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Plume activity, magmatism, and the geodynamic evolution of the Central Mediterranean

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On the basis of isotopic and geochemical data we propose that most of the volcanic activity in Italy is plume rather than subduction related. We suggest that a large plume underlies the Tyrrhenian Sea, extending westwards under Sardinia and Corsica, northwards towards the Western Alps and eastwards under the Italian mainland. The plume is isotopically defined in terms of three end-members, different from any of those found in subduction-related environments. Two of the end-members are similar to the FOZO and EM1 mantle components defined on the basis of data from OIBs, while a third, here called ITEM (ITalian Enriched Mantle), is characterized by a high $^{87}Sr/^{86}Sr$ ratio (>0.7200) and quite different from any component found in oceanic environments. The two trends that emerge in isotope ratio diagrams indicate mixing between a common end-member (FOZO) and the two others. Implied by the presence of a common end-member is the involvement of a common source and a single large-scale geodynamic system. Partial melting of an isotopically heterogeneous plume head containing both source and entrained material is one way to explain many of the features that characterize Italian magmatism. Widespread extensional tectonics, lithospheric thinning, and deep-seated CO_2 emissions add further support to mantle plume activity in Italy.

4.1. INTRODUCTION

Almost all of the volcanism in the Central Mediterranean area has been attributed to subduction-related magmatism (for review see Dercourt *et al.*, 1986; Lustrino, 2000). This is not surprising, given the closing of the Tethys Ocean and the interaction between the Eurasian, African, and Adriatic plates from 120 Ma to about 30 Ma. However, the nature of post-collisional magmatism, especially during the last 30 Ma, still presents problems, especially the sparcity of calc-alkaline rocks and eroded arc remnants along the length of mainland Italy and in the Alps and North Africa. Although many of the Cenozoic rocks, including those along peninsular Italy, as well as the Aeolian Islands, and Sicily are considered to be subduction-related, on closer inspection their chemistry seems to be more closely related to within plate magmatism, especially those centres of kamafugitic and carbonatitic affinity. Supposed shoshonites (intermediate potassic basalts with no modal leucite) have been described from some of the Aeolian Islands (see Hornig-Kjarsgaard *et al.*, 1993), as well as andesites from the Eastern and Western Alps, but few of the rock types seen in Italy characterize present-day, destructive plate-margins (see discussion in Lavecchia and Stoppa, 1996).

Although subduction is the prevailing model for Italian magmatism (*e.g.*, Serri, 1997; Lustrino, 2000), agreement has yet to be reached about the geodynamic evolution of the Mediterranean Basin, and the roles that subduction, continent-continent collisions, and ocean basin formation have played in controlling igneous activity in Italy. Another aspect is the affect that subduction has had on the chemical composition of mantle. In this paper we take a critical look at the evidence for subduction-related magmatism, and formulate a model quite different from any of the others that has been proposed before. As an alternative to subduction, we propose that most of the igneous activity in Italy is related to large-scale, plume activity.

4.2. MAGMATIC ACTIVITY IN ITALY

Volcanic activity in Italy is among the most diverse and complex seen on Earth. Rocks are extreme in composition and include kamafugites, carbonatites, lamproites and lamprophyres, as well as melilitites. In spite of this diversity, igneous rocks in Italy have been grouped into several genetically-distinct magmatic provinces among which are included the classic, ultrapotassic Roman Province of Washington (1906), the Campanian Province, the Aeolian Islands, and the Na-alkaline provinces of Sicily and Sardinia. Several of the volcanoes are presently active, including Etna, Vulcano and

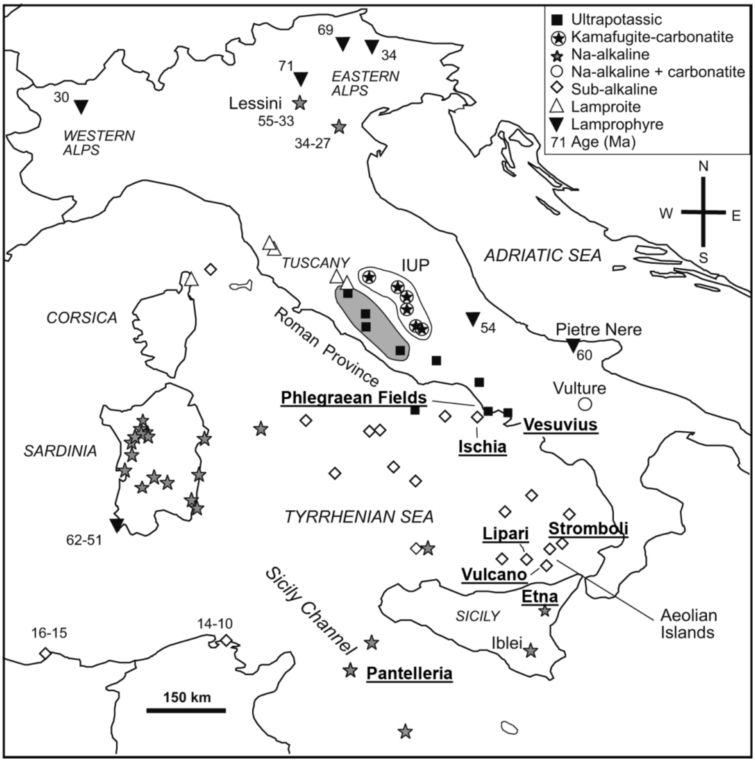

Fig. 4.1. Distribution of igneous activity in Italy. Names of active volcanoes (erupted in the last 10,000 years) are bold and underlined. Ages shown only for activity >10 Ma. IUP = Intra-montane Ultra-alkaline province.

Stromboli. The regional distribution of these rocks is shown in fig. 4.1. In spite of their diverse nature, the rocks define two chemical trends, one a silica-undersaturated trend characterized by leucitites, kamafugites and carbonatites and a second that is more silica-saturated, consisting mainly of leucite-free, mafic rocks including lamproites, and rocks of supposed calc-alkaline affinity. Many of these rocks, especially those rich in volatiles and K_2O, with high Mg#s, require compositionally-distinct and unusual mantle sources, perhaps the result of either upwelling mantle fluids (*e.g.*, Cundari, 1979) or subduction-related metasomatism (*e.g.*, Peccerillo, 1999; Conticelli *et al.*, 2002).

4.3. GEODYNAMIC MODELS

In most of the subduction-related models, the Tyrrhenian Sea forms a back-arc basin lying above a northwest-dipping subduction zone, which migrated throughout the Cenozoic to the southeast (Faccenna *et al.*, 2003, among others). Its present-day position is supposedly marked by the Calabrian Arc, and evidence cited in its favour includes the calc-alkaline magmatism seen in the Aeolian Islands (*e.g.*, Barberi *et al.*, 1973), tomographic imaging of an almost continuous high velocity body, and deep seismicity (*e.g.*, Selvaggi and Chiarabba, 1995). Magmatic activity has also been related to back-arc extension, the result of slab roll-back and detachment of the northwest subducting African Plate and subsequent asthenospheric upwelling (von Blanckenburg and Davies, 1995; Carminati *et al.*, 1998; Civetta *et al.*, 1998; Wortel *et al.*, 2003). Other models have combined mantle upwelling and subduction. Gasperini *et al.* (2002), for example, propose asthenospheric migration through a plate window, the result of rifting brought about by interaction between two plates, one fossil under Tuscany and the other active under Sicily.

Of the remaining models proposed for magmatic activity in Italy, none involve subduction. Ultrapotassic and associated magmatism were linked by Vollmer (1976, 1990) to a small plume (50-100 km in size), initially centered near Pietre Nere. During the counterclockwise rotation of Italy, the fixed plume generated volcanic activity along the length of the peninsula producing many of the volcanic fields. Passive rifting accompanied by mantle upwelling was proposed by Lavecchia and Stoppa (1996), while Hoernle *et al.* (1995) invoked melting of a thin, westerly-dipping sheet of volatile-rich mantle, which he considered the source of extensive magmatism throughout the Eastern Atlantic, Northern Africa, Central Europe and the Western Mediterranean. A model, based mainly on isotopic data, attributed most post-Oligocene volcanism to plume activity (Bell *et al.*, 2003). This model is discussed in detail below.

4.4. ISOTOPIC DATA

4.4.1. Compilation of Italian isotopic data

On the basis of isotopic data, a taxonomy that has been established for oceanic basalts (*e.g.*, Zindler and Hart, 1986; Hart, 1988; Hoffman, 1997). Several end-member components have been recognized, each characterized by distinctive Pb, Sr and Nd isotopic compositions (see table 4.I for summary). One, DMM (depleted MORB mantle), reflects a depleted mantle that is the source for normal mid-ocean ridge basalts and is characterized by high $^{143}Nd/^{144}Nd$ and low $^{87}Sr/^{86}Sr$. Three others (HIMU, EM1 and EM2) are based on data from oceanic islands. HIMU has a high U/Pb time-integrated ratio, and EM1 and EM2 are both enriched mantle components. Another end-member is FOZO (FOcus ZOne) defined by the point of convergence of linear arrays from known island groupings in three-dimensional isotope ratio diagrams involving EM1, EM2, HIMU and DMM. This rarely-seen, end-member is considered to be relatively deep-seated and common to all OIBs. Although the origin of FOZO is still the subject of active debate, it is generally considered to be globally wide-

Table 4.I. Mantle components referred to in the text.

DMM: Source with low Rb/Sr and U/Pb and high Sm/Nd time-integrated ratios.
EM1: Enriched Mantle 1. High Rb/Sr with low U/Pb and Sm/Nd ratios.
EM2: Enriched Mantle 2. High Rb/Sr (>EM1) and relatively high U/Pb ratios with a low Sm/Nd ratio.
HIMU: HIgh MU (μ=^{238}U/^{204}Pb) mantle source. Characterized by a high U/Pb ratio.
FOZO: FOcus ZOne. Focus of linear isotopic arrays from various OIBs. Supposedly a deep-seated, widespread, source region.
ITEM: ITalian Enriched Mantle. Source characterized by a high Rb/Sr ratio.

For further details see Zindler and Hart (1986); Hart (1988); Hart *et al.* (1992); Hauri *et al.* (1994); Hofmann (1997).

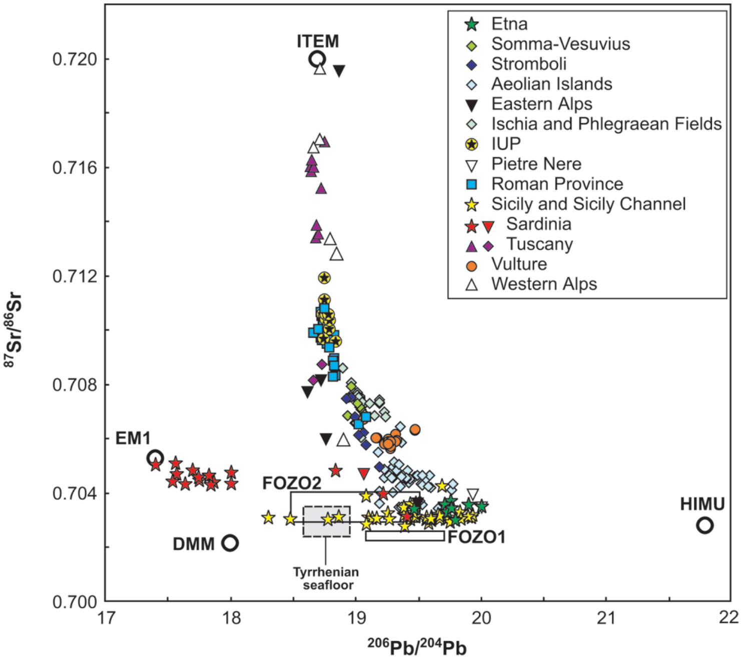

Fig. 4.2. ^{87}Sr/^{86}Sr *versus* ^{206}Pb/^{204}Pb ratios of volcanic rocks from Italy. No geochemical filtering has been used. Note the positions of HIMU, EM1 and DMM. All are based on end-member compositions and as a result are represented by distinct fields. The only end-member component from oceanic basalts that bears any similarity to the common end-member in the mixing arrays is FOZO. We show two boxes in this figure encompassing values for FOZO1 (Hart *et al.*, 1992) and FOZO2 (Hauri *et al.*, 1994). Unpublished data of Bell (Eastern and Western Alps, Etna, Oricola, Sardinia, Vulture) and Castorina (Eastern Alps, Sardinia, Vulture) are also used. Symbols can be tied into rock types given in the legend in fig. 4.1. Diversions of ^{87}Sr/^{86}Sr ratios from the main mixing trends may result from contamination during magma emplacement.

spread, and perhaps more primitive than any of the other mantle components (*e.g.*, Hart *et al.*, 1992; Hauri *et al.*, 1994).

It has been known for some time that a pronounced isotopic polarity extends along the length of Italy (northerly increase in ^{87}Sr/^{86}Sr, δ^{18}O and δ^{13}C values, southerly increase in ^{143}Nd/^{144}Nd, ^{3}He/^{4}He, and $^{206}Pb/^{204}Pb$ ratios) and this has been interpreted as possible mixing between two end-members, one depleted and the other enriched (Vollmer, 1976; Vollmer and Hawkesworth, 1980; Tedesco, 1997; Castorina *et al.*, 2000).

In figs. 4.2 and 4.3 we have compiled all of the published isotopic data from Italian igneous rocks (the references for these can be obtained from any of the authors) and have included many unpublished analyses from our own data base. Some of the new data are given in table 4.II. The isotopic patterns shown in both figures require at least three isotopic end-members. Of these, two are similar to known mantle components, while the third reflects a component much more enriched than anything so far known from oceanic basalts. If we compare the end-members to mantle components based on the isotopic data from OIBs, one is similar to EM1, and was recognized by Lustrino *et al.* (2000) and Gasperini *et al.* (2000) in lavas from Sardinia. This EM1-like component was attributed by Gasperini *et al.* (2000) to the melting of recycled plume heads stored within the deep mantle.

An alternative way of viewing the data is to relate them to the mantle plane described by the model end-members HIMU, EM1 and DMM in three-dimensional space. Zindler *et al.* (1982) showed that the plane could be depicted as a straight line by combining $^{143}Nd/^{144}Nd$ and $^{206}Pb/^{204}Pb$ values into a term plotted against $^{87}Sr/^{86}Sr$. Such an approach is a useful way to assess the possible role that these three mantle end-members may have had in producing the isotope data reflected in the Italian rocks. The distribution of the data points in fig. 4.4 support the involvement of two of the end-mem-

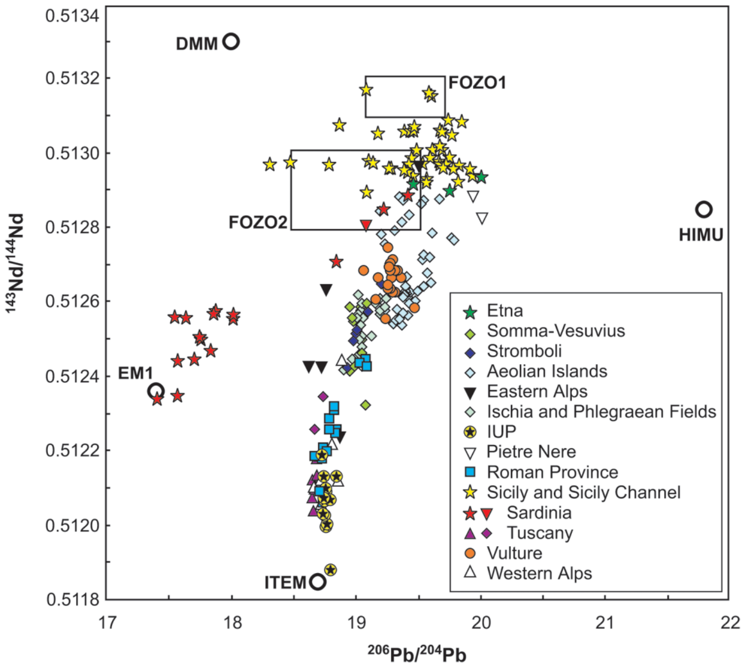

Fig. 4.3. $^{143}Nd/^{144}Nd$ *versus* $^{206}Pb/^{204}Pb$ ratios of volcanic rocks from Italy. None of the data have been filtered. Note the convergence of data towards a FOZO-like end-member. Also included are unpublished data of Bell and Castorina. References for the data shown in this figure can be obtained from the authors. Our best estimate for the common end-member based on the data shown in figs. 4.2 and 4.3 is: $^{87}Sr/^{86}Sr = 0.70250$, $^{143}Nd/^{144}Nd = 0.51320$ ($\varepsilon = +1.1$) and $^{206}Pb/^{204}Pb = 20.00$.

Table 4.II. Isotopic data.

		$^{87}Sr/^{86}Sr$	$^{143}Nd/^{144}Nd$	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$
Sardinia						
Giave	Analcite basalt lava	0.70508	0.51234	17.397	15.560	37.706
Pozzomaggiore	Analcite basalt lava	0.70446	0.51256	17.540	15.567	37.718
Dorgali	Analcite basalt lava	0.70478	0.51256	18.011	15.601	38.299
Colle Fabri						
CF-13	Leucite wollastonite melilitolite plug	0.70970	0.51207	18.747	15.660	38.747
CF-18	Leucite wollastonite melilitolite plug	0.71063	0.51219	18.868	15.683	38.946
Cuppaello						
COP-4	Melilite kalsilitite lava	0.71112	0.51210	18.750	15.676	38.963
COP-8	Melilite kalsilitite lava	0.71193	0.51200	18.755	15.680	38.972
Etna						
ET01	Alkali basalt lava	0.70326	0.51292	19.467	15.646	39.114
ET02	Alkali basalt lava	0.70350	0.51294	20.011	15.626	39.543
Oricola						
OR1	Calciocarbonatite tuff	0.71071	0.51220	18.745	15.681	38.996
OR1b	Calciocarbonatite lapillus	0.71077	0.51214	18.744	15.680	38.995
Polino						
IT 120	Calciocarbonatite tuffisite	0.71039	0.51207	18.774	15.690	39.003
IT 121	Massive calciocarbonatite	0.71043	0.51206	18.767	15.679	38.978
San Venanzo						
VEN-5	Kalsilite leucite olivine melilitite lava	0.71056	0.51207	18.742	15.662	38.929
VEN-10	Kalsilite leucite olivine melilitite lava	0.71056	0.51207	18.747	15.667	38.952
Stromboli	Olivine basalt pumice	0.70616	0.51262	19.083	15.683	39.123
Vulture						
VUT-69	Leucite melilitolite dyke	0.70633	0.51261	19.457	15.711	39.509
VUT-106	Phonolitic foidite lava	0.70579	0.51263	19.296	15.690	39.301
VUT-255	Melanite phonolite pumice	0.70600	0.51261	19.162	15.673	39.119
VUT-1523	Melilite-bearing foidite lava	0.70572	0.51271	19.280	15.680	39.253

The Nd and Sr values from Colle Fabri, Cuppaello and San Venanzo are from Castorina *et al.* (2000). The reader is referred to Bell and Simonetti (1996) and Castorina *et al.* (2000) for analytical details.

bers based on OIBs. The third end-member is much more radiogenic than anything that has so far been found in oceanic basalts, and lies well above the mantle plane.

The best match we can make of the common end-member shown in fig. 4.2 to any of the mantle components that are known so far is with FOZO. Attempts to constrain a common component in ocean basalts have shown considerable differences both within and between the various estimates, *e.g.,* FOZO1 (Hart *et al.*, 1992), FOZO2 (Hauri *et al.*, 1994), PHEM (Farley *et al.*, 1992), and «C»

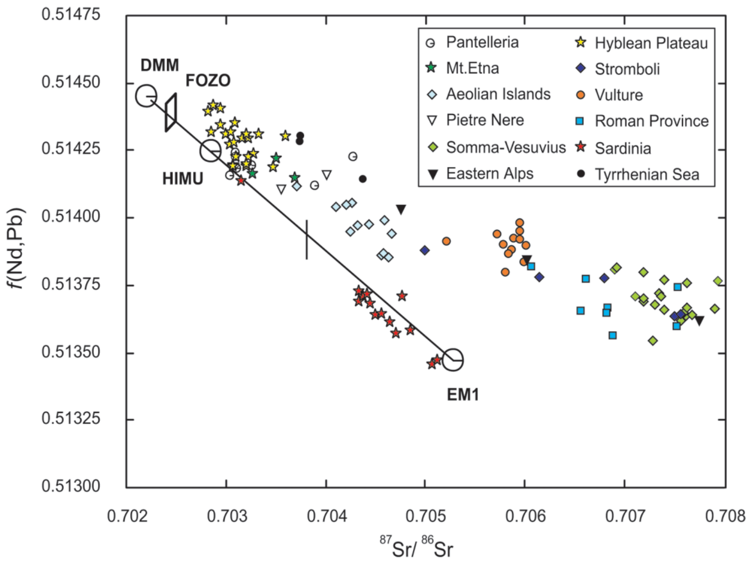

Fig. 4.4. End on view of model mantle plane as defined by HIMU, EM1 and DMM. The equation for the mantle plane as given by Tilton *et al.* (1998) is: $-0.42881(^{87}\mathrm{Sr}/^{86}\mathrm{Sr})-1.358437(^{143}\mathrm{Nd}/^{144}\mathrm{Nd})-8.75115\times10^{-5}(^{206}\mathrm{Pb}/^{204}\mathrm{Pb})+1=0$. $f(\mathrm{Nd,Pb})$ (after Zindler *et al.*, 1982)$=[(^{143}\mathrm{Nd}/^{144}\mathrm{Nd})^2+(^{206}\mathrm{Pb}/^{204}\mathrm{Pb})^2]^{1/2}\times\{\sin[\arctan[(^{143}\mathrm{Nd}/^{144}\mathrm{Nd})/(^{206}\mathrm{Pb}/^{204}\mathrm{Pb})]+0.000064]\}$. Error bar shown by the vertical line. Note the convergence of data towards FOZO, and the Sardinian data that all lie close to the mantle plane. Only data are plotted with $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}$ ratios <0.708.

(Hanan and Graham, 1996). Both FOZO1 and FOZO2 are based on different estimates of the point of convergence of the isotopic data. The FOZO-like component in Italy is best seen in data from the active volcanoes of Pantelleria, the more sodic parts of Etna, as well as the much older centre of Pietre Nere. It is interesting to note that Gasperini *et al.* (2002) chose not to accept FOZO as one of their two end-members but instead considered it to be a mixture of DMM and HIMU, neither of which has been found as pure end-members in any of the Italian lavas.

We have proposed the name «ITEM» (ITalian Enriched Mantle) for the third component, best represented by data from the leucitites of the Roman Region, the kamafugites-carbonatites of Central Italy and the lamprophyres and lamproites from Tuscany and the Eastern and Western Alps. Although the isotopic signature of ITEM has yet to be finalized, the present best estimate for ITEM based on our own data and those of J. Owen (personal communication) is $^{87}\mathrm{Sr}/^{86}\mathrm{Sr}=0.7200$, $^{143}\mathrm{Nd}/^{144}\mathrm{Nd}=0.5118$ and $^{206}\mathrm{Pb}/^{204}\mathrm{Pb}=18.70$. With such enriched signatures, ITEM has to be an ancient reservoir, similar to continental crust or metasomatized mantle lithosphere, probably >2 Ga old, with moderately high U/Pb and Th/Pb, very high Rb/Sr, and low Sm/Nd time-integrated ratios.

The crustal-like ITEM signatures for many of the lamproites/lamprophyres, melilitites and carbonatites from Italy have previously been attributed to enrichment processes brought about by continental crust-mantle interaction, either by partial melts or fluids generated from sediments or by direct involvement at crustal levels. Because many of the mafic magmas are primary, based on their high Ni, Cr and high Mg#s (see Lavecchia and Stoppa, 1996; and references therein), the latter model can be ruled out. In addition, interaction with crust would probably result in melts with much higher SiO_2 contents.

It is also difficult to match the highly enriched signature with basement rocks in Italy. Although D'Antonio *et al.* (1996) noted that the Sr and Nd isotope ratios of alkaline lavas from Central and

Southern Italy are similar to those found in rocks from the Calabrian basement, the Pb isotope ratios are much too low for a given Sr ratio and instead D'Antonio *et al.* (1996) attributed the crustal-like signature to the involvement of sediments associated with a sunken lithospheric slab subducted during the Eurasian-African collision.

ITEM is much more enriched in radiogenic Pb than estimates of subducted sediment *e.g.,* «erosion mix» (Kramers and Tolstikhin, 1997), but is similar to some estimates for modern marine pelagic sediments (Holm and Munksgaard, 1982; Taylor *et al.*, 1984; Ben Othman *et al.*, 1989; Cousens, 1994), and is supported by the Hf and Nd relationships and low Hf/Nd ratios of rocks from Tuscany and the Roman Province (see discussion in Gasperini *et al.*, 2002). Another model, yet to be applied to Italy, involves long-term storage of a highly enriched part of the mantle that has been isolated from convection since the Archean (McKenzie, 1989). Even within ocean basins, a component considerably more enriched than EM2, (the most enriched of the mantle components), has been identified in hotspot-related metasomatism brought about by carbonatitic melts (Hauri *et al.*, 1993). It is interesting to note that carbonatitic material is widespread among many of the eruption products (Stoppa and Woolley, 1997) and in the mantle sources of ultrapotassic rocks from Italy (Panina *et al.*, 2003; Solovova *et al.*, 2005).

What emerges from figs. 4.2 and 4.3 are two, binary mixing curves, one between the two end-members ITEM and FOZO, and the other between an EM1-like component and FOZO. The most significant feature to be seen from the isotopic patterns in figs. 4.2 and 4.3 is that both data sets converge towards the FOZO-like component. This end-member is not too different from that proposed for the LVA (low velocity anomaly) by Hoernle *et al.* (1995) based on convergence of isotopic data from the Eastern Atlantic Ocean region, the Eastern Atlantic continental margin, Central Europe and the Western Mediterranean. Worth emphasising, too, is the minimal role that DMM (depleted MORB mantle) has played in supplying melt material. This is particularly well indicated by the data shown in the plot of ^{143}Nd/^{144}Nd *versus* ^{206}Pb/^{204}Pb in fig. 4.3. The absence of any mixing between ITEM and the EM1-like end-members probably reflects the spatial distribution of the two end-members.

4.4.2. Isotopic evidence vis-à-vis active subduction

There is little in the data shown in figs. 4.2, 4.3 and 4.4 that can be used as evidence for recent, subduction-related magmatism. None of the three isotopic end-members are found in active, subduction zones. Although ITEM has an isotopic composition close to that of average sediments, it does not seem to characterize present-day, arc-related volcanicity. In addition, the spatial and temporal distribution of ITEM do not seem to fall into any trend that could potentially mark the site of either a fossil or active subduction zone. There are other considerations too. Samples from the Aeolian Islands, long considered to be arc-related, lie closer in figs. 4.2 and 4.3 to FOZO than any of the other end-members. The same characteristic is shared from other samples from the Sicily Channel Rift (Iblei, Pantelleria) as well as samples from Etna and the Tyrrhenian ocean-floor basalts. ITEM signatures are also shown by lamprophyres, lamproites and rocks of the kamafugite-carbonatite association which are rarely, if ever, associated with consuming plate margins. It is interesting that the data from Vulture lie, as well as the data from the Aeolian Islands, along the FOZO-ITEM mixing line, yet no one has considered this volcanic centre to be subduction-related on the basis of its structural setting.

Given that FOZO is based on isotopic findings from OIBs, and is considered an important component in all oceanic basalts, and ITEM does not seem to characterize present subduction-related environments, it seems unlikely that the isotopic data are consistent with any model that invokes melting of a recently-metasomatized mantle wedge. Even the sodic-rich basalts from Sardinia, involving mixtures of FOZO and EM1-like end-members appear to be inconsistent with arc-related volcanicity.

The spatial distribution of the isotopic data is interesting. Using both published and unpublished data we have been able to generate contours based on the ^{87}Sr/^{86}Sr, ^{143}Nd/^{144}Nd and ^{206}Pb/^{204}Pb ratios. Contours are shown in figs. 4.5a-d. Instead of using the raw isotope ratios, we have used values that represent the difference between the measured isotope ratios and an arbitrary reference value. This removes any problem in interpreting the isotopic ratios, especially for those not familiar with isotope geochemistry, and makes the data much easier to follow. Only data from the more primitive rock types have been used. Although the data base is limited and hence the geometry of the contours could

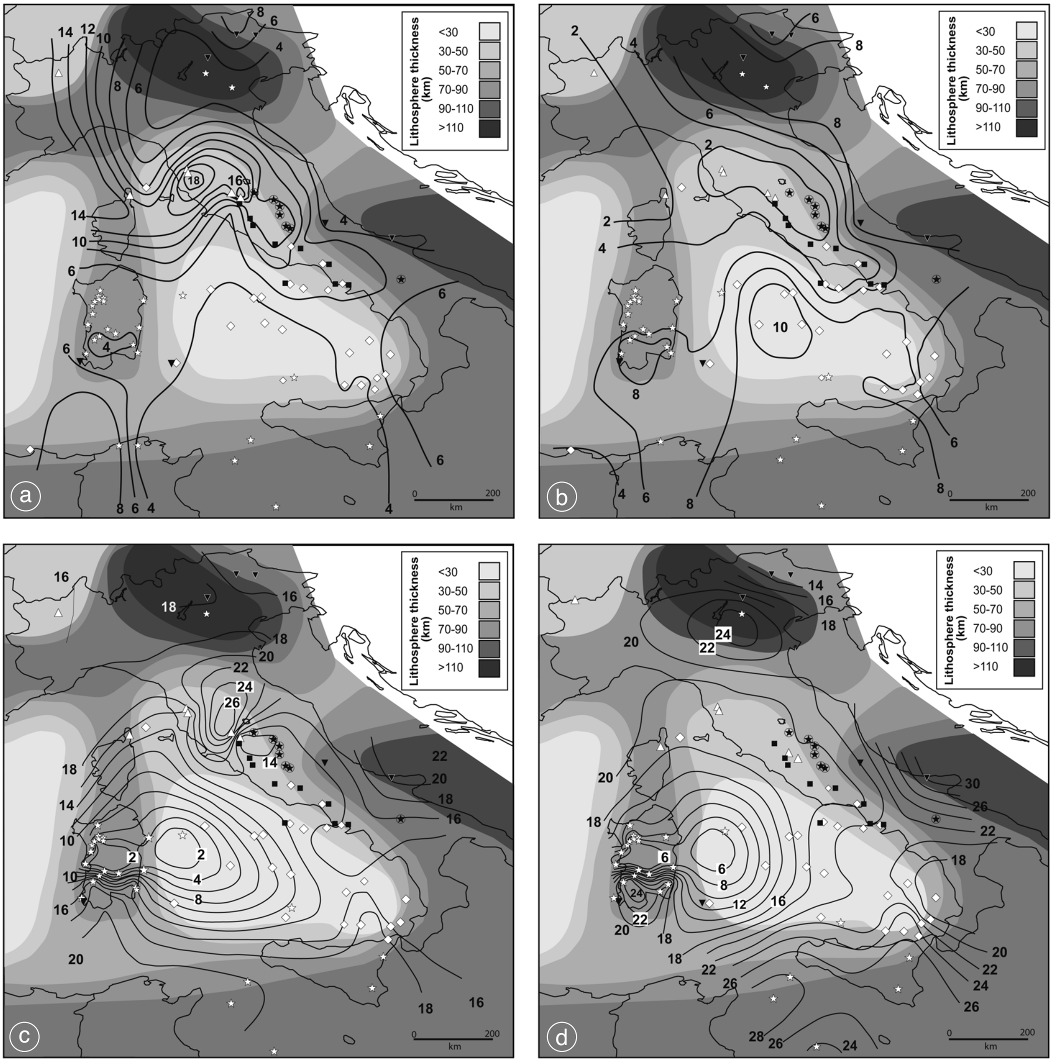

Fig. 4.5a-d. Isotope contour diagrams. Contours are based on data from what we consider to be the most primitive rocks, *i.e.* Mg#s (>65) and Ni+Cr values >250 ppm. The isotopic ratios are mainly from the literature, but also include unpublished data of Bell and Castorina. Note that the contours do not follow lithospheric thicknesses (lithospheric thicknesses after Panza and Suhadolc, 1990). Contour figures are based on the following: a) $\mathrm{Sr_N} = (^{87}\mathrm{Sr}/^{86}\mathrm{Sr_s} - 0.7000) \times 10^3$; b) $\mathrm{Nd_N} = (^{143}\mathrm{Nd}/^{144}\mathrm{Nd_s} - 0.5120) \times 10^4$; c) $^{208}\mathrm{Pb_N} = (^{208}\mathrm{Pb}/^{204}\mathrm{Pb_S} - 37.5) \times 10$; d) $^{206}\mathrm{Pb_N} = (^{206}\mathrm{Pb}/^{204}\mathrm{Pb_s} - 17.0) \times 10$, where $\mathrm{R_s}$ is the value for the sample. FOZO is best reflected in those samples from the Sicily Channel. Arcview was used to construct the contour distribution.

be better constrained, features worth pointing out are: 1) the contours form concentric patterns that cut across all major crustal structures; 2) the contours appear to be independent of lithosphere thicknesses (see fig. 4.5a-d); and 3) they enclose major igneous provinces considered to belong to different tectonic and geodynamic settings. Although we realize that we have used data from rocks of quite different ages, there appears to be a systematic variation in the contouring.

The most radiogenic signatures for Sr (values >10), and the least radiogenic for Nd (<2) are marked by a node in fig. 4.5a,b, centred to the north between the Tuscan lamproites and the Alps, reaching maximum values near the Cupaello kamafugite and the Polino carbonatite centres. A slightly different story emerges from the Pb data. A radiogenic node in the same area as that indicated by the Sr isotopic data is marked by the $^{208}Pb/^{204}Pb$, (see fig. 4.5c), but not by the $^{206}Pb/^{204}Pb$ isotopic ratios. A node, however, marking the lowest Pb isotopic ratios is seen in both fig. 4.5c,d in the Western Tyrrhenian area to the east of Sardinia.

Although the significance of the contours requires further work, we only wish to show that the distribution of the isotopic data does not appear to be random and, in particular, marks a distinct source with high $^{87}Sr/^{86}Sr$ ratios in the region of Cupaello and Polino.

4.5. THE PLUME MODEL

On the basis of the isotopic data, our preferred model is one involving plume activity. The absence of any contribution from DMM, the presence of EM1 and the widespread nature of FOZO are best explained by deep-mantle upwellings. There is now general acceptance that plumes play a key role in explaining magmatism located far from plate boundaries (for review see Ernst and Buchans, 2002) and can be initiated either at the 660 km discontinuity or at much deeper levels, perhaps as low as the D'' layer. Starting off as thin vertical columns, plume spread laterally under their own buoyancy as they approach the surface. Reaching a point of stagnation, the ascending plume will migrate laterally to form a mushroom-shaped head that can reach diameters of up to 2000 km (Campbell, 1998). One feature of plume migration to the surface, is entrainment of other parts of the mantle, resulting in a plume head that can be isotopically heterogeneous and even chemically and thermally zoned (*e.g.*, Davies, 1990; Kempton *et al.*, 2000; De Paolo *et al.*, 2001; Dixon *et al.*, 2002). Decompression melting at the leading edge of the plume is normally marked by vast outpourings of basalts, such as those associated with the Deccan or Columbia River events, or in ocean basins by plateaux basalts such as those seen at the Ontong-Java Plateau or Kerguelen. These outpourings can be preceded, accompanied or even followed by the emplacement of low-volume, low-degree, volatile-rich partial melts such as lamprophyres, nephelinites, carbonatites and kimberlites (Bell, 2001).

Of the main models proposed for volcanism in Central and Western Europe, only two involve plume activity. A low-velocity structure between 670 and 2000 km depth was proposed by Goes *et al.* (1999), and interpreted as a lower, mantle-plume upwelling that forms smaller scale, upper-mantle plumes that act as feeders to the different volcanic fields found in Central Europe. Wilson and Patterson's (2001) model for alkali magmatism in Western and Central Europe, involves the upwelling of small-scale mantle plumes («hot fingers») from the 670 km discontinuity. This plume cluster was attributed to variable degrees of partial melting of a uniform HIMU-like reservoir situated at the base of the upper mantle, and extending beneath a huge region from Spain to the Polish border. This so-called European Asthenospheric Reservoir (EAR) contains a plume component introduced into the thermal boundary layer, and perhaps fed by the present Icelandic mantle plume. In an alternative model, based on tomography and geochemical data, a large-scale, sheet-like mantle upwelling lying beneath the Eastern Atlantic and Western and Central Europe is envisaged by Hoernle *et al.* (1995), that they relate to volcanism in the Cape Verdes and the Canary Islands. Their arguments against a plume-related model included the size of the anomaly (too large), the $^{3}He/^{4}He$ ratios (too low), and a low *S*-wave velocity zone that extends to depths of only 600-700 km.

Geotectonic constraints imposed on any plume model for Italian magmatism must include the counterclockwise rotation of Italy, the opening of the Ligurian and Balearic basins between 30-15 Ma, rifting without rotation between 15 to 10 Ma, and the opening of the Tyrrhenian Sea starting 10 Ma ago coupled with crustal shortening in the Apennines. At about 30 Ma a seminal event produced a major adjustment from overall compression to extension that continues to dominate to this day.

In their evaluation of our proposed plume-related magmatism, Lavecchia and Creati (2006) assessed some numerical plume types proposed by Brunet and Yuen (2000), and led them to favour one involving a plume head trapped within the transition zone. In this model, the boundary layer at the 660 discontinuity results in strong changes in flow direction while at 400 km there is a very fast migration from the central part of the plume which produces a narrow outlet above for the hot, low viscosity material to escape to upper levels. Any hot material that is ejected from the transition zone is episodic in nature and can take place over a period of tens of millions of years. The volume excess within the asthenosphere created by intrusion of the plume tongue results in concomitant stretching and thinning of the overlying lithosphere. Using a simple area-balance methodology, Lavecchia and Creati (2006) estimated the plume tongue to be about 1000 km across, and related the Appenine-Maghrebian fold-and-thrust belt to plume-induced orogenesis. The tomographic anomalies found in the Western Mediterranean in their model is related to chemical rather than thermal variations. Faster zones within the transition zone reflect dehydrated plume tongues, while the overlying low velocity zones they consider to be metasomatized lithosphere resulting from chemical release from the plume.

On the basis of the FOZO1- and EM1-like signatures found in some Italian lavas, as well as some of the geophysical data, we attribute the volcanism in Italy to a model involving a large mantle upwelling with a diameter of at least 1000 km underlying the Tyrrhenian Sea. The isotopic data cannot be attributed to a simple, relatively shallow, asthenospheric upwelling because of the presence of a FOZO-like signature and this forces us to place the common source component into the deep mantle. Other evidence is consistent with plume activity. Lithospheric thinning below the Tyrrhenian Sea (Panza and Suhadolc, 1990), and thermal highs with nodes in the Roman and South Tuscany regions and the Tyrrhenian Sea (*e.g.*, Rehault *et al.*, 1987; Della Vedova *et al.*, 1995) support the presence of an upwelling mantle plume. In addition, the presence of numerous hot springs, and CO_2 anomalies can be attributed to mantle upwelling. It is interesting to note that the CO_2 emissions from Central Italy represent about 10% of the estimated CO_2 discharged globally to the atmosphere from all of the active volcanoes on Earth and Etna produces more CO_2 than any other volcano on Earth. Although the CO_2 emissions were once attributed to dissociation of limestones that are so abundant in Italy, the evidence from stable isotopic data contradicts this and points to a deep-seated source (Minissale *et al.* 1997; Tedesco, 1997; Chiodini *et al.*, 2001).

If the spatial distribution of the isotopic data is compared with a distribution based on chemical composition there is some similarity between the two. Chemical discrimination diagrams based on about one thousand selected analyses show a clear geographic zonation for each of the different rock types. The most sodic rocks are restricted to a zone that includes Sardinia, Pantelleria, Etna and Lessini, while the potassium-rich rocks and carbonatites are restricted to an area that includes the Tuscan and Roman provinces. Transitional basalts mostly occur in the Southern Tyrrhenian area, and lamprophyres, such as those at Sisco and the Alps, are restricted to the outer margins.

Uplift and subsidence during the Tertiary and Quaternary might also be a response to plume-related activity. Quaternary uplift in Central and Southern Italy produced a long wavelength (150-200 km) topographic bulge in the Central Apennines and Calabria with a general uplift estimated to be about 1.2 mm/yr, and about 850 m during the last 700,000 years (D'Agostino *et al.*, 2001). Active deformation and the localization of active extension along the crests of the uplifted areas have been attributed to convective activity associated with a mantle upwelling and considered to be the dominant geodynamic process that occurred during the Quaternary (D'Agostino *et al.*, 2001).

The main objection to our model is the absence of any flood basalts, considered to be *prima facie* evidence for plume activity. Comparison, however, need only be made with East Africa, an area known to be underlain by a deep-seated mantle plume, yet continental flood basalts are absent. The absence of flood basalts in the Tyrrhenian area can be attributed to a plume head that has not yet reached a sufficiently high enough level to produce basaltic liquids, a model previously proposed and cited as an explantion for the absence of flood basalts in East Africa (Griffiths and Campbell, 1991).

4.6. CONCLUDING REMARKS

The geodynamic model for magmatism in Italy that we present is much more unified than any other so far proposed. In our model we attribute the chemical heterogeneities in the mantle below Italy to melting of both source material contained in, and associated with, a plume head, without relating them to recent, subduction-related processes. The diversity of the magmas throughout Italy we consider to be a consequence of low-degree partial melting of an isotopically-heterogenous plume and associated mantle involving at least three different source components, each characterized by quite different Sr, Nd and Pb isotopic compositions. FOZO, as a common end-member for most of the igneous rocks in Italy, is difficult to relate to subduction because of its extensive spatial distribution, and even the other two components, ITEM and EM1, do not characterize any present-day destructive, plate margins. Many features of Italian magmatism, such as styles of eruption, melt characteristics, and isotope systematics, are consistent with intra-plate magmatism, *i.e.* plume-derived/hot-spot-related products.

The fact that all of the mantle-derived products in Italy contain a common end-member adds a new dimension to understanding the nature of Italian magmatism, particularly that along the length of peninsular Italy. Mixing that involves the same end-member requires a single, large-scale, geodynamic system that tapped the same source over a period of at least 30 Ma. The FOZO end-member is best reflected in samples from Pietre Nere, which is the oldest centre, and from Etna which is one of the youngest. It is interesting that most of the active or dormant volcanoes in Italy (*e.g.*, Phlegraean Fields, Etna, Ischia, Pantelleria, Stromboli, Vesuvius and Vulcano) lie in the southern part of the Tyrrhenian Sea or in the Sicily Channel, and the isotope data from them lie close to the FOZO-like end-member as seen in figs. 4.2 and 4.3. It is tempting to relate this observation to a greater input from the more primitive, FOZO-like reservoir in more recent times, but many more data are needed before accepting this connection.

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