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Compositional variations of Plio-Quaternary volcanism in Italy: Deep vs. shallow mantle processes

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Abstract

Plio-Quaternary volcanism in Italy shows strong compositional variations, which reveal heterogeneous mantle sources spanning both subduction-related and intraplate compositions.

Major and incompatible trace element abundances and ratios show variable values, which allow several compositionally distinct magmatic provinces to be distinguished. These are separated by deep faults and are characterised by distinct lithospheric mechanical characteristics, *e.g.*, Moho depth and lid thickness. Radiogenic isotope compositions (Sr, Nd, Pb) of mafic rocks show continuous variations connecting three distinct mantle reservoirs: HIMU-FOZO, EM2 and a high-$^{87}Sr/^{86}Sr$ low-$^{206}Pb/^{204}Pb$ mantle reservoir. The latter is typical of the Italian region and is called ITEM (Italian Enriched Mantle).

The smooth trends of radiogenic isotopes have been interpreted as mixing between deep reservoirs, emplaced into the upper mantle by uprising plumes. However, the strong regionality of major and trace elements, together with structural geology and geophysical evidence, support shallow mantle processes in the generation of Italian Plio-Quaternary magmatism.

Introduction

Plio-Quaternary magmatism in Italy (Figure 1) is extremely variable in composition, spaning almost the entire spectrum of magmatic rocks occurring world-wide. Volcanic rocks 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 (Figure 2). Trace element contents are also highly variable, covering both intra-plate and orogenic compositions (Figure 3). This extreme diversity requires a complexly zoned mantle, revealing an unusual geotectonic setting. Understanding the origin and evolution of the mantle beneath Italy is a challenge for igneous petrology, geochemistry, and geodynamics.

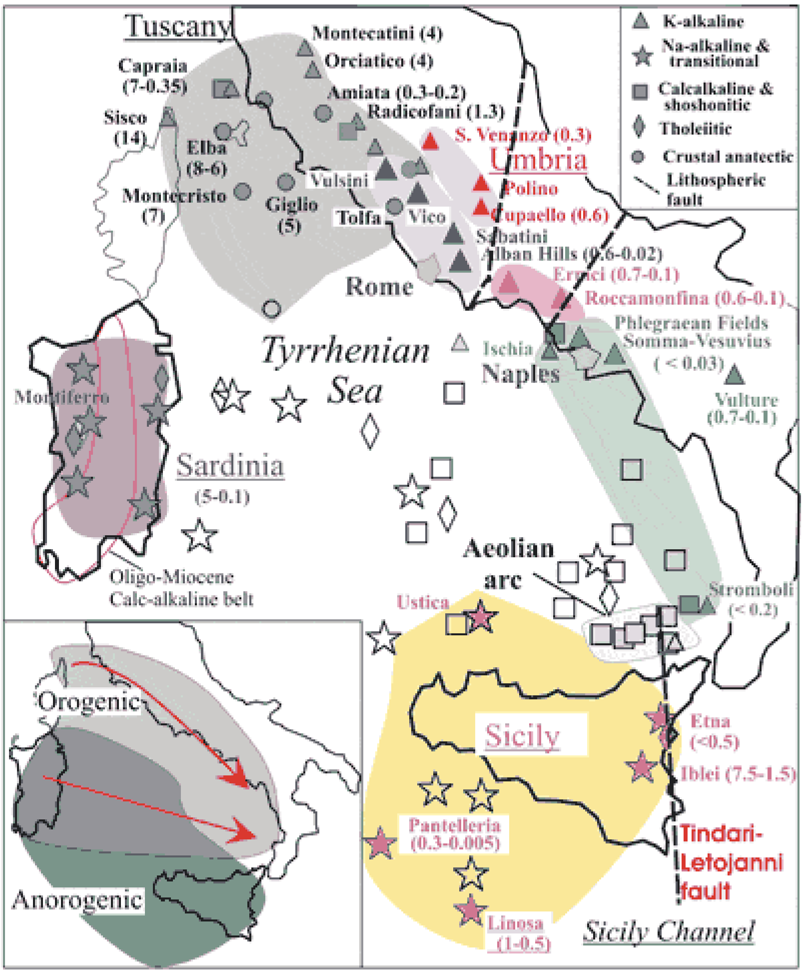

Figure 1: Distribution of Recent magmatism in Italy. Open symbols indicate seamounts. Ages (in Ma) are given in parentheses. Different colours denote various magmatic provinces. Inset: schematic distribution of orogenic and anorogenic volcanism: red arrows show migration of orogenic magmatism with time.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

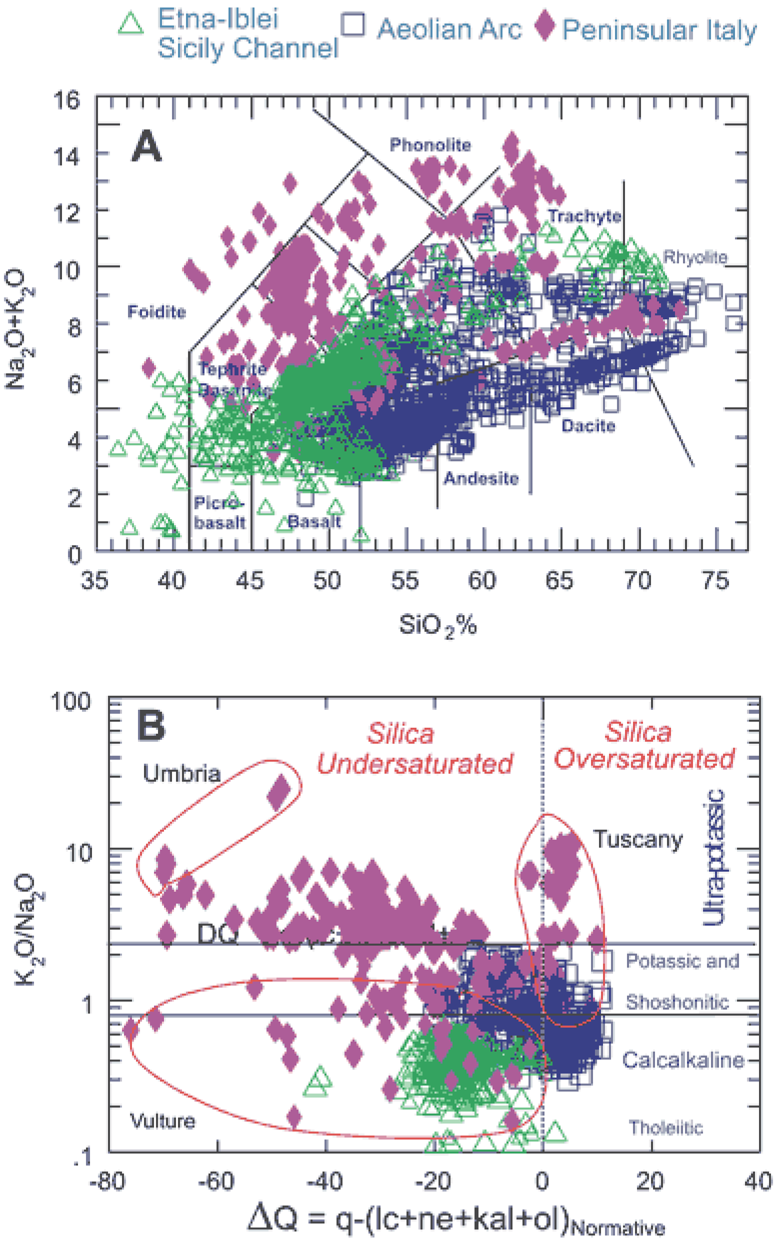

*Figure 2. **A**: Total alkali vs. silica classification diagram for Italian Plio-Quaternary magmatic rocks (Peccerillo, 2002). **B**: delta-Q vs. K_2O/Na_2O classification diagram for Plio-Quaternary mafic volcanic rocks (MgO > 4%) from Italy. Delta-Q is the algebraic sum of normative quartz (q), minus leucite (lc), nepheline (ne), kalsilite (kal) and olivine (ol). Silica oversaturated rocks have delta-Q > 0, whereas silica undersaturated rocks have delta-Q < 0. Click on figure for enlargement.*

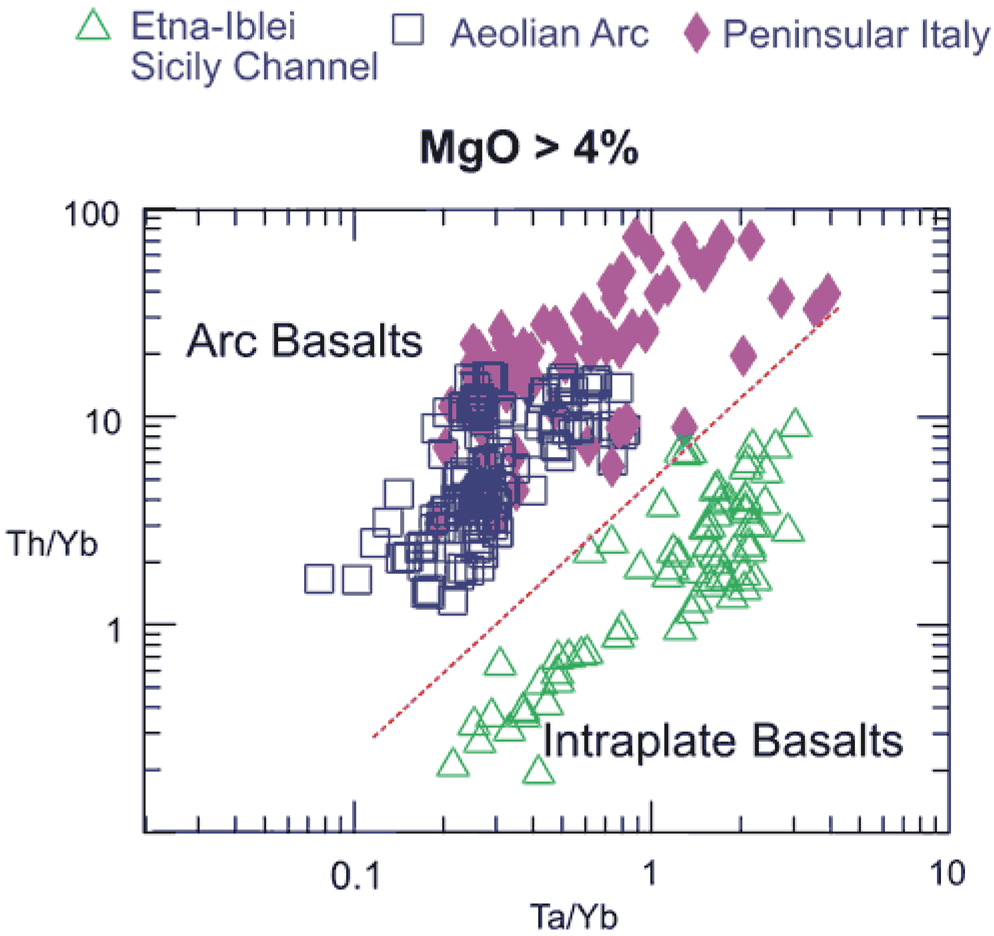

Figure 3: Th/Yb vs. Ta/Yb diagram for Plio-Quaternary mafic rocks from Italy, discriminating between intraplate and arc basalts.

Regional distribution of magma types

There is a strong correlation between the petrological characteristics of Plio-Quaternary magmas in Italy and their regional distribution (Figure 1). Tholeiitic, transitional and Na-alkaline rocks with typical intraplate geochemical signatures (*e.g.*, low LILE/HFSE ratios, Figure 3) occur in western Sicily and Sicily Channel (Etna, Iblei, Linosa, Pantelleria), in Sardinia (*Lustrino et al.*, 2000), and in the Tyrrhenian Sea (e.g. Ustica). Calcalkaline, shoshonitic and K-alkaline rocks with island-arc geochemical signatures (high LILE/HFSE ratios, Figure 3) are concentrated in the Aeolian arc, and along the Tyrrhenian side of the Italian peninsula, but also occur as seamounts on the Tyrrhenian Sea floor. Orogenic magmas displays an overall decrease in age from west to south-east (Figure 1, inset).

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

Italian Plio-Quaternary magmatism mostly consists of intermediate and silicic rocks, derived from a mafic parent by complex evolutionary processes. Mafic rocks (MgO > 4 wt%) occur in minor amounts but they are particularly helpful for understanding mantle composition and processes. Mafic rocks in Italy have variable abundances and ratios of incompatible trace elements (Figure 4). These are rather independent on the major petrological characteristics and are strongly correlated with regional distribution. For instance, calcalkaline and shoshonitic rocks from Tuscany, in the north, fall into a distinct field with respect to rocks of equivalent petrologic composition from the Aeolian arc (*Peccerillo*, 1999, 2002). Such a strong regionality of trace element characteristics allows several magmatic provinces to be distinguished (Figure 1). These provinces are also characterised by their distinct lithospheric structures, *e.g.*, Moho depth, lid thickness and depth of earthquake foci, (*Peccerillo & Panza*, 1999) and are often divided by fault systems that are transverse to the volcanic belt and to the Apennine chain (Figure 1).

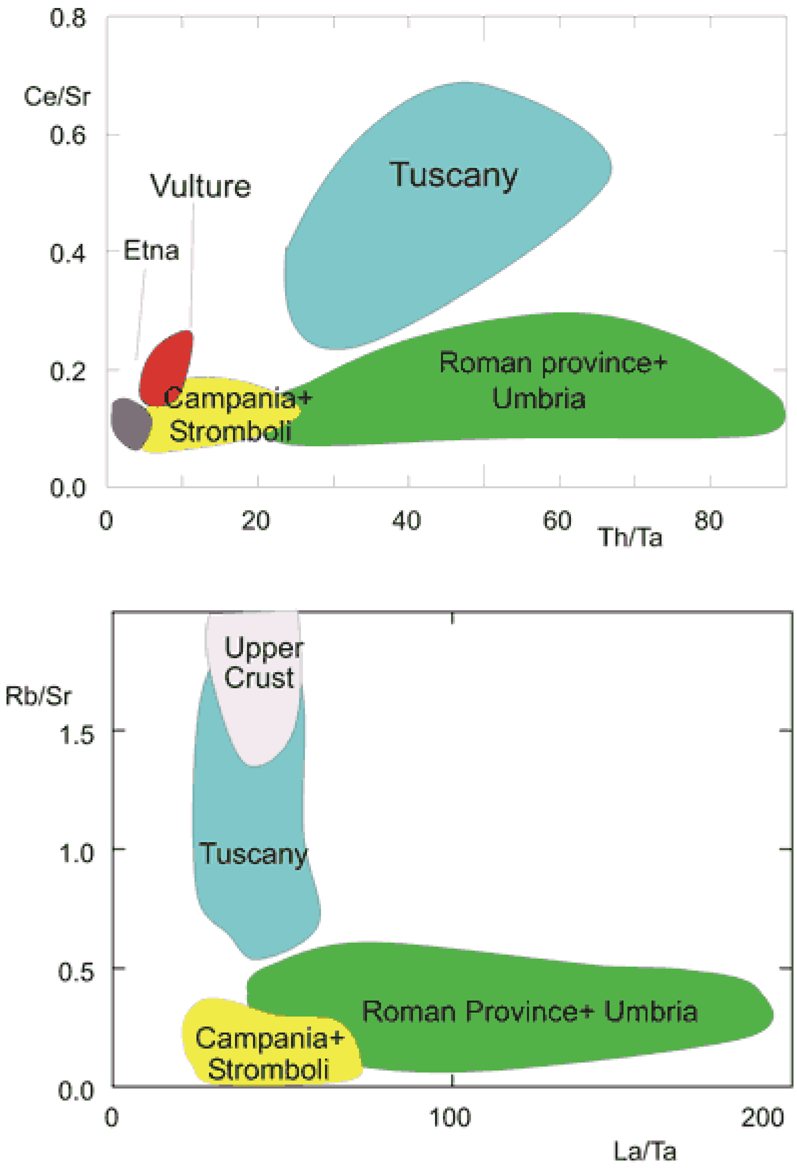

Figure 4: Incompatible trace element ratios in mafic Plio-Quaternary volcanic rocks from Italy. Note the strong regional variation.

Radiogenic isotope compositions (Sr, Nd, Pb, Hf) define smooth trends (Figure 5). There is an overall increase of $^{87}Sr/^{86}Sr$ and a decrease of $^{143}Nd/^{144}Nd$ and Pb isotopes from south to the north, with the various regions displaying distinct isotopic signatures.

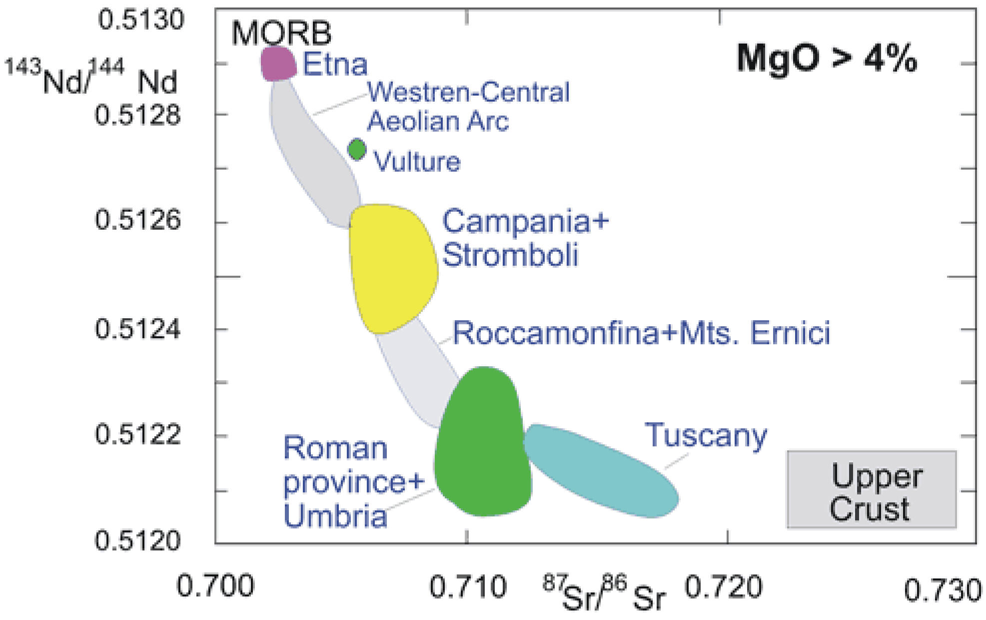

Figure 5: Sr-Nd isotope diagram for Plio-Quaternary mafic volcanic rocks from Italy. Note the strong regional variation.

The $^{87}Sr/^{86}Sr$ vs. $^{206}Pb/^{204}Pb$ diagram (Figure 6) reveals that all magmatism in Italy may be described in terms of interaction between three end-members:

- A low – $^{87}Sr/^{86}Sr$ high – $^{206}Pb/^{204}Pb$ end-member, close to HIMU or FOZO. The main representatives of this reservoir are rocks from Etna, Iblei and Ustica.
- A low – 206Pb/204Pb low – $^{87}Sr/^{86}Sr$ end-member, resembling EM1. Such rocks occur in Sardinia.
- A high – $^{87}Sr/^{86}Sr$ low – $^{206}Pb/^{204}Pb$ end-member with Pb isotopic ratio close to EM2, but with much higher $^{87}Sr/^{86}Sr$. This has been called ITEM (Italian Enriched Mantle) by *Bell* (2002) and is represented by ultrapotassic rocks from central Italy.

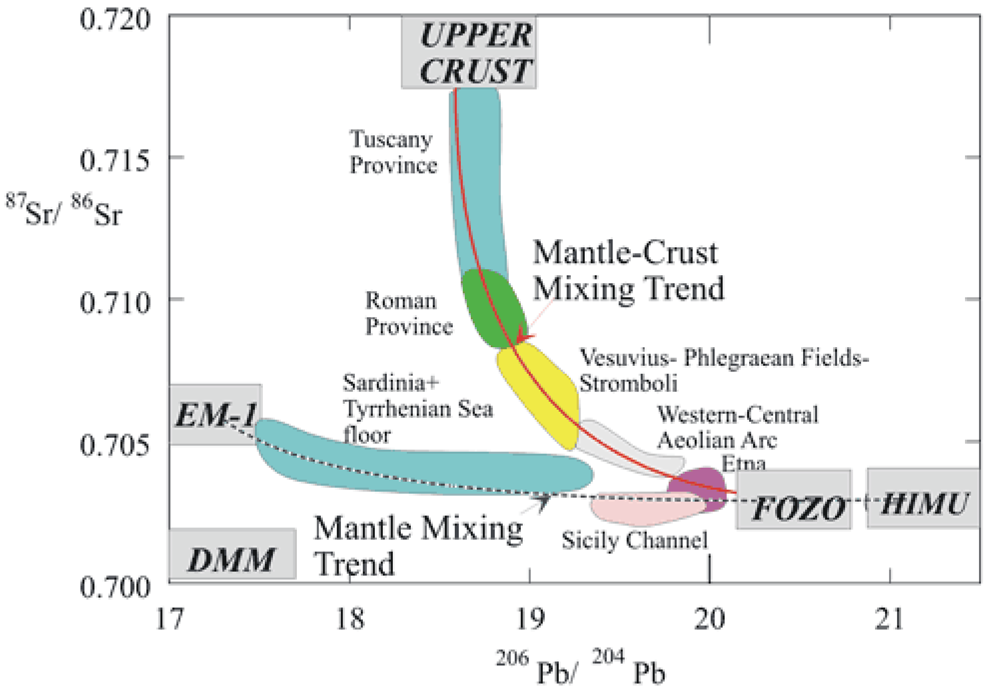

Figure 6: $^{87}Sr/^{86}Sr$ vs. $^{206}Pb/^{204}Pb$ variations of Plio-Quaternary Italian mafic rocks. Central Italy orogenic magmatism falls along a mantle-crust mixing trend involving HIMU-FOZO and Upper Crust. Sicily, Sicily Channel, Sardinia and some Tyrrhenian Sea seamounts (anorogenic magmatism) plot along a mantle-mantle mixing trend involving two or three end members (HIMU-FOZO, EM1, and DMM).

Petrogenesis

The variable petrological characteristics of Italian Plio-Quaternary magmatism call for a wide variety of mantle compositions and petrogenetic processes, including degrees and pressure of partial melting, mantle mineral compositions, and fluid pressure. The Na-alkaline rocks are believed to be generated in mantle sources similar to those of OIBs. Calcalkaline, shoshonitic and potassic rocks show many geochemical characteristics in common (*e.g.,* high LILE/HFSE ratios), although they display different enrichments in incompatible elements. These rocks are probably derived from anomalous mantle sources which were enriched in incompatible elements by the subduction processes. There is a debate about the age of mantle enrichment. It has been suggested to have occurred during the Tertiary evolution of the Alpine-Apennine chains (*Peccerillo*, 1999), or some 1-2 Ga ago (*e.g., Castorina et al.*, 2002). Establishing the age of mantle contamination has profound implications for understanding the geodynamic evolution of the Tyrrhenian Sea and surrounding areas (see *Peccerillo*, 1999, 2002 for discussion).

Geodynamic significance: Plume vs. shallow mantle processes

Much of the discussion on the geodynamic significance of Italian Plio-Quaternary magmatism has addressed the problem of whether it relates to subduction processes or it represents intraplate magmatism possibly connected with the emplacement of deep mantle plumes (*e.g.*, *Ayuso et al.*, 1997; *Peccerillo*, 1999, 2002, 2003; *Gasperini et al.*, 2002; *Bell*, 2002). Some authors suggest that only the Etna-Iblei-Ustica (*i.e.*, HIMU-FOZO) and Sardinia (*i.e.*, EM2) rocks derive from mantle plumes, whereas the rest of the magmatism represents mixtures of plume material and subducted upper crustal components (*Gasperini et al.*, 2002). Other authors suggest the more extreme hypothesis that all the magmatism reflects interaction among various plume-reservoirs (*Bell*, 2002).

Evidence invoked in favour of the plume hypothesis includes:

1. The ultrapotassic nature of a large portion of the magmatism, which is typical of settings such as East Africa, classically believed to have developed above mantle plumes,

2. The occurrence of carbonate-rich rocks in Central Italy, which have been suggested represent carbonatites, an alleged “pathfinder” of mantle plumes,

3. The smooth trends of Sr-Nd-Pb isotopes connecting discrete mantle reservoirs. FOZO, HIMU and EM1 are universally believed to represent plumes. ITEM displays very radiogenic Sr signatures, which has been suggested to require recycling and aging of subduction-contaminated mantle for at least 2 Ga (*Hawkesworth & Vollmer*, 1979; *Vollmer*, 1989),

4. The very similar radiogenic isotope compositions of some Italian rocks (e.g. Etna, Iblei) to other Na-alkaline rocks from central and western Europe, which would derive from a wide European Asthenospheric Reservoir (EAR) representing a plume head (*Wilson & Bianchini*, 1999).

Objections to these points are:

1. Italian ultrapotassic rocks have incompatible element distributions, which are totally different from East Africa. The latter show enrichment in Ta and Nb and depletion in Rb, Cs, Th and other LILE. In contrast, Italian potassic rocks show high enrichment in LILE and depletion in HFSE.

2. Carbonate rich rocks in Central Italy represent ultrapotassic volcanics that have experienced secondary addition of carbonate material from carbonate wall rocks. This is demonstrated by the high delta-^{18}O (around +20 to +25) of the carbonate material, amongst other things (see discussion in *Peccerillo*, 1998),

3. Points 3. and 4. above are the strongest arguments in favour of the plume hypothesis. However, the smooth trends of radiogenic isotopes may be generated by other processes than mantle plumes. For instance, the main trend connecting HIMU-FOZO to ITEM could be simply related to mantle contamination by upper crustal material brought into the upper mantle by subduction processes, which affected the Apennines during the Tertiary and are still active in the southern Tyrrhenian Sea. Moreover, the mantle xenoliths occurring in Italian and other European rocks have similar isotopic signatures to the host lavas (*Downes*, 2001), which suggests a lithospheric origin for the magmas.

Evidence in favour of shallow-mantle processes includes:

1. The strong regionality in the distribution of magma types and the relations between the geochemistry of the volcanic rocks and the mechanical characteristics of the lithosphere in the various areas.

2. The geochemical features of the ultrapotassic rocks, which resemble very closely the upper crust (*Peccerillo*, 1999) and require recently subducted crustal material rather than long periods of recycling into the mantle.

3. Na-alkaline rocks with HIMU-FOZO characteristics occur along normal or transcurrent lithospheric faults. In the plume hypothesis, this requires that plumes were emplaced just, and only along, these faults. This is an ad hoc explanation. A simpler hypothesis is to assume that magmatism is triggered by faulting and that the composition of magma erupted at the surface depends on the particular nature of the upper mantle in this zones: ***simplex sigillum veri*** !

A good example of fault-related volcanism is in the Etna-Aeolian arc zone, where a lithospheric fault (the Tindari-Letojanni fault) cuts both the Aeolian arc and its foreland, separating the actively subducting Ionian oceanic crust from Sicily (Figure 1). The active volcanoes of Etna, Vulcano and Lipari occur along this fault. However, while Etna is Na-alkaline and has a HIMU-FOZO signature, Lipari and Vulcano are calcalkaline to shoshonitic and have island-arc signatures.

Conclusions

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 province is continent-continent convergence in which the leading edge of the African plate is subducted beneath the Italian peninsula to generate heterogeneous mantle sources that then produce the wide variety of volcanic rocks observed (from calcalkaline to ultrapotassic) with subduction-related geochemical signatures (*Doglioni et al.*, 1999). The large amount of potassic rocks requires extensive and repeated episodes of mantle metasomatism (*Peccerillo*, 1999; 2002). Mantle end-members (HIMU, FOZO and EM1) could be plume-related, but they could also represent resident mantle material, which exhibits similar isotopic compositions all over Europe.

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