THE PLIO-QUATERNARY MAGMATISM OF SOUTHERN TUSCANY AND NORTHERN LATIUM: COMPOSITIONAL CHARACTERISTICS, GENESIS AND GEODYNAMIC SIGNIFICANCE

Angelo Peccerillo, Giampiero Poli and **Carmelita Donati**

Dipartimento di Scienze della Terra, Università di Perugia, Piazza Università 1, 06100, Perugia, Italy (e-mail: pecceang@unipg.it; polig@unipg.it).

Keywords*: lamproites, crustal anatexis, magma mixing. Alps-Apennines, Southern Tuscan, Italy.*

ABSTRACT

Southern Tuscany has been traditionally considered as a typical crustal anatectic magmatic province. However, extensive petrological and geochemical investigations carried out in the last years revealed a much more complex magmatic setting given by the occurrence of a large variety of rock types. The main rock associations are represented by: 1) acid volcanics and intrusives of crustal anatectic origin; 2) Ultrapotassic rocks with lamproitic (LMP) affinity; 3) Hybrid rocks between LMP and Roman-type (ROM) potassic and highly potassic magmas; 4) High-potassium calcalkaline (HKCA) and shoshonitic (SHO) magmas. Acid anatectic rocks are generally associated and mixed with mafic lavas and enclaves of variable composition.

LMP, HKCA, SHO, and ROM-LMP hybrid magmas are of mantle origin. Their high enrichment in incompatible elements and the crustal-like isotopic signatures are consistent with a genesis in an anomalous upper mantle that was metasomatized by addition of subduction-related upper crustal material. However, variations of some key petrological and geochemical parameters reveal significant compositional heterogeneity of mantle beneath Tuscany.

Petrological and geochemical data for mafic magmas suggest a complex evolutionary history of mantle sources, with at least two metasomatic events. These affected lithospheric and asthenospheric mantle, generating strong vertical and lateral compositional heterogeneity. The close similarity of Tuscany LMP rocks as those occurring in the Western Alps suggests that the earliest metasomatic modification was likely related to Alpine subduction processes. Younger mantle modifications occurred during subduction of the Adria Plate; this was responsible for the widespread Roman magmatism, but also produced some effects in the Tuscany province, as indicated by the occurrence of hybrids between Roman-type and lamproitic magmas.

INTRODUCTION

The Tuscany province consists of a large variety of magma types. The widespread occurrence of acid peraluminous volcanic and intrusive bodies has brought early authors to suggest an overall crustal anatectic origin for the entire province (Marinelli, 1975; Marinelli, 1983; Ferrara and Tonarini, 1985; De Rita et al., 1988). Such a hypothesis was apparently confirmed by Sr, Nd, Pb and O isotopic data, which are invariably closer to typical crustal rather than to mantle values (e.g. Turi and Taylor, 1976; Vollmer, 1976; Hawkesworth and Vollmer, 1979; Poli et al., 1984; Ferrara et al., 1986; Giraud et al., 1986; Peccerillo et al., 1988).

However, a large number of magmatic centers in Tuscany have a mafic composition, and some of these contain high-pressure ultramafic xenoliths (Peccerillo et al., 1988; Conticelli and Peccerillo, 1990; Conticelli and Peccerillo, 1992). Moreover, mafic rocks are often found as microgranular enclaves and veins in most if not all the acid extrusive and intrusive bodies. Mafic rocks and some enclaves have high contents in MgO, Ni, Cr, which reveals a mantle origin; petrological and geochemical signatures are variable, thus calling for heterogeneous mantle sources (e.g. Conticelli and Peccerillo, 1992). Yet, the reasons of this heterogeneity and the processes that generated the various magma types within the upper mantle, are still matter for debate.

In this paper we summarize the main compositional characteristics of the mafic rocks in the Tuscany province, discuss possible petrogenetic processes and explore geodynamic implications of petrological and geochemical data.

GENERALS

The Tuscany magmatic province consists of a series of centers, with a small to moderate size and variable age, scattered through southern Tuscany and the Tuscan archipelago (Fig. 1); the acid centers of Tolfa-Cerveteri-Manziana area, northwest of Rome, are traditionally considered as part of the Tuscan magmatic province, and will be also briefly discussed in this review. Tuscany magmatism partially overlaps with the potassic (KS) to ultrapotassic rocks (HKS) of the Roman province.

The Tuscany province consists of various stocks, dykes, necks, lava flows and domes, and of the large volcanic edifices of Monte Amiata, Monti Cimini and Capraia Island. Age ranges from 8-7 Ma to 0.2 Ma (e.g., Ferrara and Tonarini, 1985; Fornaseri, 1985; Villa et al., 1987; Serri et al., 1993; Aldighieri et al., 1998), and shows a tendency to decrease from west to east (Civetta et al., 1978). An outcrop of lamproitic rocks at Sisco (Corsica) is about 14 Ma old, and is here also considered as belonging to the Tuscany province. Fig. 1 gives an overview of location, age and the main compositional characteristics of the Tuscany magmatism.

The basement and wall rocks of volcanic and intrusive bodies consist of metamorphic terranes overlain by allochthonous and autochthonous formations of different nature (see Abbate et al. 1970). The thickness of the continental crust is moderate, and reaches a minimum beneath the Tyrrhenian border of Southern Tuscany, where the Moho has been detected at a depth of about 25 km. This reveals a mantle doming beneath south Tuscany. Heat flow is high, as testified by the occurrence of well known geothermal fields.

An important and puzzling geophysical feature of Southern Tuscany is given by a zone of low seismic velocities

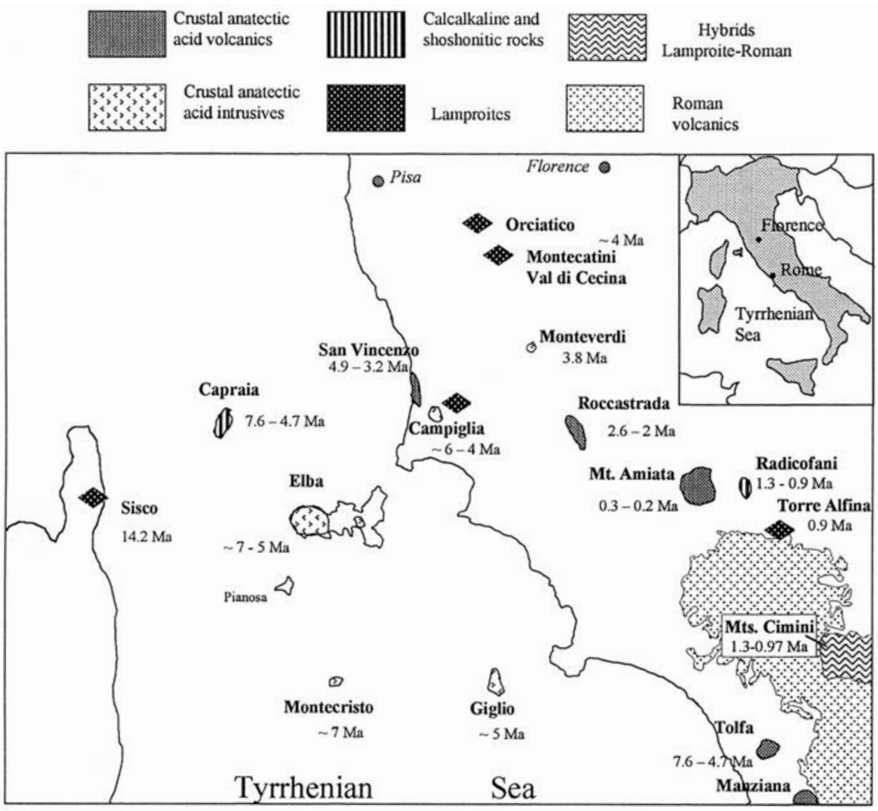

Fig. 1 - Location and age of intrusive and extrusive rocks of the Tuscany magmatic province.

within the upper mantle. This has been interpreted as due to the occurrence of a layer with a crustal-type density. There is debate on the physical nature of this layer, which has been suggested to represent an upper crustal slice within the upper mantle (crustal doubling), or partially molten mantle material (e.g., metasomatic veins) (Morelli 1982; Locardi 1988; Peccerillo and Panza, 1999). Therefore, south Tuscany magmatism appears to be associated with thin crust, high heat flow and mantle doming.

High velocities of S-waves (up to 4.6 km/s) in the north-central Apennine area, below a depth of about 70 km suggest the presence of deep-seated lithospheric roots (e.g., Panza and Mueller, 1979; Babuska et al., 1985), which are almost vertical and seem to interrupt the asthenospheric low-velocity layer. These roots have been interpreted to represent a relict of an undergoing lithospheric slab (see Peccerillo and Panza, 1999 and references therein).

COMPOSITIONAL CHARACTERISTICS OF SOUTH TUSCANY MAGMATISM

As mentioned, the Tuscany province is very complex, far away from the simple and typical crustal anatectic province envisaged by early papers. Peccerillo et al. (1987) demonstrated that several types of magmas can be recognized. These include crustal anatectic acid peraluminous rhyolites and granites, and a wide range of mafic to intermediate rocks such as lamproites (LMP), high-potassium calcalkaline (HKCA) and shoshonitic (SHO) rocks, hybrids between LMP magmas and Roman-type (ROM) potassic and ultrapotassic magmas. Most of the acid rocks appear to have suffered mixing and mingling with various types of mantle-derived calc-alkaline to potassic melts (Poli, 1992). Alkali and K_2O vs. SiO_2 classification diagrams are shown in Fig. 2. Variation diagrams of major and some key trace elements are reported in Fig. 3 and 4. These clearly show the overall composition of the Tuscany province.

Acid magmatism

Petrological and geochemical characteristics

Acid rocks in the Tuscany province occur as lavas at San Vincenzo, Roccastrada, Monte Amiata and Monti Cimini, and as intrusive bodies at Elba (Monte Capanne and Porto Azzurro), Montecristo, and Giglio islands, and at Gampiglia. Other granite bodies occur as seamounts in the northern Tyrrhenian Sea (Vercelli) (Barbieri et al., 1986) and as hidden intrusions encountered by drilling (Monteverdi). Notably, pyroclastic rocks are scarce or absent, except at Monti Cimini where the lowest exposed rocks consist of rhyodacitic ignimbrites. There is still disagreement on the occurrence of ignimbrites at Amiata. In our opinion, the scarcity of pyroclastic rocks may be relevant to petrogenetic interpretation, as it will be discussed later.

Almost all the acid rocks are associated with variable amounts of mafic material. At Monti Cimini rhyodacitic pyroclastic rocks and domes are associated with olivine latitic lavas. Monte Amiata and San Vincenzo lavas, and the intrusive bodies contain microgranular mafic enclaves and dykes, which represent blobs of mafic melts intruded into and mingled with the acid host magma (Poli, 1992; Poli et al., 1989). Instead, no mafic material has been described for the Roccastrada rhyolites. Petrological data on mafic lavas and enclaves associated with acid rocks suggest a variable petrogenetic affinity, from calcalkaline to ultrapotassic.

The association of mafic and acid material does not imply that acid and mafic magmatism are genetically related; rather, mafic magma uprising from the mantle provided the heat for crustal melting, which generated acid magmas.

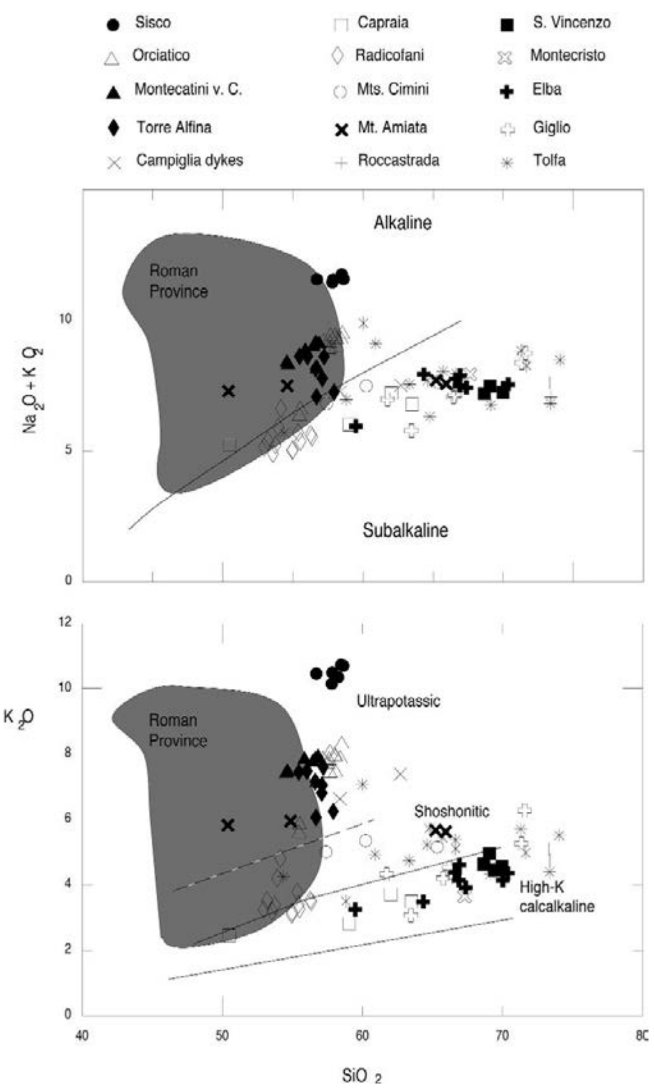

Fig. 2 - Na_2O+K_2O and K_2O vs. SiO_2 diagrams for magmatic rocks of the Tuscany province. The least acid composition for Elba, Giglio, Tolfa, and Mt. Amiata represent mafic enclaves. Composition of the Roman province is indicated in gray. Data from: Conticelli and Peccerillo (1992), Ferrara et al. (1986), Giraud et al. (1986), Hawkesworth and Vollmer (1979), Pinarelli (1987; 1991), Pinarelli et al. (1989), Peccerillo et al. (1987; 1988), Poli et al. (1984), Vollmer (1976), and references herein.

At Roccastrada acid rocks consist of rhyolitic lava flows and dome emitted from NW-SE trending factures (Mazzuoli, 1967; Giraud et al. 1986; Pinarelli et al., 1989). $^{87}Sr/^{86}Sr$ isotope ratios are high and not very variable (0.718-0.720 ca), and $^{143}Nd/^{144}Nd$ is low (= 0.51222). Geochemical and petrological data clearly suggest a genesis by partial melting of upper crustal material of probable metapelitic composition (Giraud et al., 1986; Pinarelli et al., 1989). The poorly variable compositional characteristics and the absence of mafic material suggest that this magma represents a pure anatectic melt, which did not interact significantly with subcrustal magmas.

At San Vincenzo, acid lavas show lower silica contents and more variable isotopic composition than at Roccastrada. Sr isotopic ratios range from 0.7133 to 0.7255, Nd isotopic ratios range from 0.51214 to 0.51225. (e.g. Vollmer, 1976; Giraud et al., 1986; Ferrara et al., 1989; Feldstein et al., 1994). Strong isotopic disequilibrium among phenocrysts and between phenocrysts and groundmass have been detected (Ferrara et al. 1989; Feldstein et al., 1994). All these features suggest that San Vincenzo rhyolites result from mixing between crustal anatectic melt and minor but significant amounts of subcrustal mafic-intermediate magma. The presence of xenoliths with andesitic texture and composition led Ferrara et al. (1989) to suggest a calcalkaline affinity for the subcrustal end-member.

Monte Amiata is built up by quartz-latite to trachyte lava flows and domes. Sr isotope ratios cluster around 0.711 (Poli et al., 1984). Mafic enclaves are abundant in the summit domes (Ferrari et al., 1996).

The Monti Cimini acid rocks consist of rhyodacitic domes and ignimbrites, which resemble closely the acid rocks of Monte Amiata. Late mafic olivine latite lava flows are present in this volcano. The Monti Cimini rocks show important geochemical and isotopic variations that reveal mixing between crustal anatectic and mafic subcrustal magma (Poli et al., 1984).

The intrusive bodies of Montecristo, Capanne, Giglio, Gavorrano and Monteverdi range in composition from granodiorite to alkali-granite, with a strong predominance of monzogranites. Granite porphyry bodies crop out mainly at Elba. Variable amounts of mafic microgranular enclaves occur in the intrusive bodies. Rock compositions straddle the I and S fields of Chappel and White (1974); mineralogical and chemical characteristics indicate that the more basic rocks are broadly I-type, whereas the high-silica rocks are S-type (Poli et al., 1989; Macera and Bruno, 1994; Westerman et al., 1997).

Petrogenesis

Petrological, geochemical and isotopic data reveal a genesis by crustal anatexis for acid rocks of the Tuscany province. Petrographic and geochemical features, variable Sr isotope ratios, and the presence of mafic enclaves claim for interaction between upper crustal anatectic melt and mafic melts with variable enrichment in potassium (Poli, 1992; Poli et al., 1989). Geochemical modelling suggests that melting of a gneiss with a compositions as those occurring in Tuscany, can explain the genesis of the crustal end-members (e.g. Pinarelli et al., 1989). However, geobarometric studies suggest a deep origin for these magmas (at least 4-5 kbar). Therefore the need of having an upper crustal rock at high depth, supports the hypothesis of crustal doubling beneath Tuscany. The scarcity of pyroclastic material agrees with this hypothesis since deep rocks may have undergone dehydration during their residence at a high depth. Anatexis was triggered by input of mafic magma arising from the mantle.

Mafic-intermediate magmatism

Petrological and geochemical characteristics

Alkali vs. silica diagram (Fig. 2) shows that the mafic rocks from Tuscany have variable degree of enrichment in alkalies, from transitional to alkaline compositions. SiO_2 vs. K_2O diagram shows HCKA and shoshonitic to ultrapotassic affinity. Mafic rocks display variable major, trace elements and isotopic signatures (Fig. 3, 4). Classification diagrams for potassic and ultrapotassic magmas (Foley et al., 1987) show that several Tuscany mafic rocks (MgO > 2wt%) plot in the field of lamproites (Group I of Foley et al., 1987), whereas others plot in the field of the Roman province (Group III of Foley et al., 1987) (Fig. 5). Some rocks (e.g. Monti Cimini) plot in the Group I lamproite field on some diagrams, whereas in other diagrams they plot in the Group III field, or across the boundary between the two domain.

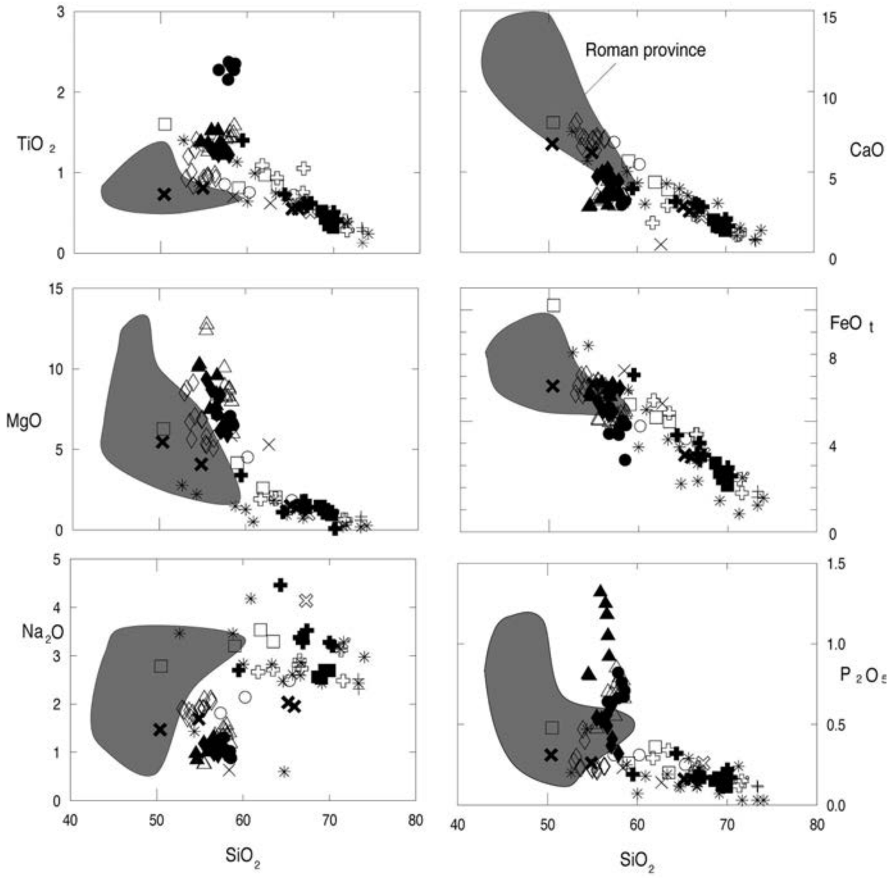

Fig. 3 - Variation diagrams of major oxides for Tuscany magmatic rocks. Symbols and source of data as in Fig. 2. Composition of the Roman province is indicated in gray.

Overall, the following main groups of mafic rocks can be recognized:

i- lamproitic rocks (Sisco, Montecatini val di Cecina, Orciatico, Campiglia dykes and Torre Alfina);

ii- high potassium calcalkaline (Capraia) and shoshonitic rocks (Capraia and Radicofani);

iii- ultrapotassic rocks with intermediate characteristics between lamproites and Roman rocks (Monti Cimini, mafic enclaves in Monte Amiata domes).

Lamproites are ultrapotassic, silica oversaturated, high-silica rocks with Mg# (Mg/Mg+Fe atomic ratio) as high as 75-80, high Ni (up to 350 ppm) and Cr (up to 800 ppm) and low Al, Ca, Na (Fig. 3-5). Contents of Large Ion Lithophile Element (LILE: Rb, Th, K, Light REE, etc.) and ratios of LILE/HFSE (High Field Strength Elements: Ta, Nb, Zr, etc.) are high and the mantle normalized incompatible element patterns (Fig. 6) closely resemble those of some upper crustal rocks (e.g. shale, gneiss, granitoids) (Peccerillo et al., 1988). Sr, Nd and Pb isotopic compositions also fall in the range of the upper crust (Vollmer, 1976; Hawkesworth and Vollmer, 1979; Peccerillo et al., 1988; Conticelli, 1998; Conticelli et al., 2001). The Sisco lamproite has higher contents of HFSE and lower Sr isotope ratios as the other Tuscany lamproites.

Calcalkaline and shoshonitic rocks are well represented at Capraia. The Radicofani trachybasalts are shoshonitic in composition and resemble the latest erupted rocks of Capraia (Punta dello Zenobito). Sr isotope ratios are moderate at Capraia (about $^{87}Sr/^{86}Sr$ = 0.708-0.709) and much higher at Radicofani (about $^{87}Sr/^{86}Sr$ = 0.713-0.716) (Poli et al., 1984; Conticelli et al., 2001; Poli , unpublished data).

Hybrid Roman-LMP rocks have intermediate compositions between lamproite and Roman-type potassic or ultrapotassic rocks. The most important outcrop is that of Monti Cimini; however, also the enclaves in the Monte Amiata domes, and to some extent Radicofani, appear to belong to this group. Incompatible element patterns resemble those of lamproites (Fig.6). Several petrological and geochemical characteristics of these rocks are intermediate between ROM and LMP rocks (see Peccerillo, 1999) (Fig. 7). This suggests hybridism between ROM and LMP end-members.

Petrogenesis

The high Mg#, Ni and Cr, of most of the mafic rocks in Tuscany as well as the occurrence of ultramafic xenoliths in some outcrops, testify to a mantle origin. The variable petrological and geochemical composition reveals a strongly heterogeneous mantle source. Major elements of magmas depend on the mineral composition of the sources and on the phases entering the melt; therefore, the low Ca, Na, Al (Fig. 3,5) of lamproites suggests a genesis by melting of a peridotite depleted in clinopyroxene (i.e., residual peridote); the silica oversaturation and the high silica contents point to a genesis in the uppermost mantle; note that experimental data (e.g., Foley, 1992) demonstrate that mantle derived potassic magmas have increasing silica contents as the pressure of melting decreases, and liquids with silica contents as those of Tuscany lamproites can be generated within the lithospheric mantle at a maximum pressure of 10-15 kbar. On the other hand, trace element abundance and ratios, and isotopic signatures depend on source geochemical characteristics; therefore, the high contents of incompatible elements in the LMP point to anomalous metasomatic sources. Incompatible element patterns and isotopic signatures strongly support source metasomatism by upper crustal material. Ac-

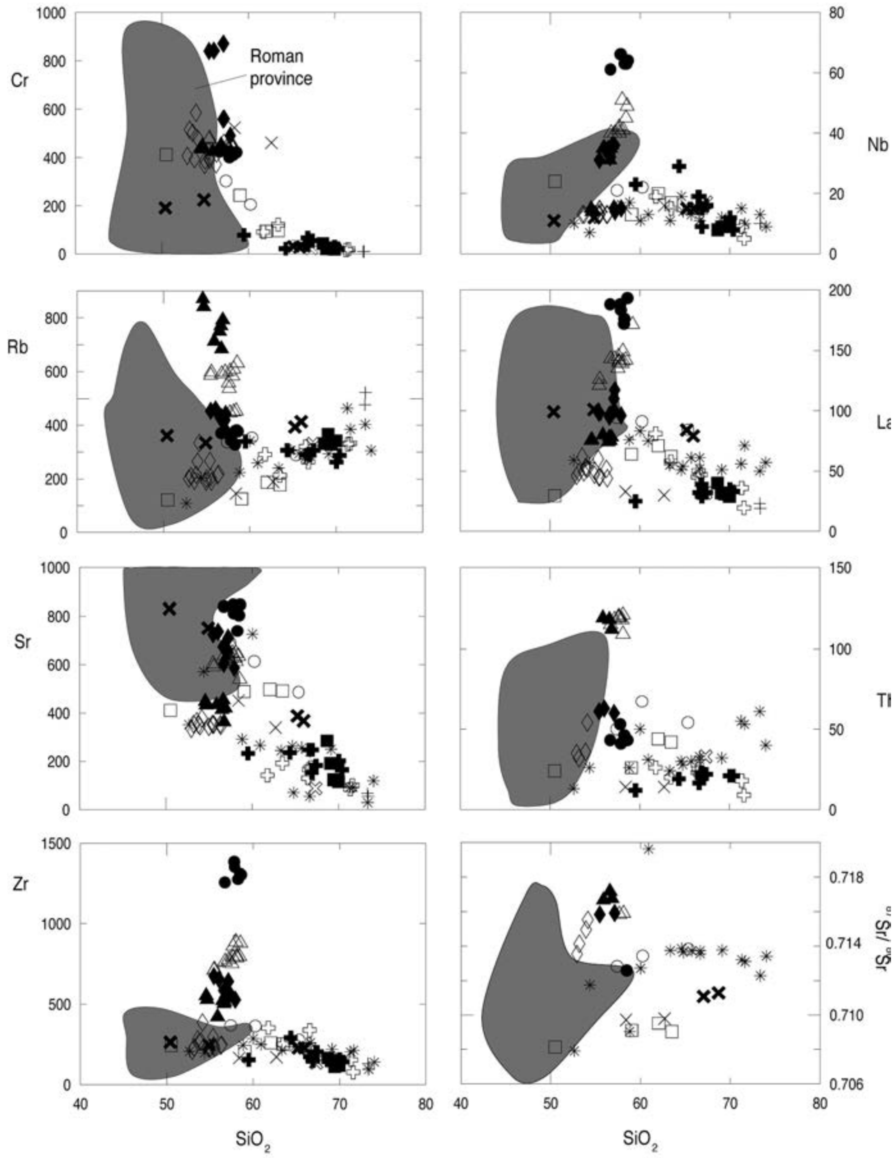

Fig. 4 - Variation diagrams of trace elements and Sr isotope ratios for Tuscany magmatic rocks. Symbols and source of data as in Fig. 2. Composition of the Roman province is indicated in gray.

cordingly, the LMP magmas appear to derive from a residual, lithospheric upper mantle which had been contaminated by upper crustal rocks (e.g. Peccerillo et al., 1988; Conticelli and Peccerillo, 1992; Peccerillo, 1999). This contamination con only be generated by subduction processes.

Calcalkaline rocks have lower enrichment in potassium and incompatible elements than lamproites, whereas CaO, Al_2O_3, and Na_2O are higher. However, incompatible element patterns are similar to lamproites and are different from those of typical shoshonitic rocks, e.g. from the Aeolian arc (e.g., De Astis et al., 1997). Therefore, we envisage a genesis of calcalkaline magmas by melting of a source which was more fertile than that of lamproites, but had a similar type of enrichment in incompatible elements. The lower abundance of potassium and other incompatible elements suggests either a higher degree of partial melting or a less strongly metasomatized source for calcalkaline rocks than for lamproites.

Variation diagrams of incompatible element ratios and isotopes shows distinct compositions for Tuscany lamproites (i.e. Sisco, Montecatini Val di Cecina, Orciatico, Torre Alfina) and Roman magmas (Fig. 7). This has been interpreted as an evidence for two distinct metasomatic events in Tuscany and in the nearby Roman region (Peccerillo, 1999; Peccerillo and Panza, 1999). However, most of the Tuscany mafic rocks, including enclaves in acid hosts, plot midway between Roman rocks and lamproites. This suggests either mixing between lamproitic and Roman magma, or/and the superimposition of distinct (i.e. Roman and Tuscan) metasomatic events in the mantle source beneath Tuscany.

In conclusion, the overall petrogenetic history for the Tuscany province consists of the following main steps:

1- Subduction-related metasomatism with introduction of upper crustal material and formation of a heterogeneous source. Both fertile (asthenospheric) and residual (lithospheric) mantle were affected by such a process. Two types of metasomatism did probably take place, one affecting Tuscany area and one beneath the Latium region; the latter also gave some effects in Tuscany, as indicated by hybrid melts between LMP and Roman-type magmas.

2- Variable degrees of partial melting of heterogeneous mantle with generation of various types of magmas. This was related to mantle doming and isotherm uprise, which accompanied the opening of the Tyrrhenian basin

3- Injection of mafic magma into the continental crust, uprise of isotherms, onset of crustal anatexis, and mafic-acid magma mingling.

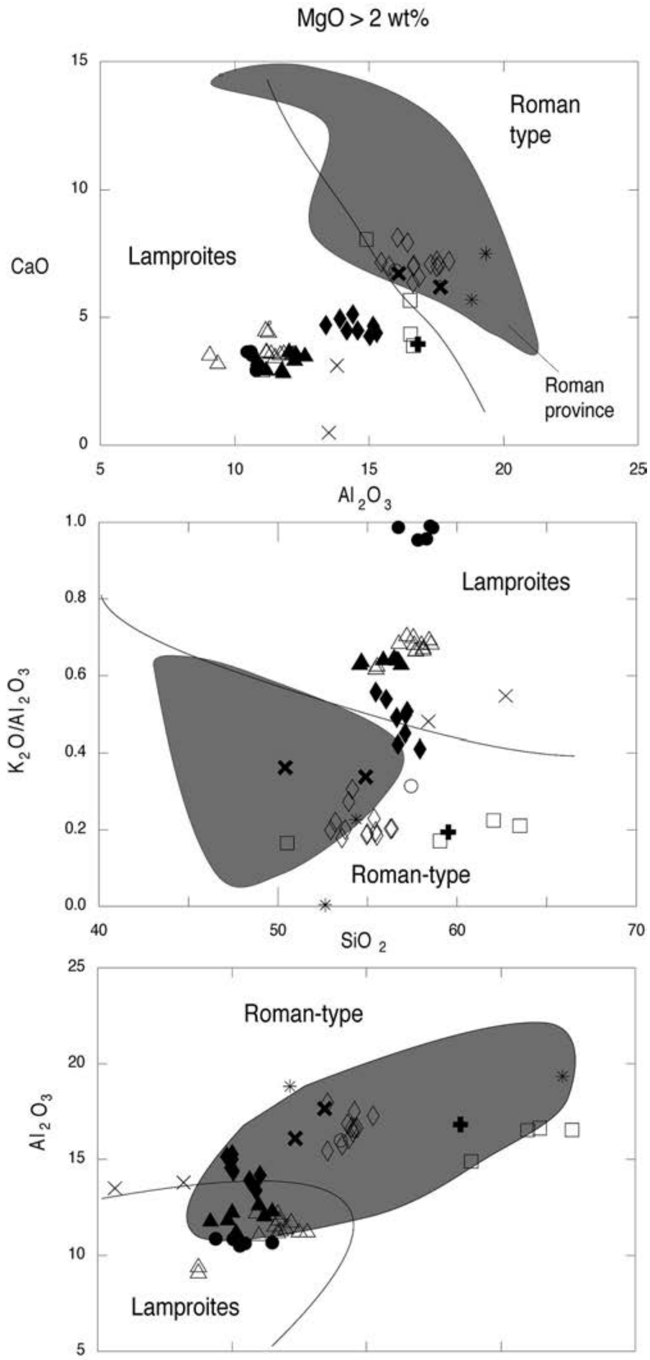

Fig. 5 - Classification diagrams for ultrapotassic mafic rocks (Foley et al., 1987). The lines divide the fields of lamproites and Roman-type rocks. Tuscany rocks with MgO > 2% have been reported. Symbols and source of data as in Fig. 2. Composition of the Roman province is indicated in gray.

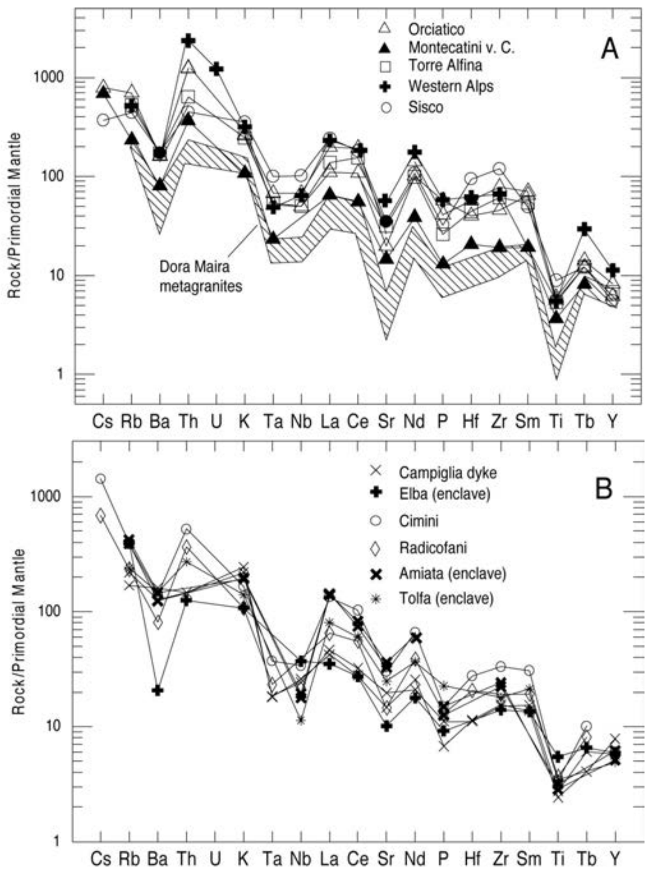

Fig. 6 - Incompatible element patterns for Tuscany mafic rocks, and for a lamproite from Western Alps (Venturelli et al., 1984). Source of data as in Fig. 2.

Tolfa, Cerveteri and Manziana volcanics

This volcanic complex is traditionally included in the Tuscany province. It represents a multi-center acid volcanic complex formed by lava flows and domes ranging from quartz-latites to high silica rhyolites. The age is 4.2 to 2.3 Ma (Fornaseri, 1985). Recent investigations (Pinarelli, 1987; 1991; Bertagnini et al., 1995) have suggested that the Tolfa-Cerveteri-Manziana magmatism is generated by crustal melting and variable mixing with mafic potassic liquids. This clearly suggests a petrogenesis very similar to that of the acidic Tuscan magmatism. Incompatible element patterns of mafic enclaves occurring in the acid volcanics are similar to those of mafic rocks from Tuscany. Although additional studies are necessary on enclaves, their composition provides further support to the hypothesis that the Tolfa magmatism represents the southernmost end of the Tuscany province.

TIMING, NATURE AND GEODYNAMIC IMPLICATIONS OF METASOMATIC EVENTS

A crucial problem for exploring geodynamic implications of petrological and geochemical data is that of finding constraints on the age of metasomatic processes that affected the upper mantle beneath Tuscany and Central Italy (Peccerillo, 1999). Isotopic data, which could help to elucidate this problem are scarce and not easy to interpret; the mafic magmas from Tuscany have variable and positively correlated Rb/Sr vs. $^{87}Sr/^{86}Sr$ isotope ratios (Fig. 7). However, the following unlikely assumptions have to be made in order to attach age significance to the above correlation:

1- Rb/Sr ratio and Sr isotopic ratios of magmas reflect those of the source;

2- variable Sr isotopic signatures of the source developed from aging of mantle, which was isotopically homogeneous and had variable Rb/Sr at the time of metasomatism.

It is much more probable, however, that positive correlation between Rb/Sr vs $^{87}Sr/^{86}Sr$ reflects variable degrees of mantle metasomatism and/or mixing of compositionally dis-

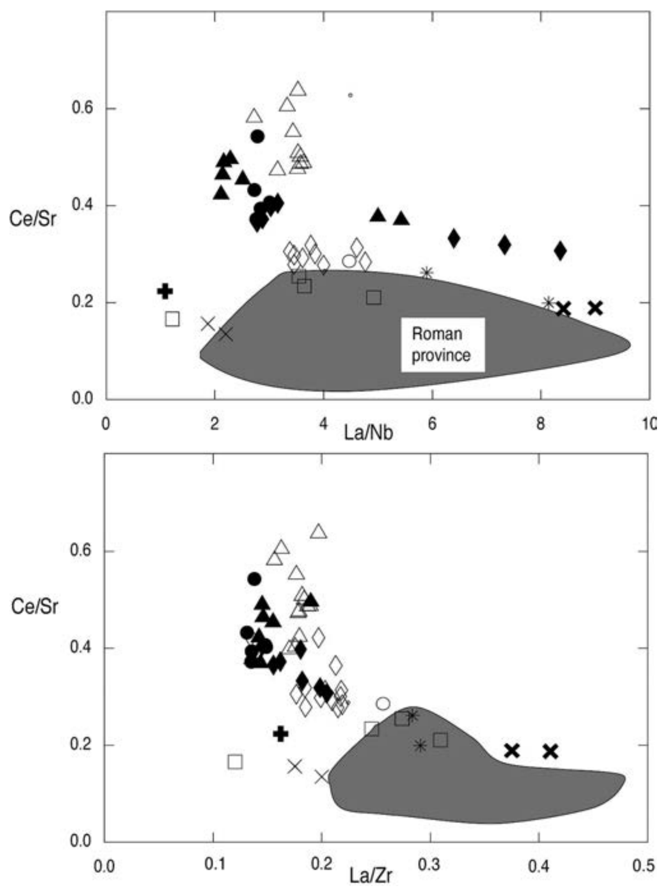

Fig. 7 - Variation diagrams of key trace element ratios and $^{87}Sr/^{86}Sr$ for the Tuscany mafic rocks (MgO > 2 wt%). Tuscany lamproites define distinct trends as the Roman province (indicated in gray); other rocks plot in the middle between Roman rock and lamproites. Symbols and source of data as in Fig. 2.

tinct magmas. In such a case, the Rb/Sr vs $^{87}Sr/^{86}Sr$ correlation has no age significance.

Because of the lack of solid isotopic evidence, the only reasonable indication on age of metasomatism comes from petrological and geological evidence.

A clue to the age of metasomatism beneath Tuscany can be furnished by the volcanism occurring in the Western Alps. In this area lamproites with trace element and isotopic composition very similar to that of Tuscany lamproites, occur (Fig. 6). Western Alps lamproites are about 30 Ma old and are associated with calcalkaline and shoshonitic magmatism, a feature which is encountered also in Tuscany. They were emplaced during a late Alpine, post collisional extensional phase, but metasomatic modification of their source occurred during the Alpine subduction process (Venturelli et al., 1984). Western Alps and Tuscany lamproites have almost identical geochemical compositions (Fig. 6a), and this requires the same type of source. All these occurrences are sited east of the Alpine collision front, i.e. on the margin of the overriding plate above the east-dipping Alpine subduction zone (Gueguen et al., 1997; Doglioni et al., 1999). Therefore, geological and geochemical evidence suggests that the lamproites from Western Alps and Tuscany had a common source, which had a similar evolutionary history. If this hypothesis is accepted, the obvious conclusion is that both the mantle sources were affected by metasomatic modification during Alpine subduction.

Instead, the metasomatism of Roman magma sources was probably younger. This is suggested by the young age of Roman volcanism, which is invariably lower than about 0.6 Ma. Since the outcrop area of Roman volcanics has experienced extension since Miocene, a plausible reason for the younger age of Roman-type rocks is that their sources were affected by a young metasomatic event. This may be related to the subduction of the Adria Plate, whose presence in the upper mantle is detected by seismic data (see Peccerillo and Panza, 1999 and references therein).

An Alpine age of metasomatism for the Tuscany magmatism requires that mantle sources were dismembered during opening of the Provençal and Tyrrhenian basins; fragments of anomalous lithosphere were shifted toward the east and underwent partial melting at various times to give the range of magmatic rocks occurring from Corsica to Southern Tuscany. Dismembering and melting of the Alpine lithosphere was related to the opening of Tyrrhenian sea behind the Adria subduction zone.

Therefore, a model for the evolution of the mantle sources of potassic magmatism in south Tuscany can be hypothesized as consisting of the following main stages:

Stage 1. Subduction of the European Plate beneath the African margin generated mantle metasomatism. Upper crustal material was brought into the mantle wedge. The very high pressure undergone by the Dora Maira Massif, supports the possibility that upper crustal rocks can indeed reach the upper mantle. The incompatible element patterns of LMP are virtually identical to those of Dora Maira granites (Peccerillo, 1999) (Fig. 6a), thus supporting this hypothesis; this similarity also requires bulk addition of upper crust to the mantle wedge, without significant element fractionation. Melting did not occur during subduction, probably because of the low temperatures in the wedge, possibly related to a low dipping angle of the east-directed subduction zone (Doglioni et al., 1999).

Stage 2. West-dipping subduction of the Adria Plate produced opening of the Provençal and Tyrrhenian backarc basins, a fragmentation and boudinage of the Alpine orogen and the rotation of Corsica-Sardinia and Italian peninsula (Mantovani et al., 1996; Gueguen et al., 1997). Uprise of hot asthenosphere accompanied the rotation of lithospheric blocks, generating an uprise of isotherms with consequent melting of old and fragmented lithospheric mantle wedge, which had preserved the metasomatic composition acquired during Alpine subduction.

Stage 3. The latest stages of Adria Plate subduction brought new upper crustal material into fertile asthenospheric mantle beneath the Roman region; melting of newly contaminated mantle gave the Roman province. This process also occurred beneath the Tuscany province, where the Roman-type magmas mixed with those derived by melting of older lithosphere to give the LMP-ROM hybrid melts. Superimposition of the Roman over Tuscany metasomatism may represent another, not necessarily alternative, explanation for the hybrid characteristics of some mafic magmas in Tuscany.

CONCLUSIONS

The magmatism in Tuscany shows variable age and genesis. The acid rocks are mostly represented by crustal anatectic liquids that have been affected by various degrees of mixing with subcrustal magmas of variable composition.

Mafic and intermediate rocks range from high-K calc-alkaline to ultrapotassic. Incompatible element composition and isotopic signatures suggest an origin from a metasomatic upper mantle, which was contaminated by addition of upper crustal material, by means of subduction.

Metasomatism beneath Tuscany was different in composition from that of the Roman province.

These conclusions are all based on geochemical data and can be considered as strongly constrained by solid evidence.

There is uncertainty on the age of metasomatism in Tuscany and in the Roman province. The younger age of Roman rocks suggest a younger age also for metasomatism.

Acknowledgements

Research on magmatism from central-southern Italy is financially supported by CNR and the University of Perugia

REFERENCES

Abbate E., Bortolotti V., Passerini P. and Sagri M., 1970. Introduction to the geology of Northern Apennines. In: Sestini G. (Ed.), Development of the Northern Apennines geosyncline, Sedim. Geol., 4: 521-558.

Aldighieri B., Gamba A., Groppelli G., Malara F., Pasquarè G., Testa B. and Wijbrans J., 1998. Methodology for the space-time definition of lateral collapse: the evolution model of Capraia island (Italy). In: A. Buccianti, G. Nardi and R. Potenza (Eds.), Proceedings of IAMG'98, p. 79-85.

Babuska V., Plomerova J., Sileny J. and Baer,M., 1985. Deep structure of the lithosphere and seismicity of the Alps. In: Schenk V. and Schenkova Z. (Eds.), Proc. 3rd. Intern. Symp. Analysis of seismicity and seismic risk, Geophys. Inst. Czechoslovak. Acad. Sci., Prague, p. 265- 270.

Barberi F., Innocenti F. and Mazzuoli R., 1967. Contributo alla conoscenza chimica-petrografica e magmatologica delle rocce intrusive, vulcaniche e filoniane del Campigliese (Toscana). Mem. Soc. Geol. Ital., 6: 643-681.

Barbieri M., Gasparotto G., Lucchini F., Savelli C. and Vigliotti L., 1986. Contributo allo studio del magmatismo del Mar Tirreno: l'intrusione granitica tardo-Miocenica del Monte sub-marino Vercelli. Mem. Soc. Geol. Ital., 36: 41-54.

Bertagnini A., De Rita D. and Landi P., 1995. Mafic inclusions in the silica-rich rocks of the Tolfa-Ceriti-Manziana volcanic district (Tuscan Province, Central Italy): chemistry and mineralogy. Mineral. Petrol., 54: 261-276.

Chappell B.W. and White A.J.R., 1974. Two contrasting granites types. Pacific Geol., 8: 173-174.

Civetta L., Orsi G., Scandone P. and Pece R., 1978. Eastward migration of the Tuscan anatectic magmatism due to anticlockwise rotation of the Apennines. Nature, 276: 604-605.

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

Conticelli S., D'Antonio M., Pinarelli L. and Civetta L., 2001. Source contamination and mantle heterogeneity in the genesis of Italian potassic and ultrapotassic volcanic rocks: Sr-Nd-Pb isotope data from Roman Province and Southern Tuscany. Mineral. Petrol, in press.

Conticelli S. and Peccerillo A., 1990. Petrological significance of high-pressure ultramafic xenoliths from ultrapotassic rocks of Central Italy. Lithos, 24: 305-322.

Conticelli S. and Peccerillo A., 1992. Petrology and geochemistry of potassic and ultrapotassic volcanism from Central Italy: inferences on its genesis and on the mantle source evolution. Lithos, 28: 221-240.

De Astis G.F., La Volpe L., Peccerillo A. and Civetta L., 1997. Volcanological and petrological evolution of the Vulcano Island (Aeolian Arc, Southern Tyrrhenian Sea). J. Geophys. Res., 102: 8021-8050.

De Rita D., Funiciello R. and Sposato A., 1988. Complessi vulcanici. In: Accordi G. and Carbone F. (Eds.), Carta delle litofacies del Lazio-Abruzzo ed aree limitrofe. Note illustrative. C.N.R. Quaderni Ricerca, 114: 201-215.

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

Feldstein S.N., Halliday A.N., Davies G.R. and Hall C. M., 1994. Isotope and chemical microsampling constraints on the history of a S-type rhyolite, San Vincenzo, Tuscany (Italy). Geochim. Cosmochim. Acta, 58: 943-958.

Ferrara G., Petrini R., Serri G. and Tonarini S., 1989. Petrology and isotope-geochemistry of San Vincenzo rhyolites (Tuscan, Italy). Bull.Volcanol., 51: 379-388.

Ferrara G., Preite Martinez M., Taylor H.P., Tonarini S. and Turi B., 1986. Evidence for crustal assimilation, mixing of magmas and a ^{87}Sr-rich mantle. An oxygen and strontium isotope study of the Monti Vulsini volcanic area, Central Italy. Contrib. Miner. Petrol., 92: 269-280.

Ferrara G. and Tonarini S., 1985. Radiometric geochronology in Tuscany: Results and problems: Rend. S.I.M.P., 40: 111- 124.

Ferrari L., Conticelli S., Burlamacchi L. and Manetti P., 1996. Volcanological evolution of the Monte Amiata, Southern Tuscany: ne geological and petrochemical data. Acta Vulcanol., 8: 41-56.

Foley S.F., 1992. Vein-plus-wall-rock melting mechanisms in the lithosphere and the origin of potassic alkaline magmas. Lithos, 28: 435-453.

Foley S.F., Venturelli G., Green D.H. and Toscani L., 1987. The ultrapotassic rocks: characteristics, classification and constraints for petrogenesis. Earth Sci. Rev., 24: 81-134

Fornaseri M., 1985. Geochronology of volcanic rocks from Latium (Italy). Rend. S.I.M.P., 40: 73-106.

Giraud A., Dupuy C. and Dostal J., 1986. Behaviour of trace elements during magmatic processes in the crust: application to acid volcanic rocks of Tuscany. Chem. Geol., 57: 269-288.

Gueguen E., Doglioni C. and Fernandez M., 1997. Lithospheric boudinage in the Western Mediterranean back-arc basin: Terra Nova, 9: 184-187.

Hawkesworth C.J. and Vollmer, R., 1979, Crustal contamination versus enriched mantle: ^{143}Nd/^{144}Nd and ^{87}Sr/^{86}Sr evidence from the Italian volcanics. Contrib. Mineral. Petrol., 69: 151-165.

Locardi E., 1988. The origin of the Apenninic arc, In: Wezel F.C. (Ed.), The origin and evolution of the arcs, Tectonophysics, 146: 105-123.

Macera P. and Bruno A., 1994. Geochemical and isotopic (Sr-Nd) investigations on the Mt. Capanne pluton (Elba Island) and its mafic enclaves. Mem. Soc. Geol. Ital., 48: 695-697.

Marinelli G., 1975. Magma evolution in Italy. In: Squyres C. (Ed.), Geology of Italy. The Earth Sci. Soc. Lybian Arab Republic, 2: 165-219.

Marinelli G., 1983. Il magmatismo recente in Toscana e le sue implicazioni minerogenetiche. Mem. Soc. Geol. Ital., 26: 111-124.

Mazzuoli R., 1967. Le vulcaniti di Roccastrada (Grosseto). Atti Soc. Toscana Sci. Nat. Mem., A., 84: 315-373.

Morelli C., 1982. Le conoscenze geofisiche dell'Italia e dei mari antistanti. Mem. Soc. Geol. It., 24: 521-530.

Panza G. F. and Mueller S., 1979. The plate boundary between Eurasia and Africa in the Alpine area. Mem. Soc. Geol. Ital., 33: 43-50.

Peccerillo A., 1999. Multiple mantle metasomatism in central-southern Italy: geochemical effects, timing and geodynamic implications. Geology, 27: 315-318.

Peccerillo A., Conticelli S. and Manetti P., 1987. Petrological characteristics and the genesis of Recent magmatism of Southern Tuscany and Northern Latium. Period. Mineral., 56: 157-172.

Peccerillo A. and Panza G., 1999. Upper mantle domains beneath central-southern Italy: petrological, geochemical and geophysical constraints. Pure Appl. Geophys., 156: 421-443.

Peccerillo A., Poli G. and Serri G., 1988. Petrogenesis of orenditic and kamafugitic rocks from Central Italy. Canad. Mineral., 26: 45-65.

Pinarelli L., 1987. Genetic and evolutive models of Tolfa-Cerveteri-Manziana volcanic complex (Italy): geochemical and petrological evidence. Rend. S.I.M.P., 42: 312-313.

Pinarelli L., 1991. Geochemical and isotopic (Sr, Pb) evidence of crust-mantle interaction in acidic melts - The Tolfa-Cerveteri-Manziana volcanic complex (Central Italy): a case history. Chem. Geol., 92: 177-195.

Pinarelli L., Poli G. and Santo A., 1989. Geochemical characterization of recent volcanism from the Tuscan Magmatic Province (Central Italy): the Roccastrada and San Vincenzo centers. Period. Mineral., 58: 67-96.

Poli G., 1992. Geochemistry of Tuscan Archipelago granitoids, Central Italy: the role of hybridisation processes in their genesis. J. Geol., 100: 41-56.

Poli G., Frey F.A. and Ferrara G., 1984. Geochemical characteristics of the south Tuscany (Italy) volcanic province: constraints on lava petrogenesis. Chem. Geol., 43: 203-221.

Poli G., Manetti P. and Tommasini S., 1989. A petrological review on Miocene-Pliocene intrusive rocks from Southern Tuscany and Tyrrhenian sea (Italy). Period. Mineral., 58: 109-126.

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

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

Venturelli G., Thorpe R. S., Dal Piaz G. V., Del Moro A. and Potts P. J., 1984. Petrogenesis of calcalkaline, shoshonitic and associate Oligocene volcanic rocks from the northwestern Alps, Italy. Contrib. Mineral. Petrol, 86: 209-220.

Villa I.M., Gianelli G., Puxeddu M., Bestini G. and Pandeli E., 1987. Granitic dykes of 3.6 Ma age from 3.5 km deep geothermal well at Larderello (Italy). “Granite and their surrounding”, Soc. Ital. Mineral. Petrol., 42: 364.

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

Westerman D.S., Innocenti F., Tonarini S. and Ferrara G., 1993. The Pliocene intrusion of the island of Giglio. Mem. Soc. Geol. Ital., 49: 345-363.

Received, May 1, 2000
Accepted, November 18, 2000