by Angelo Peccerillo

Plio-Quaternary magmatism in Italy

Dipartimento di Scienze della Terra, University of Perugia, Piazza Università, 06100 Perugia, Italy. E-mail: *pecceang@unipg.it*

Plio-Quaternary magmatism in Italy exhibits an extremely variable composition, which spans almost entirely the spectrum of magmatic rocks occurring worldwide. Petrological and geochemical data provide a basis for distinguishing various magmatic provinces, which show different major element and/or trace element and/or isotopic compositions. The Tuscany province (14–0.2 Ma) consists of silicic magmas generated through crustal anatexis, and of mantle-derived calcalkaline to ultrapotassic mafic rocks. The Roman, Umbria, Ernici-Roccamonfina and Neapolitan provinces (0.8 Ma to present) are formed by mantle-derived potassic to ultrapotassic rocks having variable trace element and isotopic compositions. The Aeolian arc (?1 Ma to present) mainly consists of calcalkaline to shoshonitic rocks. The Sicily province contains young to active centers (notably Etna) with a tholeiitic to Na-alkaline affinity. Finally, volcanoes of variable composition occur in Sardinia and, as seamounts, on the Tyrrhenian Sea floor. Magmas in the Aeolian arc and along the Italian peninsula have a subduction-related geochemical character, whereas the Sicily and Sardinia provinces display intraplate signatures. Intraplate and orogenic volcanics coexist on the Tyrrhenian Sea floor.

The geochemical and isotopic complexities of Plio-Quaternary magmatism reveal that the upper mantle beneath Italy consists of various domains, spanning both orogenic and anorogenic compositions. Isotopic data suggest that compositional heterogeneity originated from mixing between various mantle reservoirs, and between these and subduction-related crustal material. This probably occurred during the Cenozoic-Quaternary geodynamic evolution of the western Mediterranean.

Introduction

The Italian peninsula is one of the most complex geodynamic settings on Earth (e.g. Wezel, 1985; Doglioni et al., 1999 and references therein). One expression of this complexity is the wide variety of Plio-Quaternary volcanic rocks, which range from subalkaline (tholeiitic and calcalkaline) to Na- and K-alkaline and ultra-alkaline, from mafic to silicic, and from oversaturated to strongly undersaturated in silica. Trace element contents and isotopic signatures are also highly variable, covering both mantle and crustal values, and ranging from typical intra-plate to orogenic compositions. This extreme magmatic diversity requires the occurrence of a complexly zoned mantle, which reveals an unusual geotectonic setting for the Italian region. Understanding the origin and evolution of the mantle beneath Italy is a challenge for igneous petrology, geochemistry, and geodynamics.

This paper describes the most important geochemical and petrological characteristics of the Plio-Quaternary volcanism in Italy, with the aims of (i) clarifying the first-order processes of magma genesis and evolution and (ii) providing constraints for models of geodynamic evolution of the Italian peninsula and adjoining regions.

Petrological characteristics of Plio-Quaternary magmatism in Italy

The Plio-Quaternary magmatism in Italy occurs along a belt parallel to the Tyrrhenian Sea border, in Sicily and Sicily Channel, on the Tyrrhenian Sea floor, and in Sardinia (Figure 1). The erupted volcanic rocks exhibit a large compositional variability, which is best illustrated by the Total Alkali vs. Silica diagram (TAS) shown in Figure 2. It is evident that Recent magmatism in Italy ranges from ultrabasic to acid, and from sub-alkaline to ultra-alkaline, covering

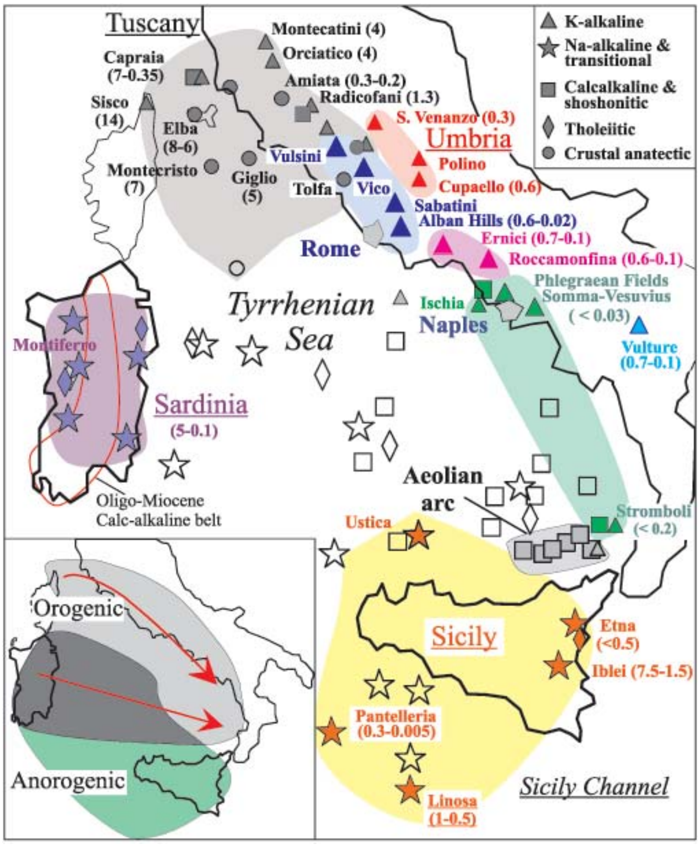


***Figure 1** Distribution of Recent magmatism in Italy. Open symbols indicate seamounts. Ages (in Ma) are given in parentheses. Different colours denote various magmatic provinces. Inset: schematic distribution of orogenic and anorogenic volcanism: red arrows indicate migration of orogenic magmatism with time.*

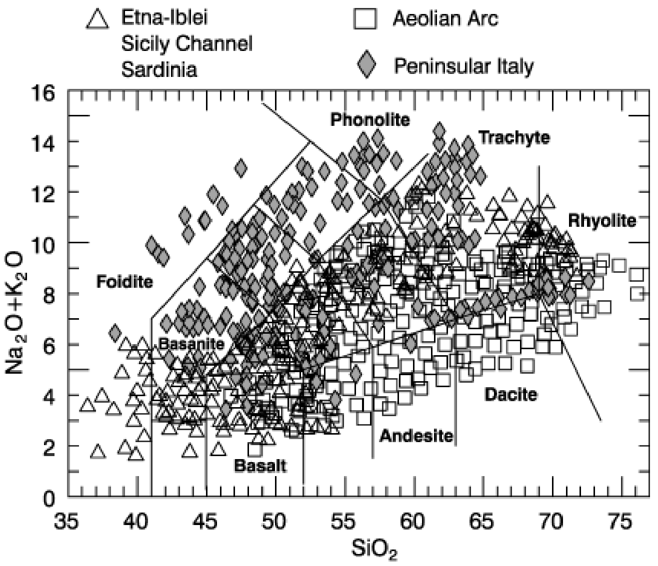


Figure 2 Total alkali vs. silica classification diagram for Italian Plio-Quaternary magmatic rocks. For source of data see Peccerillo (2002).

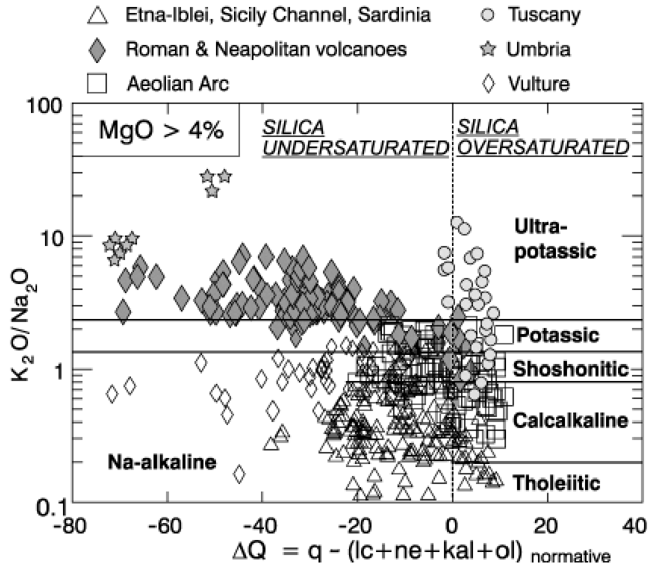


Figure 3 ΔQ vs. K_2O/Na_2O classification diagram for Plio-Quaternary mafic (MgO > 4%) volcanic rocks from Italy. ΔQ is the algebraic sum of normative quartz (q), minus leucite (lc), nepheline (ne), kalsilite (kal) and olivine (ol). Silica oversaturated rocks have $\Delta Q > 0$, whereas silica undersaturated rocks have $\Delta Q < 0$.

almost entirely the compositional field of igneous rocks occurring worldwide. Similarly, large variations are also observed for trace elements and isotopes, as discussed below.

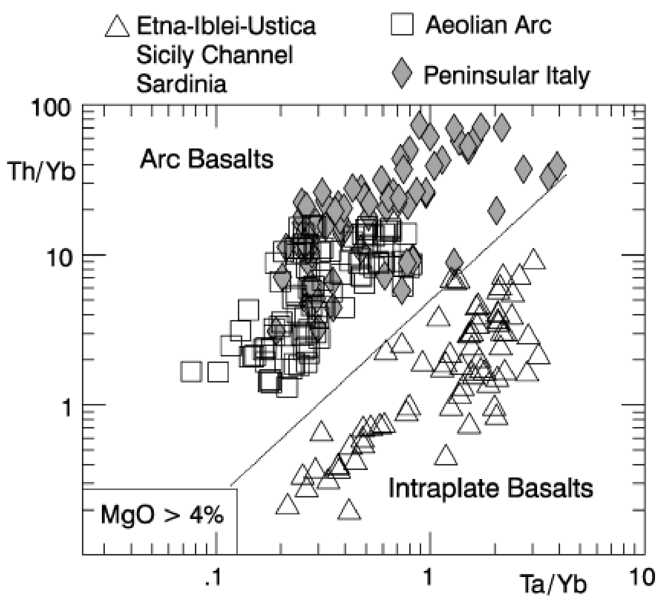
A large proportion of Italian Plio-Quaternary volcanic rocks have high-silica, low-MgO compositions. However, mafic rocks (MgO>3–4 wt%) deserve particular attention, since they are the closest relatives of primary mantle-derived magmas that were parental to erupted lavas, and can furnish the maximum of the information on mantle sources. Figure 3 is a classification diagram (Peccerillo, 2002), which shows that Italian mafic volcanics range from compositions that are strongly undersaturated to oversarturated in silica, from tholeiitic, calcalkaline, and shoshonitic to Na-alkaline, potassic, and ultrapotassic.

Regional distribution of magma types

There is a strong correlation between petrological characteristics of recent magmas and their regional distribution (Figure 1). Tholeiitic rocks occur in western Sicily (e.g. older Etna and Iblei), Sardinia, and on the Tyrrhenian sea floor (MORB and island arc tholeiites). Calcalkaline and shoshonitic rocks are concentrated in the Aeolian arc, although they are also found in the Naples area and in Tuscany (e.g. Capraia). Other calcalkaline and shoshonitic volcanoes occur as seamounts on the Tyrrhenian Sea floor, where they show an age decreasing south-eastward, from the Oligo-Miocene calcalkaline volcanic belt of Sardinia to the active Aeolian islands and seamounts (e.g. Beccaluva et al., 1989; Santacroce et al., 2003 and references therein). Na-alkaline and transitional rocks occur at Etna, Iblei, in the Sicily Channel (e.g. Pantelleria), in the Tyrrhenian Sea (Ustica and some seamounts) and extend to Sardinia (Lustrino et al., 2000). Potassic and ultrapotassic rocks represent the most typical compositions in central Italy. These occur over a large belt, from southern Tuscany to the Naples area (Vesuvius, Ischia, Phlegraean Fields); some potassic rocks occur at Vulcano and Stromboli in the Aeolian arc. Note, however, that potassic and ultrapotassic rocks from Tuscany differ from potassium-rich rocks from central-southern Italy on the basis of their silica saturation and K_2O/Na_2O ratios (Figure 3). Moreover, ultrapotassic volcanoes in Umbria are characterised by extremely high K_2O/Na_2O and very low degrees of silica undersaturation. Finally, undersaturated alkaline rocks, which are rich in both Na and K, with variable K_2O/Na_2O ratios, occur at Mount Vulture, east of Vesuvius.

Regional variation of trace element and Sr-Nd-Pb-Oxygen isotope compositions of mafic rocks

The mafic rocks from Italy have variable abundances and ratios of trace elements. Large Ion Lithophile Elements (LILE, e.g. K, Rb, Th) generally have high concentrations in calcalkaline, potassic, and ultrapotassic rocks. High Field Strength Elements (HFSE, e.g. Ta, Nb, Zr, Ti) have high concentration in Na-alkaline rocks, and low values in calcalkaline and potassic volcanics. Trace elements ratios (especially LILE/HFSE) are useful to distinguish intraplate and subduction-related basalts. The Th/Yb vs. Ta/Yb discriminant diagram of Wood et al., 1979 (Figure 4) is used here to show that mafic rocks from eastern Sicily, Sicily Channel, Ustica, and Sardinia fall in the



Figures 4 Th/Yb vs. Ta/Yb diagram for Plio-Quaternary mafic rocks from Italy, discriminating between intraplate and arc basalts.

field of intraplate (anorogenic) basalts, whereas the magmas occurring in the Aeolian arc and along the Italian peninsula have clear island-arc (i.e. orogenic) signatures. Subduction-related and intraplate volcanics coexist on the Tyrrhenian Sea floor (Figure 1, inset).

Additional petrogenetic information can be obtained by other trace element ratios and isotopes (Figures 5, 6). These highlight important variations that are heavily correlated to regional distribution, and are rather independent on the major petrological characteristics. For instance, calcalkaline and shoshonitic rocks from Tuscany fall in a distinct field with respect to rocks of equivalent petrologic composition from the Aeolian arc (Peccerillo, 1999, 2002).

The variation of $^{87}Sr/^{86}Sr$ vs. $^{143}Nd/^{144}Nd$ ratios of mafic rocks (Figure 6) show that the Italian volcanics define a curved trend between typical mantle compositions (MORB, Etna, Sicily channel, etc.) and upper crust values. Moreover, there is an overall increase of $^{87}Sr/^{86}Sr$ and a decrease of $^{143}Nd/^{144}Nd$ from south to the north, and the various regions display distinct isotopic compositions. Similar trends are shown by Pb isotope ratios (Conticelli et al., 2001 and references therein).

Oxygen isotopic data are also variable in the volcanic rocks from central-southern Italy. The lowest values are found in the south (e.g. $\delta^{18}O \approx +5.5$ to 6‰, in the mafic rocks from the Aeolian arc). Higher values ($\delta^{18}O \approx +7$ to +8‰) are found on mafic potassic and ultrapotassic rocks and separated minerals from central Italy (Harmon and Hoefs, 1995 and references therein).

Magmatic provinces in central-southern Italy: a new classification scheme

Plio-Quaternary magmatism of central-southern Italy has been classically subdivided into various magmatic provinces, represented by Tuscany, the Roman-Neapolitan area (the so-called Roman Comagmatic Province), the Aeolian arc, the Sicily and Sicily Channel (Etna, Iblei, Ustica, Pantelleria, Linosa), and Sardinia. Major, trace element and isotopic data reported above (Figures 3–6) provide evidence for a much more varied magmatic setting. These data permit subdivision of the Italian volcanism into several provinces that exhibit distinct major element compositions and/or incompatible trace element ratios and/or radiogenic isotope signatures (Peccerillo, 1999, 2002). These differences reveal distinct petrogenetic histories. The newly-established magmatic provinces are indicated in Figure 1. Their petrological characteristics and ages are summarised in Table 1.

Petrogenesis

Low-pressure magma evolution

As stated earlier, the largest proportion of Recent volcanism in Italy consists of high-silica lavas, such as andesites, rhyolites, trachytes and phonolites. Except for the Tuscany acid rocks, which are of crustal anatectic origin, these intermediate to silicic magmas were derived predominantly through fractional crystallisation from mafic parents. Mixing between various types of magmas and assimilation of crustal rocks also played an important role in magmatic compositional evolution for some volcanoes (Peccerillo, 2002, and references therein).

However, it is unlikely that such evolutionary processes, including contamination through magma-crust interaction, are responsible for the range of petrological, geochemical and isotopic variations observed in mafic volcanic rocks along the Italian peninsula. It is pertinent to recall that the high concentration of incompatible trace elements (e.g. Th, Sr, REE, etc.) of Italian rocks effectively buffers modifications of trace element and isotope ratios during magma evolution. This holds also true for mafic melts whose evolution degree is low to moderate (see discussion in Conticelli et al., 2001; Peccerillo, 1999, 2002). Therefore, the large geochemical and isotopic variations observed in Italy basically reflect compositional characteristics of mantle sources.

Genesis of mafic magmas

The variable petrological characteristics of Italian recent magmatism require a wide variety of mantle compositions and petrogenetic processes (i.e. degrees and pressure of partial melting, mantle mineral compositions, fluid pressure, etc.) to be generated (see Peccerillo, 2002). The potassic nature of most of the mafic Italian magmas require that a K-rich mineral, such as phlogopite, was present in the upper mantle and melted to produce the potassic magmas. The variable potassium contents probably reflect melting of different amounts of phlogopite. However, phlogopite is not a typical mantle mineral and its presence in the upper mantle reveals compositional anomalies. These can be generated at different spatial scales by introduction of K-rich fluids or melts: this process is known as mantle metasomatism. The large amount of potassic magma within the Italian peninsula requires very extensive mantle metasomatism (Peccerillo, 1999).

Isotopic data furnish further insight into mantle metasomatic processes. The curved trend of Sr-Nd isotope ratios (Figure 6) clearly suggests that the magmatism in central-southern Italy results

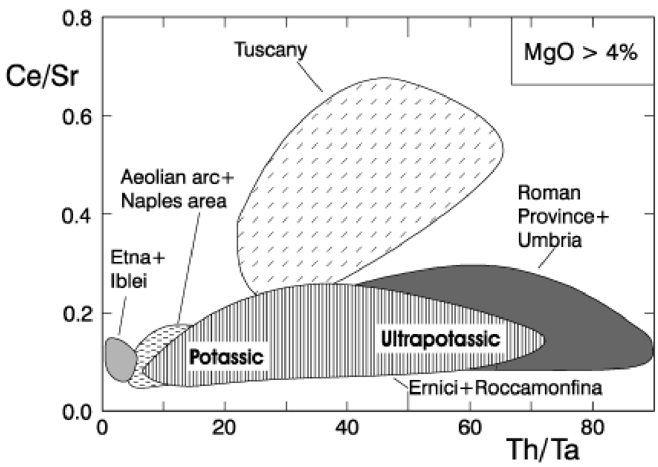


Figure 5 Variation of trace element ratios in Plio-Quaternary Italian mafic rocks. Note strong regional variation.

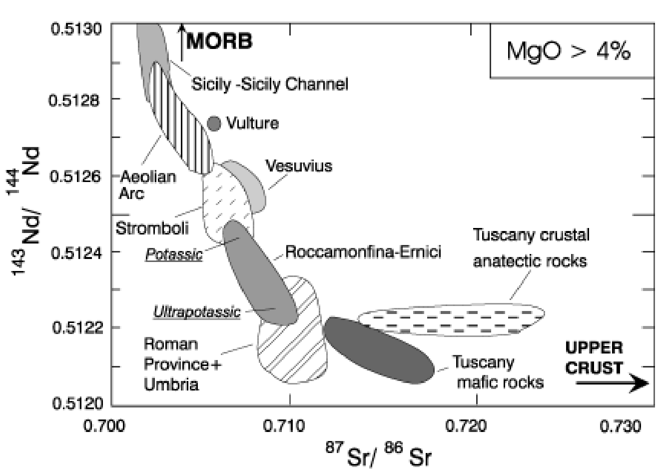


Figure 6 Sr vs. Nd isotope diagram for Plio-Quaternary mafic volcanic rocks from Italy. Note strong regional variation.

Table 1 Petrological characteristics and ages of Plio-Quaternary volcanic provinces in Italy.

MAGMATIC PROVINCE (age in Ma)	MAIN MAGMATIC CENTERS AND AGES (in Ma)	MAIN ROCK TYPES AND VOLCANIC STRUCTURES
TUSCANY (14-0.2)	***Acid intrusions***: Elba (8-6), Montecristo (7), Giglio (5), Campiglia-Gavorrano (5-4). ***Acid volcanics***: San Vincenzo (4.5), Roccastrada (2.5), Amiata (0.3-0.2), Cimini (1.4-1.1), Tolfa (3.8-1.8). ***Mafic centers***: Sisco (14), Capraia (7-3.5), Orciatico and Montecatini val di Cecina (4), Cimini (0.9), Radicofani (1.3), Torre Alfina (0.8)	***Crustal anatectic rocks***: Granitoid intrusions, aplites, pegmatites. Monogenic lava flows and domes, and stratovolcanoes (Mt. Amiata, Cimini Mts.). ***Mafic rocks***: monogenic extrusive and subvolcanic bodies with potassic and ultrapotassic (*lamproites*) composition; calcalkaline and shoshonitic rocks at Capraia.
UMBRIA (0.6-0.3)	San Venanzo (0.3), Cupaello (0.6-0.5), Polino (0.3)	Monogenic pyroclastic centers and lava flows with an ultrapotassic melilititic (*kamafugites*) composition.
ROMAN PROVINCE (0.6-0.02)	Vulsini (0.6-0.15), Vico (0.4-0.1), Sabatini (0.6-0.04), Alban Hills (0.6-0.02)	Large volcanoes formed by potassic (trachybasalt, latite, trachyte) and ultrapotassic (leucite-tephrite, leucitite, phonolite) lavas and pyroclastics.
MONTI ERNICI – ROCCAMONFINA (0.7-0.1)	Ernici: Pofi, Ceccano, Patrica, etc. (0.7-0.1) Roccamonfina (0.6-0.1)	Monogenic cinder cones and lava flows (Ernici), and a stratovolcano with caldera (Roccamonfina) formed by ultrapotassic (leucite-tephrite to phonolite) and potassic (trachybasalt to trachyte) rocks.
CAMPANIA – STROMBOLI (0.8 – Present)	Somma-Vesuvius (0.03-1944 AD), Phlegraean Fields (0.05-1538 AD), Ischia (0.13-1302 AD), Procida (0.05-0.01), Ventotene (0.8-0.1), Stromboli (0.2 – Present)	Stratovolcanoes with calderas formed by calcalkaline, shoshonitic, potassic (trachybasalts to trachytes) and ultrapotassic (leucite-tephrite to phonolites) rocks.
VULTURE (0.7 - 0.1)	Vulture, Melfi	Stratovolcano with caldera formed by Na-K-rich tephrites, phonolites, foidites with abundant hauyne. Carbonatite(?)
AEOLIAN ARC (1(?) – Present)	Panarea (0.15-0.05), Vulcano (0.12-1888 AD), Lipari (0.2-580 AD), Salina (0.5-0.13), Filicudi (1(?)-0.04), Alicudi (0.06-0.03)	Stratovolcanoes with dominant calcalkaline (basalt-andesite-rhyolite) and shoshonitic compositions.
SICILY (7.5 – Present)	Etna (0.5-Present), Iblei (7.5-1.5), Ustica (0.7-0.1), Pantelleria (0.3-0.005), Linosa (1-0.5)	Tholeiitic basalts to Na-alkaline rocks (basanite, hawaiite, trachyte, peralkaline trachyte and rhyolite) forming stratovolcanoes, diatreme, small plateau, etc.
SARDINIA (5.3 - 0.1)	Capo Ferrato (5), Montiferro (4-2), Orosei-Dorgali (4-2), Monte Arci (~ 3), Logudoro (3-0.1)	Tholeiitic basalts to Na-alkaline rocks (basanite, hawaiite, trachyte, alkaline trachyte and rhyolite) forming stratovolcanoes, basaltic plateau and monogenic centres.
TYRRHENIAN SEA FLOOR (7 – Present)	Magnaghi (3), Marsili (1.7-0), Vavilov, Anchise, Lametini, Palinuro, Pontine Islands (?) (~4-1), etc.	Coexisting intraplate (oceanic tholeiites, Na-transitional and alkaline) and arc (arc-tholeiitic, calcalkaline and shoshonitic) rocks.

from mixing between mantle and crustal end-member, revealing input of crustal material into the mantle (mantle contamination). The increase in crustal signatures from Sicily to Tuscany (increase of $^{87}Sr/^{86}Sr$ and decrease of $^{143}Nd/^{144}Nd$) reveals an enhancement in the amount of crustal contaminant going northward. The mantle-like isotopic signatures of Sicily and Sardinia magmatism indicate that the sources of these magmas were not subjected to significant compositional modification by input of crustal material, and probably represent largely pristine and uncontaminated mantle reservoirs.

Geodynamic significance

Much of the discussion on the geodynamic significance of the Recent Italian magmatism has addressed the problem of whether it relates to subduction processes or it represents an intraplate magmatism (e.g. Ayuso et al., 1997). The hypothesis that the variable and anomalous composition of volcanism in the Italian peninsula reflects addition of crustal material to the upper mantle, inevitably leads to the conclusion that at least the magmatism occurring from the Aeolian arc to Tuscany is indeed related to subduction processes. By contrast, the volcanoes in the Sicily and Sardinia provinces and some Tyrrhenian seamounts are intraplate and reflect derivation from mantle source unmodified by subduction. Therefore, the answer to the old question of whether Italian magmatism is subduction-related or not, is simply answered by saying that some volcanoes are subduction-related, whereas other volcanoes are not (Figure 1, inset).

This concept is well explained by a $^{87}Sr/^{86}Sr$ vs. $^{206}Pb/^{204}Pb$ diagram (Figure 7). This shows that the Italian volcanics define two main trends, both emanating from a high $^{206}Pb/^{204}Pb$ and low $^{87}Sr/^{86}Sr$ mantle composition: these mantle reservoirs are called "HIMU" (high-μ, where μ = Th/Pb ratio) and FOZO (Focal Zone) by isotope geochemists (e.g. Zindler and Hart, 1986). One trend includes the Aeolian arc and peninsular Italy, and points to moderately low $^{206}Pb/^{204}Pb$ and high $^{87}Sr/^{86}Sr$ compositions, which are typical of the upper crust. A second trend includes Etna-Iblei, Sardinia and some Tyrrhenian seamounts, and points to a mantle reservoir characterised by low $^{206}Pb/^{204}Pb$ and $^{87}Sr/^{86}Sr$: this is called EM1 (Enriched Mantle 1). The first trend is suggestive of mantle

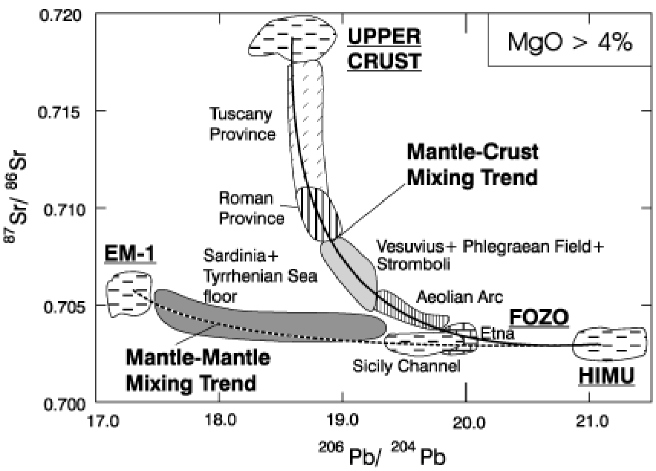


Figure 7 ***$^{87}Sr/^{86}Sr$ vs. $^{206}Pb/^{204}Pb$ variations of Plio-Quaternary Italian mafic rocks. Central Italy orogenic magmatism falls along a mantle-crust mixing trend involving HIMU-FOZO and Upper Crust. Sicily, Sicily Channel, Sardinia and some Tyrrhenian Sea seamounts (anorogenic magmatism) plot along a mantle-mantle mixing trend involving at least two end members (HIMU-EM1).***

(HIMU or FOZO) contamination by upper crustal material transported into the zone of magma genesis by subduction processes. The second trend suggests interaction between different types of mantle reservoirs.

Important problems to address are those dealing with the timing of mantle contamination event(s) beneath peninsular Italy (i.e. the age of subduction processes), and with the significance of HIMU, FOZO and EM1 mantle reservoirs. Although the problem of contamination timing is still debated, geophysical and isotopic evidences favour young events by recent to active subduction. Mantle tomography (Spakman et al., 1993) and S-waves velocity studies (e.g. Panza and Mueller, 1979) have shown that a rigid body occurs within the mantle beneath the Apennines. This mass is actively subducting beneath the eastern Aeolian arc, where deep-focus earthquakes are recorded. Shifting of this subduction zone, from Corsica-Sardinia toward its present position in the southern Tyrrhenian Sea, is responsible for orogenic volcanism inside the Tyrrhenian Sea basin and its time-related migration toward south-east (Beccaluva et al. 1989). Young contamination does not conflict with isotopic evidence, since mafic rocks from single provinces have poorly variable $^{87}Sr/^{86}Sr$ with changing Rb/Sr ratios (see Peccerillo, 2002 for discussion). The significance of HIMU, FOZO, EM1 and other mantle reservoirs are still much debated (see Hofmann, 1997). HIMU compositions are generally believed to represent mantle plumes, whereas EM1 may represent old metasomatised mantle lithosphere. Therefore, the overall picture of the Plio-Quaternary magmatism in Italy would be that of deep mantle material uprising as plumes, mixing with EM1, impinging in an ongoing subduction process and contaminated by subduction-related upper crustal material (Gasperini et al., 2002). Research is actively going on to shed further light on these issues.

Conclusions

The Plio-Quaternary volcanism in Italy shows strong compositional variations, which reveal heterogeneous compositions and complex evolution processes of mantle sources. Both subduction-related and intraplate signatures are observed.

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 calcalkaline to ultrapotassic) with subduction-related geochemical signatures. Mantle end-member could be partially represented by plume material, on the basis of isotopic evidence. Mixing among various mantle reservoirs generated anorogenic volcanism in Sardinia, Sicily, Sicily Channel and for some Tyrrhenian seamounts. The coexistence of orogenic and anorogenic seamounts on the Tyrrhenian Sea floor reflects both the southeastward migration of the subduction zone, and the mantle uprise beneath the Tyrrhenian Sea basin.

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Angelo Peccerillo *is full professor of Petrology at the University of Perugia, where he has been teaching igneous and metamorphic petrology, and volcanology. His main fields of interest are igneous petrology and trace element geochemistry. His research has been concentrated on ultrapotassic rocks, subduction-related magmatism and rift volcanism. He is author or co-author of some 130 scientific and of several popular and didactic publications, including three books.*