BOLLETTINO DI GEOFISICA TEORICA ED APPLICATA VOL. XXXVI, N. 141-144 - MARCH-DECEMBER 1994

L. FRANCALANCI and P. MANETTI

GEODYNAMIC MODELS OF THE SOUTHERN TYRRHENIAN REGION: CONSTRAINTS FROM THE PETROLOGY AND GEOCHEMISTRY OF THE AEOLIAN VOLCANIC ROCKS

Abstract. Petrological studies of Aeolian volcanic rocks have placed serious constraints on the formulation of geodynamic models of the Tyrrhenian basin. In particular, it has been recently pointed out that: a) the subducted lithosphere is oceanic in nature; b) the mantle source of the magmas is a MORB-like source metasomatized by crustal components, specifically oceanic crust and pelagic sediments; c) the amount of crustal material added to the mantle increases from west to east in the arc; d) the metasomatizing agent consists of aqueous fluids or melts released from the slab in variable proportions in the three different sectors of the arc. The ages and distribution of the submerged and subaerial orogenic volcanoes reveal the presence of two volcanic arcs: the first is of Pliocene age, and developed in step with the formation of the Vavilov basin. It was followed by a second arc, the present Aeolian arc, which is associated with the marginal basin of Marsili. The Quaternary magmatism of Ustica, which has an intra-plate affinity, developed following the Pliocene subduction and outside the present subduction zone. The beginning of the subduction processes responsible for the opening of the Tyrrhenian basin has been set at the end of the Miocene, when a new lithosphere began plunging NW under the Appeninic margin.

INTRODUCTION

Even though widespread magmatic activity is one of the most obvious geologic processes operating in the Southern Tyrrhenian area (Fig. 1), it has rarely been discussed in the geodynamic models proposed for the region. However, it is well known that detailed petrological investigations of magmatic rocks can provide substantial contributions to the understanding of many aspects of geologic processes. Since the middle eighties, many general petrological and geochemical studies of Southern Tyrrhenian magmatism have been published (e.g. Beccaluva et al., 1989; Francalanci et al., 1989b, 1993; Ellam et al., 1989; Serri, 1990), casting light on some of the most important characteristics of this convergent tectonic setting. In particular, they have served to reveal: a) the nature of the lithospheric slab and the origin of the mantle wedge metasomatizing components, and b) the overall nature of the magma source. In addition to this, several other topics which can be approached through the study of magmatic rocks must be addressed when formulating geodynamic models of the region, and especially: c) the presence of an older submerged inner-arc in the Tyrrhenian sea, and d) the possibility that the lithospheric slab could have been active from the late Eocene to the present. The discussion of the latter topic has been based mainly upon investigations of the rate at which the Tyrrhenian basin opened (e.g. Patacca et al., 1990), and on seismic tomography studies of the asthenospheric-lithospheric domain of the Southern Italian peninsula (e.g. Spakman, 1990). To address the other points, however, petrographic, geochemical, and isotopic studies will be necessary. Even though further petrological data and radiometric age determinations are needed to better address the point (c), in the following discussion some crucial constraints that are presently available will be used.

In any case, the CROP profile data for the Southern Tyrrhenian area could provide a decisive

Manuscript received April 24, 1993; accepted September 10, 1993.

Dipartimento di Scienze della Terra, via La Pira 4, 50121 Firenze, Italy.

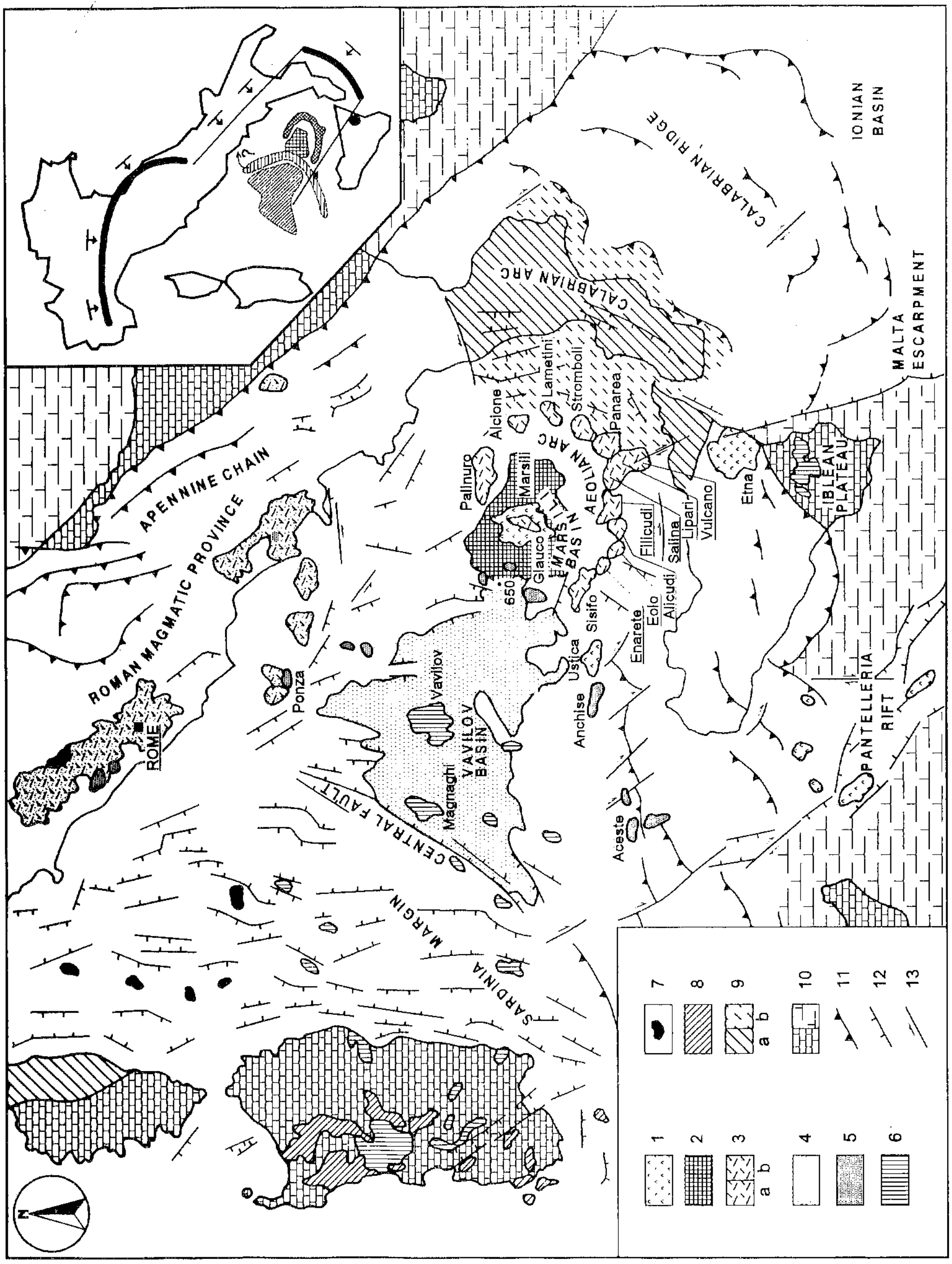

Fig. 1 - Map of the main tectonic and magmatic units of the Tyrrhenian Sea and adjoining areas (modified after Ferrari and Manetti, 1993). (1) Extension-related volcanism of Pleistocene with mainly alkaline and minor MORB affinity (base of the Marsili Seamount); (2) Oceanic crust of Pleistocene; (3) Subduction-related volcanism of Pleistocene, a=Aeolian Arc, b=Roman Magmatic Province; (4) Oceanic crust of Pliocene; (5) Subduction-related volcanism of Pliocene; (6) Extension-related volcanism of Pliocene with mainly alkaline and minor MORB affinity (Seamounts of the Vavilov Basin); (7) Northern Tyrrhenian plutonic bodies of Late Miocene; (8) Subduction-related volcanism of Oligocene-Early Miocene; (9) Calabrides Units, a=emerged, b=submerged; (10) Hinterland and foreland areas, a=emerged, b=submerged; (11) Thrust; (12) Extensional fault; (13) Strike-slip fault. Dot with number refers to ODP drilling site.

Inset - Simplified tectonic sketch of the Tyrrhenian Sea and adjoining area (after Patacca and Scandone, 1989) with the position of the Pleistocene and Pliocene volcanic arcs along with their marginal basins, the Marsili and Vavilov Basins, respectively. The position of the island of Ustica and Mt. Etna is also reported.

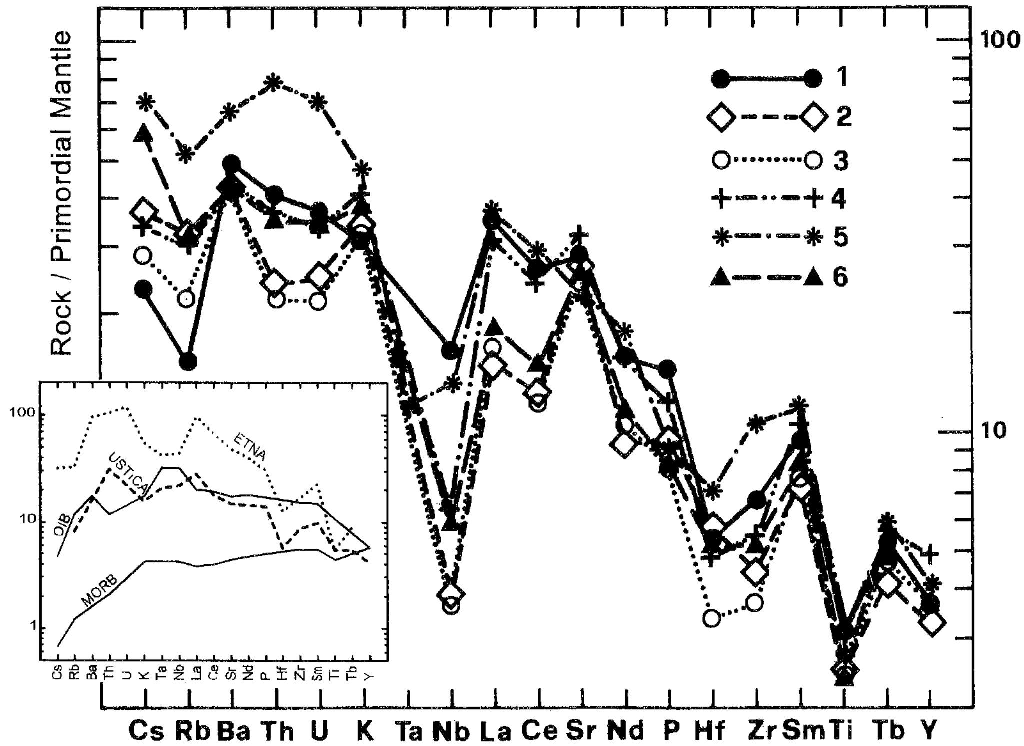

Fig. 2 - Spidergrams of incompatible elements normalized to the primordial mantle (Wood, 1979) for calc-alkaline representative rocks of Aeolian islands (data from Francalanci et al., 1993). Legend: 1, Alicudi; 2, Panarea; 3, Salina; 4, Filicudi; 5, Stromboli; 6, Lipari. For comparison, the patterns of typical MORB (Sun and Nesbitt, 1977; Sun et al., 1979) and OIB (USGS rock standard BHVO-1, Gladney and Goode, 1981), together with those of Ustica (Cinque et al., 1988) and Etna (Cristofolini et al., 1991) rocks are reported in the inset.

contribution to understanding the presence of the remnant Tyrrhenian arc and to knowledge of the subducted lithosphere.

NATURE OF THE SUBDUCTED LITHOSPHERE

A Benioff zone dipping NW 50° (Ritsema, 1970) or 60° (Caputo et al., 1970) was identified at the end of the sixties through the study of the intermediate and deep earthquake hypocenter distribution in the Southern Tyrrhenian Sea. Due to the paucity of seismic data available, the Benioff zone in the area was interpreted as discontinous, with its deepest part detached (Keller, 1974). Recently, however, a detailed analysis of seismic data by Giardini and Velonà (1991) has shown that the lithospheric slab is continuous down to a depth of 500 km, and that the curvature proposed by Gasparini et al. (1982) is absent.

With regard to the nature of the lithospheric slab, some authors (e.g. Scandone, 1979; Boccaletti et al., 1984; Patacca et al., 1990) suggest it is subducted continental crust (mainly lower continental crust). However, several lines of geochemical evidence derived from Aeolian arc volcanic rocks indicate an oceanic nature for the subducted slab. The latter hypothesis is also supported by geophysical data on the distribution of earthquake hypocenters which define a Benioff zone down to a depth of 500 km, a depth deep enough to rule out the penetration of a relatively light continental lithosphere (Finetti and Del Ben, 1986).

As for the petrological evidence, the nature of the subducted lithosphere has been studied from geochemical and isotopic characteristics of basic rocks from the Aeolian arc. It is, in fact, thought that fluids or melts released from the slab mix with the mantle wedge, giving rise to a metasomatized mantle. Partial melting of this mantle generates magmas that reflect some of the geochemical features of the subducted lithosphere. In particular, for these studies, Sr, Nd, and Pb isotope ratios, Sr contents, and the Sr/Nd and Sr/Ce ratios are the most useful parameters (Ellam et al., 1989; Serri, 1990; Francalanci et al., 1993). The high Sr contents of most of the Aeolian calc-alkaline basic magmas, which produce the positive Sr anomalies in the spidergrams shown in Fig. 2, in association with the relatively low Sr isotope ratios (0.70352-0.70538; Francalanci et al., 1993), indicate that an oceanic, rather than continental, lithospheric slab is involved in generating the geochemical features of the magmas. This hypothesis is clarified by Fig. 3a, which shows that a high Sr content, of around 200 ppm in the mixed source (in abscissa), is needed to obtain the Sr abundances of the various volcanoes (in ordinate) with source partial melting (batch melting) of about 20-30% (Green, 1973; 1976). The high Sr concentration of the mixed source can be produced by a variable degree of mantle mixing with a lithospheric component having heterogeneous but generally high Sr contents. In this case, the lithospheric component must also have very low Sr isotope ratios to reach the low $^{87}Sr/^{86}Sr$ ratios of Aeolian volcanics. For example, Fig. 3b shows that the Sr contents and the low Sr isotope ratios (around 0.7042) of the Panarea, Salina, and Lipari rocks can be modelled by a 10% contamination with a crustal component (C_3) having a Sr content of 2000 ppm (mantle: Sr = 18ppm, $^{87}Sr/^{86}Sr = 0.703$) and an $^{87}Sr/^{86}Sr$ of 0.7043. A component with these characteristics can be only represented by a fluid or a melt released from a subducted oceanic lithosphere.

Conversely, the Plio-Quaternary magmatic rocks exposed N of the Tyrrhenian discontinuity at the 41° parallel, and N of the Ortona-Roccamonfina line (the boundary between the Northern and Southern Appeninic arcs) always have Sr isotope ratios higher than 0.70600, which indicates a major involvement of the continental lithosphere in their genesis (Serri et al., 1991).

NATURE OF MANTLE CONTAMINANTS

Even though the geochemical and isotopic data have revealed that the subducted lithosphere is oceanic in nature, oceanic crustal contaminant by itself cannot account for the higher $^{87}Sr/^{86}Sr$ of Stromboli and the quite low $^{143}Nd/^{144}Nd$ ratios (0.512869-0.512426; Ellam et al., 1989; Francalanci et al., 1993) of Aeolian volcanics, which are lower than those usually found in basaltic oceanic crust. Keeping this in mind, two different mantle contaminants are needed: one with a high "unradiogenic" Sr content and a high $^{143}Nd/^{144}Nd$ ratio, represented by oceanic crust, and another with high $^{87}Sr/^{86}Sr$ and low $^{143}Nd/^{144}Nd$ ratios, represented by a continental crust component. In figure 3b, the mixing line between the crustal contaminant C_2 and the mantle M_2 (which has a high Sr content) shows that two metasomatizing components are necessary to model the Sr contents and $^{87}Sr/^{86}Sr$ of the Stromboli rocks. A similar hypothesis was also suggested by Ellam et al. (1989), on the basis of other considerations relative to Nd/Sr and Th/Ta ratios.

With regards to the type of continental crust component, the characteristics of the Sr, Nd and Pb isotope ratios have suggested that oceanic sediments can better account for the isotopic features of the Aeolian rocks (Francalanci et al., 1993), and particularly the high $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios (Fig. 4).

These different metasomatizing crustal components interact with the mantle wedge in a complex manner, as testified by the wide compositional variations observed among the Aeolian volcanics. In fact, all the rock types usually found in continental and oceanic arcs occur: tholeiites, calc-alkalines, HK calc-alkalines, shoshonites and more potassic rocks (leucit-tephrites of Barberi et al., 1974; KS of Francalanci et al., 1989a). Moreover, the well known correlations between K-enrichment and age or trench distance are absent. In addition, it has recently been shown that complex variations also occur among the basic rocks of the calc-alkaline series of the different arc sectors (Francalanci et al., 1989b; 1993). Alicudi-Filicudi (to the west), Panarea-Lipari-Salina (in the middle) and Stromboli (to the east) are characterized by distinct Sr, Nd and Pb isotope ratios and incompatible element contents and ratios. The increase in the $^{87}Sr/^{86}Sr$

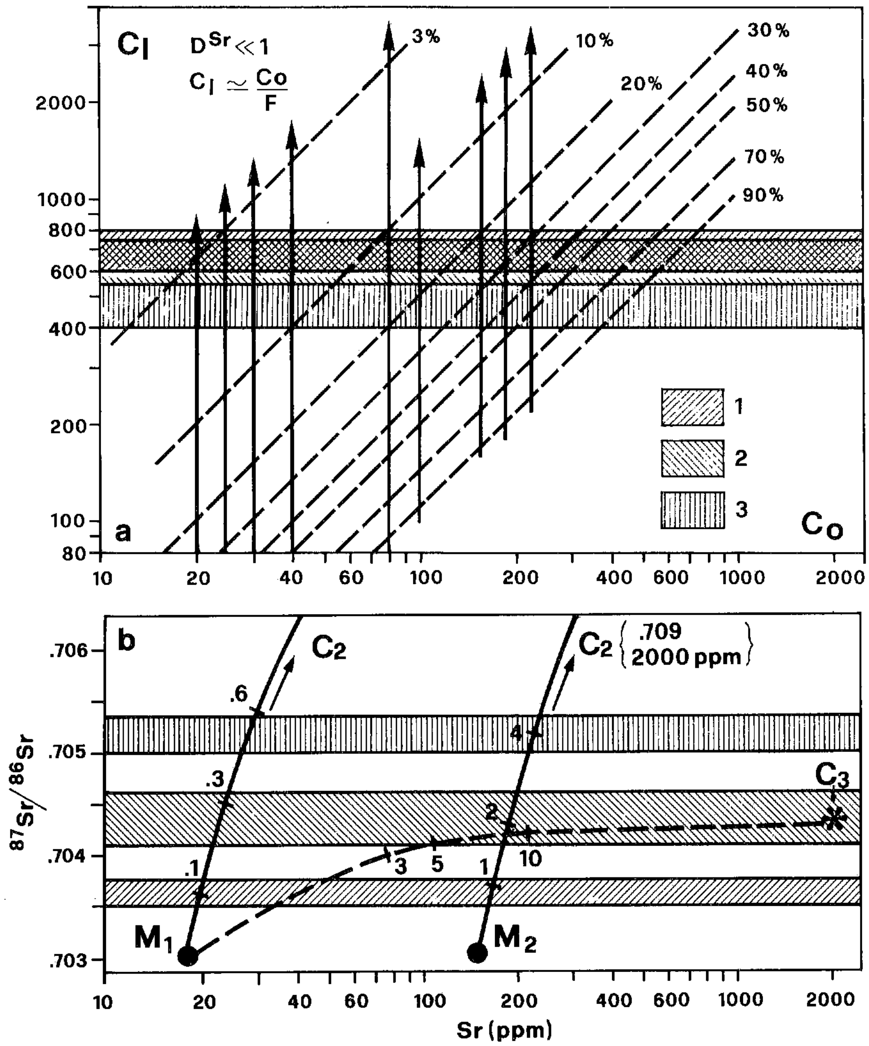

Fig. 3 - Modelling of Sr and Sr isotope ratios of Aeolian calc-alkaline rocks. The lined areas indicate the Sr (Fig. a) and the $^{87}Sr/^{86}Sr$ (Fig. b) ranges of Alicudi, to the west (1), Panarea-Salina-Lipari, in the central part (2), and Stromboli to the east (3) (data from Francalanci et al., 1993). Figure (a), which reports C_l versus C_0 of the batch melting equation for Sr (simplified for D«1 as shown in figure), shows how C_l^{Sr} varies (full lines) with the variation of C_0^{Sr} and of the melting degree (whose values are indicated for each dashed line). Figure (b), where the $^{87}Sr/^{86}Sr$ are plotted against Sr, shows various mixing lines between different hypothetical mantle sources (M_1, M_2) and different contaminants (C_2, C_3). The numbers on the lines indicate the amount (%) of the respective contaminants in the different mixing cases. For other explanations see text.

(0.70352 to 0.70538) and the decrease in the $^{143}Nd/^{144}Nd$ ratios (0.512869 to 0.512557) from west to east have been attributed to an increase in the amount of crustal contaminant added to the mantle wedge. On the other hand, the variations in incompatible element contents and ratios among the calc-alkaline rocks have revealed a different role for fluids and melts released from the slab in the different sectors of the arc (Francalanci et al., 1989b; 1993). In fact, fluids modify the geochemical characteristics of the mantle differently to melts. It has been shown that the incompatible elements with low ionic potentials, which are highly enriched in aqueous fluids, are more abundant in the central arc rocks, than they are in the western rocks (Alicudi-Filicudi). The reverse occurs for the incompatible elements with relatively high ionic potentials, which are enriched in the melts. Thus, it has been suggested that the mantle contaminant agents are mainly melts in the western sector, aqueous fluids in the central part

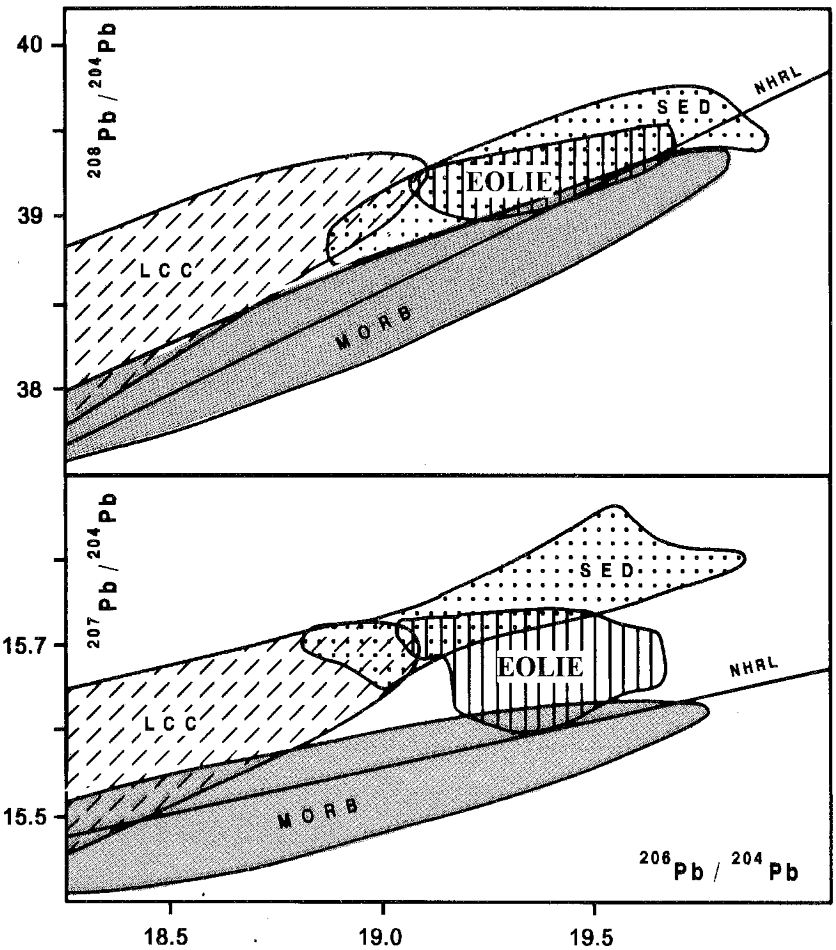

Fig. 4 - Pb isotopic composition of the Aeolian arc rocks (EOLIE) (Cortini, 1981; Ellam et al., 1989; Francalanci et al., 1993), pelagic sediments (SED) (White et al., 1985), MORB and lower continental crust (LCC) (Wilson, 1989).

and, similar proportions of melts and fluids in the eastern part of the arc. Finally, it has been recognized that higher volumes of aqueous fluids added to the mantle promote higher degrees of mantle partial melting in the central sector (Francalanci et al., 1989, 1993). In this context, the intense volcanic activity that characterizes the central part of the arc can be taken as evidence corroborating this hypothesis.

NATURE OF THE PRE-CONTAMINATION MANTLE WEDGE

Different authors have proposed different pre-contamination mantle sources for the Aeolian magmas. The high $^{206}Pb/^{204}Pb$ values of the volcanics studied (Fig. 4) led Ellam et al. (1989) to suggest a magma source similar to those of oceanic island basalts (OIB-like). Taking into account the low HFSE contents of the rocks, and that the $^{206}Pb/^{204}Pb$ values still plot in the MORB field, which is a characteristic of enriched-type (E-type) MORB (Saunders et al., 1988), Francalanci et al. (1989b; 1993) suggest a pre-contamination source more similar to the MORB source (MORB-like). The same hypothesis was proposed by Serri (1990) on the basis of trace element contents.

Focussing our attention on the Panarea magma, we note from Fig. 2 that it has HFSE and

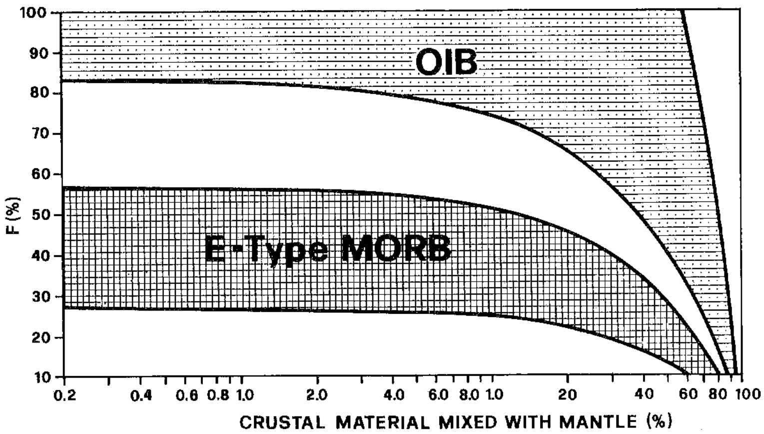

Fig. 5 - Modelling of Panarea Nb contents (2.4 ppm) using the ranges of Nb values displayed by OIB sources (2-6ppm) and by E-type MORB sources (0.7-1.4ppm) (Wood, 1979), $D^{Nb}=0.02$, and the batch model for mixed mantle melting. In the diagram the mixed mantle partial melting (F%) is plotted against the proportion of crustal material (with 0ppm of Nb) mixed with mantle. Note that with an OIB-like source, small proportions of mixing with crustal material are possible only if there are unreasonably high degrees of partial melting of the mixed source, but this is not the case for an E-type MORB-like source. For further explanation see text.

REE contents lower than those of OIB, but similar to or higher than those of MORB. Thus the content of Nb, which is taken as a representative element of the HFSE group, can be particularly useful in discriminating between pre-enrichment OIB- and MORB-like sources. Mass balance calculations lead us to suggest an (E-type) MORB-like source for the pre-contamination mantle source of the Aeolian magmas. These calculations indicate that a very large volume (»50%) of subducted material devoid of Nb would have to mix with an OIB-like mantle source, to obtain the Nb content of Panarea, after around 30% melting of the mixed assemblage (the experimental results of Green, 1973; 1976, were used to estimate a likely degree of melting). Conversely, small mixing proportions would only be possible with unrealistically high degrees of partial melting of an OIB-like source. This is shown in Fig. 5, where degree of melting is plotted against mixing proportions (%). However, these calculations also demonstrate that, if the pre-enrichment source is similar to an E-type MORB source, which has a lower Nb content, small proportions of mixing are possible with about 30% partial melting. Obviously, with an N-type MORB-like source, lower degrees of melting would be necessary.

Therefore, on the basis of Pb isotope and HFSE contents, it is possible to conclude that a pre-contamination source similar to E-type (or N-type) MORB, rather than OIB, is better able to explain the overall geochemical features of the rocks studied.

THE REMNANT TYRRHENIAN ARC AND THE AEOLIAN ARC STRUCTURE

On the basis of their age and geographic location, the submerged and subaerial volcanoes with an orogenic affinity are distributed along two distinct lines, which suggests the occurrence of two different volcanic arcs. The presence of the older one, which is Pliocene in age, and is located between the Vavilov and Marsili basins, has already been reported by Kastens et al. (1988), Savelli (1988), Ferrari and Manetti (1993), and implicitly by C.N.R. (1989). It appears to be formed by the calc-alkaline volcanoes of Glauco, Aceste and Anchise, and by other minor volcanoes located at the western boundary of the Marsili basin. The presence of Early Pleistocene basalts with a calc-alkaline affinity at site 650 (ODP, Leg 107; Beccaluva et al., 1990) offers further evidence for the older volcanic arc in the Tyrrhenian sea. The highly vesicular nature of the basalts and the presence of benthic foraminifera in the overlying sediments, which are now at the depth of 4100 m, indicate an extreme rate of subsidence for the Tyrrhenian basin, three times the average rate for young oceanic basins. The older arc was entirely submerged, as is indicated by the absence of tephra deposits in the different DSDP and ODP drillings (Kastens and Mascle, 1990). We hypothesize that this arc could also continue NE to the Neapolitan area, where Pliocene-Early Pleistocene HK andesites are found (Di Girolamo e Morra, 1988). Finally, the western Pontine islands (Ponza, Palmarola and Zanone), as well as the submerged volcano Albatross and other minor seamounts, could be remnants of this old Aeolian arc.

Due to the absence of fresh samples, no radiometric age determinations from the submerged volcanoes are available, and the date of the beginning of the older volcanic arc activity is unknown. Nevertheless, if the Pontine islands do belong to this arc, we can reasonably date the beginning of activity around 4.5 Ma, in the Early Pliocene. This age corresponds to the initial opening of the Vavilov basin (4.3 Ma), which continued to widen until 2.6 Ma (Sartori, 1989). The activity of the older arc also appears to have ended around 2 Ma. The submerged Tyrrhenian arc and the Vavilov basin should, therefore, represent the first arc - marginal basin system of the Southern Tyrrhenian region, which developed in the Pliocene age. This would also explain the apparent diversity of the Tyrrhenian system with respect to other arc - trench - marginal basin systems, where the magmatic activity generally preceds or is contemporaneous with the marginal basin development: if the present arc was the only arc in the Tyrrhenian Sea, the opening of the marginal basin would have preceded the magmatic activity by about 3 Ma.

During Quaternary times magmatism resumed, but shifted to the south. With the exception of a dubious age of 1.3 Ma, the rocks from the recent Aeolian volcanism have yielded ages younger than 0.9 Ma. The oldest volcanics are found in the submerged western volcanoes Sisifo (1.3-0.9 Ma), Enarete (0.78-0.67 Ma) and Eolo (0.85-0.72 Ma), whereas the emerged volcanism is younger than about 0.4 Ma (Gillot, 1987). The Marsili basin with its tholeiitic basement represents the marginal basin of the young volcanic arc, which has developed since the Middle Pleistocene. The unique ring-like shape of the recent arc (Fig. 1) has been interpreted as due to the effects of an unstable subduction regime that causes torsion and segmentation of the lithospheric slab (Beccaluva et al., 1989), which tends to decrease in size with respect to the Pliocene slab, and to concentrate in a narrow sector of the South Tyrrhenian region. The western boundary of the subduction regime should be west of Alicudi, trend in a NW-SE direction, and roughly correpond to the boundary proposed by Patacca and Scandone (1989). Ustica and Etna appear to be located outside the convergent tectonic system. Ustica, in fact, is formed by Na-alkaline volcanics having an intra-plate affinity and an age younger than about 0.7 Ma (Cinque et al., 1988). Its position between calc-alkaline volcanoes is, therefore, only apparent, because the western volcanic centers belong to the remnant arc, whereas the eastern ones are part of the recent and active Aeolian arc.

AGE OF THE SUBDUCTED LITHOSPHERE

Several subduction models proposed for the South Tyrrhenian region have indicated that since Upper Eocene-Oligocene times the NW dipping lithospheric slab has been responsible for both: a) the Sardinian Oligo-Miocene magmatism and the opening of the Ligurian-Balearic marginal basin, and b) the Aeolian magmatism and opening of the Tyrrhenian Sea with the formation of oceanic crust (Malinverno and Ryan, 1986; Beccaluva et al., 1989).

On the other hand, on the basis of a calculated opening rate of 6cm/y for the last 8 Ma for the Tyrrhenian Sea, Patacca et al. (1990) suggest that, to reach its present depth the lithospheric slab began to subduct in Tortonian times. Thus, it cannot be a relict of the subducted lithosphere linked to the Sardinian Oligo-Miocene magmatism and to the opening of the Ligurian-Balearic basin.

We believe that the latter hypothesis is better able to account for the general structural setting of the Tyrrhenian region. In fact, considering that gravitational sinking of lithosphere caused the opening of the Tyrrhenian basin (Malinverno and Ryan, 1986), the configuration of the lithosphere in Oligo-Miocene time most likely resembled the configuration observed today, because the Ligurian-Balearic basin was opening at that time. If this is the case, however, it is doubtful that the sunken lithosphere, which has already driven the opening of one basin, could produce the driving force responsible for the high rate at which the Tyrrhenian Sea is opening.

CONCLUSIONS

In recent years, petrological and geochemical data on the Aeolian magmatic rocks have made possible hypotheses on the structure of the Southern Tyrrhenian convergent system. The following issues have been addressed:

a) the oceanic nature of the subducted lithosphere;

b) the nature of the subducted crustal material mainly responsible for the petrological variations observed in the Aeolian primitive rocks: it seems to be represented by pelagic sediments whose metasomatizing contribution increases from west to east throughout the arc;

c) the petrological features of the different sectors of arc reflecting different behaviours of the subducted lithosphere, which lead to different rates of magma eruption;

d) the nature of the pre-contamination mantle wedge, which is similar to those with MORB sources.

Moreover, comparisons with typical arc-trench-marginal basin systems and the available petrological data have confirmed the presence of a Pliocene remnant arc and resolved the problem posed by Ustica, which shows an intra-plate magmatism in a convergent tettonic setting. Finally, the hypothesis that a single lithospheric slab has been continuously active since the late Eocene is considered unlikely. The geological data on the opening velocity of the Tyrrhenian Sea, in fact, suggest that a new subduction process started at the end of the Miocene, with a higher velocity than that usually found in present convergent systems.

Acknowledgements. The work was financially supported by M.U.R.S.T. 60% and by C.N.R., Centro di Studi per la Minerogenesi e Geochimica Applicata, Firenze.

REFERENCES

Barberi F., Innocenti F., Ferrara G., Keller J. and Villari L.; 1974: *Evolution of Aeolian Arc volcanism (Southern Tyrrhenian Sea).* Earth Planet. Sci. Letters, **21**, 269-276.

Beccaluva L., Brotzu P., Macciotta G., Morbidelli L., Serri G. and Traversa G.; 1989: *Cainozoic tectono-magmatic evolution and inferred mantle sources in the Sardo-Tyrrhenian area.* Atti Convegni Lincei, **80**, 229-248.

Beccaluva L., Bonatti E., Dupuy C., Ferrara G., Innocenti F., Lucchini F., Macera P., Petrini R., Rossi P.L., Serri G., Seyler M. and Siena F.; 1990: *Geochemistry and mineralogy of volcanic rocks from ODP sites 650, 651, 655 e 654 in the Tyrrhenian Sea.* In: Kastens K. and Mascle J. et al. (eds), Proceedings of the ODP, Scientific Results, **107**, pp. 49-74.

Boccaletti M., Nicolich R. and Tortorici L.; 1984: *The Calabrian Arc and the Ionian sea in the evolution of the central Mediterranean.* Mar. Geol., **55**, 219-245.

Caputo M., Panza G.F. and Postpischl D.; 1970: *Deep structure of the Mediterranean Basin.* J. Geophys. Res., **75**, 4919-4923.

Cinque A., Civetta L., Orsi G. and Peccerillo A.; 1988: *Geology and geochemistry of the island of Ustica (Southern Tyrrhenian Sea).* Rend. Soc. It. Miner. Petrol., **43**, 987-1002.

C.N.R.; 1989: *Synthetic structural-kinematic map of Italy, scale 1:2,000,000.* Pubbl. P.F. Geodinamica, Roma, Pre-print copy for the 28° Inter. Geol. Congr., 1989.

Cortini M.; 1981: *Aeolian Island arc (south Tyrrhenian sea) magma heterogeneity in historical lavas: Sr and Pb isotopic evidence.* Bull. Volcanol., **44**, 711-722.

Cristofolini R., Corsaro R.A. e Ferlito C.; 1991: *Variazioni petrochimiche nella successione etnea: un riesame in base a nuovi dati da campioni di superficie e da sondaggi.* Acta Vulcanol., **1**, 25-37.

Di Girolamo P. e Morra V.; 1988: *Il magmatismo mesozoico-quaternario della Campania: petrologia e significato geodinamico.* Mem. Soc. Geol. It., **41**, 165-179.

Ellam R.M., Hawkesworth C.J., Menzies M.A. and Rogers N.W.; 1989: *The volcanism of Southern Italy: role of subduction and the relationship between potassic and sodic alkaline magmatism.* J. Geophys. Res., **94**, 4589-4601.

Ferrari L. and Manetti P.; 1993: *Geodynamic framework of the Tyrrhenian volcanism: a review.* Acta Volcanol., **3**, 01-09.

Finetti I. and Del Ben A.; 1986: *Geophysical study of the Tyrrhenian opening.* Boll. Geofis. Teor. Appl., **28**, 75-155.

Francalanci L., Manetti P. and Peccerillo A.; 1989a: *Volcanological and magmatological evolution of Stromboli volcano (Aeolian Island): the role of fractional crystallization, magma mixing, crustal contamination and source heterogeneity.* Bull. Volcanol., **51**, 355-378.

Francalanci L., Taylor S.R., McCulloch M.T. and Woodhead J.D.; 1989b: *Petrological and geochemical variations across the calc-alkaline rocks of Aeolian arc (Southern Tyrrhenian Sea).* In: IAVCEI General Assembly, Santa Fe, New Mexico, USA, Abstracts, pp. 96.

Francalanci L., Taylor S.R., McCulloch M.T. and Woodhead J.D.; 1993: *Geochemical and isotopic variations in the calc-alkaline rocks of Aeolian Arc, Southern Tyrrhenian Sea, Italy: Constraints on magma genesis.* Contrib. Miner. Petrol., **113**, 300-313.

Gasparini G., Iannaccone G., Scandone P. and Scarpa R.; 1982: *Seismotectonic of the Calabrian Arc.* Tectonophysics, **84**, 267-286.

Giardini D. and Velonà M.; 1991: *The deep seismicity of the Tyrrhenian Sea.* Terra Nova, **3**, 57-64.

Gillot P.Y.; 1987: *Histoire volcanique des Iles Eoliennes: arc insulaire ou complexe orogenique anulaire* Doc. et Trav. IGAL, **11**, 35-42.

Gladney E.S. and Goode W.E.; 1981: *Elemental concentrations in eight new United States Geological Survey rock standards: a review.* Geostandards Newsl., **5**, 31-64.

Green D.H.; 1973: *Experimental melting studied on a model upper mantle composition at high pressure under water-saturated and water-undersaturated conditions.* Earth Planet. Sci. Letters, **19**, 37-53.

Green D.H.; 1976: *Experimental testing of "equilibrium" partial melting of peridotite under water-saturated, high pressure conditions.* Can. Mineral., **14**, 255-268.

Kastens K., Mascle J. and ODP Leg 107 scientific party; 1988: *ODP Leg 107 in the Tyrrhenian Sea: insight into passive margin and back-arc basin evolution.* Geol. Soc. Am. Bull., **100**, 1140-1156.

Kastens K. and Mascle J.; 1990: *The geological evolution of the Tyrrhenian Sea. An introduction to the scientific results of the ODP Leg 107.* In: Kastens K. and Mascle J. (eds), Proceedings of the ODP, Scientific Results, **107**, pp. 3-29.

Keller J.; 1974: *Petrology of some volcanic rocks series of the Aeolian Arc, Southern Tyrrhenian Sea: calc-alkaline and shoshonitic associations.* Contrib. Mineral. Petrol., **46**, 29-47.

Malinverno A. and Ryan W.B.F.; 1986: *Extension in the Tyrrhenian Sea and shortening in the Apennines as result of arc migration driven by sinking of the lithosphere.* Tectonics, **5**, 227-245.

Patacca E. and Scandone P.; 1989: *Post-Tortonian mountain building in the Apennines. The role of the passive sinking of a relic lithosphere slab.* Atti Convegni Lincei, **80**, 157-176.

Patacca E., Sartori R. and Scandone P.; 1990: *Tyrrhenian basin and Apenninic arcs. Kinematic relations since Late Tortonian times.* Mem. Soc. Geol. It., **45**, 425-451.

Ritsema A.R.; 1970: *On plate tectonics in the Mediterranean Region.* 1st draft paper ESC, Luxembourg.

Sartori R.; 1989: *Evoluzione neogenico-recente del bacino tirrenico e suoi rapporti con la geologia delle aree circostanti.* Giorn. Geol., **51**, 1-39.

Saunders A.D., Norry M.J. and Turney J.; 1988: *Origin of MORB and chemically-depleted mantle reservoirs: trace elements constraints.* J. Petrol., Special Lithosphere Issue, 415-445.

Savelli C.; 1988: *Late Oligocene to Recent episodes of magmatism in and around the Tyrrhenian Sea: implications for the processes of opening in a young inter-arc basin of intra-arc-orogenic (Mediterranean) type.* Tectonophysics, **146**, 163-181.

Scandone P.; 1979: *Structure and evolution of the Calabrian Arc.* Boll. Soc. Geol. It., **98**, 27-34.

Serri G.; 1990: *Neogene-Quaternary magmatism of the Tyrrhenian region. Characterization of the magma sources and geodynamic implications.* Mem. Soc. Geol. It., **41**, 219-242.

Serri G., Innocenti F., Manetti P., Tonarini S. e Ferrara G.; 1991: *Il magmatismo neogenico e quaternario dell'area tosco-laziale-umbra: implicazioni sui modelli di evoluzione geodinamica dell'Appennino settentrionale.* Studi Geologici Camerti, **spec. vol. (1991/1)**, 429-463.

Spakman W.; 1990: *Tomographic images of the upper mantle below central Europe and the Mediterranean.* Terra Nova, **2**, 542-553.

Sun S. and Nesbitt R.W.; 1977: *Chemical heterogeneity of the Archaean mantle, composition of the earth and mantle evolution.* Earth Planet. Sci. Letters, **35**, 429-448.

Sun S., Nesbitt R.W. and Sharaskin A.Y.; 1979: *Geochemical characteristics of mid-ocean ridge basalts.* Earth Planet. Sci. Letters, **44**, 119-138.

White W.M., Dupre B. and Vidal P.; 1985: *Isotope and trace element geochemistry of sediments from the Barbados Ridge-Demerara Plain region, Atlantic ocean.* Geochim. Cosmochim. Acta, **49**, 1875-1886.

Wilson M.; 1989: *Igneous petrogenesis - a global tectonic approach.* Unwin Hyman Pub., London, 466 pp.

Wood D.A.; 1979: *A variably veined sub-oceanic upper mantle. Genetic significance for mid-ocean ridge basalts from geochemical evidence.* Geology, **7**, 499-503.