexistence of Latium- and Neapolitan-type magmatism at Ernici and Roccamonfina, is explained by suggesting that in this area contamination by both the Adria and the Ionian plates took place.

The anorogenic tholeiitic to Na-alkaline magmatism in Sardinia and in some Tyrrhenian seamounts could be related to passive uprise and decompression melting of mantle, as an effect of back-arc extension. The calc-alkaline volcanoes coexisting with intraplate magmatism in the Tyrrhenian Sea floor would represent remnant arcs, left behind during SE-ward migration of the subduction zone from Sardinia to the Aeolian Arc (Beccaluva *et al.*, 1989).

Finally, the Etna and Iblei volcanism could have tapped asthenosphere material and melting occurred as an effect of passive mantle uprise along the Tindari-Letojanni fault (Gvirtzman and Nur, 1999; Doglioni *et al.*, 2001).

ROLE OF MANTLE PLUMES

Several authors have suggested that deep mantle plumes may have played an important role during the recent evolution of the Tyrrhenian Sea area, contributing significantly to magmatic heterogeneities (e.g., Ayuso *et al.*, 1998; Gasperini *et al.*, 2002; Bell *et al.*, 2003).

Some authors suggest that while the Sicily and Sardinian magmatism are related to mantle plumes with HIMU-like and EM1-like compositions, the rest of the magmatism represents mixtures of plume material and subducted upper crustal components (Gasperini *et al.*, 2002). Other authors favour the more extremist hypothesis that all the magmatism reflects interaction among distinct mantle-plume compositions (Bell *et al.*, 2003).

Evidence invoked in favour of the plume hypothesis include:

1. The occurrence of ultrapotassic magmatism, which has been suggested to be typical of intraplate continental settings, such as Toro-Ankole Province (East Africa; Lloyd *et al.*, 1991), classically believed to have developed above mantle plumes.

2. The occurrence of carbonate-rich rocks in Central Italy, which have been suggested to represent carbonatites.

3. The smooth trends of Sr-Nd-Pb isotopes connecting discrete mantle compositions (HIMU, DMM, EM1), which have been suggested to represent mixing lines between plume end-members.

4. The similar radiogenic isotope compositions of some Italian rocks (e.g. Etna, Iblei) as other Na-alkaline rocks from central and western Europe (e.g. Massif Central, etc.), which have been suggested to indicate a derivation of all this volcanism from a wide European Asthenospheric Reservoir (EAR), possibly representing an expanded plume head (Hoernle *et al.*, 1995; Granet *et al.*, 1995; Sobolev *et al.*, 1997; Goes *et al.*, 1999; Ritter *et al.*, 2001; Wilson and Patterson, 2001).

However, there are several objection to these arguments (Peccerillo and Lustrino, submitted). First of all, the Italian ultrapotassic rocks have incompatible element distribution and isotopic signatures, which are totally different from East Africa (Fig. 5a). Incompatible element patterns of Italian potassic rocks show depletion in Ta, Nb and other HFSE, and an enrichment in LILE. In contrast, the Africa potassic rocks show a bell-shaped pattern with a maximum for Ta-Nb. Moreover, the carbonate rich rocks in the Intra-Apennine Province most probably represent ultrapotassic volcanics that have suffered a secondary addition of carbonate material from the wall rocks. This is demonstrated, among others, by the high $\delta^{18}O$ (around +20 to +25) of the carbonate material (see discussion in Peccerillo, 1998; Peccerillo, this issue) and by the high MgO content of olivine (Fo up to 99 mol%) found in these rocks (Rosatelli *et al.*, 2000).

The EM1, HIMU and DMM compositions responsible for magmatism in Sardinia and Sicily may well represent deep components emplaced in the shallow mantle by plume mechanisms, as suggested for intra-oceanic islands (e.g. Hofmann 1997). However, alternative hypothesis have been also suggested. For instance, the Sardinia EM1 composition could result from contamination of the lithospheric mantle by deep crustal material delamitated from thickened continental crust during Hercynian collision (Lustrino, 2000; Lustrino and Dallai, 2004). On the other hand, the occurrence of depleted mantle sources (DMM) in the Tyrrhenian Sea area could be related to extraction of basaltic magmas, e.g. during formation of the Ligure-Piemontese oceanic basin. Therefore, these reservoirs could have been formed by shallow mantle processes of element depletion and enrichments occurred during the last 200 Ma, and giving a range of isotopic composition with time (Esperança and Crisci, 1995; Trua *et al.*, 1998).

Conclusions

The Plio-Quaternary volcanism in Italy shows strong compositional variations, which reveal heterogeneous compositions and complex evolutionary processes for mantle sources.

The hypothesis that best explains this complex magmatic setting is continent-continent convergence in which the leading edge of African plate is subducted beneath the Italian peninsula to generate heterogeneous mantle sources that then produced the wide variety of volcanic rocks (from calc-alkaline to ultrapotassic) with subduction-related geochemical signatures (Doglioni *et al.*, 1999). The large amounts of potassic rocks requires extensive and repeated episodes of mantle metasomatism (Peccerillo, 1999; 2002). Some magmas could be plume related, but could also represent resident mantle asthenosphere-lithosphere, which underwent passive ascent and melting in zones of back-arc extension (Sardinia and Tyrrhenian Sea floor), or along strike-slip faults (Etna-Iblei) .

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