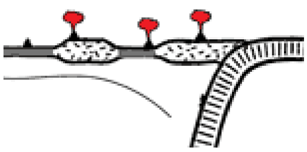
Mantle plume beneath Italy? No thanks



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Background

The idea that the complex magmatism occurring around the Tyrrhenian Sea results from a deep mantle plume dates back to 1970 (*e.g. Vollmer*, 1976). This theory was recently resurrected in a much revised form by *Gasperini et al.* (2002), who suggest that the entire compositional variation of Plio-Quaternary magmatism in Italy results from mixing a HIMU-like mantle plume and components of subduction origin.

In a joint paper by myself and Lustrino, shortly to appear in the forthcoming GSA book "*Plates, Plumes & Paradigms*", this subject is fully discussed (for aPDF download of our paper, click here). We accept the idea of mixing, as do a wealth of previous papers, but we consider the occurrence of a mantle plume beneath Italy unlikely, and at best unnecessary.

A recent paper by *Bell et al.* (2004) proposes a yet more extreme and simplistic variant of the plume hypothesis. These authors suggest that Tyrrhenian Sea magmatism is related (and it is not clear what this means. Does the magma come from the plume? Does the plume trigger magmatism in the asthenosphere and lithosphere?) to a large-scale asymmetric plume beneath the Mediterranean region. This plume has lain at a depth of 600 to 400 km for at least 30-35 Ma, but may have begun its activity as early as 60-70 Ma. Although remote from the lithosphere, this plume apparently has been able to open the western Mediterranean basins, to determine, by rift-push forces, the compressional forces responsible for formation of the Apennine-Maghrebian chain, and, of course, to generate (and it is not clear how) the magmatism that has occurred during the last 60-70 My. According to this hypothesis, the diversity of compositions encountered in Italian magmatism is due to heterogeneity in the plume resulting from entrainment of upper-mantle wall rocks during ascent. The implication is that all the magmatism comes from the plume and its surroundings, i.e. from a depth of more than 400 km.

This hypothesis, proposed by *Bell et al.* (2004), is based essentially on two Sr-Nd-Pb isotope diagrams. These show smooth trends which, as suggested in numerous previous papers (*e.g., D'Antonio et al.*, 1996; *Esperança and Crisci*, 1995; *Gasperini et al.*, 2002), indicate mixing among three distinct and discrete end-members. These are assumed to represent mantle plumes.

In my opinion, the plume hypothesis, in particular this present version, is a much worse explanation than subduction-related models for the bulk of Italian magmatism. The plume hypothesis stems from a very limited type of evidence (mainly Sr-Nd-Pb isotopes) and ignores many petrological and geochemical data which characterise the first-order features of the Italian magmatism.

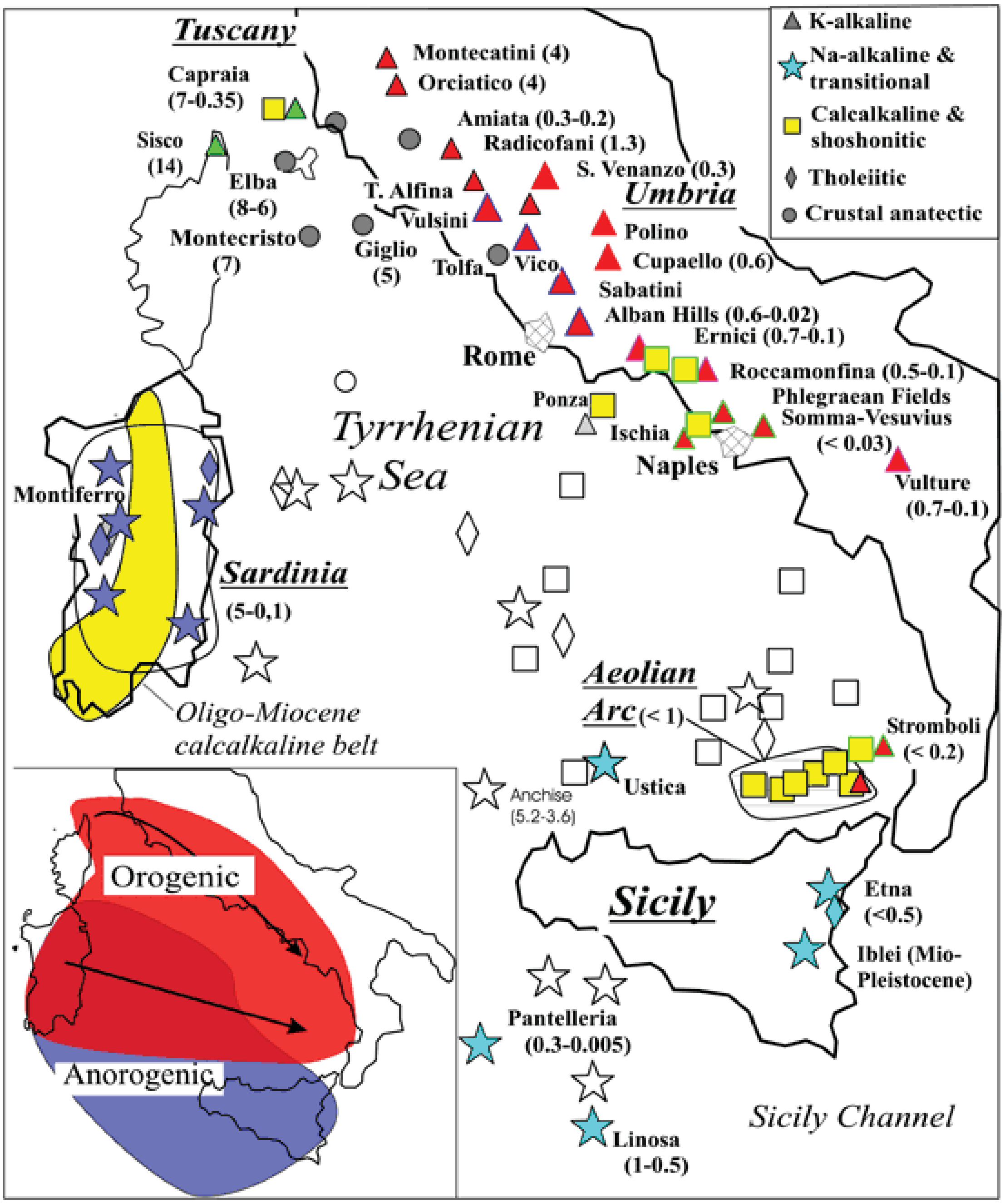

Figure 1. Schematic diagram showing the distribution of Plio-Quaternary magmatism in Italy. Inset: schematic distribution of orogenic (i.e. high LILE/HFSE ratios) and unorogenic (low LILE/HFSE ratios) volcanism. Arrows indicate age variation for orogenic magmatism.

The potassic-alkaline rocks represent the most important magma types in central Italy. They show a wide range of potassium enrichment and degree of silica saturation, from nearly saturated shoshonites and ultrapotassic lamproites to strongly undersaturated kamafugites and Roman-type leucite-bearing rocks (*Peccerillo*, 2002, 2003). In spite of this, all show obvious arc-type trace-element signatures with negative HFSE anomalies and high LILE/HFSE ratios. Some of the most mafic rocks from Tuscany (Mg# ~ 70-75; Ni ~ 200-300 ppm, Cr ~ 500-700 ppm) range from calc-alkaline to shoshonitic and ultrapotassic, but all have incompatible element patterns with negative HFSE anomalies. Interestingly, these rocks, although obviously of mantle origin, resemble very closely upper crustal material in both trace elements and radiogenic isotopes (*e.g.*, the Tuscany gneiss or the Dora Maira metagranites; Figure 2). It has been demonstrated that these rocks also resemble calc-alkaline-shoshonitic-ultrapotassic rocks from the Western Alps, although the latter are older (30 My; *Peccerillo*, 1999; *Peccerillo*, 2002).

In addition to rocks with arc-type geochemical signatures, another group of rocks shows intraplate compositional characteristics. These range from tholeiitic to Na-alkaline and nephelinitic, and have low LILE/HFSE ratios. These rocks are subordinate to arc-type rocks and are located either on the African plate (*e.g.*, at Iblei, Pantelleria and Etna) or in back-arc positions with respect to the Apennine compressional belt (*e.g.*, Tyrrhenian floor MORB- and OIB-like rocks, Sardinia Plio-Quaternary magmatism).

From an isotopic point of view, there is continuous variation in Sr-Nd-Pb isotopes from southern Italy to Tuscany and Sardinia. Rocks in the south (Etna, Iblei and the Sicily Channel) have compositions intermediate between DMM and HIMU. Rocks in Sardinia have compositions close to EM1. Finally, the magmatism in the Italian peninsula and the Aeolian arc shows intermediate characteristics between Etna and Tuscany-Western Alps composition. This has been highlighted by several people, including *Vollmer* (1976), *Hawkesworth & Vollmer* (1979), *Vollmer & Hawkesworth* (1980) and many others. In particular, *D'Antonio et al.* (1996) and *Gasperini et al.* (2002) published Pb vs. Sr and Nd isotopic diagrams similar to those shown in Figure 1 of the recent paper by *Bell et al.* (2004) in discussing the isotopic variability of Italian magmatism. As mentioned earlier, these authors pointed out that the isotopic signatures reflect the mixing of three end-members, as reiterated by *Bell et al.* (2004). *Gasperini et al.* (2000) suggest that only two of these end-members (HIMU-type and EM1) are of plume origin and the other is of subduction origin.

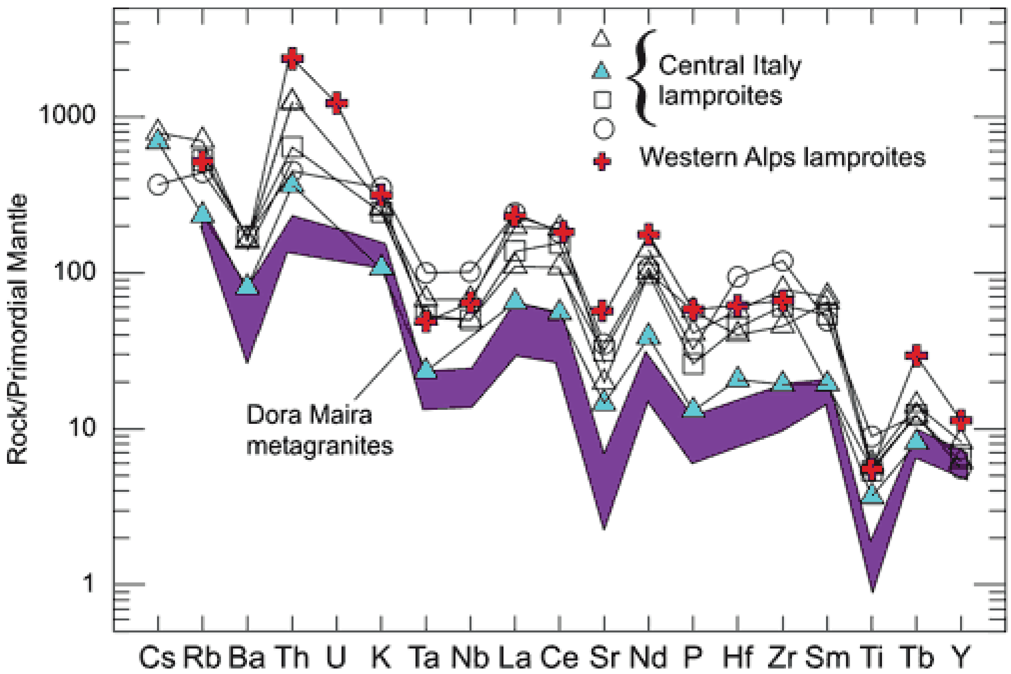

Figure 2. Incompatible element concentrations normalised to mantle composition for Tuscany mafic lamproites (Mg# > 75%; Ni > 200 ppm; Cr > 500 ppm), Western Alps lamproites and Dora Maira metagranites. Note the very similar distribution patterns of mantle-derived lamproites and upper crustal rocks such as Dora Maira metagranites. For source of data see Peccerillo (1999).

Subduction-related vs. plume-related hypotheses for Italian magmatism

It is unlikely that the complex magmatism in Italy is due to a single type of process and related to a single type of geodynamic setting ([*Peccerillo & Lustrino*, 2005]). The various mantle contamination and melt extraction events that occurred at different stages of the evolution of the area gave a very heterogeneous mantle. Basically, all the rocks displaying arc-type compositional signatures (*e.g.,* calc-alkaline to shoshonitic compositions, as well as potassic rocks from central Italy) are directly related to mantle sources modified by recent subduction processes during convergenece between Africa and Europe (*Doglioni et al.*, 1999). In contrast, rocks with intraplate compositions situated on the African plate or in back-arc positions are probably generated by melting mantle sources which have not been contaminated by recent subduction.

There are several variants of the subduction-related hypothesis for orogenic Italian magmatism. However, all these models agree that the arc-type Oligocene to Quaternary magmatism in the Tyrrhenian Sea area is genetically related to subduction of the Adriatic and Ionian plates beneath the southern European margin and by the eastward and south-eastward migration of the subduction zone (Figures 3 & 4). Such a hypothesis explains the occurrence of widespread subduction-type magmatism, its age variation from west to east, and the occurrence of extensional basins in the Western Mediterranean, due to back-arc opening (*e.g., Doglioni et al.*, 1997, 1999). The variable compositions of orogenic magmas (in both trace elements and radiogenic isotopes) are basically related to different types of subducted material being added to mantle sources. For example, the calc-alkaline volcanism of Sardinia (32 to 15 Ma) and of the southern Tyrrhenian Sea is interpreted as the consequence of subducting oceanic-type crust. In contrast, the volcanism in central Italy is related to subduction of a continental-type Adriatic plate. The crust-like trace element patterns and radiogenic isotope compositions of magmas from central Italy obviously suggest the addition of crustal material to the mantle, a process which can be accomplished easily by subduction processes. The possibility that continental crust can be subducted to great depths (more than 100-120 km) within the upper mantle is demonstrated by very high pressure metamorphism of rocks in some orogenic areas, *e.g.*, the Dora Maira Massif of Western Alps.

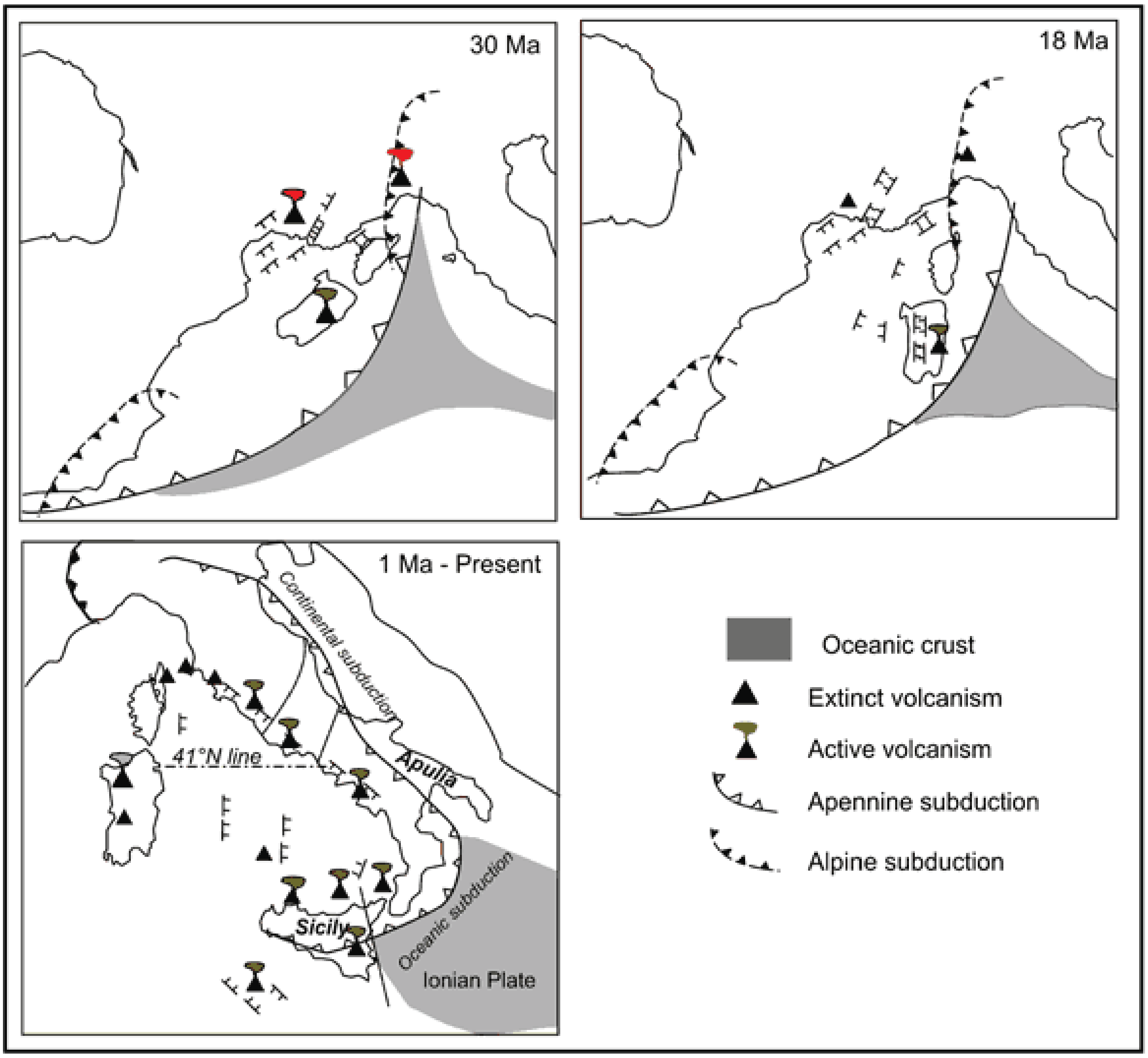

Figure 3. Schematic model of the evolution of the Western Mediterranean and the Tyrrhenian Sea from Oligocene to Present. Simplified after Carminati et al. (1998) and Cavazza & Wezel (2003).

Subduction-related hypotheses also provide a satisfactory explanation for:

1. Deep seismicity beneath the eastern Aeolian arc, which defines a steep Benioff zone

extending to a depth of about 500 km up to the Vesuvius area; this is generated by subduction of the Ionian plate.

2. The occurrence of a vertical rigid body cutting the asthenosphere beneath the Apennine chain, interpreted as a remnant of a young subduction zone (*Panza et al.*, 2003);

3. The occurrence of a belt of cold mantle around the Apennine-Maghrebian chain revealed by tomographic studies, which suggests recent introduction of cold material into the upper mantle (Wortel & Spakman 2000; Piromalli & Morelli 2003).

All the above features are ignored by the plume-related hypotheses proposed by *Bell et al.* (2004). Calc-alkaline rocks are mentioned only once or twice throughout the paper. It is ignored that the potassic and ultrapotassic rocks of central Italy also have arc-type geochemical characteristics and some of the northern occurrences have incompatible element patterns and radiogenic isotope signatures which resemble closely the upper crust. This holds also for kamafugites and for the so-called carbonatites . Therefore, all this magmatism is geochemically and isotopically different from the equivalent rocks from intracontinental rifts, as discussed by now in hundreds of papers. If a deep plume is the explanation (the source?) for Italian magmatism, why do the majority of volcanic rocks have arc signatures and why do the ultrapotassic rocks have crust-like geochemical and isotopic compositions? What processes imparts on deep plume material a geochemical and isotopic composition identical to upper crustal rocks? If the observed magmas represent old crust recycled through the deep mantle and then sampled by a plume, is it credible that the geochemical characteristics of upper crustal material have been preserved throughout such a long journey through the Earth without appreciable element fractionation? Additional objections to the plume hypothesis include the implausibility that such a body, stalled at 600-400 km depths for tens of million years, could generate lithospheric extension of several hundreds of km (some 600 km west-east, along with north-south Europe-Africa covergence of about 120 km), the absence of large-volume LIP-type magmatism, and the presence of a rigid instead of a soft layer at about 400 km, to mention but a few.

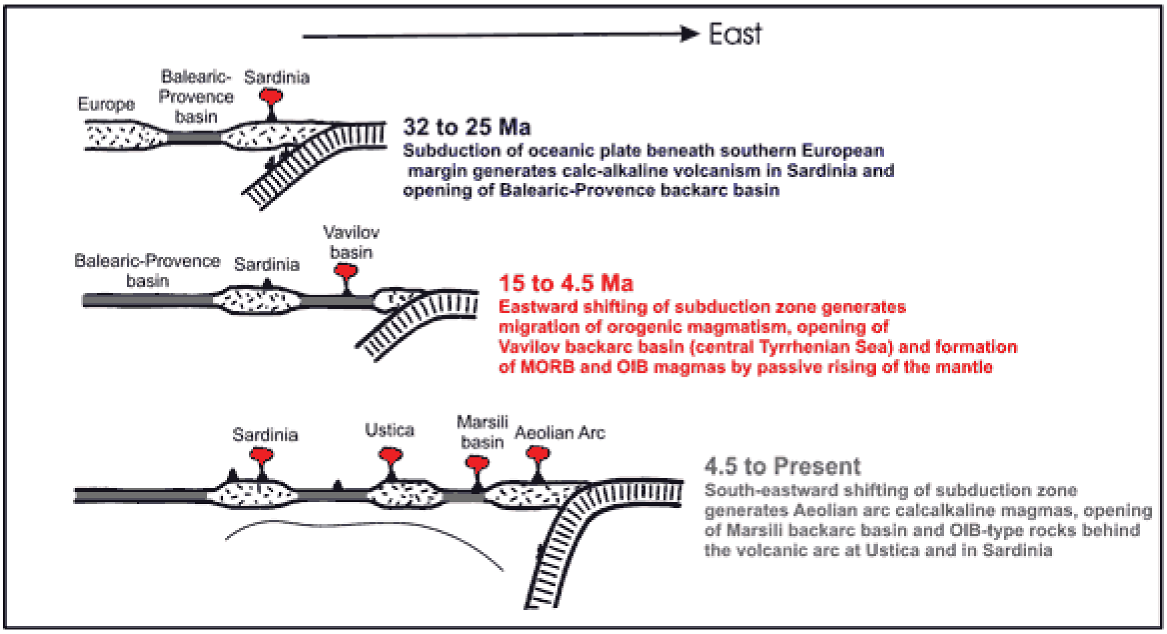

Fig. 4. Section across the Tyrrhenian Sea showing eastward and south-eastward migration of the subduction zone and orogenic magmatism, along with dyachronous opening of backarc basins.
Click here for enlargement.

In conclusion, although subduction-related hypotheses, as with any other scientific hypothesis, still present unanswered questions, they do explain several primary compositional features and the age and distribution of orogenic magmatism in Italy. They also explain the occurrence of rocks with anorogenic signatures, which would be formed during passive upwelling in the lithosphere-asthenosphere in the extensional zones (*e.g.*, along strike-slip faults and in back-arc areas) between the converging European and African plates.

So, why a plume?

The main argument presented by *Bell et al.* (2004) in favour of a mantle plume origin for Italian magmatism is the large and continuous Sr-Nd-Pb isotope variation in Italian rocks. They suggest that these isotopes form smooth trends requiring mixing between three distinct and discrete end-members: FOZO, EM1 and a third end-member which they call ITEM (Italian Enriched Mantle). The FOZO composition (first invoked by *Hoernle et al.*, 1996 but rejected by *Gasperini et al.*, 2002) is represented by Sicilian rocks (Etna, Iblei and Pantelleria); the EM1 composition is represented by Sardinian Plio-Quaternary rocks (*Gasperini et al.*, 2000; *Lustrino et al.*, 2000). The ITEM end member closely resembles the upper crust, as has been repeatedly mentioned in recent years (*Peccerillo*, 1999, 2002, 2003). The only new point is the acronym.

The objection that isotopic compositions do not necessarily indicate mantle plumes has been discussed widely (see several papers in the forthcoming GSA book "*Plates, Plumes & Paradigms*") and will not be reiterated here. I emphasise that the interpretation of a complex province such as the Italian magmatic province cannot be understood by studing only two diagrams. Any petrogenetic hypothesis must be able to explain all the petrological data, something that the plume hypothesis cannot do.

Isotopic variation in mafic Italian volcanics is not smooth if looked in detail. In Figure 5 I use my own database of mafic rocks to enlarge parts of the Sr-Nd-Pb isotope diagrams. It is clear that there are many possible trends which I have indicated by arrows. Whatever their significance, these multiple trends do not support a model of simple mixing between three end-members. Rather they concur with trace element data in indicating multiple mantle contamination events (see *Peccerillo*, 1999).

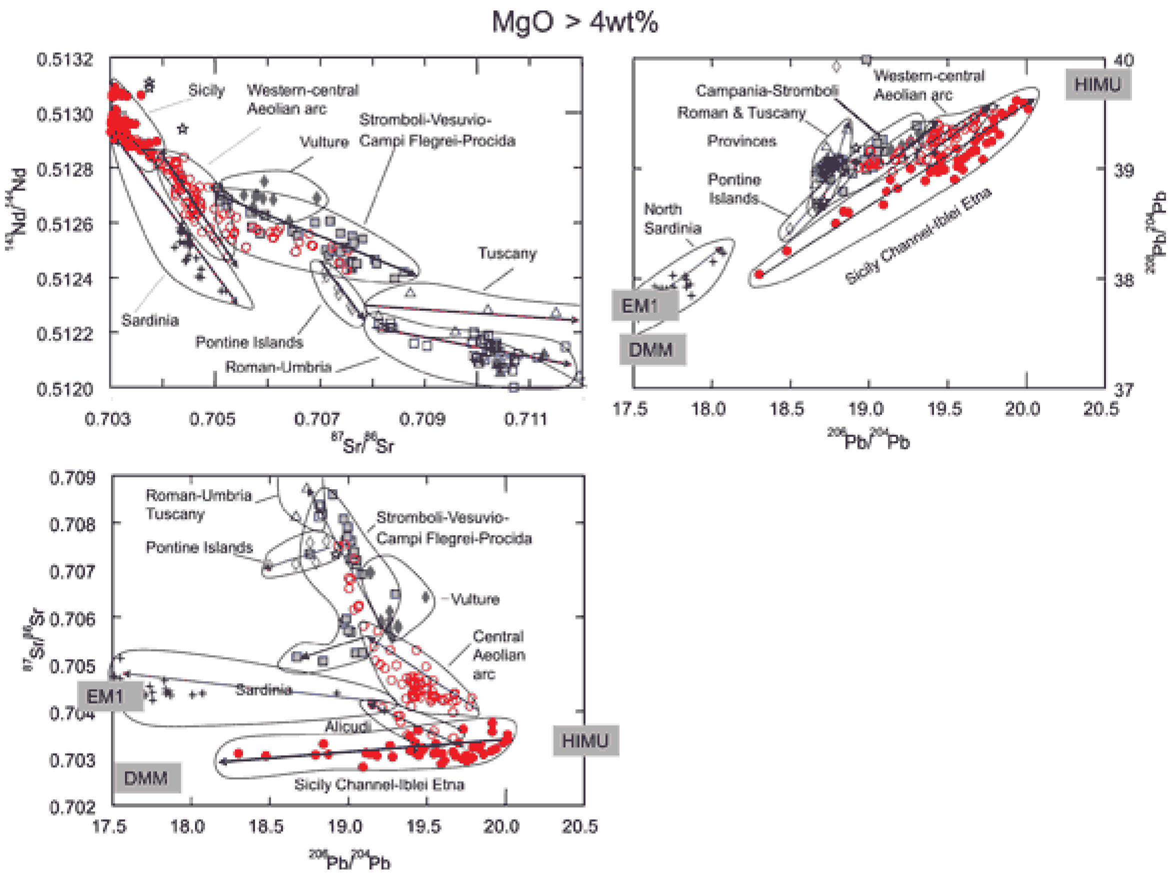

Figure 5. Detailed Sr-Nd-Pb isotope diagrams for Plio-Quaternary Italian mafic volcanics. Click here for enlargment.

Conclusions

The plume hypothesis is inadequate to explain the compositional complexities of Italian magmatism. There is much more supporting evidence for a model involving subduction than for a plume. The plume hypothesis is based on limited use of a few radiogenic isotopes. As *Bell et al.* (2004) recognise, isotopic data reflect sources rather than processes. In spite of this, they apply these data to build a global geodynamic and petrogenetic hypothesis for a very complex area.

The hypothesis of *Bell et al.* (2004) is a new variant of an old idea dating from the early 1970s. New ideas (or even new variants) are always welcome, but the plume model for Italy is not new. Furthermore, new ideas are not necessarily better simply because are new. An important prerequisite of a good new hypothesis is that it must explain more data better than older hypotheses. This is not the case for the variants of the plume hypothesis proposed by *Bell et al.* (2004).

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For additonal references and data on Italian Plio-Quaternary magmatism see: http://www.unipg.it/~pecceang

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