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Trace element and isotopic variations from Mt. Vulture to Campanian volcanoes: constraints for slab detachment and mantle inflow beneath southern Italy

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Abstract New Sr–Nd–Pb isotopic ratios and trace element data for volcanic mafic rocks outcropping along a E–W transect in southern Italy, from Mt. Vulture to Neapolitan volcanoes, are reported. The variation of LILE/HFSE, HFSE/HFSE and radiogenic isotopes along this transect indicates that all of these volcanoes contain both intra-plate and subduction-related signatures, with the former decreasing from Mt. Vulture to Campanian volcanoes. New data are also reported for the Paleocene alkaline rocks from Pietre Nere (Apulia foreland), which show isotopic ratios mostly overlapping the values for Mediterranean intra-plate volcanoes as well as the Eocene–Oligocene alkaline mafic lavas from the northern Adria plate. Pietre Nere provides evidence for an OIB mantle composition of FOZO-type, free of subduction influences, that is present beneath the Adria plate (Africa) before its collision with Europe. After this collision, and formation of the southern Apennines, westward inflow of mantle from the Adria plate to the Campanian area occurred, as a consequence of slab break off. Interaction of subduction components with inflowing Adria mantle generated hybrid sources beneath the Vulture–Campania area, which can explain the compositional features of both Mt. Vulture and the Campanian mafic rocks. Therefore, mafic magmas from these volcanoes represent variable degrees of mixing between different mantle components.

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Introduction

A wide spectrum of studies on the nature and distribution of Plio-Pleistocene magmatism in the Tyrrhenian basins and southern Italy have been published in the last two decades (e.g. Serri 1990; Savelli 2001; Peccerillo 2005 and references therein). These studies concur in the definition of an extreme variability of magma series characterizing the Italian peninsula, the Tyrrhenian basins and Sicily, from tholeiitic to ultra-potassic and undersaturated Na-alkaline. Magmatism in central-southern Italy (Fig. 1) is largely K-alkaline in character and carries variable subduction-related signatures, inherited from mantle source(s) metasomatised during one or more events (Peccerillo 1999, 2002 and references therein). Na-alkaline and intra-plate magmas are partially contemporaneous with subduction-related magmatism during the Quaternary period but have been erupted along the Adria-African margin from Sicily (Mt. Etna, Iblei) to northern Italy (Veneto Volcanic Province, VVP) since at least Eocene times (Fig. 1). Mt. Vulture volcano (0.73–0.13 Ma), which formed on the margin of the Apulia foreland, generated both Na- and K-rich magmas.

Most studies consider peri-Tyrrhenian magmatism in the light of the progressive shifting of volcanic activities from Tuscany to Campania, according to the general process of convergence between the African and European plates and eastward slab rollback. Spatial variations in magma compositions along this belt have been related to differences in the structure and composition of the underlying lithosphere (e.g. Peccerillo 2002 and reference therein), producing various primary melts. The efforts made to integrate the available petrological and geophysical data have identified different upper

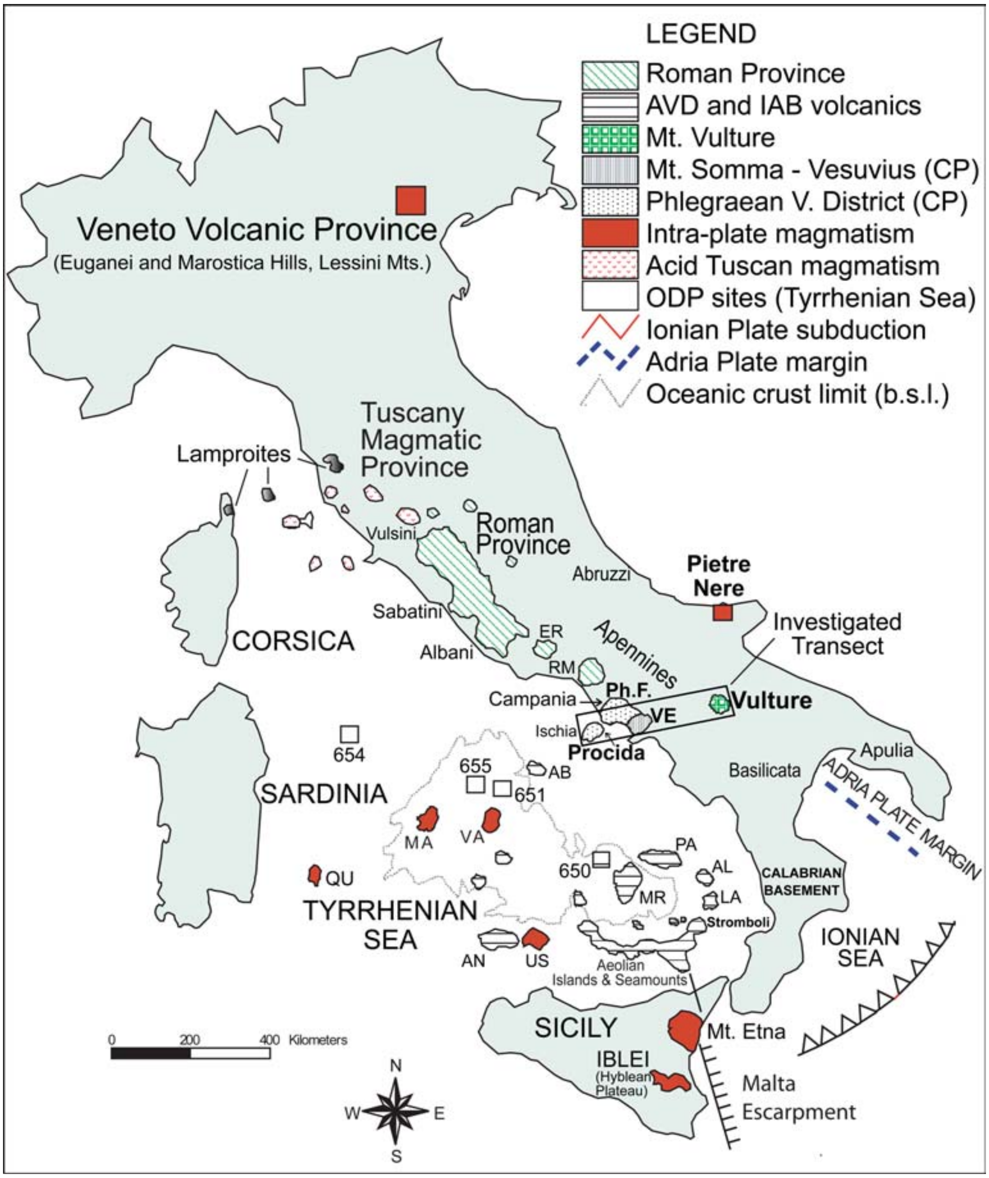

Fig. 1 Map of Italy and the Tyrrhenian Sea showing the studied transect relative to the main magmatic and geotectonic elements of the central-southern regions. Active subduction of the Ionian plate is limited to the region underneath the Calabria. ODP sites are designated by number. The peri-Tyrrhenian volcanism from Tuscany to AVD shows K-alkaline character. The Sardinian volcanism is not reported. Abbreviations: *CP* Campanian Province, *Ph.F.* Phlegraean Fields caldera, *AVD* Aeolian Volcanic District, *IAB* Island Arc Basalt, *AB* Albatros seamount, *AL* Alcione seamount, *AN* Anchise seamount, *ER* Mt. Ernici, *LA* Lametini seamount, *MA* Magnaghi seamount, *MR* Marsili seamount, *PA* Palinuro seamount, *QU* Quirra seamount, *RM* Roccamonfina volcano, *US* Ustica island, *VA* Vavilov seamount, *VE* Somma-Vesuvius

mantle domains (Peccerillo and Panza 1999; De Astis et al. 2003 and references therein). However, the debate on the relationship between geodynamics and magma genesis in central-southern Italy is still open. The nature of the upper mantle beneath southern Italy is not truly consistent with a simple subduction setting, and compositional data from the Mt. Vulture magmas have been considered to be ‘‘anomalous’’. Mt.Vulture shows an eruptive history overlapping those of several southern Italy volcanoes whose activity started during the Pleistocene (Phlegraean District, Somma-Vesuvius, Mt. Etna, Aeolian Islands). It lies on the border of the Apulia plate (Fig. 1), and so could be considered an intra-plate centre. However, the mafic rocks from this volcano have several trace element and isotopic features similar to those of subduction-settings, making it difficult to directly associate with an intra-plate mantle source. Moreover, some authors (De Astis et al. 2000; Peccerillo 2001) indicated that the potassic suites from Somma-Vesuvius and Phlegraean Fields, located on the western side of the Apeninnes (Fig. 1) share a common OIB-like signature with those from Stromboli island (Aeolian Islands—Fig. 1) located on the sector of the Aeolian arc where a NW-dipping Benioff zone is present. Furthermore, Serri (1990), Beccaluva et al. (1991) and Ayuso et al. (1998) also identified a contribution from an OIB source in the Vesuvius magmas and suggested that it represents the mantle beneath these volcanoes prior to a metasomatic event.

Overall, this evidence poses new questions that need answers to constrain the geodynamics and magma genesis beneath central-southern Italy. What is the ultimate origin of Vulture mafic magmas and what is the geodynamic significance of this ‘‘anomalous’’ volcano? What is the origin of the above mentioned OIB-like signature in both Campanian Province volcanoes and

Stromboli? Is there a possible genetic connection that accounts for the sequence of volcanic systems formed in southern Italy during the Pleistocene?

Here we present new geochemical and isotopic data for volcanic mafic rocks collected along a W–E transect extending from Procida Island (Phlegraean Volcanic District) through Vesuvius and to Mt. Vulture (Fig. 1). We also report new data for the Lower Paleocene alkaline mafic rocks of Punta delle Pietre Nere, which is located along the Adriatic coast (Fig. 1) and is believed to have been derived from a pristine, OIB-type mantle source (Hawkesworth and Vollmer 1979; De Astis et al. 2002) uncontaminated by subduction processes. The implications of these data for the nature of mantle beneath Italian peninsula and the geodynamic evolution of the southern Tyrrhenian region are discussed.

Geological and petrological framework

Volcanism of the central-southern Italy and Tyrrhenian Sea

The Central Mediterranean is a geologically complex region whose present state is the result of the collision between the African (plus Adria) and European plates over the last 30 Ma, associated with episodes of rifting and basin opening. Westward subduction of the continental Adria micro-plate resulted in formation of the Apennines orogenic chain along the subduction front (Fig. 1), whereas formation of the Tyrrhenian Sea dominated the evolution of the Central Mediterranean area. From ~4 Ma, two sub-basins of new ocean-like crust opened in the Tyrrhenian Sea, the Vavilov and Marsili basins (Fig. 1), which are believed to represent back arc settings. In each case, sea-floor spreading occurred prior to the onset of related arc volcanism to the east, represented by the (supposed) arc of the central Tyrrhenian Sea for the Vavilov (Kastens and Mascle 1990) and by the Aeolian archipelago (0.5 Ma—Present time) for the Marsili.

Geochemical data for Tyrrhenian rocks from different volcanic sites (Argnani and Savelli 1999; Gasperini et al. 2002; Cinque et al. 1988; Beccaluva et al. 1990; Trua et al. 2002) provide evidence for magmatism with different affinities (Fig. 1): MORB (ODP 655), intraplate (Ustica island), calc-alkaline and high-K calc-alkaline (ODP 650, 651, Marsili seamount, western Aeolian sector), shoshonitic (SHO) and potassic (Stromboli, Vulcano Islands). Concurrent with this magmatism, volcanism on the Italian peninsula progressively shifted from Tuscany in the north to the Campania region in the south (Fig. 1). All the volcanic rocks along the Italian peninsula, and those from the Aeolian arc, show orogenic-type trace element signatures, given by high ratios of LILE/HFSE. Moreover, there are strong isotopic variations from southern Tuscany to the Campanian area, with a southward decrease of Sr isotopic ratios and an increase of Nd and Pb isotopic signatures. These subduction-related magma suites range from calc-alkaline (CA) to highly potassic (HKS) and have been interpreted as evidence for different metasomatic events affecting the upper mantle beneath the Italian peninsula due to input—via subduction—of crustally derived sediments (Peccerillo 2002 and references therein). Based on major, trace element and isotopic data on mafic rocks, several magmatic provinces have been distinguished along the Tyrrhenian margin (Fig. 1): the Tuscany Province, the Roman Province, the Ernici-Roccamonfina Province, the Campanian Province (Peccerillo 2002). The Aeolian Islands and seamounts, in the southern Tyrrhenian Sea, represent another magmatic Province with general island arc signatures, but significant geochemical and isotopic variations between eastern (i.e. Stromboli) and central-western sectors. Other magmatic provinces, such as Ustica, eastern Sicily and Sicily channel (Etna, Iblei, Linosa, Pantelleria) have anorogenic-type trace element compositions, with low LILE–HFSE ratios (Peccerillo, 2005).

At the Present time, geophysical data indicate that the Ionian slab is rolling back under the Calabrian arc (Gvirtzman and Nur 2001), whereas the Adria slab beneath southern Italy should be detached (Wortel and Spakman 2000).

Mt. Vulture

Mt. Vulture is a Pleistocene composite volcano located between the eastern side of the Apennines chain and the western margin of the Apulia foreland, about 100 km east of the Campanian Province (Fig. 1). It lies at the intersection between the NW–SE (Apenninic) and the NE–SW (Ofanto-Sele) fault systems. Lithosphere thickness beneath the area is ~90–100 km (Doglioni et al. 1996), with the crustal portion of about 35–40 km. ^{40}Ar/^{39}Ar radiometric data indicate that volcanism occurred from ~730 to 480 ka, with renewal of activity at 132 ka (Villa 1986; Brocchini et al. 1994). The variability and petrological features of Mt. Vulture magmas are unlike any other Italian volcano. The older volcanic products are represented by lavas and pyroclastics ranging in composition from basanites and foidites to phonolites, with several intermediate rock types (De Fino et al. 1982). Some phono-trachytic ignimbrites from the lowest exposed units contain lava xenoliths of different composition (tephrites, phonotephrites, etc.), which suggests that there may have been volcanic activity older than the dated products. The most recent eruptions of Mt. Vulture produced multiple WNW–ESE aligned monogenic cones (Giannandrea et al. 2004). These volcanics have a carbonatitic–melilititic composition (Stoppa and Principe 1997), although the primary origin for the carbonate fraction is currently debated. Some products erupted during this period contain ultramafic xenoliths and megacrysts of clinopyroxene, amphibole, olivine and phlogopite. The

Table 1 Geochemical and isotopic data for selected volcanic rocks from Procida (Pro), Vesuvius (ANS, LPG), Vulture (VU and VLM)

Samples	Pro 11/1b	Pro 7/2b	PRO 1/1	PRO 4/3a	Pro 5/8	Pro 5/11a	Pro 7/11	Pro 7/12a	Pro 6/2	LPG 2	ANS 20	VUT 215a	VU 621	VU 883	VU 906	VU 931	VU 1163
Provenance	Tufi di Vivara	Formiche di Vivara I	T. Fiumicello	T. Fiumicello	T. Fiumicello	Formiche di Vivara II	Tufi di Solchiaro I	Tufi di Solchiaro II	Tufi di Solchiaro III	Mt. Somma	Mt. Somma	Basal Expl. Breccia	S. Caterina	Fontana Giumentari	M. Vulture-S.Michele	M. Vulture-S.Michele	Prete della Scimmia
Age	75–55 ka	75–55 ka	55–37 ka	55–37 ka	55–37 ka	55–37 ka	19–14 ka	19–14 ka	19–14 ka	> 25 ka	> 25 ka	> 646 ka	646-557 ka	646-557 ka	646-557 ka	646-557 ka	646-557 ka
Rock type	Lava Clast	Scoriaceous lapilli	Scoriaceous lapilli	Scoria	Scoria	Scoriaceous lapilli	Dense Scoria	Scoria	Lava clast	Lava Caldera wall	Lava from A14well	Lava Bl. -Ph. Tephrite	Lava—Melafoidite	Basanite Dyke	Alc.Tephrite (ha + lc)	Basanite	Melilitite Dyke
SiO_2	47.6	47.64	46.89	48.03	47.8	52.23	48.17	51.66	52.4	50.99	47.41	52.92	38.56	43.75	48.96	45.1	39.21
MgO	4.59	5.98	5.32	5.38	5.35	3.35	8.56	3.28	4.04	4.56	5.65	2.67	3.86	10.39	3.58	9.02	3.65
$K_2O + Na_2O$	6.22	5.13	5.59	5.97	5.94	7.18	4.62	7.78	7.13	9.17	5.44	8.04	7.49	6.45	9.55	6.41	9.27
LOI	1.38	1.62	1.99	0.87	0.93	1.25	−0.1	0.86	1.3	0.27	4.87	2.54	1.29	1.87	0.69	1.49	3.11
Ba	999	1,097	1,105	1,149	1,180	859	561	861	1,706	1,792	1,642	2,433	1,617	1,740	1,821	1,763	2,234
Rb	73	134	109	110	128	104	57	136	191	361	134	142	65	101	118	118	122
Sr	886	863	867	949	931	684	532	596	890	855	938	2,408	2,510	1,647	1,877	1,794	2,463
Y	26.3	23	22	24	24	23	22	29	28	22	27	42	49	37	41	37	70
Zr	118	131	122	129	121	115	114	191	186	198	196	388	406	323	433	339	601
Nb	13	18	15	16	15	17	13	22	22	32	28	78	76	47	62	51	121
Ni	36	34.2	26.2	54.9	25.5	8.6	125	29.9	19.2	63	81	7	15	141	21	157	18
Cr	53	51	16	56	14	14	338	45	39	115	174	8	2.7	363.7	15.8	483.3	6.6
V	281	254	226	247	242	209	202	244	205	192	277	138	274	183	171	194	250
Sc	ND	ND	ND	ND	ND	ND	ND	ND	ND	0	0	7.7	9.9	30.7	16.6	28.1	12.6
Co	33.7	34.6	30.6	34.6	33.4	22.8	40.0	26.3	21.1	26.3	34	ND	47.5	37.4	25.5	61	28.1
La	31	31	31	33	32	30	18	44	53	42	55	226	173	151	184	165	226
Ce	66	67	64	69	70	61	38	90	106	86	111	384	318	270	327	291	432
Nd	35.5	33.9	34	35	36.5	31.7	22.3	42.5	49.0	40.2	53.4	132	123	110.9	129.1	114.7	182.4
Sm	7.7	7.47	7.45	7.83	7.90	6.62	5.11	8.64	9.71	8.13	10.7	21.8	25.4	22.44	24.67	23.37	37.78
Eu	2.36	1.98	2.13	2.28	2.33	2.10	1.64	2.36	2.34	1.96	2.62	4.8	5.73	4.87	5.26	5.06	8.11
Tb	0.98	0.96	0.94	0.90	0.94	0.83	0.75	1.04	1.10	0.85	1.12	1.4	2.1	1.75	1.95	1.83	3.38
Dy	5.08	4.93	4.73	4.92	4.73	4.75	4.16	5.7	5.62	4.39	5.68	ND	ND	ND	ND	ND	ND
Yb	2.31	1.94	1.74	1.77	1.80	2.28	1.86	2.71	2.57	1.84	2.02	3.2	4.42	2.5	2.65	2.48	4.34
Lu	0.33	0.30	0.28	0.24	0.27	0.34	0.30	0.40	0.43	0.28	0.3	0.44	0.57	0.32	0.21	0.3	0.41
Ta	0.84	1.11	1.06	1.05	1.01	1.27	0.89	1.46	1.51	2.12	1.65	4.2	5.43	2.79	3.97	3.89	6.95
Hf	3.08	3.43	3.33	0	3.05	3.03	2.75	4.50	4.74	4.75	4.79	6	7.11	6.25	8.62	6.46	11.3
Cs	2.37	4.93	6.32	6.14	5.36	3.25	2.19	6.06	10.61	19.7	9.8	21	2.32	8.65	6.95	9.92	6.48
Pb	9.8	13.8	14.8	15.2	13.9	12.3	7.9	19.6	35.5	23.3	24.5	ND	ND	65.1	ND	72.0	ND
Th	4.2	7.3	8.5	8	6.9	5.3	3.4	11.2	15.6	18.9	15.5	60.7	40.5	35.5	49.3	39.5	53.9
U	1.3	2.2	2.8	2.6	2.2	1.3	0.9	3.0	4.3	5.98	3.2	16.7	11.2	10.5	12.2	10.5	11.7
$^{87}Sr/^{86}Sr$	0.706085	0.706664	ND	ND	ND	ND	0.705238	ND	ND	ND	ND	ND	0.705864	0.706936	0.706112	0.706935	0.70642
$^{143}Nd/^{144}Nd$	0.51263	0.512553	ND	ND	ND	ND	0.512685	ND	ND	ND	ND	ND	0.512564	0.51269	0.512682	0.512686	0.512605
$^{206}Pb/^{204}Pb$	19.156	19.149	ND	ND	ND	ND	19.088	ND	ND	ND	ND	ND	19.211	19.131	19.263	19.142	19.492
$^{207}Pb/^{204}Pb$	15.687	15.689	ND	ND	ND	ND	15.678	ND	ND	ND	ND	ND	15.683	15.686	15.688	15.685	15.714
$^{208}Pb/^{204}Pb$	39.242	39.279	ND	ND	ND	ND	39.153	ND	ND	ND	ND	ND	39.192	39.157	39.279	39.17	39.558
CO_2	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	0.66	0.5	0.3	0.3	0.73
Cl	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	0.44	0.24	0.48	0	0.84
SO_3	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	0.66	0.5	0.3	0.3	0.73

ND not determined

xenolith association includes residual spinel lherzolites and harzburgites, as well as cumulate wehrlites and dunites (Jones et al. 2000).

The Campanian Province (Mt. Somma-Vesuvius, Phlegraean Volcanic District)

The volcanoes of the Campanian Province (Fig. 1), which include Mt. Somma-Vesuvius (hereafter called Vesuvius) the Phlegraean Fields caldera, with several intra-caldera centres, and the Islands of Procida and Ischia, developed within a NE–SW and NW–SE extensional field that has been active since the mid-Pleistocene and formed the Campanian Plain (Hyppolite et al. 1994; Bruno et al. 1998; Acocella et al. 1999). Within this Plain, NE–SW fractures and faults have often predominated in facilitating the magma ascent to the surface, even from great depth (De Astis et al. 2004 and references therein). Radiometric age dating on Vesuvius rocks indicate ages of ~25–30 ka for the lowest exposed products (Ayuso et al. 1998), whereas analyses of Phlegraean District volcanics (Ischia) give ages of 150 ka (Gillot et al. 1982) or older (De Vivo et al. 2001). However, much older ages have been obtained for volcanics from Vesuvian drilling (~360 ka; Brocchini et al. 2001). The crust–mantle boundary beneath the Campanian Plain is located at 25–30 km, and it rises moving westward, to less than 25 km beneath Ischia (Ferrucci et al. 1989 and references therein). Moreover, the plumbing systems beneath the Vesuvius and Phlegraean areas have experienced different structural conditions and tectonic regimes at least in the last 50 ka, which have influenced magma genesis and evolution (see Piochi et al. 2005 for a review). Rocks from the Campanian Province volcanoes are compositionally variable and range from the SHO of the Phlegraean Fields to the mildly to highly undersaturated basalts (HKS suites) of Vesuvius (D'Antonio and Di Girolamo 1994; Peccerillo 2002 and references therein). Mafic rocks from Procida have some of the highest Mg numbers of Italian volcanics and, for a given MgO content, are usually less enriched in K_2O compared to Vesuvian and Phlegraean Fields rocks. They mainly have a SHO affinity and a few and Pietre Nere (G)

VU 1457	VU 1461	VU 1513	VU 1514	VU 1520	VU 1523	VU 694b	VUT 93 b	VU LGM1	LGM1 1.1	VLM 1B/vd	VLM 2C/vd	VLM 2C/L	VLM 1B/Mxx	G 19	G 28	G 99	G 52
F. Gelosia	F. Madonna	Barile	Barile	Rionero-Laghi Road	Melfi	Piana Ciaulino	Piana Ferriera	Molino Vecchio	Molino Vecchio	L. Monticchio F.	L. Monticchio F.	L. Monticchio F. ?	L. Monticchio F.	P. Pietre Nere	P. Pietre Nere	P. Pietre Nere	P. Pietre Nere
646-557 ka	646-557 ka	646-557 ka	646-557 ka	646-557 ka	557 ka	480 ka	480 ka?	ND	ND	132 ka	132 ka	ND	132000	62.2 Ma	62.2 Ma	58.5 Ma	58.5 Ma
Foidite tefritica	Foidite	Foidite	Foidite	Tefrite	Hauynophire	Scoria	Scoria	Scoria Bomb	Lava block	Tuffisitic Lapilli	Tuffisitic Lapilli	Lava fragment in T.L.	Megacrysts/ Lapilli	AlkMela-sieniti	AlkMela-sieniti	AlkMela-gabbri	Melagabb. Porf. Type
45.94	43.41	43.57	46.43	47.38	41.57	42	42.25	45.07	43.59	38.31	37.89	44.37	ND	39.63	39.25	43.39	44.12
4.01	4.82	6.2	3.5	2.82	2.7	5.76	5.11	4.41	10.37	16.78	12.86	7.2	ND	7.07	7.77	13.8	10.27
8.46	7.81	6.81	7.61	9.98	12.47	5.55	7.07	7.99	5.92	3.62	4.59	3.99	ND	6.41	6.45	4.79	5.66
1.57	1.9	1.8	2.54	3.68	3.43	2.35	0.92	2.4	1.78	5.03	5.89	5.06	ND	3.58	3.18	2.68	2.16
1,968	2,216	2,236	2,361	2,188	2,387	1,452	2,068	2,420	1,713	2,263	2,226	2,961	ND	1,335	1,230	602	667
126	121	123	143	116	135	95	114	174	90	36	45	119	ND	96	70	40	46
2,220	2,287	2,009	2,428	2,444	3,156	1,963	1,704	3,076	1,750	1,221	1,157	2,203	ND	709	866	625	584
47	54	52	46	43	51	53	63	29	38	34	34	49	ND	34	30	20	22
416	454	424	451	375	513	405	511	427	289	308	261	449	ND	536	524	240	266
77	77	68	78	117	155	70	96	103	50	47	43	78	ND	122	115	62	68
24	29	45	22	11	10	30	20	46	107	449	358	85	ND	72	101	391	279
6.3	7.4	28.5	7.1	22	9	38	16	45	381	986	714	147	ND	93	110	434.7	344.3
224	243	238	213	0	199	256	241	240	212	200	191	210	ND	353	239	150	171
11.3	13.4	17.2	11.3	5.9	5.2	ND	23.2	10.5	0	38	35.6	20.9	ND	24.7	17.5	22.2	22.3
110.1	76.2	72.5	40.2	ND	ND	ND	ND	24	38	ND	ND	ND	ND	48	9.3	61.5	51.5
181	214	213	216	296	327	216	168	290	156	205	182	243	ND	99	89.1	42.4	56.3
295	359	353.3	345.2	500	554	387	311	430	292	322	299	420	ND	200	172.8	83.7	110.9
133.9	188.3	185.7	175.6	157	166	151	141	162	120	104	113	175	ND	89.6	88.7	39.1	52.1
21.21	27.4	26.74	24.34	30	28.6	29.6	30.3	26.2	21.1	21.7	20.6	30.8	ND	16.3	14.91	9.41	10.52
5.11	6.77	6.3	5.73	5.9	6.2	6.7	6.6	5.5	4.98	4.6	4.8	6.5	ND	4.81	4.55	2.71	2.95
1.55	2.12	2.06	1.76	2.1	2.3	2.7	2.1	2.5	1.88	1.6	1.5	2.4	ND	1.60	1.15	0.93	1.03
ND	ND	ND	ND	ND	ND	ND	ND	ND	8.77	ND	ND	ND	ND	7.93	ND	ND	ND
2.88	3.44	3.43	3.21	4	4.3	3.4	4.1	3.3	2.31	2.1	3	3.6	ND	2.02	1.92	1.84	1.94
0.41	0.39	0.42	0.4	0.63	0.54	0.53	0.6	0.50	0.33	0.32	0.45	0.54	ND	0.27	0.24	0.24	0.25
3.92	3.77	3.51	3.49	9.1	9.1	2.5	6.3	5.7	3.15	0.5	0.9	4.6	ND	8.69	5.26	3.86	4.32
5.89	7.31	6.43	6.7	8.3	6.89	8	10	6	6.37	5	4	8	ND	11.1	9.52	5.32	5.99
7.07	5.92	5.41	7.45	20	22	5	5	16	8.77	3	4	13	ND	1.30	0.76	0.41	0.44
ND	ND	41.0	ND	ND	ND	39.1	35.0	ND	84.7	ND	ND	ND	ND	ND	ND	ND	ND
41.6	47.5	41.6	44.9	80	86	39.8	30.9	73.9	36.4	26.8	31.8	58.5	ND	11	11	5.6	6
12.9	11.6	13	15.3	22	21	7.9	7.7	20.1	11.1	5.8	4.3	11.2	ND	3.50	5.2	1.4	1.1
0.70578	0.705819	0.705768	0.705555	ND	0.705741	0.705859	0.706109	0.706204	ND	0.705732	0.705772	0.705921	0.705745	0.70355	ND	ND	0.70335
0.5127	0.512699	0.512693	0.512698	ND	0.512698	0.512686	0.512618	0.512697	ND	0.512656	0.512638	0.512686	0.512647	0.51283	ND	ND	0.51289
19.316	19.314	19.315	19.279	ND	19.256	19.286	19.484	19.22	ND	19.254	19.256	19.207	19.261	20.037	ND	ND	20.141
15.689	15.69	15.692	15.686	ND	15.686	15.687	15.715	15.697	ND	15.686	15.686	15.687	15.688	15.721	ND	ND	15.709
39.311	39.321	39.329	39.235	ND	39.264	39.232	39.535	39.245	ND	39.229	39.237	39.211	39.24	39.802	ND	ND	39.774
0.55	0.13	0.28	0.24	1.03	2.87	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
0.39	0.33	0.3	0.29	0.71	0.83	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
0.55	0.13	0.28	0.24	1.03	2.87	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND

are HKCA. However, in terms of volume, most of the magmas erupted in the Campanian Province are represented by evolved tephra and lavas ranging from tephritic phonolites and phonolites to trachytes and alkali-trachytes (Joron et al. 1987; Pappalardo et al. 2002 and references therein).

Punta delle Pietre Nere

Punta delle Pietre Nere (hereafter called Pietre Nere) igneous rocks are located on the Adria Plate, along the northern coast of the Apulian region (Fig. 1). They consist of two distinct magmatic hypo-abyssal bodies with slightly different K/Ar ages (Bigazzi et al. 1996). The older one (62.2 Ma) is an alkali mela-syenite. The younger one (58–59 Ma) is a layered mela-gabbro, with subordinate ultramafic portions and peripheral porphyritic facies. Pietre Nere rocks have geochemical and isotopic features (Hawkesworth and Vollmer 1979; De Fino et al. 1981; De Astis et al. 2002) that may be considered representative of the Adria intra-plate mantle. Other Italian volcanics showing typical intra-plate features were erupted during Tertiary (i.e. 48–33 Ma) in the south-eastern Alps, i.e. on the same plate as Pietre Nere, forming the Veneto Volcanic Province (VVP; Fig. 1—see Macera et al. 2003).

Geochemistry

New geochemical and isotopic data for samples from Procida Island, Vesuvius, Mt. Vulture and Pietre Nere are reported in Table 1. A complete major and trace element data set is available from the corresponding author on request. The rocks from these volcanoes encompass a wide range of compositions, from basalt, tephrite and foidite to trachy-phonolite and phonolite (Fig. 2—TAS), with a very wide range of alkali contents being shown by Vulture rocks. We have mostly analysed the mafic types, with MgO ranging from 4 to 16.8 wt.% in order to focus the studies on magmas as close as possible to mantle-equilibrated parents. These samples are representative of the entire sequence of mafic magmas erupted throughout the history of these volcanoes.

Chondrite-normalised REE patterns for the Campanian Province (hereafter referred to as CP), Mt. Vulture and Pietre Nere rocks are plotted in Fig. 3a–c, grouped by MgO content. Representative samples from the VVP (Fig. 3a) and Iblei (Fig. 3b) are shown for comparison. All of the rocks have fractionated REE patterns (i.e. LREE > HREE). Mt. Vulture rocks are particularly enriched in LREE, both in comparison with CP rocks and relative to Pietre Nere; they are also enriched relative to typical intra-plate volcanics around the Tyrrhenian Sea area, such as Iblei. This is true for any range of MgO considered. The samples from Pietre Nere are similar to VVP products (Fig. 3a). The mafic rocks from the CP show very similar patterns but variable REE fractionation, which is lower at Procida than in other volcanoes (Fig. 3b).

Extended incompatible trace element (ITE) diagrams are shown in Fig. 3d, e, where mafic rocks (MgO >5%) from the transect and from other Italian geotectonic environments are reported. The trace element patterns of K-alkaline mafic rocks from Procida Island and Vesuvius (CP volcanoes) are relatively similar (Fig. 3d). All show typical subduction-related features, i.e. enrichment in mobile elements like K, Rb, Ba, Cs, Sr, Pb and relative depletions in Ta, Nb, Hf and Ti. Their patterns are also similar to those shown by the samples from the Aeolian Islands (i.e. Alicudi CA suite), and a striking similarity between potassic samples of Vesuvius and Stromboli is also evident. Mt. Vulture mafic rocks with K_2O/Na_2O >1 (Fig. 3d) also have trace element patterns similar to Stromboli rocks, but differ in having much smaller troughs at Ta–Nb, negative spikes at Rb, Sr, and a slight positive spike in Th. At the same time, the Mt.Vulture pattern displays the greatest enrichments in all the elements, but not for Rb and Cs. In Fig. 3e, a Mt. Vulture mafic sample with K_2O/Na_2O <1 is plotted together with Pietre Nere and Na-alkaline rocks from intra-plate environments (i.e. Iblei). Each shows striking differences from the Procida rock with K_2O/Na_2O <1. Pietre Nere and Iblei have positive spikes of Ba, Ta, Nb, which make them strikingly different from Campanian volcanoes. Mt. Vulture has high LREE, Th, U, Pb but shows negative anomalies for Rb and K.

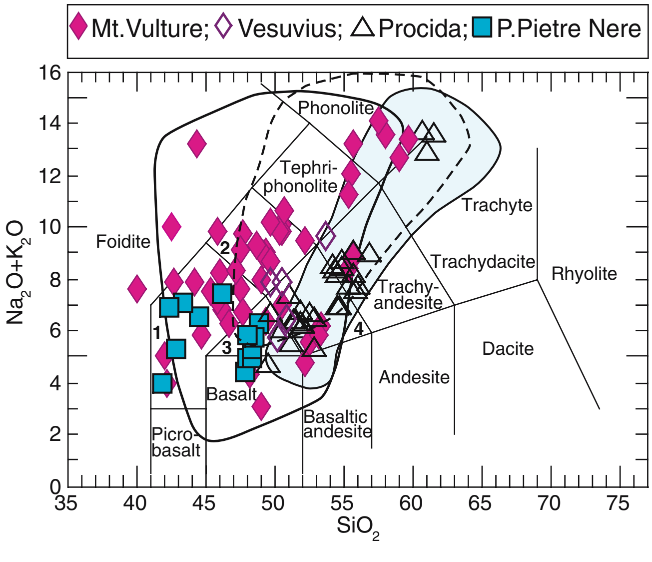

Fig. 2 Total alkali vs silica classification diagram (TAS—Le Maitre 1989) for the studied rocks (oxide values are normalised to 100% on a water-free basis). Data from literature are shown as fields: *thick black line* Mt. Vulture rocks (De Fino et al. 1982, 1986; Beccaluva et al. 2002), *dashed line* Mt.Somma-Vesuvius rocks (Joron et al. 1987; Ayuso et al. 1998; Somma et al. 2001), *shaded field with thin line* Phlegraean Volcanic District (Civetta et al. 1991; D'Antonio et al. 1999; Piochi et al. 1999; Pappalardo et al. 2002). Classification fields: *1* Tephrite Basanite, *2* Phono-tephrite, *3* Trachy-basalt, *4* Basaltic trachy-andesite

Sr–Nd–Pb isotope data

New Sr, Nd and Pb isotope data are presented in Table 1 and shown in Figs. 4 and 5. Mt. Vulture rocks have Sr- and Nd-isotope ratios similar to those previously reported (Vollmer 1976; Beccaluva et al. 2002). Values measured on Mt. Vulture cpx separated from peridotite xenoliths (Downes et al. 2002) are also reported for comparison, as they can represent isotopic composition of the lithospheric mantle beneath this volcano. Rocks from Procida Island overlap the Vulture range, although they extend to slightly lower $^{87}Sr/^{86}Sr$ values, showing the lowest $^{87}Sr/^{86}Sr$ ratios along the Italian peninsula. Collectively, the data overlap the previously defined Stromboli–Vesuvius–Phlegrean District "regional" trend (see Fig. 4), although most Mt. Vulture samples have slightly higher $^{143}Nd/^{144}Nd$ for a given $^{87}Sr/^{86}Sr$. Samples from Pietre Nere have significantly lower $^{87}Sr/^{86}Sr$ and higher $^{143}Nd/^{144}Nd$ values and are similar to the intra-plate rocks from VVP, Etna, Iblei and Pantelleria (Fig. 4).

The $^{206}Pb/^{204}Pb$ ratios of Mt. Vulture and Procida Island rocks vary between 19.131 and 19.492 and between 18.997–19.300, respectively (Fig. 5a, b and Table 1). Samples analysed by D'Antonio et al. (1996) extend the Pb isotope ratios of Procida to lower $^{206}Pb/^{204}Pb$ values (down to 18.685). The rocks from Vesuvius have lower $^{206}Pb/^{204}Pb$ than those from Mt. Vulture, and form a nearly vertical array in $^{207}Pb/^{204}Pb$ vs $^{206}Pb/^{204}Pb$ (Fig. 5a) that overlaps the field for Stromboli and partly that of VVP, pointing to MORB-type composition of rocks recovered at the ODP Site 655, in the Tyrrhenian Sea. By comparison, our new data for Procida rocks show considerably less spread in $^{207}Pb/^{204}Pb$. Pietre Nere rocks have higher measured $^{206}Pb/^{204}Pb$ than either Mt. Vulture or CP rocks, ranging between 20.037 and 20.141, and plot between Mt. Vulture and HIMU values.

In a plot of $^{208}Pb/^{204}Pb$ vs $^{206}Pb/^{204}Pb$ (Fig. 5b), the Mt. Vulture and Procida Island mafic rocks form subparallel arrays with positive slopes in which the rocks

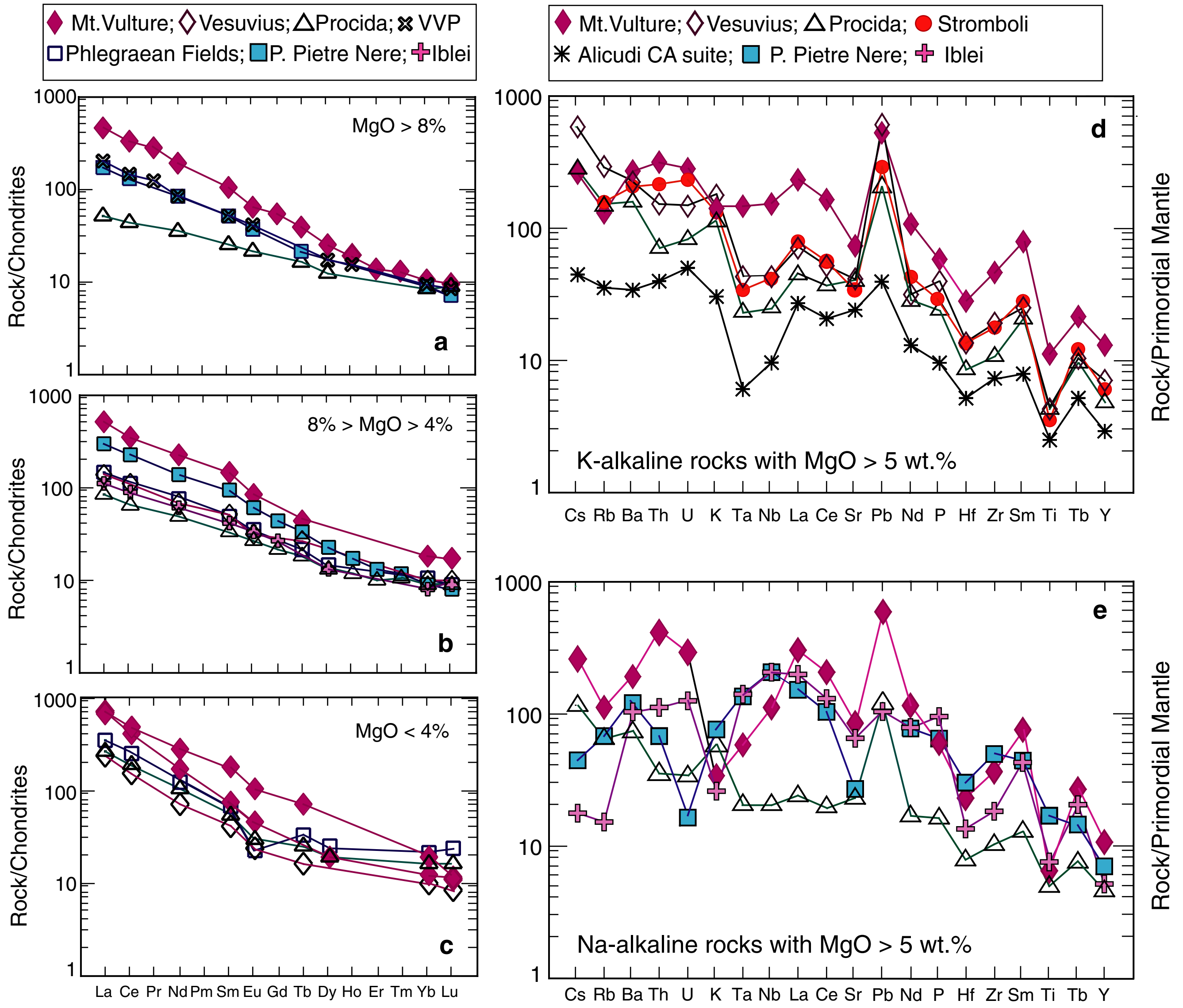

Fig. 3 **a–c** Chondrite-normalised REE patterns for samples with different MgO contents **a** MgO >8 wt.%, **b** MgO = 4–8 wt.% and **c** MgO ≤4 wt %. Normalising values from Nakamura (1940). **d, e** Extended incompatible trace element (ITE) diagrams normalised to primitive mantle values (Wood et al. 1979, except Pb from Sun and McDonough 1989), for rocks with MgO ≥5 wt.% and different K_2O/Na_2O ratios >1 (Fig. 2d) and K_2O/Na_2O ratios <1 (Fig. 2e). Legends are reported on the top of the diagrams. Data sources as follows: Vesuvius (Ayuso et al. 1998), Phlegraean Fields s.s. (D'Antonio et al. 1999), Stromboli (Ellam et al. 1989), Alicudi (Peccerillo et al. 1993), Iblei (Beccaluva et al. 1998) and *VVP* Veneto Volcanic Province (Milani et al. 1999)

from Procida are shifted to slightly lower $^{206}Pb/^{204}Pb$ than those from Mt. Vulture, suggesting a slightly higher time-integrated Th/U ratio in the Procida source. Both groups, including the rest of the CP rocks, are similar in $^{208}Pb/^{204}Pb$ to rocks from the Italian intra-plate volcanoes but are shifted to lower $^{206}Pb/^{204}Pb$, overlapping the field for Stromboli. Two Procida samples (D'Antonio et al. 1996) have lower $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ values that overlap the field of MORB-like tholeiites from the Tyrrhenian Basin (ODP 655 site). The rocks from Vesuvius overlap the range of Procida samples but show a more restricted range of $^{206}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$, most overlapping the field of Stromboli. The measured Pb isotope ratios for rocks from Pietre Nere plot along an extension of the array formed by Iblei and Etna.

Spatial variations in trace element and isotopic composition

Variations in ITE ratios and isotopes along the Pietre Nere–Vulture–Procida transect are shown in Fig. 6 where mafic rocks with MgO ≥5 wt.% have been plotted in order to visually demonstrate the differences of most primitive magmas related to southern Italy mantle source(s). $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ show maxima or minima at Vesuvius and Phlegraean Fields, respectively

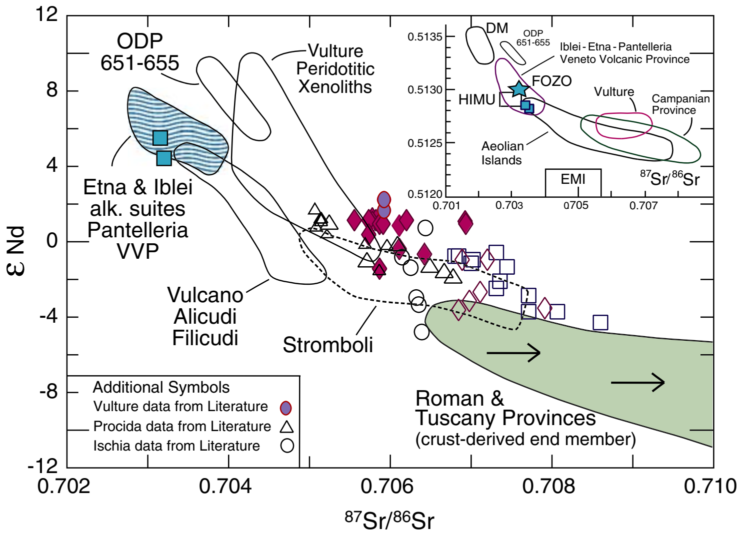

Fig. 4 εNd vs $^{87}Sr/^{86}Sr$ variation diagram showing new data for Mt. Vulture, Procida and Pietre Nere relative to representative fields for other intra-plate Italian volcanoes and for other Italian magmatic provinces: the central-western sector of the Aeolian district (Vulcano, Alicudi and Filicudi) and the eastern sector (Stromboli), Roman and Tuscany Provinces. Punte Nere samples (Palocene in age) and VVP rocks (Veneto Volcanic Province magmatism, Eocene in age) are reported with their initial $^{87}Sr/^{86}Sr$. *Arrows* indicate the extension of the field for the Roman Province mafic rocks and Italian lamproites from Tuscany Province. Symbols as in Figs. 2 and 3, with additional symbols in the left inset: two additional data for Vulture rocks (Vollmer 1976) and the smaller *open triangles* indicate literature data for Procida Island (D'Antonio and Di Girolamo 1994; Pappalardo et al. 2002; De Astis et al. 2004). Data sources for other surrounding magmatic provinces and volcanoes as follows: Phlegraean Fields and Ischia island (Civetta et al. 1991; D'Antonio et al. 1999; Piochi et al. 1999; Pappalardo et al. 2002), Vesuvius (Joron et al. 1987; Ayuso et al. 1998; Somma et al. 2001), Aeolian Islands (Ellam et al. 1989; Francalanci et al. 1989, 1993; Peccerillo et al. 1993; De Astis et al. 2000; Gertisser and Keller 2000; Santo 2000); Iblei (Beccaluva et al. 1998; Trua et al. 1998); Pantelleria (Esperanca and Crisci 1995), Etna (Tanguy et al. 1997; D'Orazio 1993; D'Orazio et al. 1997), *VVP* Veneto Volcanic Province (Milani et al. 1999; Macera et al. 2003; A. Peccerillo, unpublished data), Vulture peridotite xenoliths (Downes et al. 2002), Pietre Nere (Vollmer 1976; Hawkesworth and Vollmer 1979), ODP sites 651 and 655 (Beccaluva et al. 1990; Gasperini et al. 2002), Roman and Tuscany Provinces (Conticelli and Peccerillo 1992; De Astis et al. 2000; Conticelli et al. 2002; Peccerillo 2005)

(Fig. 6a, b), whereas they are very similar for Procida and Mt.Vulture rocks. Pb isotope compositions measured in Procida and Pietre Nere rocks represent the lower and upper limits found along the transect, respectively (Fig. 6c, d), and the former show a partial overlap with the Tyrrhenian Basin basalts (ODP Sites 651–655). Note that the compositional overlap is mainly with arc-type rocks from ODP 651, whereas basalts from ODP 655 are MORB-like (i.e. highest Nd and lowest Sr isotope ratios among the Tyrrhenian rocks). Although each locality exhibits a range of values, our ITE plots display trends along the transect: Th/Zr (and Th/Yb, Rb/Zr, not shown) show a progressive increase from west to east, with a peak at Mt. Vulture, but much lower values at Pietre Nere (Fig. 6e); average Ba/La (K/Nb, Ba/Nb and Sr/Ce, not shown) ratios increase going from Pietre Nere in the east to Campanian Province in the west, with the highest values shown among the Vesuvius rocks (Fig. 6f). In contrast, average Ta/Yb, Zr/Hf (or Nb/Y not shown) as well as $^{206}Pb/^{204}Pb$ (and to some extent $^{207}Pb/^{204}Pb$) show the opposite trend (Fig. 6c, d, g, h). In particular, we note that HFSE ratios, i.e. Zr/Hf (or Y/Nb and Ti/Nb not shown), discriminate well the group of Mt. Vulture rocks and some Pietre Nere from those of Procida and Tyrrhenian basalts; Vesuvius shows a wider range of this ratio, overlapping on both groups (Fig. 6h).

Discussion

Volcanic rocks along the E–W transect from Mt. Vulture across the Apennine chain up to Procida island show considerable compositional variation (Figs. 2, 6). It is unlikely that these variations are an effect of shallow-level evolution processes, such as fractional crystallisation or crustal contamination. As demonstrated by a wealth of studies (e.g. Conticelli 1998; Peccerillo 2005 and references therein), ITE ratios and radiogenic isotope signatures of Italian potassic magmas are not sensitive to evolutionary processes, including crustal contamination. This is due to a buffering effect of high concentrations of these elements in potassic magmas. Therefore, first-order geochemical variations of mafic rocks under consideration largely reflect regional source compositional heterogeneities, going from the Adria plate to the eastern margin of the southern Tyrrhenian Sea (Fig. 1).

Although to different extents, incompatible element patterns of mafic rocks for all the volcanoes of the transect (Fig. 3) show a relative depletion of HFSE, with troughs at Ta, Nb or negative spikes of Zr, Hf and Ti, and enrichment of LILE, with positive spikes of Ba, Th, Cs, and LREE. This spiked trace elements signature indicates an arc environment, as suggested by several

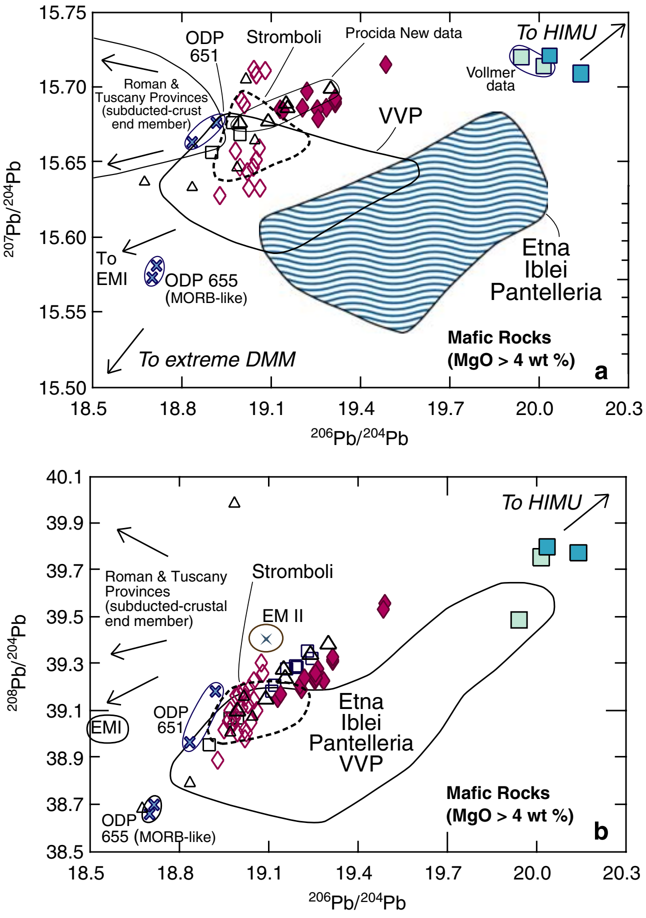

Fig. 5 Diagrams of $^{207}Pb/^{204}Pb$ (**a**) and $^{208}Pb/^{204}Pb$ (**b**) vs $^{206}Pb/^{204}Pb$. Note that the data for Pietre Nere include two measures by Vollmer (1976). All the Pietre Nere data have not been age corrected because we do not have measured Pb concentrations for our samples. Symbols as in Figs. 3, 4. Data sources as in Fig. 4. *VVP* Veneto Volcanic Province

authors (e.g. Wilson 1989 and references therein). However, the spatial variations observed in ITE and isotope ratios (Fig. 6) require that other contributions or processes have affected the southern Italy mantle, beyond that of subduction. Campanian Province rocks point to arc values for Ba/La, Ba/Nb, Sr and Nd isotopes; whereas Mt.Vulture points to OIB (or MORB) values for the same ratios as well as Ta/Yb and Zr/Hf.

The variation of Zr/Nb ratios relative to MgO is reported in Fig. 7 and, together with Fig. 6h, this figure gives an indication of the peculiar characteristics of the magma sources beneath southern Italy. The HFSE ratios have been chosen as indicative of pre-metasomatic source features, because HFSE largely behave as immobile elements during element transfer at the slab–mantle wedge boundary (e.g. Pearce and Peate 1995). Therefore, they are likely to reflect the compositions of the pristine mantle source in subduction zones (e.g. Davidson 1996). Moreover, they are not affected by source mineralogy and degree of partial melting, even in the case of Zr and Nb which have wide compatibility differences. In fact, geochemical modelling (not shown) demonstrates that variable degrees of partial melting of a primordial mantle source (e.g. Zr/Nb = 2; Sun and McDonough 1989) decreases Zr/Nb ratios by a factor of two or less. By contrast, the investigated rocks have higher values than primordial mantle for Zr/Nb and their variations along the transect are much larger than modelled by any equilibrium melting process. Other ratios of HFSE/HFSE (e.g. Ta/Hf, Y/Nb, etc., not shown) show similar patterns, although these elements are more sensitive to variable degrees of mantle melting than Zr/Nb. Fig. 7 shows that, for a given MgO content, mafic rocks from Mt. Vulture plot along trends that are between CP and Italian intra-plate volcanoes (Etna, Iblei, VVP, including Pietre Nere) and have systematically lower Zr/Nb ratios than Procida rocks. On the other hand, all the mafic rocks from CP have ratios that partially overlap with Stromboli and with Tyrrhenian basin rocks (Fig. 7). Samples from Pietre Nere tend to form a discrete group, almost strictly matching the VVP field. In particular, they have high-MgO contents combined with very low Zr/Nb ratios also observed for the fields of Italian intra-plate volcanoes (e.g. Iblei and Etna). The ranges of these ratios are very close to the typical average values of OIB–HIMU (Zr/Nb average = 6.2) or OIB-FOZO (Zr/Nb = 2.27–6.84; Sun and McDonough 1989; GEOROC data base). Therefore, the studied rocks, and in particular those from Mt. Vulture, reveal that a pristine OIB-type, common mantle component, characterizes all the magmas generated underneath the transect. This may result from a mixture of HIMU and DMM (Civetta et al. 1998; Gasperini et al. 2002), or represent the so-called FOZO mantle reservoir, as defined by Stracke et al. (2005).

Whatever the case, a main problem is whether this OIB-type composition represents resident mantle material emplaced into the mantle wedge during processes like slab-tear and slab rollback (see models of the south Tyrrhenian region by Gvirtzman and Nur 1999 or Wortel and Spakman 2000), or it is the effect of, and an evidence for, a deep mantle plume component (Gasperini et al. 2002) that has upwelled through a slab window in the Adria slab. Identifying the processes that have generated these variations is central to our understanding of mantle evolution beneath the Italian peninsula, which in turn is needed to place constraints on the geodynamic evolution in the Tyrrhenian area. Our discussion highlights two key issues: (1) magma genesis and source evolution beneath each volcano of the transect, and (2) the geodynamic evolution of southern Italy and the southern Tyrrhenian Sea from Pliocene to Present time.

Pietre Nere: evidence for the composition of African mantle prior to subduction

The magmatic rocks from Pietre Nere are characterized by LILE, REE and HFSE contents, as well as LILE/

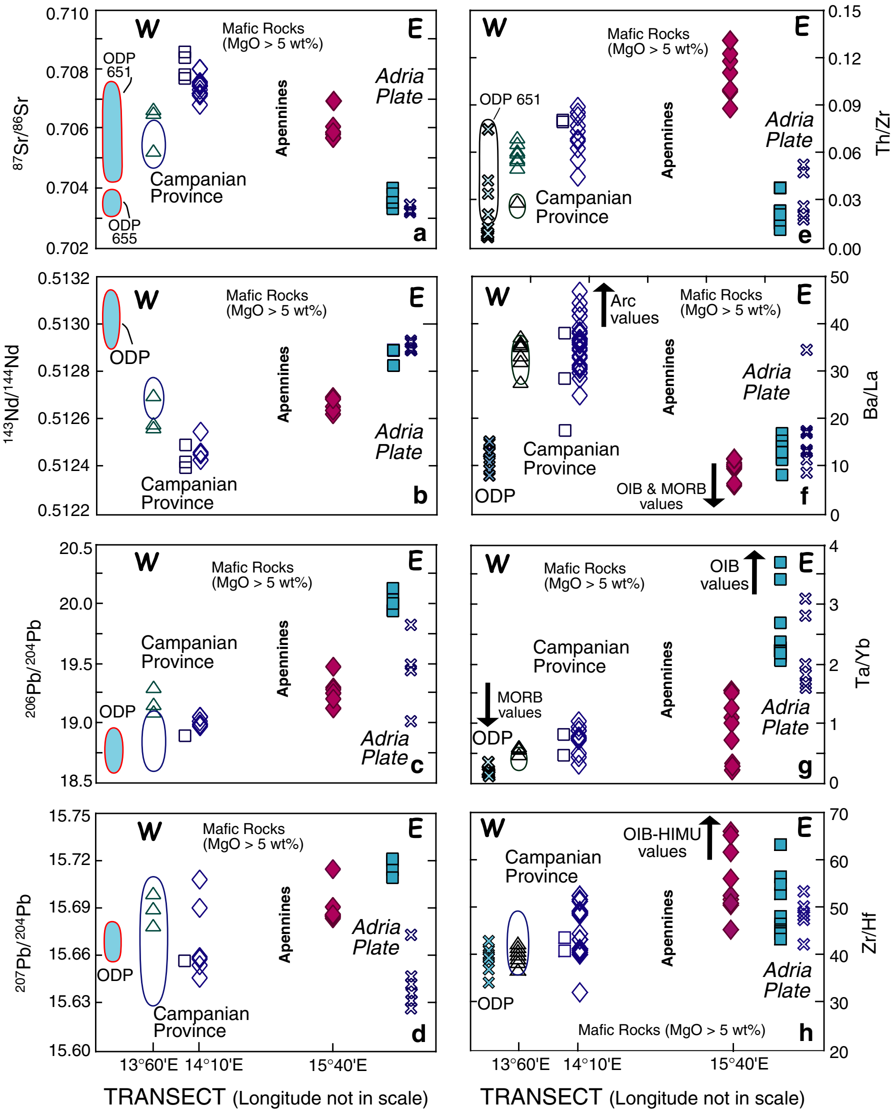

Fig. 6 Diagrams of ITE ratios and radiogenic isotope variations along the studied transect, including Pietre Nere. In order to minimise any complicating effects from shallow level magma chamber processes, we have excluded samples with MgO contents < 5 wt %. Symbols as in Figs. 3, 4. Data for the ODP Sites 651–655 (Beccaluva et al. 1990; Gasperini et al. 2002) and the VVP (Macera et al. 2003; Peccerillo, unpublished data), are reported for comparison. The former are representative of the Vavilov Basin (Tyrrhenian Sea), with ODP 655 having MORB-like and ODP 651 CA-HKCA affinity. The latter, together with Pietre Nere, are representative of the mantle beneath Adria (African) plate. The open elliptical fields encompassing the Procida rocks represent the range of data from D'Antonio and Di Girolamo (1994). Data sources for Campanian Province (Phlegraean Fields caldera, Vesuvius) as in Fig. 4

REE, LILE/HFSE and HFSE/HFSE ratios similar to recent intra-plate volcanoes of the Tyrrhenian region and especially to VVP (Fig. 8 and see also Figs. 3d, 6). In εNd vs initial ^{87}Sr/^{86}Sr (Fig. 4) the Pietre Nere rocks plot within the range of intra-plate alkaline volcanic rocks from Etna–Iblei–VVP, suggesting a similar mantle source. In terms of Pb isotope ratios, Pietre Nere rocks are isotopically distinct from the rest of the volcanoes across the transect and point toward OIB–HIMU compositions, even if age correction is not possible because Pb contents for these rocks are not available. However, because the effect of age-correction on ^{207}Pb/^{204}Pb is virtually insignificant, we can use measured values for our discussion. In an εNd vs ^{207}Pb/^{204}Pb diagram (Fig. 9) the Depleted Mantle (MORB-source) and HIMU form an array with a negative slope. Some Tyrrhenian Sea rocks, particularly those from Site 655 (Vavilov basin), plot on the DM end-member and also have MORB-like HFSE ratios (Figs. 7, 8). The intra-plate rocks from the circum-Tyrrhenian region (Etna, Iblei and VVP) plot along an extension of the DM-HIMU array and show slightly higher εNd and lower ^{207}Pb/^{204}Pb than the rocks from Pietre Nere. In other words, the intra-plate Etna–Iblei–VVP group appears to represent a variable mixture of these two sources, as also suggested by Gasperini et al. (2002). Pietre Nere plots along the DM-HIMU array, but closer to the HIMU end-member. The rocks from Mt. Vulture, the CP and Stromboli (eastern Aeolian arc) plot below the array, indicating addition of a low εNd subduction component (or sediment-derived fluid/melt). Thus, the rocks from Pietre Nere are isotopically more similar to those Italian mafic rocks that have clear intra-plate signatures than to Mt. Vulture rocks (see also Figs. 4, 5). Furthermore, Pietre Nere, VVP (mainly Eocene in age) and Iblei–Etna (Pliocene–Quaternary in age) mafic rocks are isotopically similar to those samples defined as FOZO by Stracke et al. (2005), whose role in the south Italian magmatism has been first recognised by Hoernle et al. (1996). Finally, although some heterogeneity exists,

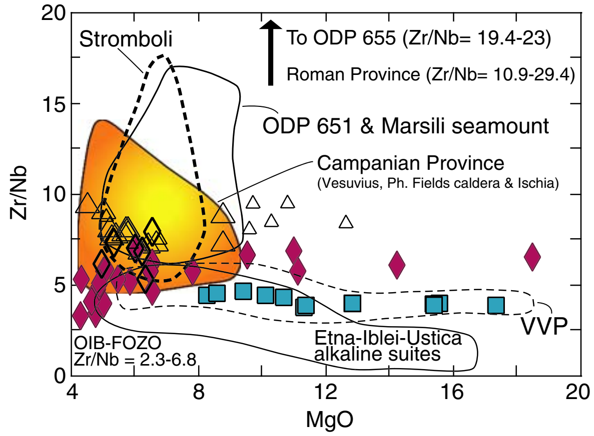

Fig. 7 Zr/Nb vs MgO (wt.%) variation diagram, based on rocks with MgO >4 wt.%. Small open triangles indicate literature data for Procida Island (D'Antonio and Di Girolamo 1994). Other symbols as in Figs. 3, 4. Data sources for the field of the Campanian Province (Phlegraean Fields caldera, Ischia and Vesuvius rocks): Joron et al. 1987; Civetta et al. 1991; Villemant et al. 1993; Ayuso et al. 1998; D'Antonio et al. 1999; Somma et al. 2001; Pappalardo et al. 2002. Mafic rocks from other surrounding magmatic districts are reported for comparison: Marsili seamount and ODP 651 rocks (from Tyrrhenian Sea) that have CA-HKCA affinity have been included in the same field. Noteworthy, KS rocks from Stromboli have Zr/Nb = 5.8–12.2 that is a range very similar to that of the CP rocks, and MORB have a range of have Zr/Nb = 22.1 ± 16.2. The range of values reported for MORB and OIB-FOZO rocks are from PETDB (http://www.petdb.ldeo.columbia.edu/petdb) and GEOROC database (http://www.georoc.mpch-mainz.gwdg.de). Data sources for south-Tyrrhenian volcanics: Stromboli (Ellam et al. 1989; Francalanci et al. 1989; Hornig-Kjarsgaard et al. 1993), ODP sites 651, 655 (Beccaluva et al. 1990; Gasperini et al. 2002), Marsili seamount (Trua et al. 2002). Data sources for fields plotted as representative of the intra-plate Italian volcanoes (Etna, Iblei, Pantelleria, Ustica, VVP) as in Fig. 4, with additional data from Bianchini et al. (1998) and Cinque et al. (1988)

Sr–Nd–Pb and ITE ratios (Figs. 4, 5, 6, 7, 8 and 9) suggest that the mantle source beneath the Adria (African) plate has a FOZO-like signature, free from subduction influences, that is recognisable in the magmas erupted in the last 60 Ma over this plate. Figure 9 also highlights the existence of other mantle components (isotopic end-members) that play a role in the magmatism of central-southern Italy. The low εNd of mafic potassic and ultrapotassic rocks from the Roman and Tuscany Provinces provides evidence for an EMII-like end-member, which is crustally derived (Peccerillo 1999; Gasperini et al. 2002; and references therein). Although a mantle component of EMI-type has been recognised in some Sardinian rocks (Gasperini et al. 2000), and is indicated by an arrow in Fig. 9, this component is not required to explain the compositions of the studied samples.

Mt. Vulture: a “hybrid” volcano

Mt. Vulture has long been considered an anomalous volcano for two reasons: (a) the composition shown by its products in comparison with those erupted in other southern Italy volcanoes (see Peccerillo 2005 and references therein); (b) its geographic position, between the eastern Apennines and the inner margin of the Bradanic foredeep (Fig. 1), external to the geodynamic active front. Its existence and age suggest that extensional tectonics and magma upwelling occurred after the end of subduction of African-Adriatic lithosphere under the Eurasia plate. According to previous studies (De Fino et al. 1982, 1986; Melluso et al. 1996; Beccaluva et al. 2002), Mt. Vulture magma evolution can largely be explained by fractional crystallisation processes, with a possible limited role for assimilation of evaporitic rocks (Marini et al. 1994; De Fino et al. 1986). Rocks in the range MgO = 2–12 wt.% also show relatively constant Sr–Nd–Pb isotopic ratios (Table 1 and Beccaluva et al. 2002). Therefore, we can use these data to gain information on the composition of the mantle source. This assumption is supported by other volcanological and petrological evidence: (1) volcanic products that appear to derive from magmas rapidly risen to the surface from great depth, without significant storage in high-level magma chambers and/or crustal contamination (i.e. xenoliths-bearing, late-stage pyroclastic deposit with tuffisitic lapilli—Giannandrea et al. 2004) have similar isotopic compositions to products with a shallower origin; (2) isotopically, mafic magmas ($^{87}Sr/^{86}Sr = 0.70573$–$0.70772$—Fig. 4) overlap the more radiogenic end of entrained mantle xenoliths (leached cpx, Downes et al. 2002: $^{87}Sr/^{86}Sr_{cpx} = 0.70424$–$0.70580$), suggesting that they originated from the same mantle source and experienced little or no interaction with overlying crust; and (3) high to very high Sr and Nd contents in Mt. Vulture rocks argue against easy modification of these isotope systems by crustal contamination.

Figures 3, 6 and 8 show that most Mt. Vulture magmas are relatively depleted in HFSE and enriched in LILE, especially Ba, Th and LREE, which is typical of subduction-related settings, but primitive rocks with K and Rb depletions also occur. Thus, they have lower K/Nb, Rb/Sr (not shown) and Ba/La and higher Th/Zr, or (not shown) Ba/Rb, Th/Yb, La/Yb, Nd/Hf than CP rocks. Magmas with low K/Nb, such as melilitites, are believed to originate in the presence of residual phlogopite in the mantle source, under CO_2-rich condition (Hawkesworth et al. 1990). Therefore, the K and Rb depletion of some undersaturated Mt. Vulture magmas could indicate the presence of residual phlogopite and/or of pargasite—characterized by variable K/Na ratio—in their source, so providing variable K/Na ratio to the Vulture rocks and different compatibility behaviour for some trace elements during partial melting. This is consistent with (1) the high modal proportion of phlogopite phenocrysts and megacrysts found in the explosive breccias erupted during the final stages of Mt. Vulture volcanic activity, and (2) the high concentration of CO_2 currently transported to the surface through aquifers beneath Mt. Vulture. Although the influence of residual phlogopite makes it difficult to use trace

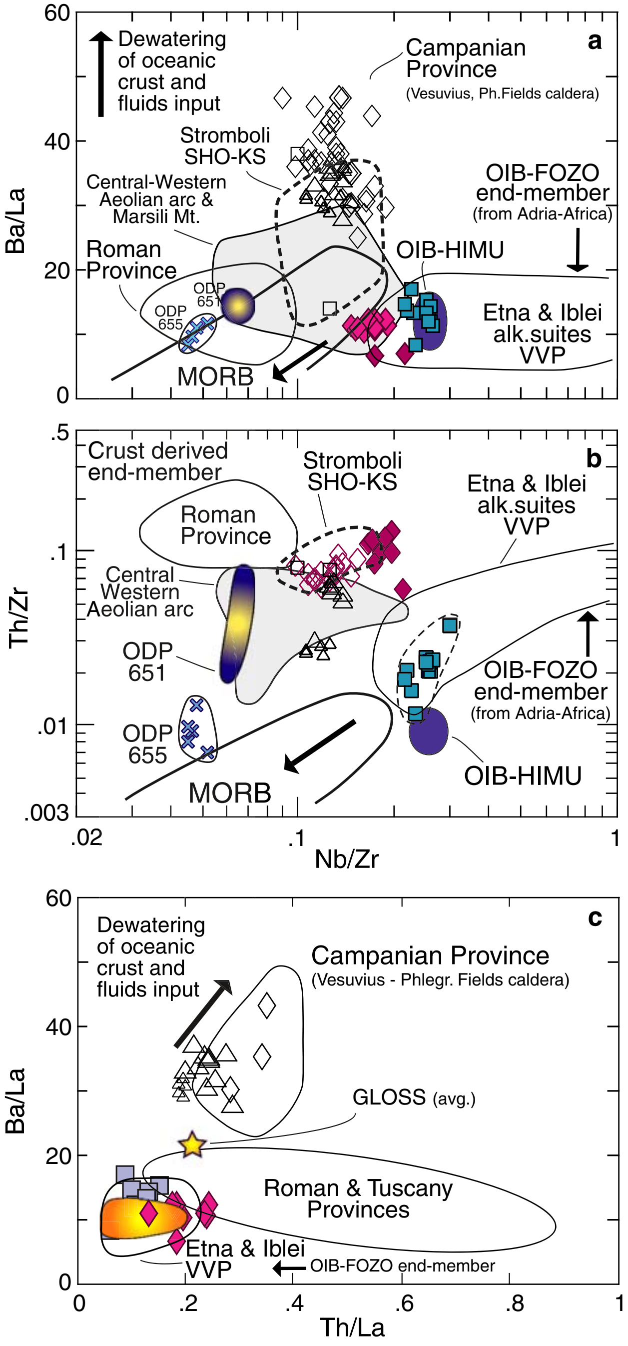

Fig. 8 Variation diagrams of **a** Ba/La and **b** Th/Zr vs Nb/Zr and **c** Ba/La vs Th/La, for mafic rocks (MgO >5 wt.%) from this study and literature. Symbols and data sources as in Figs. 3, 4. Noteworthy: the peridotite xenoliths from Vulture (Downes et al. 2002) have Ba/La (8.7–17.3) and Nb/Zr (0.12–0.29) values ranging in intervals similar to those of Vulture, Pietre Nere and other Italian intra-plate volcanoes (Iblei, Etna, etc.); the Ionian sediments (G. De Astis, unpublished data) have values of Ba/La = 6.6–13.5 and Nb/Zr = 0.04–0.12; OIB-FOZO ranges are: Ba/La = 4.3–11.5; Th/Zr = 0.01–0.04; Nb/Zr = 0.16–045; Th/La = 0.08–0.38. The range of values or the fields reported for MORB are from PETDB database (http://www.petdb.ldeo.columbia.edu/petdb), for OIB-FOZO and OIB-HIMU (St. Helena basalts—*grey fields*) are from GEOROC database (http://www.georoc.mpch-mainz.gwdg.de), for GLOSS (average) are from Plank and Langmuir (1998)

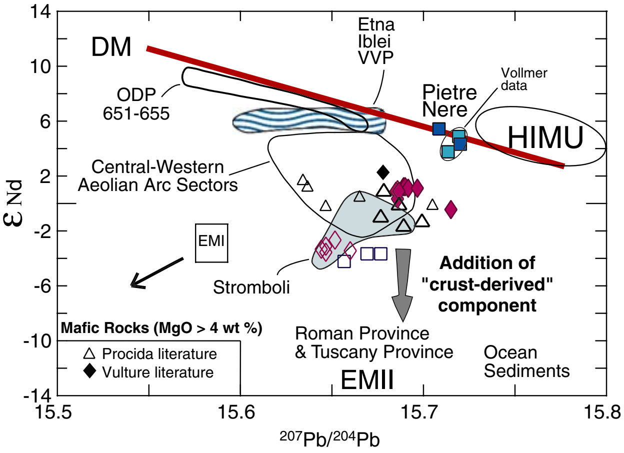

Fig. 9 Plot of εNd vs $^{207}Pb/^{204}Pb$ for mafic rocks with MgO >4 wt.%. Symbols and data sources as in Figs. 3, 4 and 5

elements to constrain the mantle source features, we can infer some aspects of the source feeding Mt.Vulture by combining the isotopic composition and the co-variations of LILE and HFSE ratios highlighted in Figs. 4, 5, 6, 7 and 8.

Isotopically, Mt. Vulture have intermediate compositions between Pietre Nere (or Etna-Iblei), i.e. OIB–FOZO type, and the composition of the average subduction component inferred for the Italian region (Gasperini et al. 2002), i.e. high $^{87}Sr/^{86}Sr$, low $^{143}Nd/^{144}Nd$ and moderate $^{206}Pb/^{204}Pb$, which we identify as a crustally derived end-member (Figs. 4, 5, 9). Most of the isotopic diagrams indicate that Mt. Vulture rocks are distinct from Tyrrhenian basins, Stromboli and CP magmas, but have some compositional similarity with Procida rocks. HFSE geochemistry also points to intermediate features between Pietre Nere and other OIB-type volcanoes, such as VVP, Etna and Iblei. Thus, the Mt. Vulture source can be described as “hybrid”, with geochemical and isotopic characteristics intermediate between OIB-type and subduction-related magmas of the Italian peninsula. In other words, geochemical data suggest metasomatic modification of an OIB source as a result of subduction-related processes. The covariation of Ba/La and Nb/Zr (Fig. 8a) suggests that Mt. Vulture has not been affected by subduction-derived fluids from the dewatering of oceanic crust and overlaying sediment film, which typically increases Ba/La ratios (Johnson and Plank 1999). Moreover, in this diagram, the data extend toward to the Roman Province field. Furthermore, Th/Zr ratios of Mt. Vulture rocks are slightly higher than those of CP rocks and comparable to the range shown by Roman Province (Fig. 8b); taken together with their very high Th contents (Fig. 3d, e), this indicates that Mt. Vulture lavas are Th enriched.

It is widely accepted that Roman Province rocks show evidence for a role of crustally derived sediments in their source (e.g. Peccerillo 2005). Moreover, addition of sediment-derived melts to the source has the typical effect of increasing Th (Class et al. 2000; Woodhead et al. 2001). The plot of Th/La vs Ba/La (Fig. 8c) shows an nearly vertical trend for the CP rocks, which is related to fluid-dominated inputs, whereas the low Ba/La and Th/La ranges shown by Mt. Vulture, similar both to Roman Province rocks and GLOSS (Plank and Langmuir 1998), may indicate sediment melts introduction.

The most obvious explanation for the whole of the compositional features shown by Mt. Vulture mafic magmas is that a pristine mantle source akin to that beneath Punte Nere or Iblei (African-type) was modified by sedimentary melts (or supercritical liquids) released from the down-going slab, which carried the more fluid-mobile elements (e.g., LREE, Ba, Th, U, Pb; Kessel et al. 2005) into the overlaying mantle, from which the Vulture magmas originated. We will return to the possible timing of these metasomatic features under southern Italy mantle in next section.

The mantle source of Campanian Province magmas

Despite numerous studies over the past 2 decades, the genesis and evolution of the CP magmas remains contentious. Crustal contamination at shallow levels has frequently been invoked to explain the geochemical and isotopic compositions of volcanic rocks from the Phlegraean District and Vesuvius (Turi and Taylor 1976; Del Moro et al. 2001). There is a little doubt that some mafic magmas erupted in the Phlegraean Fields caldera have been subject to fractional crystallization and crustal assimilation in shallow reservoirs (e.g. Pappalardo et al. 2002). However, several authors (D'Antonio et al. 1996; Peccerillo 2002 and references therein) have argued that most of the geochemical and isotopic features of the Campanian mafic rocks are controlled by enriched mantle source(s). Trace element ratios and isotopic signatures of Procida and Vesuvius mafic rocks (MgO >4–5 wt.%) considered in this paper, together with some selected mafic rocks from literature, reflect the characteristics of the enriched source from which they were derived (see Figs. 3, 4, 6). Previous papers (Rogers et al. 1985; Beccaluva et al. 1991; Serri et al. 1993) have interpreted these features as similar in style and origin to those of the potassic and ultrapotassic rocks from central-northern Italy (i.e. the Roman Province). As shown by Figs. 4, 5 and 9 the Roman Province magmas bear a strong crustal signature acquired from a mantle source metasomatised by continental sediment via subduction (see Peccerillo 1985; Gasperini et al. 2002 and references therein).

However, the limited overlap between Campanian and Roman Province data suggest the former have a significantly different crustal imprint than the latter (see Peccerillo 2005; this study in Figs. 4, 5, 8, 9) and this indicates that: (1) each magma source probably underwent different types or extent of metasomatism (Peccerillo 2005); (2) the two areas represent different magmatic provinces as already proposed by Peccerillo and Panza (1999). Ratios of LILE/HFSE and LILE/REE observed in CP magmas (e.g. those in Figs. 6, 8) are higher than those of MORBs and intra-plate basalts and are also slightly higher than most CA Aeolian arc rocks, but are very similar to the Stromboli K-alkaline rocks. A striking similarity between CP and Stromboli alkaline series is also observed for isotopic compositions (Figs. 4, 5, 9). These features in both volcanic areas can be inherited from fluid-dominated metasomatic agents, as stated in the previous section. Using the HFSE contents and Zr/Nb ratios (Fig. 7, Table 1) as "windows" to see through the added subduction component (Pearce et al. 2002) in the CP source, we observe that they are: (a) akin to those of Stromboli K-alkaline suites; (b) partially overlap the composition of Mt. Vulture and some intra-plate magmas; (c) distinct from both the Roman Province and MORB-like rocks from the Tyrrhenian Sea. In other words, the mantle source of the CP magmas prior to subduction modification provided a component enriched in HFSE that is geochemically distinct from both depleted mantle (i.e. MORB-like ODP magmas from Tyrrhenian Sea) and the "crust-derived" end-member (Roman and Tuscany Provinces). Its character is more akin to Mt. Vulture, for HFSE contents and ratios, and closer to subduction-related magmas of southern Italy (e.g. Stromboli) for LILE contents and LILE/HFSE ratios (Figs. 7, 8).

In addition, several Procida and Vesuvius mafic rocks plot along isotopic trends connecting volcanoes with OIB–FOZO features and the "crust-derived" end-member. Therefore, as suggested for Mt. Vulture, the CP source can also be regarded as "hybrid", but with a stronger subduction influence if compared to Vulture. This is consistent with the interpretation of previous authors (Beccaluva et al. 1991; Ayuso et al. 1998; Peccerillo 2001) that the source of Vesuvius formed by addition of metasomatic fluids (or melts) to an OIB-like mantle source.

However, we note that Procida basalts (MgO >5 wt%) are subtly different from Vesuvius and Phlegraean Fields basalts with comparable MgO contents. In particular, Procida samples have lower concentrations of LILE and LREE (Fig. 3d, e), and show on average lower Th/Zr, Ta/Yb and Zr/Hf ratios than Vesuvius (Figs. 6, 8). Geochemically, they show several similarities with ODP 655–651 rocks. They also extend to lower Sr and higher Nd and have a wide range of Pb isotope ratios (Figs. 4, 5, 9), such that some samples are isotopically akin to Mt. Vulture magmas. Accordingly, the composition of Procida is distinctive, not only in comparison to other CP rocks, but also relative to mafic rocks throughout southern Italy. We propose two alternative explanations for this: (1) the source of Procida magmas has been less affected by subduction-addition than the source of Vesuvius; or (2) the Procida magmas inherited a depleted mantle component not represented in the source of Vesuvius. We consider these two hypotheses and their significance more fully in the next section.

Temporal and spatial variations in the mantle source of southern Italian volcanism

We previously showed that significant compositional variation occurs progressing westward from Mt. Vulture to Vesuvius and Phlegraean Fields (i.e. ^{143}Nd/^{144}Nd, ^{206}Pb/^{204}Pb, Th/Zr, Ta/Yb, Nb/Y decrease on average, while Zr/Nb, K/Nb and ^{87}Sr/^{86}Sr increase), and some of these trends reverse moving from Vesuvius to Procida (Fig. 6). How can we account for these spatial variations in terms of source evolution and relative age of volcanism?

It has been suggested that isotopic and HFSE ratio covariations shown in Figs. 7, 8 and 9 for mafic rocks along the studied transect can be explained as mixtures of different source components (or end-members): (1) a depleted mantle (DM), represented by the MORB-like rocks from Vavilov basin (in particular Site 655); (2) an OIB-type mantle source represented by Pietre Nere; and (3) an enriched component, derived from recycled continental crust and most strongly displayed in Roman and Tuscany Province rocks. Our idea is that the relative contributions of these different end-members have varied in space and time (Fig. 10).

Mt. Vulture volcanics (0.73–0.13 Ma)—the oldest erupted magmas in the transect after Pietre Nere—have stronger affinities with intra-plate magmas (OIB-type mantle source), as exemplified by the Zr/Nb and Zr/Hf ratios (see Figs. 6, 7). We discount the possibility that this is related to recent upwelling of a HIMU plume channelled through a window in the Adria slab, as proposed by Gasperini et al. (2002) because, as shown in Geodynamic implications section, a similar OIB-type mantle has been present beneath the Adria plate and under southern Italy for at least the last 60 Ma. The Pietre Nere magma bodies testify to the formation of a CO_2–H_2O and ITE enriched (HIMU like) source through the impinging on the lithosphere of pervasive melts from ascending plume at about 60 Ma. This is akin to the model proposed for other magmatic intra-plate regions overlying the European plate (Wilson et al. 1995). Instead of recent upwelling, the OIB-type component in the Mt. Vulture magmas originated from asthenospheric mantle beneath the Adria plate that had been successively modified by sediment-derived mobile elements coming from the subducted Adria slab. This process is responsible for the higher ^{87}Sr/^{86}Sr, some LILE contents and LILE/HFSE ratios of the Mt. Vulture source compared with Pietre Nere, Etna and most European peridotite xenoliths. Partial melting of this metasomatized source, due to the transient thermal perturbation produced by detachment and sinking of the Adria slab and to the extensional tectonics, generated the Vulture alkali-basalt/basanite/nephelinite suites. The late-stage (~0.13 Ma) emplacement of xenolith-bearing, silica-poor and Ca-rich melilitic magmas, depleted in Rb and HFSE elements, suggests a change in conditions with time, such that the youngest volcanics were generated by smaller degrees of partial melting, and melt generation occurred at deeper levels in a phlogopite-bearing mantle. This change in melting regime probably reflects a waning of the thermal perturbation that occurred when the Adria slab detached beneath southern Italy.

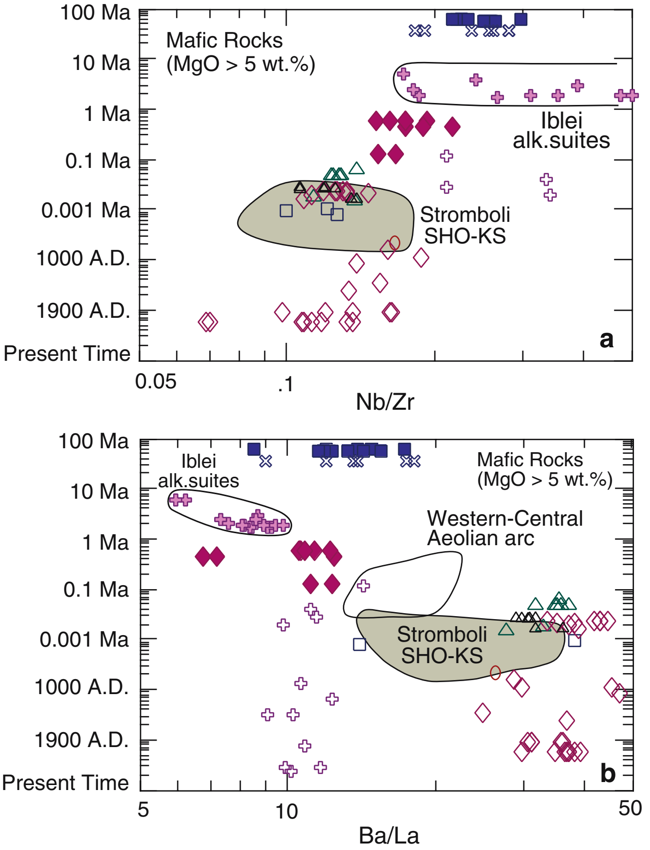

Fig. 10 Plots of age (years in log scale) vs Nb/Zr (**a**) and Ba/La (**b**) for mafic rocks from the studied transect and literature with MgO > 5 wt.%. Symbols and data sources as in Figs. 3, 4 and 5

By comparison with Mt. Vulture, most of the CP magmatism is younger. The studied mafic products range in age (De Astis et al. 2004) from 70 ka to 0 age (Fig. 9), but volcanism dates back to about 0.36 Ma (Brocchini et al. 2001). Unfortunately, no trace element and isotopic data are available for these older volcanics, and we do not know whether the change in mantle source characteristics between Mt. Vulture and the CP (Figs. 7, 8) is gradational or abrupt. However, we do know that differences exist among the three main volcanoes currently forming the Campanian Province. As previously mentioned, most Phlegraean Fields mafic rocks have undergone at least some crustal contamination in shallow-level magma chambers (Pappalardo et al. 2002), so the nature of their mantle source has been obscured for many elements. Nevertheless, several relatively robust geochemical parameters (e.g. Nb/Zr, Zr/Hf, Ta/Yb; Figs. 6, 7, 8) are akin to those of Vesuvius alkaline magmas. Therefore, we propose that both areas can be related to pristine OIB–FOZO type source, similar to that feeding Mt. Vulture activity, but differently modified by addition of fluid-mobile elements from the dewatering of the subducted slab (e.g. higher Ba/La ratios; Figs. 6, 8a, c).

Our study also indicates that mafic rocks from Procida (and some from Vesuvius) provide compositional evidence for a contribution from the Depleted Mantle source. Diagrams in Fig. 8b, c show that several Procida basalts plot in clusters intermediate between the OIB-type mantle end-member from the Adria plate and the southern Tyrrhenian Sea rocks (ODP Sites 651 and 655). Moreover, volcanics throughout Italy and the Tyrrhenian Sea reported on plots of Pb isotopes vs. $^{87}Sr/^{86}Sr$ (Fig. 11) (or $^{143}Nd/^{144}Nd$, not shown) display a predominant trend of mixing between the OIB–FOZO component (identified beneath Adria–Africa plates) and a crust-derived end-member (recycled crustal sediments). However, the Procida rocks form an array that crosscuts the main trend and extends to unradiogenic Pb isotope ratios more typical of Tyrrhenian Sea volcanics. Since the rocks that show these features are the youngest erupted from Procida (ca. 15–18 ka), we conclude that not only does the genesis of the Procida mafic magmas involve a Tyrrhenian MORB-like component, but that this involvement is a relatively recent phenomenon. A Tyrrhenian MORB-like component may also have been involved in the genesis of other CP rocks, although to a lesser extent than Procida. This is suggested by plots of Zr/Nb and Zr/Hf ratios (Figs. 6, 7) where some CP rocks also point to ODP rocks from Vavilov basin (Tyrrhenian Sea). Finally, we argue that this Tyrrhenian mantle source is unlikely to have been "pristine" Depleted Mantle (i.e. unmodified by subduction processes), since all CP rocks are strongly LREE and LILE enriched, with high Ba/La (Figs. 8, 10b). It is also clearly subordinate to the OIB–FOZO component from Adria plate.

Geodynamic implications

The nature and origin of mantle reservoirs feeding the volcanism of southern Italy have important implications for reconstructing the geodynamic evolution of the entire Central Mediterranean area. Moreover, the magmas erupted along the transect are closely associated in space and time (0.73 Ma to Present time), and this suggests a fairly fast migration of geodynamics and mantle processes. Our geochemical and petrological data demonstrate that the magmas erupted along the studied W–E transect share geochemical similarities and show differences that are related to the variable proportions of mixing provided by the OIB–FOZO mantle component and the subduction inputs from the slab to the Mt.Vulture and CP melts; a third component, the MORB-like southern Tyrrhenian source, may have influenced Procida and some Vesuvio mafic magmas. While the arc components can be attributed to subduction-related melts and/or fluids from the detached Adria slab, the origin of the OIB–FOZO-type component has never been clear. It may be related to a HIMU plume upwelling through a slab window in the central-southern Tyrrhenian Sea (Gasperini et al. 2002; Bell et al. 2003) or, alternatively, as we propose, to inflow of mantle material drawn beneath southern Italy from the African plate passing through the gap created after the detachment of the previously westward colliding Adria slab.

A deep mantle inflow origin is suggested by the fact that CP and Mt. Vulture rocks tend to plot on mixing trends between a HIMU-like mantle reservoir and a crustally derived component (Figs. 5, 9, 11). There is general agreement that HIMU represents recycled,

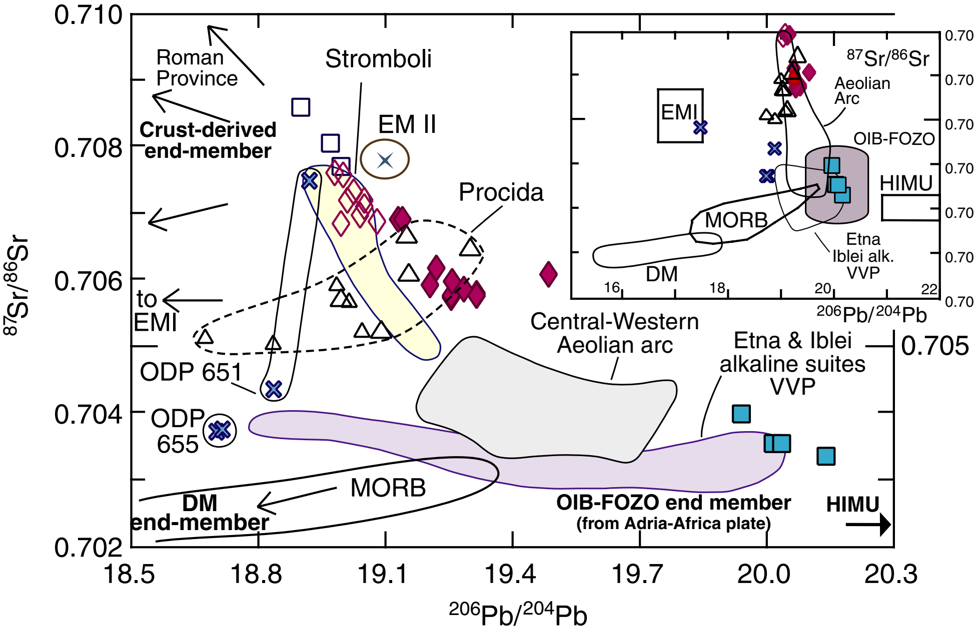

Fig. 11 Plot of $^{206}Pb/^{204}Pb$ vs $^{87}Sr/^{86}Sr$ for mafic rocks from the studied transect and literature with MgO > 4 wt %. Symbols and data sources as in Figs. 3, 4 and 5. The range of values reported for MORB, OIB-FOZO and OIB-HIMU basalts are from PETDB and GEOROC database (http://www.petdb.ldeo.columbia.edu/petdb; http://www.georoc.mpch-mainz.gwdg.de)

hydrothermally altered ocean crust that has been stored for a significant length of time in the mantle and returned to shallow levels via mantle plumes (Hofmann 1997). However, none of the analysed samples has a true HIMU composition. Moreover, all of the magmas from various ages (Paleocene to Present) erupted along the foreland of the Apennine (i.e. from the African plate: VVP, Pietre Nere and Iblei) or from the edge between African and European plates (Etna), have similar isotopic signatures. This strongly suggests that the resident mantle beneath the African plate has an isotopic composition that is intermediate between HIMU and DM, but closer to the former. It is a moderately HIMU-like component that closely resembles the FOZO component (Cook-Austral young volcanics; GEOROC database) recently redefined by Stracke et al. (2005). Moreover, this composition has remained relatively constant, at least since the Early Cenozoic. This argues against recent arrival of a HIMU plume, as suggested by (Gasperini et al. 2002; Bell et al. 2003), whereas Pietre Nere could be related to very old mantle-diapirs upwelling. Therefore, the magmatism from Mt. Vulture and the CP volcanoes is more likely the result of mantle inflowing from African plate, which then underwent subduction modification.

Seismic studies and tomographic models of the upper mantle structure in the Mediterranean region (Wortel and Spakman 2000 and reference therein) suggest that detachment of the Adria slab occurred at about 8–9 Ma, under the northern-central Apennines, triggered by incipent subduction of continental lithosphere below this area. However, S-wave tomography (Panza et al. 2004) indicates the presence of rigid lithosphere up to about 130 km, indicating a slab detachment at these depths. The initial *tear* subsequently migrated southward, developing into a large tear, until complete slab detachment occurred under the central-southern Apennines and Calabria; detachment in the latter area could be very recent or incipient (Wortel and Spakman 2000). Lateral migration was accompanied by a series of plate boundary process, i.e. the concentration of slab pull forces generated a pattern of subsidence (depocenter development) and uplift that migrated along strike; it also increased the slab roll-back (arc migration). The gap produced by slab detachment was infilled by upwelling (hot) mantle material, producing magmatism of variable composition and limited duration.

Geological data on Quaternary and very Recent uplift (last 125 ka—Cosentino and Gliozzi 1988) appears to confirm the migration of uplift along strike. Uplift rates of 0.7–1.15 mm/years in Southern Calabria and 0.23–0.32 in the Apulia foreland/Bradanic foredeep, which represents the start of uplift in the latter region, occurred together with a change in style of deformation in Calabria at ~0.7 Ma (Westaway 1993). Moreover, slab roll-back is demonstrated by the high rate (≥5 cm/years) of arc migration measured in the Southern Apenninic chain, including the Calabrian arc and not involving the Northern Apennines (Patacca et al. 1990 and references therein). The kinematic model and seismotectonic framework proposed by Meletti et al. (2000) for the Southern Apennines describe the area as a convergent margin, previously characterized by lithosphere sinking and later break off from the Adria microplate, with development of peculiar rifting within the inactive thrust belt (normal faults due to the plate divergence). A dramatic change in the geodynamic regime of the southern Apennines occurred at the beginning of the Middle Pleistocene (0.7–0.65 Ma) with the sudden interruption of flexure-hinge retreat from Eastern Abruzzi to Basilicata (Fig. 1), followed by a generalised uplift of the chain and normal faulting along the Tyrrhenian slope (Hyppolyte et al. 1994; Meletti et al. 2000). These geological processes are possibly the direct effect of slab detachment. Mt. Vulture eruptive activity occurred during this period, likely in response to the inflow of hot African mantle around the detached slab. Rifting then propagated toward the Campanian Plain, facilitating emplacement of magmas beneath this region. The strong compositional similarity between CP and Stromboli alkaline (SHO–KS) magmas, erupted over the last 25 ka, suggests that further rift propagation and suction of African mantle toward the Aeolian arc has occurred, both in response to ongoing Ionian slab roll-back and counter-clockwise rotation (Ward 1994) of Adria microplate towards NE. This movement started approximately 0.7–0.8 Ma, after the end of subduction beneath the Southern Apennines segment (Meletti et al. 2000) and may have facilitated the eastward inflow of African mantle into the region.

In summary, our petrological data, in association with tectonic, geophysical and geological evidence, support the idea that the OIB–FOZO mantle component occurring in Mt. Vulture magmas has been drawn laterally into the region as a result of detachment of the downgoing Adria slab, consistent with the model of asthenosphere suction proposed for Mt. Etna by Gvirtzman and Nur (1999, 2001) on the basis of geophysical data. The original mantle source (i.e. unmodified by subduction) feeding the Campanian Province volcanism had a similar nature, but probably also includes eastward mantle inflow locally drawn into the mantle wedge from the central Tyrrhenian basin (Vavilov) and limited to Procida. The presence of a low-velocity anomaly between 15 and 35 km beneath the Vesuvius area, revealed by teleseismic investigations (De Natale et al. 2001), agrees with this reconstruction and accounts for possible melting of the Campanian lithospheric mantle. The shallowing of isotherms required to achieve such melting was probably promoted by the extensional tectonic regime that characterises the Campanian Plain. The cartoon shown in Fig. 12 summarises our geodynamic model, showing slab detachment under the southern Italy and consequent inflow from beneath the Adria Plate (African mantle). Possible inflow of MORB-like mantle from the Tyrrhenian Basin is indicated on the western side.

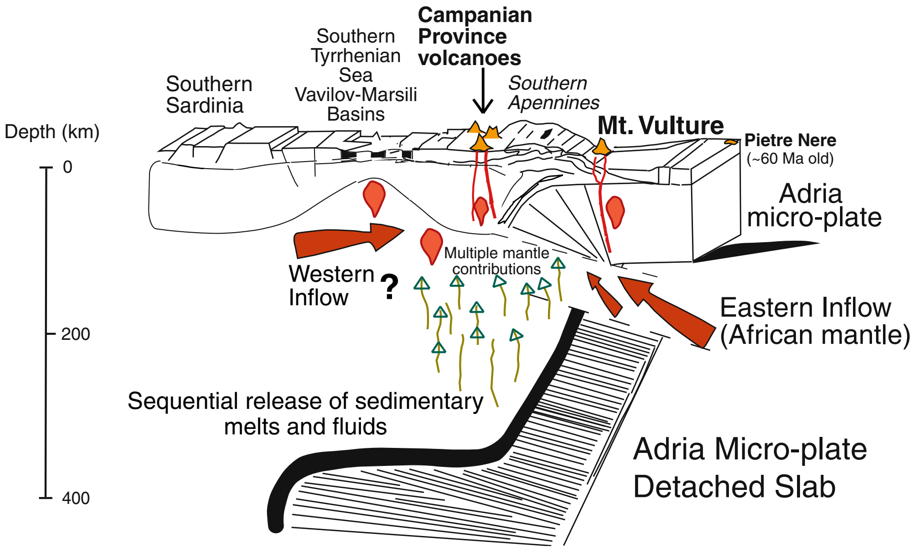

Fig. 12 Three-dimensional cartoon of the southern Italy and southern Tyrrhenian Sea. Thick *arrows* indicate the hypothesized directions of mantle inflows from the Adria (Africa) plate and the Tyrrhenian Basins. Mixing of eastern and western inflows beneath the Campanian Province (Procida) could be occurred. The southern Italy mantle experienced different types of metasomatism by subduction-related sedimentary melts or supercritical liquids (Mt. Vulture) and fluids (Campanian Province volcanoes). The depths of the detached and lying flat slab beneath southern Apennines are derived from tomographic images of P-wave velocity anomalies (Fig. 2f in Wortel and Spakman 2000)

Due to the lateral migration of the detached slab (slab-tear), the change in the geodynamic regime—from compression to distension—has progressively shifted to the west, producing the Campanian magmatism, and to south toward the eastern sector of Aeolian arc. As a final phase of this migration, the Ionian subducting slab is now retreating south-eastward under the Calabrian arc and is still facilitating the suction/inflow of African mantle. The geochemical evidence of this process can be seen in the alkaline magmas from Stromboli. A similarity in the geodynamic context and some subduction-related features in the recent Mt. Etna basalts (Schiano et al. 2001) allow us to suggest that the latter (0.3 Ma–Present time) and Mt. Vulture (0.73–0.13 Ma) may represent diachronous volcanoes formed in response to the (Adria–Ionian) slab tearing and retreating at its southern and northern edges, respectively.

Summary and conclusions

Compositional variations among volcanic mafic rocks along an E–W transect from Mt. Vulture to the Campanian Province (Vesuvius, Phlegraean Fields, Procida) provide new insights into (1) the mantle sources involved in the magmatism of central-southern Italy from Pleistocene to Present time and (2) their geodynamic significance. Magmatism at Mt. Vulture, which is located on the eastern side of the Apennines (i.e. external to the geodynamic active front) was derived from an intra-plate (OIB-like) mantle source. It originated from eastern inflow from beneath the Adria–Africa plate after subduction and detachment of the Adria slab, but which was modified by subduction-related processes (Beccaluva et al. 2002; Melluso et al. 1996). Rocks from the Campanian Province, located on the west side of the Apennines, were derived from a similar intra-plate source, enriched by metasomatic agents previously released from the Adriatic slab. Our study is consistent with models in which Adria slab detachment (Carminati et al. 1998; Wortel and Spakman 2000) is the key element controlling lithosphere dynamics in this part of the Central Mediterranean. Lateral migration of slab detachment along the plate boundary can account for many of the geological observations: arc and trench migration, along-strike variations in vertical motions and stress fields, and geochemical variability in magmatism in space and time. Mt. Vulture magmatism is the unequivocal witness to the unusual mantle dynamic that has occurred after cessation of collision between the Adria–Africa and Europe plates and the early phenomena at the surface of the inflow uprising. The main volcanic activity at Mt. Vulture (0.73–0.48 Ma) occurs in response to the arrival of upper mantle inflow from beneath the Adriatic plate, after detachment of the Adria microplate slab in the late Miocene to Pleistocene. The most recent volcanism of the Campanian Province, which developed in the extensional stress field of the Campanian plain, represents a stage of rifting magmatism which involves a lithospheric source similar to that of the Mt. Vulture, but differently metasomatised. In addition to the subduction-related component, the near primary basalts erupted on Procida Island also provide evidence for a minor contribution from the Tyrrhenian mantle.

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Appendix: analytical techniques

Major and trace elements for Pietre Nere (sample G19), Mt. Somma-Vesuvius (LPG 2 and samples from different drillings), and Procida rocks were analysed at the Centre de Recherches Petrographiques et Geochimiques (CRPG, Vandouvre Cedex, France). Details of analytical techniques used are reported in De Astis et al. (2004). Major elements, Ba, Rb, Sr, Y, Zr, Nb, Ni, Cr, V, La and Ce for Vulture and Pietre Nere rocks were obtained by X-ray fluorescence and by traditional wet chemical techniques (FeO and LOI) at the Dipartimento Geomineralogico, University of Bari and at the Dipartimento di Scienze della Terra, University of Perugia, Italy. REE, Th, U, Cs, Ta, Hf, Sc and Co on the same samples were determined by INAA at the Department of Geology, University of Western Ontario, London, Canada. Precision is better than 5% for Rb, Sr, Zr, Ba, Y, Th and U and better than 10% for the other trace elements. Samples for Nd, Sr and Pb isotope analysis were prepared at the NERC Isotope Geosciences Laboratory (NIGL) using procedures described in Royse et al. (1998), Kempton and McGill (2002); all three analytes were separated from the same dissolved sample powder. Sr was run at NIGL on a single Ta filament using a Finnigan MAT 262 multi-collector mass spectrometer in multidynamic mode. Nd was run at Durham University using using a Re-Ta filament assembly on a Finnigan Tritan (also multi-collector). The effects of fractionation were accounted for at run time by normalising $^{87}Sr/^{86}Sr$ to a value of $^{86}Sr/^{88}Sr = 0.1194$ and $^{143}Nd/^{144}Nd$ to a value of $^{146}Nd/^{144}Nd = 0.7219$. Sample data are reported relative to accepted values for NBS 987 and La Jolla of 0.71024 and 0.51186, respectively. Minimum uncertainty is derived from external precision of standard measurements, which over the course of analysis were better than 45 ppm (2σ) for $^{86}Sr/^{88}Sr$ and 10 ppm (2σ) for $^{143}Nd/^{144}Nd$. Pb isotopes were analysed at NIGL using the VG P54 MC-ICP-MS, since this instrument allows us to correct for mass fractionation during the run using the Tl-doping method. We have used a $^{205}Tl/^{203}Tl$ value of 2.388, which was determined empirically by cross calibration with NBS 981. All Pb isotope ratios have been corrected relative to the NBS 981 composition of Todt et al. (1996). Based on repeated runs of NBS 981, the reproducibility of whole rock Pb isotope measurements is better than ±0.01% (2σ). Blanks for Sr, Nd and Pb were less than 300 pg, 100pg to 200 pg, respectively.

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