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Mantle domains beneath the southern Tyrrhenian: constraints from recent seafloor sampling and dynamic implications

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ABSTRACT. — Southern Tyrrhenian Quaternary magmatism represents one example of an active arc/back-arc system where IAB- and OIB-type magmas coexist. IAB-type magmatism is the most common, in both arc and back-arc settings, whereas OIB-type magmas are restricted to few areas. Geochemical and isotopic characteristics of southern Tyrrhenian submarine volcanic samples are here summarized, with special attention to those samples recovered during recent seamounts/seafloor sampling. Petrological data of the most basic lavas have been evaluated with the aim to characterize the mantle sources of IAB and OIB magmas. These data provide important insights into the petrogenesis of the southern Tyrrhenian submarine magmatism and on the possible geodynamic scenario able to explain the coexistence of IAB and OIB magmas in this area.

KEY WORDS: *southern Tyrrhenian, calc-alkaline magmas, alkaline magmas.*

RIASSUNTO. — Il magmatismo quaternario del Tirreno meridionale rappresenta un esempio di sistema «arco vulcanico attivo/bacino di retro-arco» dove coesistono magmi di tipo IAB e OIB. I magmi IAB sono i più diffusi, sia in ambiente di arco che di retro-arco, mentre i magmi OIB si rinvengono in poche aree. Una sintesi delle caratteristiche geochimiche ed isotopiche dei magmi sottomarini di quest'area viene presentata e include dati riguardanti le vulcaniti recuperate durante le recenti campionature dei vulcani sottomarini e del fondale marino di quest'area. I dati petrologici delle lave più basiche sono stati esaminati con lo scopo di caratterizzare le sorgenti mantelliche dei magmi IAB e OIB. Questi dati forniscono importanti informazioni sia sulla petrogenesi del magmatismo sottomarino del Tirreno meridionale che sul possibile scenario geodinamico che ha controllato la coesistenza in quest'area di magmi IAB e OIB.

PAROLE CHIAVE: *Tirreno meridionale, magmi calcalcalini, magmi alcalini.*

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INTRODUCTION

The southern Tyrrhenian region is a recent active volcanic back-arc basin where a dominantly Island Arc Basalt (IAB)-type magmatism co-exists with Ocean Island Basalt (OIB)-type magmas (Selli *et al.*, 1977; Barberi *et al.*, 1978; Colantoni *et al.*, 1981; Beccaluva *et al.*, 1982, 1985; Robin *et al.*, 1987; Ellam *et al.*, 1989; Beccaluva *et al.*, 1990; Serri, 1990;

Francalanci and Manetti,1994; Serri *et al.*, 2001; Calanchi *et al.*, 2002) (Fig. 1). IAB-type magmas occur in both arc and back-arc tectonic settings and they have been erupted in the Aeolian volcanic arc; from the Marsili, Palinuro and Aeolian seamounts; and floor the

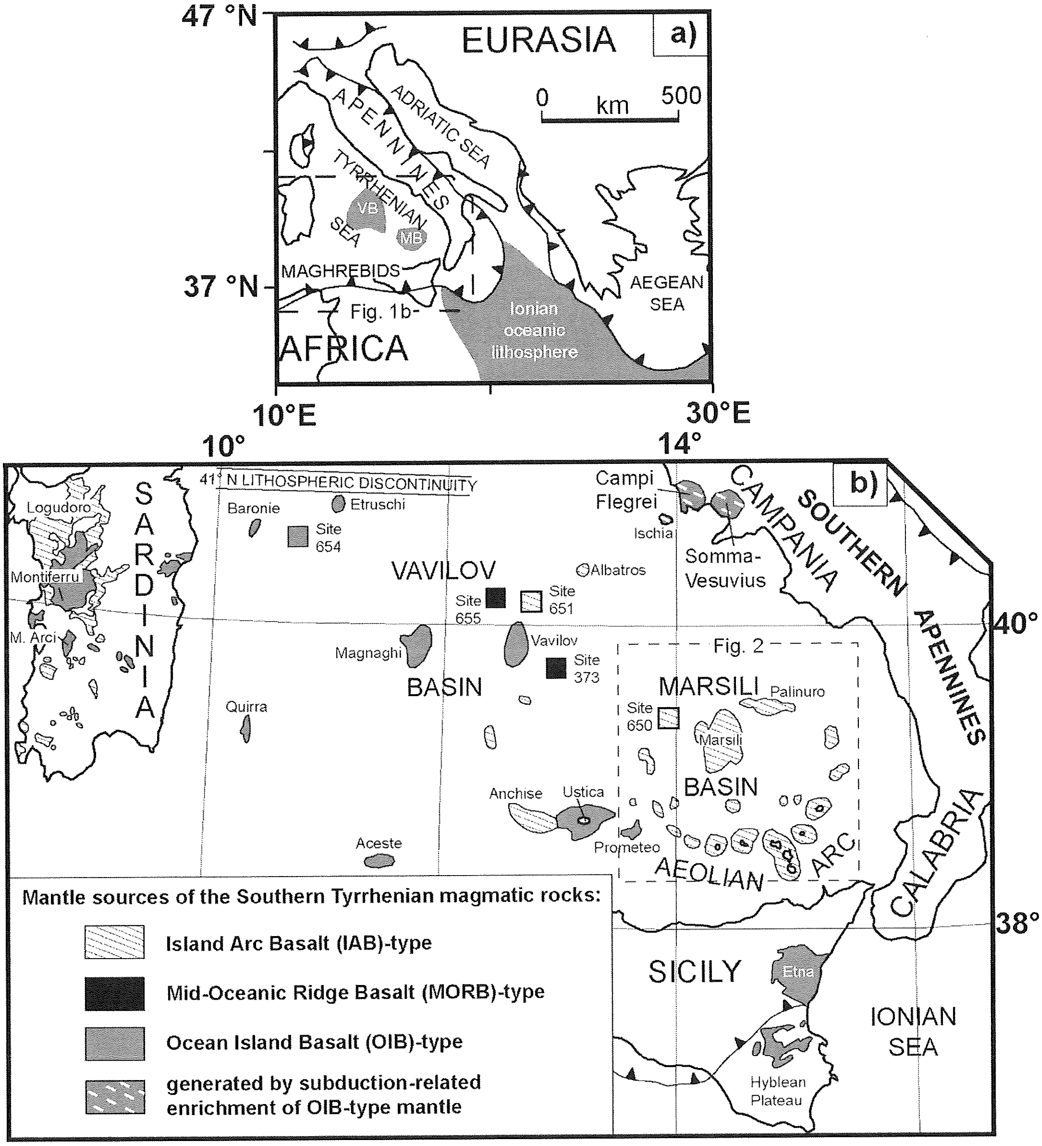

Fig. 1 – a) Outline schematically showing the main thrust fronts (barbed line) that bound Neogene fold and thrust belts of the central Mediterranean region (modified after Marani and Trua, 2002). VB, Vavilov basin. MB, Marsili basin. b) Schematic map of the Cenozoic magmatic rocks of the southern Tyrrhenian region according to their inferred dominant magma sources (modified after Serri *et al.*, 2001).

basement of the Marsili and Vavilov basins. By contrast with the extensive IAB-type magmatism, the OIB-type products are restricted to a few isolated volcanic areas. Prior to recent oceanic cruises (MAR98 and TIR2000, discussed below), the known southern Tyrrhenian OIB-type volcanic areas were: the Magnaghi, Vavilov, and Aceste seamounts; Ustica island; rocks drilled, dredged and cored in the East Sardinia rifted margin (Fig. 1). During the MAR98 and TIR2000 cruises on board the Consiglio Nazionale delle Ricerche (CNR) ship R/V Urania a detailed sampling by dredging and coring was undertaken of the southern Tyrrhenian submarine areas. The sampling revealed the presence of a previously unknown OIB-type submarine lava field, named Prometeo, located between Ustica and Alicudi islands (Trua *et al.*, 2003) (Figs. 1 and 2).

We review here the research carried out on the southern Tyrrhenian submarine volcanism since the pioneer seamount/seafloor explorations carried out in the last 30 years (Selli *et al.*, 1977; Barberi *et al.*, 1978; Colantoni *et al.*, 1981; Beccaluva *et al.*, 1985; Robin *et al.*, 1987; Beccaluva *et al.*, 1990). In this framework, special attention will be given

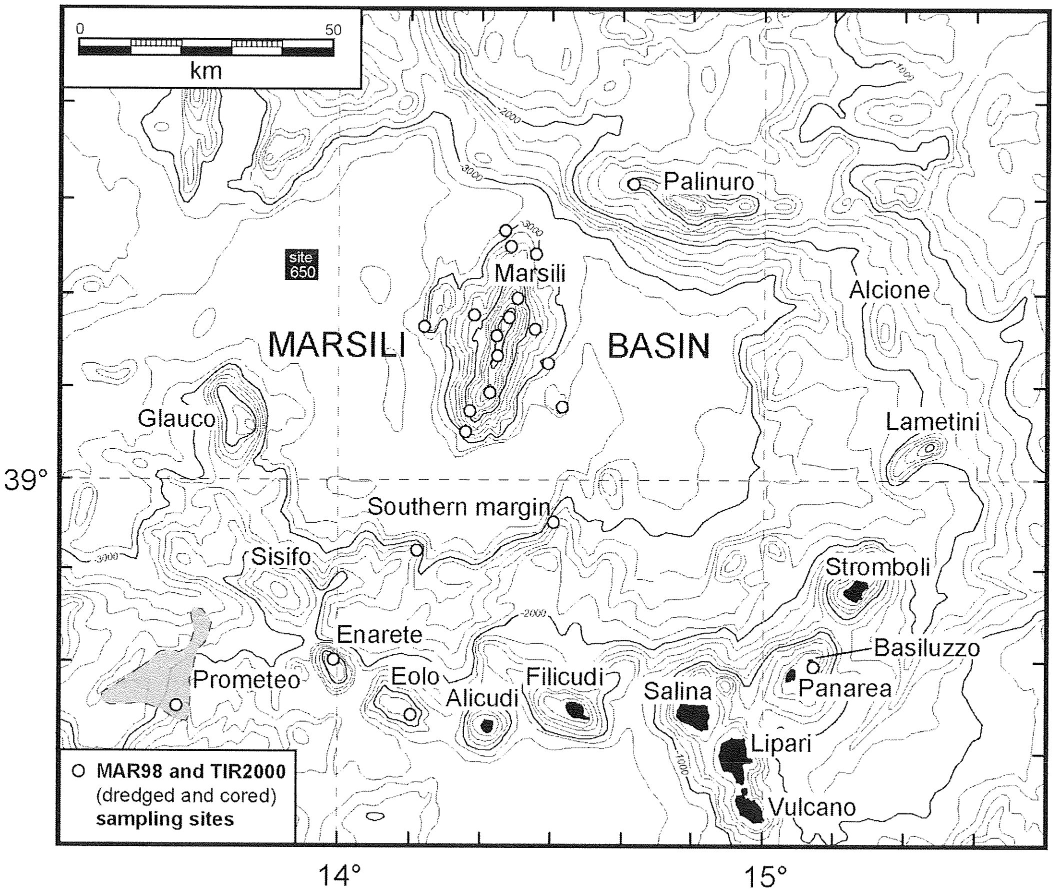

Fig. 2 – Sampling areas of MAR98 and TIR2000 cruises discussed in the text (modified after Marani *et al.*, 1999). Isobaths every 200 m.

to the petrologic data from the recent studies of the Marsili seamount, the largest seamount in the Tyrrhenian Sea, and the Prometeo lava field. We show how the geochemistry and isotopic characteristics of the more basic southern Tyrrhenian submarine lavas *i)* provide constraints on the mantle sources of the magmas, *ii)* can be used to understand the relationships between distribution of IAB- and OIB-type magmatism, and *iii)* can be used to discern the tectonic processes of this complex area.

BACKGROUND

The Tyrrhenian back-arc basin, which developed within the overall context of slow convergence (4-7 mm/year) between African and Euroasian plates (Rosenbaum *et al.*, 2002 and references therein), is separated by Serri (1990) into distinct northern and southern geological domains by the 41°N Lithospheric Discontinuity zone (Fig. 1). These regions have undergone a different structural evolution since 15 Ma. In the northern region, delamination and foundering of the Adriatic continental lithosphere occurred as a consequence of the continental collision between the Corsica block and Adriatic continental margin. The evolution of the southern region was characterized by the roll-back subduction of an old oceanic (Ionian) lithosphere and back-arc extension of the southern Tyrrhenian Sea (Serri, 1990; Serri, 1997).

The southern Tyrrhenian region reached a mature oceanic stage with the diachronous opening of the Vavilov (4.3-2.6 Ma) and Marsili (2.0-1.8 Ma) ocean-floored back-arc basins (Kastens *et al.*, 1990). Most authors agree that this diachronous opening was related to the very rapid acceleration in the subduction roll-back of the Ionian oceanic lithosphere below the southern Tyrrhenian (Kastens *et al.*, 1988, 1990; Sartori, 1990; Gueguen *et al.*, 1998; Serri *et al.*, 2001). In step with back-arc basin development, the subduction related magmatism of the southern Tyrrhenian region migrated from west to south-east, from Sardinia (32-13 Ma) to the currently active Aeolian island arc (Serri *et al.*, 2001 and references therein) (Fig. 1).

Southern Tyrrhenian magmatism is characterized by the coeval eruption of IAB- and OIB-type lavas. IAB-type magmatism is by far the most common in both arc and back-arc settings. Calc-alkaline (CA) and shoshonitic (SHO) suites dominate the submarine and subaerial magmatism of this region, notably the Marsili (ODP site 650) and Vavilov (site 651) basins, the Marsili seamount, the Anchise seamount, and the Aeolian islands and related seamounts. Arc tholeiites (A-Th) have been only recovered from Lametini seamount but these rocks also seem to be present along the lowermost northern Aeolian slope, interpreted by Marani *et al.* (1999) as the faulted southern margin of the Marsili Basin. Transitional Mid Oceanic Ridge Basalts (TMORB) have been recovered from the Vavilov basin (sites 655 and 373). Both A-Th and TMORB are absent among the subaerially erupted lavas. Potassic rocks (KS) are present at two Aeolian volcanoes (*i.e.*, Vulcano and Stromboli), along the eastern margin of the southern Tyrrhenian Sea (*i.e.*, Phlegrean Fields and Mt. Somma-Vesuvius volcano), and probably in the Albatros seamount. By contrast, OIB-type magmas are restricted to few areas: the Magnaghi, Vavilov and Aceste seamounts; rocks drilled (site 654), dredged, and cored in the East Sardinia rifted margin; at Ustica island; and in the Prometeo submarine lava field (Figs. 1 and 2).

Mantle sources beneath the southern Tyrrhenian region

Because much of the discussion that follows will focus on IAB- and OIB-type magmas, it would be useful to summarise the diagnostic features of these two distinct magma types.

IAB magmas: IAB-type magmas can range in character from those resembling magmas formed by partial melting of the depleted mantle (DM) at a mid-ocean ridge (mid-ocean ridge basalt (MORB)-like) to those approaching magmas generated by interaction of subducted lithosphere with the mantle wedge in a subduction zone (arc-like) (*e.g.,* Wilson, 1989). Many subduction-related magmas exhibit a distinctive trace element signature, namely high «large ion lithophile element» (LILE) and low «high field strength element» (HFSE) contents relative to normal MORB (NMORB). Such geochemical signature testifies to the contributions of subducted sediments and/or altered oceanic crust that occurred via aqueous or silicate fluids to the mantle source of IAB-type magmas (Pearce and Parkinson, 1993). The composition of IAB-type basalts erupted in the southern Tyrrhenian region range from those with a MORB-like character to those resembling arc-like magmas (Figs. 1 and 3).

OIB magmas: OIB-type magmas are particularly variable in composition and several isotopically distinct OIB-type mantle-derived components (*e.g.,* EMI, EMII, HIMU, FOZO, C; Hofmann, 1997) are required to explain their variability. Among these mantle components, an HIMU (high-μ)-like mantle component dominates the most primitive southern Tyrrhenian OIB-type magmas, *e.g.* those erupted at Ustica and Prometeo (Trua *et al.*, 2003).

IAB-TYPE SOURCES

Magmas with geochemical and isotopic features compatible with a generation by partial melting of IAB-type sources dominate both the submarine and subaerial magmatism of the southern Tyrrhenian region during the last 2 Ma. IAB-type magmas occur within the Vavilov and Marsili basins, at the Marsili seamount, and in the Aeolian islands and associated seamounts.

The seafloor of the Vavilov basin was drilled during the ODP and DSDP projects (sites: 655, 373, 651; Barberi *et al.*, 1978; Beccaluva *et al.*, 1990). Most of Vavilov Basin samples have suffered a variable degree of hydrothermal alteration that prevents from inferring their magmatic affinity from the total alkalis vs. silica (TAS) or K_2O *vs.* SiO_2 diagrams (Figs. 3 and 4). However, ratios of elements only slightly affected by secondary mobilization (*i.e.*, Ti, Zr, Hf, Nb, Ta, Y, and Rare Earth Elements (REE)) of the least altered samples have been used for this purpose (Barberi *et al.*, 1978; Beccaluva *et al.*, 1982; Beccaluva *et al.*, 1990; Serri, 1990).

Compared to NMORB, basalts recovered at Sites 655 and 373 have high Cs, K, Pb respect

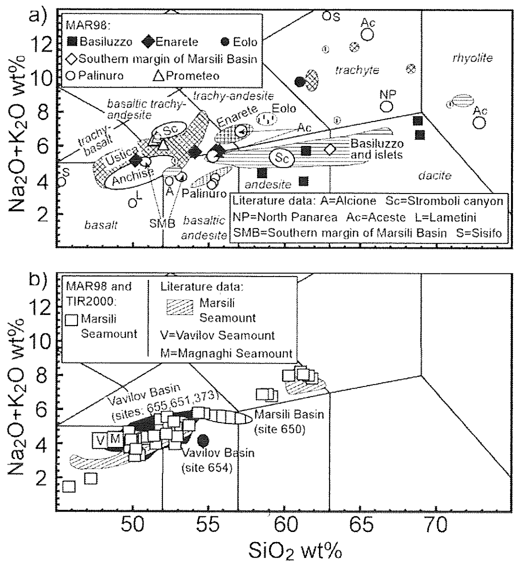

Fig. 3 – Total alkalis-silica diagram (Le Bas *et al.*, 1986) for Neogene-Quaternary southern Tyrrhenian volcanic rocks. MAR98 and TIR2000 data from Trua *et al.* (1999), Trua *et al.* (2002 c) and Table 2 (this work). Other data: Sisifo, Alcione, Lametini, Stromboli canyon, Southern Margin of Marsili Basin, Enarete and Eolo (Beccaluva *et al.*, 1985); Palinuro (Colantoni *et al.*, 1981; Beccaluva *et al.*, 1985); Aceste (Beccaluva *et al.*, 1984); Ustica (Calanchi *et al.*, 1984; Cinque *et al.*, 1988; Trua *et al.*, 2003); Vavilov and Magnaghi seamounts (Selli *et al.*, 1977; Robin *et al.*, 1987; Serri, 1990); Marsili seamount (Selli *et al.*, 1977; Savelli and Gasparotto, 1994); Anchise (Calanchi *et al.*, 1984); Vavilov Basin, sites: 373, 651, 654 and 655 (Barberi *et al.*, 1978; Beccaluva *et al.*, 1982; Beccaluva *et al.*, 1990; Serri, 1990; Gasperini *et al.*, 2002); Marsili Basin, site 650 (Beccaluva *et al.*, 1990); Basiluzzo and associated islets (Calanchi *et al.*, 1999). Note that Marsili basin, Sisifo and Southern Margin of Marsili Basin samples, although reported in this classification digram, are too altered (*i.e.,* LOI>3 wt%) to be classified according to these chemical parameters.

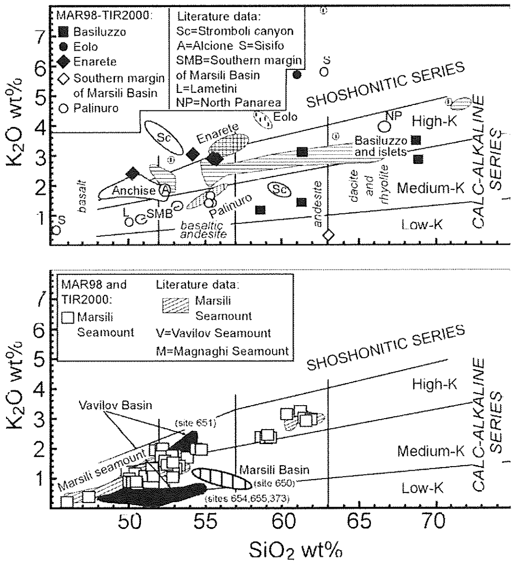

Fig. 4 – K_2O vs SiO_2 diagram, showing the major subdivision of the island-arc volcanic rock suites (Wilson, 1989), for the Neogene-Quaternary Southern Tyrrhenian volcanic rocks. Data source as in Fig. 3.

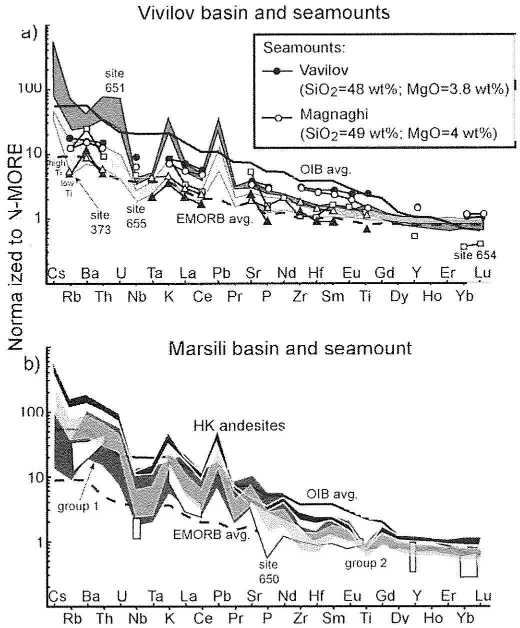

Fig. 5 – Normal MORB (N-MORB) normalized incompatible element variation diagrams (normalizing values from Sun and MacDonough, 1989) for: a) Vavilov basin and seamounts lavas; b) Marsili basin and seamount lavas. Southern Tyrrhenian data source as in Fig. 3. Average OIB (thick line) and E-MORB (dashed line) from Sun and McDonough (1989).

to Nb, Ta (Fig. 5a), although none of these characteristics are as pronounced as they are in the samples from site 651. It is worth noting that only the basalts from sites 655 and 373 (high-Ti basalts) show light REE (LREE) enrichment ($1<(La/Sm)_N<1.5$, using the normalizing values for chondrite from Sun and McDonough, 1989), Zr/Nb ratios (16<Zr/Nb<25), and isotopic features (Fig. 6) typical of TMORB. Moreover, only one sample from site 655, that has the lowest Zr/Nb ratio (=16), shows a slight LREE depletion ($(La/Sm)_N=0.88$) approaching NMORB more than any other Tyrrhenian sea basalt (Beccaluva *et al.*, 1990). According to Beccaluva *et al.* (1982, 1990), the geochemical features of 373 site-low Ti basalts, as well as those of basic rocks from the more recent axial part of Vavilov basin (site 651: high K-CA basaltic andesites; Fig. 4), may result from the addition of a small amount of subducted slab fluids to a TMORB type mantle source akin to that of Sites 655 and 373 (high-Ti) basalts. The Sr-Nd isotopic compositions of Sites 655 and 651 rocks are distinct from the rest of the southern Tyrrhenian primitive rocks with MgO>5 wt% (Fig. 6). The hydrothermal alteration suffered by these samples did not affect their Nd isotopic compositions, which approach that of Mid Atlantic Ridge EMORB, whereas their Sr isotopic ratios have been modified by basalt/seawater interaction (Fig. 6).

The Marsili back-arc basin is located southeast of the Vavilov basin. ODP drill hole 650 (Figs. 1 and 2) recovered medium K-CA basaltic andesitic lavas at ca. 4100 m b.s.l. from the external (*i.e.* oldest) part of the basin (Beccaluva *et al.*, 1990; Kastens *et al.*, 1988, 1990). Although these samples have suffered strong hydrothermal alteration, they are characterized by a NMORB-normalized incompatible element pattern with a relative enrichment of Rb, Ba, Th, K in respect to Nb

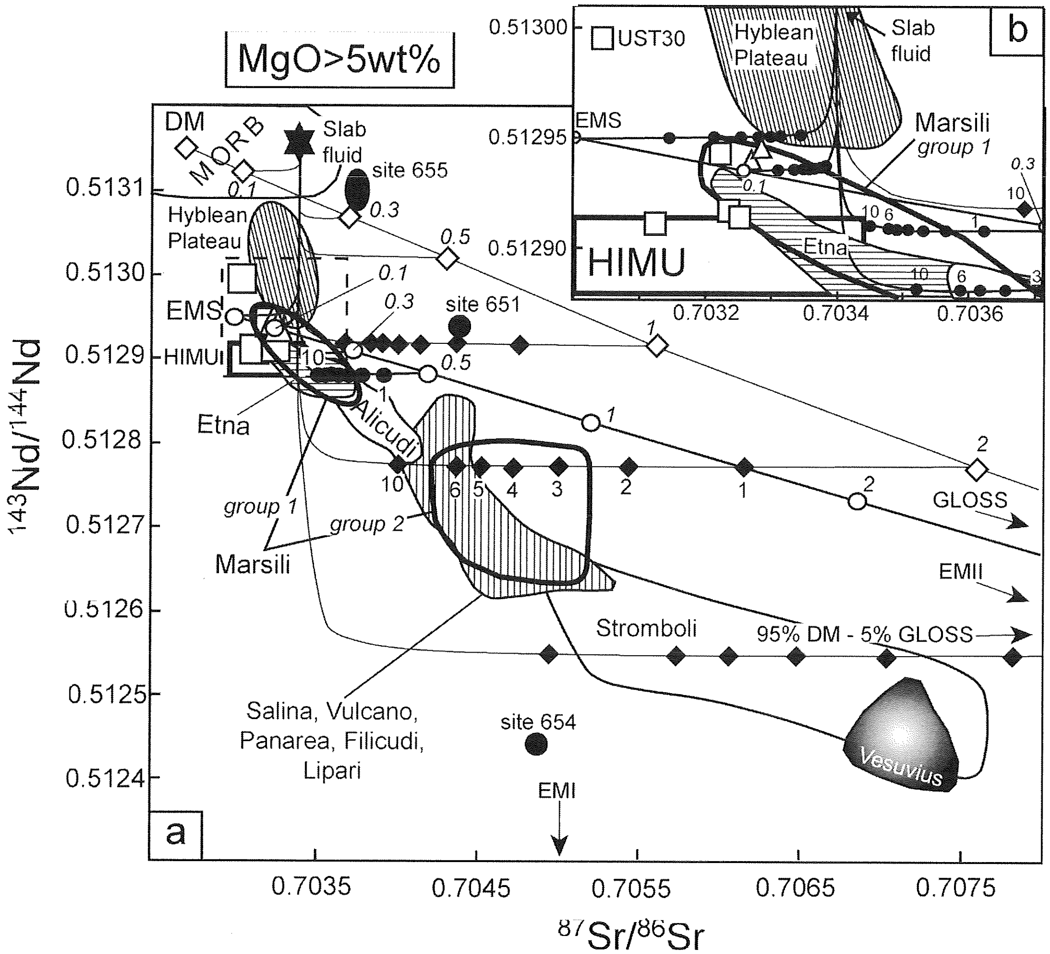

Fig. 6 – a) $^{87}Sr/^{86}Sr$ *vs.* $^{143}Nd/^{144}Nd$ diagram for Neogene-Quaternary southern Tyrrhenian and African foreland lavas (MgO>5 wt%) compared with model calculations. The dashed frame marks the location of (b). OIB Ustica (empty squares) and Prometeo (empty triangles) (Trua *et al.*, 2003); Marsili (Trua *et al.*, 2002 a,b); Vavilov Basin: sites 651, 654, 655 (Beccaluva *et al.*, 1990); Alicudi, Filicudi, Salina, Lipari, Vulcano, Panarea and Stromboli (Ellam *et al.*, 1988, 1989; Francalanci *et al.*, 1993; Peccerillo *et al.*, 1993; De Astis *et al.*, 2000; Calanchi *et al.*, 2002); Hyblean OIB-type alkaline rocks (Trua *et al.*, 1998); recent Etnean lavas (Tonarini *et al.*, 2001a); Vesuvius (Ayuso *et al.*, 1998; Somma *et al.*, 2001). MORB field (Wilson, 1989). HIMU, EMI and EMII: OIB end-member mantle components (Zindler and Hart, 1986). As the composition of Ionian Sea sediments is not available, we have used the estimated global subducting sediment composition (GLOSS, from Plank and Langmuir, 1998) in the mixing model. In this model, an enriched mantle source (EMS) or a depleted mantle source (DM) is mixed with slab sediments and fluids derived from the altered oceanic crust. The EMS is isotopically similar to that invoked for the genesis of Etnean OIB lavas (Tonarini *et al.*, 2001a) and geochemically similar to the OIB-source peridotite having an HIMU signature (Reiners *et al.* 2000; Tonarini *et al.*, 2001a). The end-member compositions used in the source bulk mixing calculations are the same reported in Trua *et al.* (2003). Numbers along the mixing curves represent the contribution (percentages) of slab-derived fluids (filled dots and diamonds) and GLOSS (empty dots and diamonds) with enriched and depleted sources, respectively. Note that all the southern Tyrrhenian Quaternary lavas have $^{143}Nd/^{144}Nd$ ratios lower than those obtained by mixing of DM source with a contribution of 0.1%, 0.3% and 0.5% GLOSS and slab derived fluids. It is clear that these three mixing curves are not able to explain the genesis of southern Tyrrhenian Quaternary lavas, therefore they are not marked with filled diamonds in this figure and are not reported in Fig. 10.

(Fig. 5b) and have similar geochemical composition to CA lavas drilled from the basement of Vavilov basin (site 651). These geochemical features may be due to the interaction of subducted slab fluids with a TMORB type mantle source akin to that involved in the genesis of Vavilov basin oceanic crust (Beccaluva *et al.*, 1990). Unfortunately, it is not possible to isotopically compare the oceanic crust of Marsili and Vavilov basins because the isotopic data for the former are lacking.

The Marsili seamount, which is the most stately IAB-type submarine volcanic edifice in the southern Tyrrhenian area, is located in the central, youngest part of the Marsili back-arc basin (Fig. 1). The new, more thorough, sampling of the Marsili seamount (Fig. 2) recovered only CA volcanic rocks (Table 1), ranging from basalts and basaltic andesites to trachyandesites in terms of the TAS diagram (Fig. 3). On the K_2O vs. SiO_2 diagram, the basalts plot within the medium-K CA series, whereas the basaltic andesites range between the medium-K and high-K CA fields (Fig. 4). The evolved trachyandesites, which were erupted only from small cones on the summit axial zone of the volcano, plot within the high-K CA andesite field (Fig. 4). Petrological and geochemical characteristics of the least differentiated Marsili CA basalts reveal that at least two types of magmas have been erupted on the volcano (Trua *et al.*, 2002a,b,c): *group 1* basalts have plagioclase and olivine as dominant phases (Table 1) and show lower Al, Ca, K, Ba, Rb, and Sr but higher Fe, Na, Ti, and Zr with respect to *group 2* basalts, which include the presence of clinopyroxene as additional phenocryst phase (Table 1). Compared to NMORB, both types of magmas have high LILE and LREE respect to HFSE (Fig. 5b). These geochemical deviations from MORB are typical of IAB lavas. Nevertheless, the two lava groups exhibit very different LILE/HFSE ratios (*i.e.*, *group 1* basalts have Ba/Nb=20 whereas *group 2* basalts have Ba/Nb which ranges from 30 to 80) and only *group 2* basalts display NMORB normalized patterns similar in shape, but enriched in all the incompatible elements, respect to the low-lying CA oceanic crust (site 650) of the Marsili basin (Fig. 5b). We have analysed Sr-Nd isotopic compositions of samples representative of the geochemical range defined by Marsili basalts (Trua *et al.*, 2002 a,b). These represent the first isotopic data for Marsili seamount lavas. Respective isotope ratios of Sr and Nd for the Marsili lavas range from 0.70322 to 0.70511 and 0.51266 to 0.51293 (Fig. 6). Among the Marsili samples, *group 1* basalts have the lowest $^{87}Sr/^{86}Sr$ ratios and the highest $^{143}Nd/^{144}Nd$ ratios. These lavas are very similar to Alicudi lavas, which represent the least radiogenic composition of the entire Aeolian Arc. On the other hand, *group 2* basalts tend to have more enriched Sr and Nd isotopic ratios, *i.e.*, displaced toward the arc values and isotopically similar to CA rocks from the other Aeolian islands.

The Marsili high-K andesites display NMORB normalized patterns similar in shape to the *group 2* basalts, but are enriched in all the incompatible elements (Fig. 5b). Interestingly, these evolved rocks show less variable Sr and Nd isotopic ratios, which are similar to *group 2* basalts. According to fractional crystallization calculations, they can be derived exclusively from a low-pressure fractionation of magmas, compositionally similar to the least evolved *group 2* basalts (Trua *et al.*, 2002c).

The Marsili basin is bounded to the northeast by the E-W trending Palinuro seamount and to the southeast by the active Aeolian volcanic arc (Fig. 1). The Palinuro seamount is a volcanic complex consisting of five coalesced edifices (Marani *et al.*, 1999). It is located in a crucial position between the oceanic-crust floored Marsili basin and the Campanian-Calabrian continental slope (Fig. 1). Despite the fact that it represents one of the main volcanic complexes in the Tyrrhenian region, it was poorly studied from a petrological point of view. Among the few samples recovered from the seamount during previous seafloor explorations, only two have been chemically

TABLE 1

Synthetic petrographic features of dredged and cored volcanics from the southern Tyrrhenian basin during MAR98-TIR2000 cruises and comparison with literature data.

Locality	Magma series (1)	Rock type (2)	Phenocrysts and micro-phenocrysts (3)	Age (Ma) (4)	Reference
Marsili seamount	CA	MK-/HK-B and BA	*group 1:* pl, ol, opq *group 2:* pl, ol, cpx, opq	0.7-<0.1	Selli *et al.*, 1977; Serri, 1990; Savelli and Gasparotto, 1994; Trua *et al.*, 2002c
		HK-A	pl, cpx, opq ±opx ±ol		
Eolo seamount	SHO	B	pl, cpx, ol, ap	0.85-0.66	Beccaluva *et al.*, 1985; Trua *et al.*, 1999
		S	pl, cpx, bt, opx, ol, opq, ap		
		L	pl, cpx, ol, opq, ap ±bt ±opx		
		T	pl, bt, ap, opq		
	CA	HK-D	pl, hb, cpx, bt, opx, opq, ap		
		R	pl, bt, cpx, opq, ap		
Enarete seamount	SHO	B	pl, bt, cpx	0.78-0.67	Beccaluva *et al.*, 1995; Trua *et al.*, 1999
		S	pl, bt, cpx ±opx, ±opq, ±ap		
Basiluzzo and islets	CA	MK-/HK-A	pl, cpx, opx, hb, opq	0.05	Calanchi *et al.*, 1999 Trua *et al.*, 1999
		MK-/HK-D	pl, cpx, opx, hb, opq		
		HK-R	pl, cpx, hb		
Palinuro seamount	CA	MK-BA	pl, cpx, opx, ol, opq	0.35	Colantoni *et al.*, 1981; Trua *et al.*, 1999
SMB	TH	B	pl, cpx, ol	n.a.	Beccaluva *et al.*, 1985; Trua *et al.*, 1999
	CA	tonalite	qz, pl, opq		
Prometeo	A	Mug	pl, ol, cpx, opq	n.a.	Trua *et al.*, 1999; Trua *et al.*, 2003
Ustica	A	B	pl, ol, cpx	0.75-0.13	Calanchi *et al.*, 1984; Cinque *et al.*, 1988; Serri, 1990; de Vita *et al.*, 1998
		Haw	pl, ol, cpx		
		Mug	pl, ol, cpx, opq		

SMB=Southern margin of Marsili Basin. (1) A= alkaline; CA= calcalkaline; TH= tholeiitic; SHO= shoshonitic. (2) LK-= low K; MK-= medium K; HK-= high K; B= basalt, BA= basaltic andesite; A= andesite; D= dacite; R= rhyolite; S=shoshonite; L=latite; T=trachite; Haw= hawaiite; Mug= mugearite. (3) ol=olivine, opx=orthopyroxene; cpx=clinopyroxene, pl=plagioclase, bt=biotite, hb=hornblende, opq=opaque, ap=apatite, qz=quartz. (4) n.a.=not available.

studied (Colantoni *et al.*, 1981). Furthermore, as illustrated in Fig. 2, only three volcanic samples were recovered from the summit and on the south-eastern flank of the Palinuro volcanic complex during the MAR98 cruise (Marani *et al.*, 1999) and chemical analyses of these samples are given in Table 2. Our samples from Palinuro belong to the CA series and have a basaltic andesite composition similar to that observed for rocks previously studied from this seamount (Fig. 4).

The Quaternary Aeolian arc comprises seven major volcanic islands and several submarine volcanoes that continue the arc westwards and northwards. Few samples recovered during the MAR98 cruise come from the Eolo and Enarete seamounts (Fig. 2) located west of the emerged Aeolian arc (Fig. 1) and oriented in a WNW-ESE direction (Marani *et al.*, 1999). The chemical composition of these rocks is shown in Table 2. On the K_2O *vs.* SiO_2 diagram, most of these samples plot in the SHO field and range from shoshonitic basalts (Enarete) to shoshonites (Enarete, Eolo) to latite (Eolo). Only few rocks display a high-K CA affinity and a basaltic andesite (Enarete) or dacite composition (Eolo) (Fig. 4). Few samples have been also dredged from the submarine area nearby the rhyolite dome of Basiluzzo in the Aeolian Islands (Fig. 2). The chemical composition of recovered samples is shown in Table 2. These samples have a CA affinity and range from medium-K andesites up to medium- or high-K dacites in composition (Fig. 4).

Palinuro, Eolo, Enarete, and Basiluzzo samples closely resemble, both petrographically and geochemically, to previous samples recovered from these areas (Table 1; Figs. 3 and 4). All these samples display typical calc-alkaline signature, *i.e.* NMORB normalized patterns with enrichment of LILE and depletion of Nb, Ta, Ti (Fig. 7).

Few dredge hauls were made during MAR98 cruise in the poorly studied southern margin of the Marsili basin (Fig. 2). Fragments of volcanic microbreccia, basic lavas, and intrusive (tonalite, Table 1) rocks were recovered. Textural aspect of recovered tonalite samples reveals that they are not cumulates. Both lavas and the tonalite samples are affected by a strong degree of hydrothermal alteration, which is documented petrographically by the presence of abundant secondary minerals and reflected chemically in high LOI (from 4 up to 13 wt%). The less altered sample (tonalite, LOI=4wt%; Table 2) shows geochemical features similar to the low-K CA andesites (Fig. 4) and has incompatible trace element patterns similar to the tholeiitic basalts with IAB affinity previously recovered by Beccaluva *et al.*, (1985) from this area (Fig. 7). It is to note that these basalts represent, together with the tholeiitic basalt recovered from the North Lametini seamount, the only A-Th rocks so far recovered from the southern Tyrrhenian basin.

OIB-TYPE SOURCES

In the Southern Tyrrhenian, OIB-type magmas are restricted to the following volcanic areas: Ustica island; Prometeo lava field; Aceste seamount; rocks drilled, dredged, and cored in the East Sardinia rifted margin; the Magnaghi and Vavilov seamounts (Fig. 1).

Comprehensive trace elements and radiogenic isotope (Sr, Nd) data for Ustica and Prometeo lavas (Trua *et al.*, 2003) provide clear evidence about the chemical character of the OIB-type magmatism of this region (Table 1; Fig. 3). Both Ustica and Prometeo are formed from Na-alkaline rocks. Ustica lavas range in composition from alkaline basalts to hawaiites and mugearites, with few evolved trachytes (Beccaluva *et al.*, 1982; Cinque *et al.*, 1988; Trua *et al.*, 2003), whereas Prometeo samples consist of mugearites that are petrographically and geochemically similar to the mugearites of Ustica island (Trua *et al.*, 2003). These alkaline magmas show similar NMORB normalized patterns, with positive anomalies for LILE and LREE elements and a relative depletion in less incompatible elements (from Zr to Ti) compared to average OIB-magmas (Fig. 8). The high La/Nb (1.2-1.7),

TABLE 2

Major and trace element data of samples selected among those recovered during MAR98-TIR2000 cruises from the southern Tyrrhenian basin.

	Basiluzzo						Enarete	
Sample	**BAS8** (1)	**BAS4F** (1,2)	**BAS4C** (1)	**BAS9B** (1)	**BAS2F** (1)	**BAS12E** (1)	**ENAR4n** (1,2)	**ENAR1C** (1)
SiO_2	57.02	56.06	59.67	61.17	66.6	66.81	48.48	53.08
TiO_2	0.4	0.674	0.69	0.65	0.67	0.48	0.737	0.595
Al_2O_3	13.49	17.29	16.96	15.35	17.19	15.4	19.98	15.46
Fe_2O_3	3.97	5.99	5.54	5.57	1.97	2.95	8.67	7.26
MnO	0.1	0.11	0.11	0.09	0.02	0.07	0.13	0.22
MgO	3.49	3.08	3.53	4.36	0.47	1.09	4.31	6.17
CaO	4.64	8.17	6.89	6.53	3.11	2.86	8.76	9.32
Na_2O	5.05	3.12	2.47	2.69	3.68	3.89	2.66	2.54
K_2O	2.58	1.13	1.4	3.04	2.79	3.43	2.32	3.00
P_2O_5	0.18	0.15	0.13	0.15	0.13	0.16	0.46	0.37
LOI	9.09	4.24	2.61	0.4	3.36	2.87	3.57	2.34
Total	100.01	100.02	100.00	100.00	99.99	100.01	100.08	100.35
Mg_V*(3)				67.09				
Cs		5.16					0.34	
Sc		30					25	
V	45	240	235	181	173	86	253	200
Cr	5	61	55	123	29	8	69	152
Ni	4	12	12	30	12	8	34	59
Rb	96	44	62	104	76	125	37	97
Sr	343	485	454	374	408	391	723	725
Y	15	18.5	17	19	11	15	17.9	20
Zr	157	71	98	118	154	180	114	113
Nb	12	5.9	5	12	8	13	12.4	10
Ba	457	361	375	680	602	865	556	684
La	27	20	21	26	26	47	36	43
Ce	43	39	38	42	49	74	61	67
Pr		4.7					8	
Nd		18					30	
Sm		3.9					5.7	
Eu		1.04					1.68	
Gd		3.61					4.66	
Tb		0.57					0.65	
Dy		3.3					3.5	
Ho		0.69					0.68	
Er		1.96					1.84	
Tm		0.31					0.3	
Yb		1.87					1.77	
Lu		0.26					0.25	
Hf		2.1					3.2	
Ta		0.35					0.66	
Pb		9.5					14.8	
Th		6.2					12.9	
U		2.2					0.7	

TABLE 2 *(continued)*

	Enarete	(continued)	Eolo	SMB	Palinuro		
Sample	**ENAR1C2** (1)	**ENAR1C1** (1)	**EOLO1B** (1,2)	**MRG1** (1,2)	**PLN9A1** (1)	**PLN9A2** (1)	**PLN9A3** (1,2)
SiO_2	54.67	54.86	59.62	60.57	54.77	54.82	54.83
TiO_2	0.61	0.61	0.60	0.74	0.74	0.69	0.67
Al_2O_3	16.11	16.12	18.92	14.1	17.42	16.27	15.55
Fe_2O_3	6.73	6.8	5.07	7.59	8.04	7.84	8.13
MnO	0.24	0.29	0.03	0.09	0.13	0.14	0.15
MgO	6.1	5.67	0.93	4.21	5.79	6.45	6.15
CaO	8.07	8.21	2.82	3.07	8.36	8.41	9.64
Na_2O	2.76	2.73	3.92	5.3	2.31	2.71	2.12
K_2O	2.85	2.85	5.64	0.29	1.4	1.4	1.64
P_2O_5	0.34	0.34	0.2	0.11	0.17	0.13	0.18
LOI	1.52	1.52	2.48	4.33	0.87	1.14	1.19
Total	100.00	100.00	100.23	100.40	100.00	100.00	100.25
Mg_V*(3)	70.24	68.47			64.41	67.41	65.55
Cs			1.57	0.08			3.46
Sc			14	27			34
V	199	197	149	257	263	236	228
Cr	154	152	3.3	2.8	85	120	126
Ni	60	63	5.7	17	18	32	33
Rb	103	101	184	2.7	56	51	49
Sr	679	685	425	263	442	405	444
Y	19	18	25.2	23	22	22	23.5
Zr	117	117	242	17	124	122	116
Nb	10	9	19.2	2.5	12	12	12.5
Ba	680	675	584	65	531	550	558
La	41	46	46	5.6	36	38	33
Ce	73	73	81	12	74	80	65
Pr			8.6	1.7			7.7
Nd			30	7.9			29
Sm			5.4	2.4			6
Eu			1.44	0.8			1.34
Gd			4.2	3			5.12
Tb			0.7	0.57			0.76
Dy			4.1	3.8			4.2
Ho			0.86	0.8			0.82
Er			2.5	2.35			2.2
Tm			0.44	0.4			0.36
Yb			2.84	2.27			2.06
Lu			0.41	0.34			0.3
Hf			6	0.7			3.1
Ta			1.16	0.17			0.7
Pb			47	1.2			12.1
Th			21.8	0.8			10.3
U			6.5	0.3			2.9

SMB=Southern margin of Marsili Basin. LOI= total volatile lost on ignition. (1) Elements determined by XRF at the University of Pisa (analyst: M. Menichini). (2) Trace elements determined by ICP-MS at the University of Pisa (analyst: Dr. M. D'Orazio). Mg_V* =[Mg/(Mg+Fe^{2+})]*100, with Fe^{3+}/Fe^{2+} as suggested by Middlemost (1989). (3) Only for samples with LOI <2.

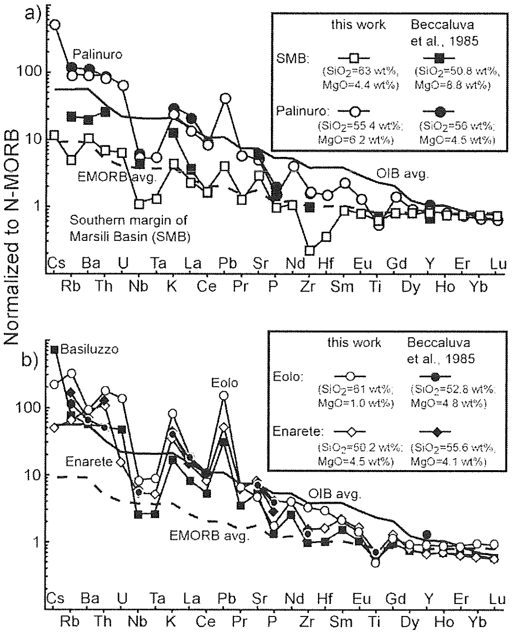

Fig. 7 – Normal MORB (N-MORB) normalized incompatible element variation diagrams (normalizing values from Sun and MacDonough, 1989) for: a) Palinuro seamount and Southern Margin of Marsili basin; b) Eolo and Enarete seamounts and Basiluzzo. Southern Tyrrhenian data source as in Fig. 3. Average OIB (thick line) and E-MORB (dashed line) from Sun and McDonough (1989).

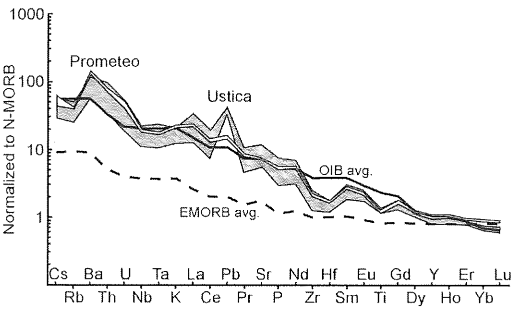

Fig. 8 – Normal MORB (N-MORB) normalized incompatible element variation diagrams (normalizing values from Sun and MacDonough, 1989) for Ustica and Prometeo OIB lavas (data source from Trua *et al.*, 2003). Southern Tyrrhenian data source as in Fig. 3. Average OIB (thick line) and E-MORB (dashed line) from Sun and McDonough (1989).

Th/Ta (3-4), and Pb/Ce (0.04-0.22) ratios of the Prometeo and Ustica alkaline lavas, compared to those of OIB-type lavas (Weaver, 1991; Elliot *et al.*, 1997), point to the involvement of a subduction-related component in the genesis of these lavas (Trua *et al.*, 2003). Prometeo and Ustica lavas have Sr- and Nd-isotopic compositions that are more consistent with OIB-type magmas than their trace-element characteristics (Fig. 6). These lavas exhibit a small range in $^{87}Sr/^{86}Sr$ (0.70304 to 0.70329) and $^{143}Nd/^{144}Nd$ (0.51300 to 0.51291) ratios approaching the isotopic composition of HIMU OIB-type basalts (Weaver, 1991). Interestingly, as shown in Fig. 6, an HIMU-type component is also present in the mantle source of the Plio-Pleistocene Hyblean and the most recent (post-1970) Etna OIB-type magmas (Beccaluva *et al.*, 1998; Trua *et al.*, 1998; Schiano *et al.*, 2001; Trua *et al.*, 2003), both erupted on the same side of the African plate adjacent to the subduction-related Aeolian island arc (Fig. 1). The discussion below will consider how this observation provides useful geochemical tracers to infer mantle structure beneath the southern Tyrrhenian basin.

It is difficult to compare Ustica and Prometeo samples to the other OIB-type volcanic areas of the southern Tyrrhenian region because comprehensive geochemical and isotopic studies for the latter are still lacking. Only few samples had been recovered during previous explorations from the two large central volcanoes of the Vavilov Basin, Magnaghi (3.0-2.7 Ma) and Vavilov (Late Pliocene - 0.1 Ma) seamounts, built after cessation of the seafloor-spreading tectonic regime (Selli *et al.*, 1977; Robin *et al.*, 1987; Kastens *et al.*, 1988, 1990; Savelli, 1988). These rocks are basalts (Fig. 3) that are more enriched in incompatible elements than EMORB and exhibit no LILE enrichment or HFSE depletion (Fig. 5a). According to Serri (1990) and references therein, the geochemical characteristics of basaltic rocks from the Vavilov and Magnaghi seamounts are compatible with a derivation by partial melting of an OIB-type mantle source. As shown in

Fig. 3,4, and 5a, incompatible trace element characteristics similar to Magnaghi and Vavilov basalts have been observed for basaltic andesite rocks recovered from the eastern Sardinia rifted margin (Site 654) in spite of their tholeiitic affinity (Serri, 1990). According to Serri (1990), a derivation from an OIB-type mantle source can be also suggested for these rocks.

Explanation of the coexistence of OIB- and IAB-type magmas in the southern Tyrrhenian

Trace element and isotopic data of the most primitive southern Tyrrhenian volcanic rocks (MgO>5.0 wt%) can be combined to address this central issue. These basic rocks approximate primitive magma compositions and offer a more detailed picture of the mantle sources of southern Tyrrhenian magma types. Our cutoff at 5.0 wt% of MgO, instead of a higher MgO content, was chosen to maximize the available literature data on the Neogene-Quaternary magmatism of this region. Some volcanic areas are still represented by relatively small numbers of analyses or there are no radiogenic isotope data.

Concentration ratios of incompatible trace elements and radiogenic isotopic ratios are very useful geochemical tools to characterize the mantle source regions of basaltic lavas (MORB, OIB, IAB) as the melt «copies» the tracer ratios from the source of the mantle from which derived and (at least) in oceanic environments it delivers them to the surface with little or no subsequent modification through magma-crust interaction. However, for detailed source characterization for IAB-type magmas the trace element ratios have to be suitable to discriminate between the effects of the intra-mantle melt-related trace element enrichment and the addition of slab-derived components in the mantle source. Pearce and Parkinson (1993) and Pearce and Peate (1995) advocated the use of a plot of the type Zr (as representative of a conservative element)/Yb vs. Nb/Yb to estimate the mantle source composition of IAB rocks, prior to its modification by slab-derived components. The great majority of southern Tyrrhenian IAB-type magmas plot within the MORB array in the Zr/Yb vs. Nb/Yb diagram, suggesting a derivation from sources enriched with respect to an average normal MORB and broadly comparable to T-/E-MORB sources (Fig. 9a). It is to be noted that only *group 1* Marsili basalts and Stromboli basic rocks have high Zr/Yb ratios approaching those of Prometeo, Ustica, and Vesuvius OIB-lavas. Nevertheless, the

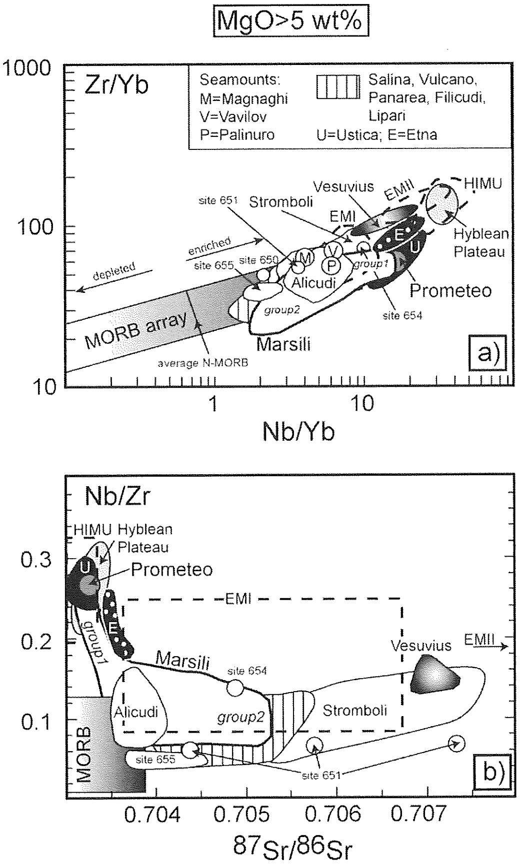

Fig. 9 – Regional variation of some key incompatible trace element ratios and $^{87}Sr/^{86}Sr$ ratios in mafic rocks (MgO >5 wt%) from the Neogene-Quaternary southern Tyrrhenian and African foreland volcanic areas. MORB array in Zr/Yb vs. Nb/Yb diagram (Pearce and Parkinson, 1993); HIMU, EMI and EMII OIB fields (Weaver, 1991; Zindler and Hart, 1986); Aeolian seamounts (Beccaluva *et al.*, 1985). Other data source as in Figs. 3 and 6.

mantle sources of these high Zr/Yb lavas have to be different, as emphasized by the $^{87}Sr/^{86}Sr$ vs Nb/Zr diagram (Fig. 9b). In this diagram, *group 1* Marsili basalts show high Nb/Zr and low $^{87}Sr/^{86}Sr$ similar to those of Prometeo and Ustica OIB-lavas, whereas Stromboli basic rocks have lower Nb/Zr and higher $^{87}Sr/^{86}Sr$ ratios approaching those of Vesuvius lavas. These observations show that different components are involved in the petrogenesis of the southern Tyrrhenian magmas. Systematic variations in $^{143}Nd/^{144}Nd$ or incompatible element ratios (such as Ba/Nb, Th/Nb, La/Nb) against $^{87}Sr/^{86}Sr$ among the southern Tyrrhenian mafic lavas (Fig. 10) give fundamental information on the nature of these components. Mafic rocks from each area display well-defined positive correlation of the incompatible element ratios (*i.e.*, Ba vs. Nb, Th vs. Nb, and La vs. Nb, not shown). This indicates that these ratios are not significantly fractionated during partial melting of the sub-oceanic mantle or during fractional crystallization. In addition, with negligible crustal contamination processes these ratios closely reflect those of their source.

Trends shown by southern Tyrrhenian lavas in $^{87}Sr/^{86}Sr$ *vs.* $^{143}Nd/^{144}Nd$ (Fig. 6), or *vs.* Ba/Nb, Th/Nb, and La/Nb diagrams (Fig. 10) are consistent with mixing between the following end-members: *(i)* an enriched mantle source (EMS) isotopically similar to that invoked for the genesis of Etnean OIB-like lavas (Tonarini *et al.*, 2001a); *(ii)* a depleted mantle (DM); *(iii)* subduction related components (*i.e.*, fluids derived from the oceanic crust, bulk melts derived from subducted sediments) (Figs. 6 and 10).

The mixing calculations of Trua *et al.* (2003) suggest that Ustica and Prometeo OIB-type magmas could have been produced by the mixing of an EMS with a small amount of *(i)* fluids derived from the altered oceanic crust (<2%) and *(ii)* bulk melt derived from subducted sediments (<0.1%). Similar subduction-related components have been already invoked in the genesis of southern Tyrrhenian IAB magmas (*i.e.* Aeolian Arc), but the mantle component of these magmas should range from DM to EMS (Tonarini *et al.*, 2001b and references therein). Interestingly, Marsili basalts have radiogenic isotope signatures and trace element ratios that plot along a continuous trend that extends from the Ustica and Prometeo OIB-type magmatism to the IAB-type magmatism of the Aeolian Arc (Figs. 6 and 10). Since Marsili seamount magmas erupted on oceanic crust, it is likely that they preserved the geochemical and isotopic features of their mantle-derived primitive precursors. Therefore, the geochemical and isotopic similarity between Marsili seamount lavas and Aeolian rocks suggest that the main compositional differences between primitive Aeolian magmas are mostly inherited from an heterogeneous «primitive» mantle source, metasomatized by subduction-related components, instead of having been acquired during shallow-level magma contamination.

A much more thorough investigation of the geochemical and isotopic variations of Marsili basalts is necessary to define the relative role of the different mantle sources involved in the magmatism of this seamount. However, some important preliminary observations arise from consideration of $^{87}Sr/^{86}Sr$ *vs.* $^{143}Nd/^{144}Nd$ ratios (Fig. 6). *Group 1* Marsili IAB-type basalts have significantly different Sr, Nd isotopic compositions to those of the remaining southern Tyrrhenian IAB lavas (*i.e.*, *group 2* Marsili basalts and Aeolian volcanic basic rocks) approaching the isotopic compositions of the Ustica and Prometeo OIB lavas. By contrast, *group 2* Marsili IAB-type basalts plot in the same field as the Aeolian IAB volcanic basic rocks, extending down to the field of Stromboli. Interestingly, the most primitive potassic rocks from Stromboli are geochemically and isotopically similar to the most primitive rocks of Vesuvius, which represents the southern end of the potassic magmatic belt of central Italy (Serri, 1990; Peccerillo, 2001). The similarity between Stromboli and Vesuvius rocks suggest they could be derived from similar mantle sources, *i.e.* an originally OIB-type mantle, whose

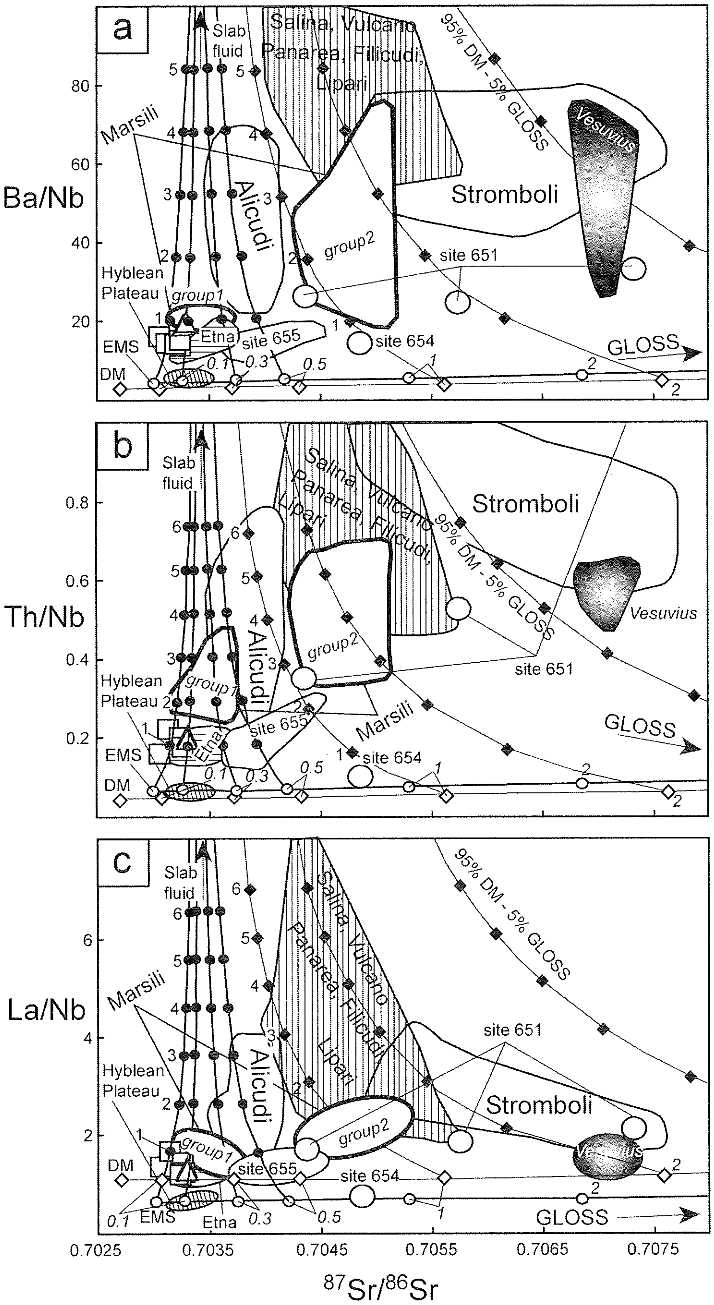

Fig. 10 – Trace element and isotopic variations in southern Tyrrhenian Quaternary OIB and IAB lavas and African foreland OIB lavas (MgO>5 wt%) compared to model calculations. a) Ba/Nb *vs.* $^{87}Sr/^{86}Sr$; b) Th/Nb *vs.* $^{87}Sr/^{86}Sr$; c) La/Nb *vs.* $^{87}Sr/^{86}Sr$. The end-member compositions used in the source bulk mixing calculations are the same reported in Trua *et al.* (2003). Mixing curves as in Fig. 3.

nature (HIMU, EMI, EMII) is still unclear, metasomatized by subduction-related fluids or melts (Serri, 1990; Beccaluva *et al.*, 1991; Peccerillo, 2001).

If this hypothesis is reasonable, the variations in Sr-Nd isotopes and $^{87}Sr/^{86}Sr$ vs. Ba/Nb, Th/Nb, La/Nb observed within the basic Marsili IAB-type lavas could also be modelled in terms of interaction between three mantle sources: *(i)* a pre-existing DM wedge (inferred by the samples drilled from the basement of the Vavilov basin); *(ii)* an EMS akin to that involved in the genesis of Ustica/Prometeo OIB magmas (HIMU-like) and *(iii)* a «subduction-related enriched OIB-type mantle» source whose melting gave rise to Stromboli and Vesuvius magmas.

Implications for mantle dynamics

The geochemical tracers discussed so far can be used to map mantle structure in the southern Tyrrhenian basin and represent a significant contribution to the debate on the recent geodynamics of mantle flow in this region (Gvirtzman and Nur, 1999; Doglioni *et al.*, 2001; Gasperini *et al.*, 2002; Trua *et al.*, 2003).

Geochemical and radiogenic isotope data reveal a similarity of OIB alkaline magmas across the Sicilian Maghrebide orogen, erupted on the African (Etna and Hyblean Plateau) and the southern Tyrrhenian (Ustica and Prometeo) lithospheres (Fig. 1). According to Trua *et al.* (2003), this similarity indicates the continuity of the OIB source mantle across the complex collisional African-European margin beneath the Sicilian continental lithosphere and the nearby Tyrrhenian oceanic lithosphere. These Authors explain the volcanic alignment defined by Ustica, Prometeo and Etna and the similarity of their erupted OIB-like magmas with the presence of a north-northwestward asthenospheric African mantle flow below and across the Sicilian Maghrebide orogenic root (Fig. 11). This flow would be channelled along the south-western edge of the Ionian oceanic plate, which is undergoing roll-back subduction. Such African mantle flow has been invoked to explain the genesis of Etna volcano

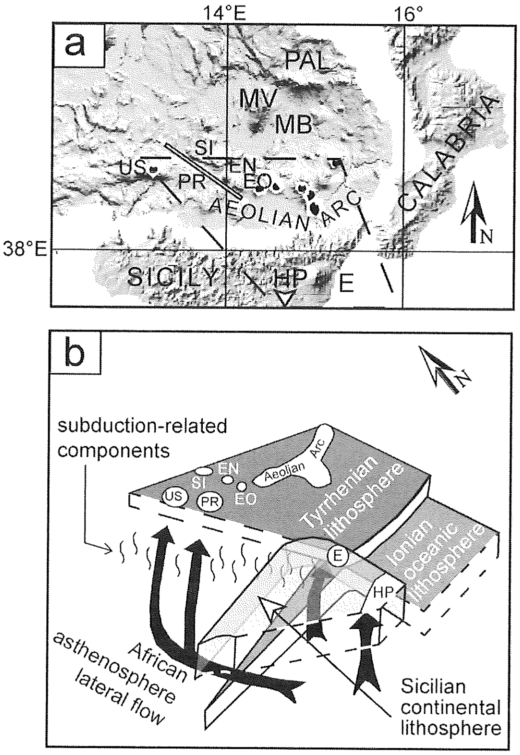

Fig. 11 – a) Shaded relief of the southern Tyrrhenian basin (modified after Marani and Trua, 2002) obtained from gridded swath bathymetry, illumination from 30°N, showing major offshore and land features discussed in the text: Ustica Island (US), Prometeo submarine lava flow (PR), Etna volcano (E), Hyblean Plateau (HP), Aeolian arc submarine volcanoes (Eolo (EO), Enarete (EN), Sisifo (SI) and Palinuro (PAL)), the ocean-floored Marsili back-arc basin (MB) and the Marsili volcano (MV) within it. EO, EN and SI seamounts define a volcanic alignment (shown by the offset white line) that could represent the surface track of the deep slab tear. The white arrow indicates the Hyblean Plateau location. The dashed frame marks the location of the sketch of Figure 1b. b) Three-dimensional sketch of the southern Tyrrhenian subduction zone (after Trua *et al.*, 2003). Black arrows represent local patterns of African mantle flow below and across the Sicilian continental lithosphere. Note that the volcanic activity of Etna volcano (<500 kyr, Gillot *et al.*, 1994), which postdates the Plio-Pleistocene fissure eruptions occurring on the northern edge of the Hyblean plateau (Trua *et al.*, 1998), is coeval to that of Ustica (750-130 kyr, de Vita *et al.*, 1998). Tyrrhenian lithosphere extension to the west is omitted for clarity of figure.

by Gvirtzman and Nur (1999) and Doglioni *et al.* (2001). The possibility that OIB-like magmas from Etna and Ustica could be associated with a first order lateral discontinuity of the subducted Ionian slab was first proposed by Beccaluva *et al.* (1982). The finding of the Prometeo OIB-like submarine lava field along the same NW-SE volcanic alignment strongly supports this idea, showing that lateral African asthenospheric flow extends into the southern Tyrrhenian back-arc region along a southern tear of the subducted Ionian plate (Marani and Trua, 2002).

The similarity between most of the geochemical features of the primitive magmas from Stromboli and Vesuvius in terms of their geochemical and radiogenic isotope signatures likely points to compositionally similar mantle sources (Peccerillo, 2001 and references therein). These mantle sources, which consist of a mixture of an OIB-type mantle and slab-derived components (Serri, 1990 and references therein; Peccerillo, 2001 and references therein), could be related to the inflow of asthenospheric mantle into the southern Tyrrhenian mantle-wedge along the northern edge of the subducting Ionian plate (Gvirtzman and Nur, 1999). However, detailed petrological studies on the poorly known submarine volcanic areas (e.g., Palinuro, Aceste, Anchise, Albatros, Alcione and Lametini) are required to better define the mantle dynamics and magma-generation processes occurring in this sector of the southern Tyrrhenian back-arc basin.

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