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Cenozoic Italian magmatism – Isotope constraints for possible plume-related activity

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ABSTRACT

Assessment of the isotope systematics and the magmatotectonic history of mainly Cenozoic igneous rocks from Italy shows them to be inconsistent with subduction-related magmatism. We attempt to fit these data into an alternative model involving long-term, recurrent plume activity that extended over a period of about 100 Ma, that involved mantle expansion and subsequent mixing between isotopically-distinct, mantle components. Sr, Nd and Pb isotopic compositions of Cenozoic Italian igneous rocks, rather than being random, reflect binary mixing involving a common end-member similar to FOZO. Most isotopic data from along the entire length of Italy, from the Aeolian Islands to the Alpine belt, define a Main Italian Radiogenic Trend (MIRT), characterized by mixing between FOZO and a highly radiogenic Sr, mantle end-member (ITEM, ITalian Enriched Mantle). Data from the Adria foreland, Sicily and the south-western Tyrrhenian Sea and Sardinia deviate from MIRT suggesting mixing with other components, perhaps HIMU and EM1. Both the absence of pure DMM, and the presence of isotopic end-members not recognized in present-day consuming-plate margins are incompatible with subduction-related models. Two models are discussed, one in which ITEM is attributed to melting of pre-Alpine sediments/upper continental crust entrained in a FOZO-like mantle and the other to widespread metasomatic activity involving deep-seated plume activity. In the latter, the widespread nature of FOZO is attributed to a late Triassic–early Jurassic plume that preceded the opening of the Alpine Tethys and led to modification of the lithosphere and/or asthenosphere. Late Jurassic–early Cretaceous plume activity produced mantle expansion and the opening of the Alpine Tethys. A new phase of plume activity started during the Oligocene with the opening of the western and central Mediterranean Basins. Stretching and large-scale extension of the Mediterranean lithosphere was caused by the progressive eastward growth and volume increase of a plume head trapped within the Transition Zone. Plume-generated fluids/melts enriched in K–Ca–CO_2–H_2O, produced mantle sources capable of generating widespread alkaline, mafic, and carbonatitic magmatism. Lithospheric unloading controlled the Tyrrhenian and peri-Tyrrhenian magmatic activity.

1. Introduction

Since the acceptance of a plate tectonic model to the Tyrrhenian–Apennine system of Italy (e.g. Malinverno and Ryan, 1986), the Neogene to Quaternary magmatism in Italy has been attributed to subduction, accommodated by the eastern migration of a westerly-dipping slab, involving conventional trench retreat and back-arc extension (Doglioni et al., 1997; Wortel et al., 2003; Faccenna et al., 2004 among others). However, the general picture is made more complicated by the large chemical and isotopic variation of the associated magmatism. Compositions range from sub-alkaline to alkaline basalts, ultrapotassic mafic to ultramafic rock-types, reflecting different processes and/or mantle sources with very depleted to highly enriched radiogenic isotopic signatures. The presence of leucitites, kamafugites, carbonatites, lamprophyres and lamproites, typical of intraplate associations, as well as the isotopic compositions of many of the igneous rocks, challenge any subduction-related model. As a consequence, authors have been forced into creating complex geodynamic scenarios where the subducted slab had been cross-cut, pierced or straddled by a rising plume (see Gasperini et al., 2002 and reference therein). Several articles have questioned the involvement of subduction-related processes in Italy and have, instead, proposed intra-continental passive rifting (e.g. Cundari, 1979, 1994; Lavecchia, 1988; Locardi

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and Nicolich, 1988; Lavecchia and Stoppa, 1996). A more recent model involves a trapped plume which has physically expanded the asthenospheric mantle in the western and central Mediterranean, leading to lithospheric stretching and associated magmatism without any involvement of subduction (e.g. Bell et al., 2004; Lavecchia and Creati, 2006; Bell et al., 2006; Lavecchia and Bell, 2011). This Mediterranean plume might have initiated in the Atlantic at deep levels and migrated to shallower depths in the western and central Mediterranean areas and regions elsewhere (e.g. Hoernle et al., 1995; Oyarzun et al., 1997; Piromallo et al., 2008; Duggen et al., 2009).

Recent evidence for plume activity in Italy, an idea by no means new (e.g. Vollmer, 1976), involves the recognition of isotopic mantle components found in OIBs, especially FOZO (FOcus ZOne, see Hart et al., 1992), but not in subduction-related environments (Bell et al., 2004, 2005; Cadoux et al., 2007). Other plume-related or intraplate mantle components that may have played a role in Italy are HIMU (e.g. Wilson and Patterson, 2001; Gasperini et al., 2002; Harangi et al., 2006; Rotolo et al., 2006; Lustrino and Wilson, 2007; Beccaluva et al., 2007; Bianchini et al., 2008) and EMI (e.g. Lustrino et al., 2000; Downes et al., 2001). A strongly enriched mantle component, named ITEM (ITalian Enriched Mantle) and never found in subduction environments, has also been recognized along the length of Italy, from the Aeolian Islands to the Alps (Bell et al., 2005, 2006; Owen, 2008). Characterized by an extremely high $^{87}Sr/^{86}Sr$ ($>$0.7220, initial ratio), it is mostly seen in Oligocene lamprophyres from the western Alps (Venturelli et al., 1984; Owen, 2008).

In this paper, based on an updated regional database of published and unpublished Sr, Nd and Pb isotope analyses (Table 1 and references therein), we assess the minimum number of isotopic end-members needed to explain the mixing trends for the Italian igneous occurrences (peninsular Italy plus the Alps, Sardinia, Sicily and the Tyrrhenian Sea), from Late Cretaceous to present day. We then discuss the role of plume activity and its direct or indirect interaction with the asthenosphere and the lithosphere in controlling mantle source modification, magmatism, and tectonics. We take into consideration the overall long-term magmatotectonic history since Cretaceous times, but specifically focus on the late Miocene–Quaternary extensional phase that opened up the central Mediterranean and generated lithospheric stretching, unloading and resulting volcanism. This is then followed by an assessment of the evolution of the Mediterranean through the use of chemical geodynamics, an approach pioneered by Allègre (1982).

2. Magmatotectonic framework

Fig. 1 schematically shows the geometry and tectonic location of the western (e.g. Algerian and Provençal-Ligure Basins) and central (e.g. Tyrrhenian Sea) Mediterranean Basins and of the Alpine-Betic and Apennine-Maghrebide compressional chains. Table 1 summarizes the isotopic data, the tectonic phases and associated igneous activity. The late Cretaceous–Paleocene compressional phase, which was essentially amagmatic, lead to the progressive consumption of the Alpine Tethys with formation of the internal sheets of the Europe-verging Alpine-Betic thrust belt. It was, only subordinately, accompanied by two cycles of lamprophyric activity, one at the end of the early Cretaceous (~110–90 Ma) and the other during the late Cretaceous and the early Paleocene (~80–60 Ma) (Vichi et al., 2005). The first cycle is well represented in southern Tuscany (Faraone and Stoppa, 1990), while the second is recognized at several isolated localities including Calceranica and Corvara in Badia in the south-eastern Alps (68–70 Ma), Nuraxi Figus in south-eastern Sardinia (62–60 Ma), Punta delle Pietre Nere in Puglia (70 Ma, Conticelli et al., 2002) and La Queglia in Abruzzo (58–54 Ma) (see Stoppa, 2008 and references therein) (Fig. 2).

The late Paleocene–Eocene collisional stage between the Africa and Europe continental plates, which pre-dated the Mediterranean extensional phase, produced the nucleation of Africa-verging Alpine sheets. This phase was coeval with basaltic volcanism in the Veneto foreland of the south-eastern Alps (Macera et al., 2003; Beccaluva et al., 2007) and with lamprophyric volcanism in the south-eastern (Val Fiscalina, 34 Ma) and the south-western Alps (Sesia-Lanzo, Combin and Biellese, 29–33 Ma) (see Stoppa, 2008 and references therein). In Oligocene–early Miocene times a narrow belt of calc-alkaline activity developed along the Peri-Adriatic lineament in the Alps, the French coast in Provençe and in south-eastern Sardinia (e.g. Pamić et al., 2002).

At the beginning of late Oligocene times, the extensional process lead to the progressive opening of the Mediterranean wide-rift basins and extension started to dominate over compression. The Neogene to Quaternary Mediterranean phase also involved fold-and-thrust belt tectonics, with formation of the Apennine-Maghrebide belt, but the compressional structures were always confined outward from the progressively eastward-stretching and thinning lithospheric domains (Fig. 1). Two distinct deformational stages, separated by a tectonic break, may be distinguished: the late Oligocene–early Miocene, Ligure–Balearic stage (~25 to ~16 Ma) and the middle Miocene–Quaternary, Tyrrhenian stage (~13 Ma to present) (Lavecchia and Bell, 2011). The Tyrrhenian stage led to the progressive stretching and thinning of the roots of the pre-existing Alpine chain and to the progressive involvement in the compressional tectonics of the Adriatic foreland terranes, as well as formation of the Apennine fold-and-thrust belt. At present, the Tyrrhenian Sea is characterized by a thinned lithosphere which reaches a minimum thickness of only 30 km in its southern bathyal plane, containing the Magnaghi, Vavilov and Marsili volcanoes. In Fig. 2 it is evident that most of the Tyrrhenian and circum-Tyrrhenian magmatic occurrences lie within the thinned lithosphere domain encompassed by the 50 km lithosphere–asthenosphere contour line (Fig. 2; see Panza et al., 2007). Most rocks in the western and southern sides of this domain are sodic basalts (Ustica, Etna, Hyblean Plateau and some of the Tyrrhenian ODP dredged samples). In the Tyrrhenian basinal area (Magnaghi, Vavilov, Marsili), most volcanic rocks are transitional basalts, but along the eastern rift side (from the Aeolian Islands to Campania, Latium and Tuscany), potassium-rich products dominate. They consist of lamproites in Tuscany, of near silica-saturated and leucite-free rocks (trachybasalts plus calc-alkaline rocks) in the Aeolian insular arc, and of silica-undersaturated, leucite-rich, high potassium rocks (leucitites and melilitites; olivine melilitite/kamafugites) within the Roman–Campanian Province. Both saturated and undersaturated trends co-exist in the same province (Conticelli et al., 2007 and references therein). Mid Pleistocene carbonatitic monogenic centres occur within the Intra-montane Ultra-alkaline Province (IUP) of central Italy and at Vulture, both underlain by unthinned lithospheric where the lithosphere–asthenosphere boundary lies at a depth of nearly 90–110 km (e.g. Stoppa and Woolley, 1997; Lavecchia et al., 2006 and references therein).

An independent extensional phase, still active, developed mainly in Mio-Pliocene times, led to the opening of the north-westerly striking, narrow Sicily Channel thrust system, which cross cuts the Sicily-Maghrebide rift system and continues north-west as the Campidano graben in Sardinia (Corti et al., 2006). These relationships are shown in Figs. 1 and 2. The associated Na-alkaline activity, typical of intra-plate rift related magmatism, started during late Miocene times (e.g. Graham Bank, still active), climaxing during the Pleistocene at Linosa and Pantelleria and within the Campidano graben in Sardinia. Associated with extensional tectonics unrelated to the Tyrrhenian opening, such magmatism also characterizes the Hyblean foreland in south-eastern Sicily. For recent reviews, the

Table 1
Summary of rock types, provinces plus centres, ages and range of isotopic compositions.

Major tectonic Phases		Abb.	Igneous provinces and/or centres	Most primitive rock type/s	Age (Ma)	Radiogenic isotopes					Main mixing rend
						$^{87}Sr/^{86}Sr$	$^{143}Nd/^{144}Nd$	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$	
LATEST ALPINE TETHYS EXTENSION		TCP*	Tuscan Cretaceous	Alkaline lamprophyre	110–90	0.7047–0.7065	0.5128–0.5129	18.53–19.65	15.56–15.65	38.25–39.30	**MIRT?**
ALPINE COMPRESSION	Alpine Tethys closure ~90 to 55 Ma	EA1*	Eastern Alps 1	Alkaline lamprophyre	70–68	0.7037–0.7082	0.5124–0.5130	18.50–18.78	15.66–15.68	38.87–39.36	**MIRT**
		NF*	*Nuraxi Figus (Sardinia)*	Alkaline lamprophyre	62–60	0.7048	0.5128	19.08	15.65	39.23	**FE?**
		PN*	*P.Pietre Nere (Puglia)*	Alkaline lamprophyre	62–58	0.7035–0.7040	0.5127–0.5129	19.94–20.04	15.71–15.72	39.49–39.75	**FH#**
		LQ*	*La Queglia (Abruzzo)*	Ultramafic lamprophyre	62–54	0.7031–0.7034	0.5030–0.5131	19.94–21.50	15.70–15.78	39.37–41.50	**FH#**
	Africa-Europe collision ~55 to 35 Ma	VP1	Veneto Province 1	Alkali basalt, nephelinite	65–40	0.7031–0.7039	0.5129–0.5130	18.87–19.51	15.58–15.66	38.94–39.24	**FH#**
	Transition between Alpine collision and Mediterranean extension (~35–30 Ma)	VP2	Veneto Province 2	Alkali basalt	36–26	0.7032–0.7037	0.5128–0.5129	18.80–19.79	15.60–15.69	38.22–39.49	**FH#**
		WA*	Western Alps	Calc-alkaline lamprophyre	33–29	0.7059–0.7220	0.5120–0.5124-	18.67–19.04	15.67–15.72	38.87–39.51	**MIRT**
		EA2*	Eastern Alps 2	Alkaline lamprophyre	34	0.7060	0.5126	18.78	15.67	39.00	**MIRT**
		PAL	Periadriatic Lineament	Calc-alkaline basalt	42–24 (peak34–28)	0.7040–0.7160	0.5128–0.5129	18.60–18.30	15.55–15.75	38.30–39.20	**MIRT**
		SAT	Sardinian Trough	Calc-alkaline basalt	38–15 (peak 22–18)	0.7041–0.7110	0.5120–0.5123	18.61–18.71	15.63–15.65	38.41–38.70	**MIRT? FE?**
TYRRHENIAN WIDE RIFT	Lower mid Miocene	SS	*Sisco (Corsica)*	Lamproite	14.5	0.7126	0.5122	18.86	15.70	39.34	**MIRT**
	Late Miocene-early Pliocene stage	TS	Tyrrhenian Sea ODP 654-655-651	Olivine basalt	7.3–1.7	0.7037–0.7049	0.5124–0.5131	17.45–18.83	15.54–15.64	37.50–38.97	**MIRT? FE?**
		CA	*Capraia*	Trachybasalt	7.5–4.6	0.7082–0.7088	0.5122–0.5124	18.67–18.74	15.67–15.70	38.99–39.09	**MIRT**
		TPP*	Tuscan Pliocene Province	Lamproite	4.1	0.7152–0.7170	0.5120–0.5121	18.67–18.76	15.64–15.72	38.96–39.19	**MIRT**
	Middle Pleistocene-Holocene stage	TQP	Tuscan Quaternary Province	Lamproite, olivin latite	1.35–0.2	0.7124–0.7169	0.5121–0.5122	18.68–19.09	15.62–16.23	38.77–39.98-	**MIRT**
		VU*	*Mt. Vulture* (Lucania)	Ol melilitite, foidite and carbonatite	0.74–0.13	0.7052–0.7067	0.5126–0.5128	19.06–19.48	15.67–15.70	39.02–39.54	**MIRT**
		CP*	Campanian Province	Leucite-tephrite	0.13–0.0	0.7061–0.7086	0.5123–0.5126	18.90–19.25	15.63–15.98	38.96–39.36	**MIRT**
		E-R*	Ernici *Roccamonfina*	Leucite-tephrite	0.63–0.13	0.7065–0.7112	0.5121–0.5122	18.79–19.15	15.66–15.73	38.94–39.24	**MIRT**
		RP*	Roman Province	Leucitite, melilitite	0.6–0.02	0.7072–0.7115	0.5120–0.5123	18.67–18.83	15.62–15.73	39.09–38.91	**MIRT**
		IUP*	IUP	Carbonatite, kamafugite	0.64–0.26	0.7096–0.7119	0.5119–0.5122	18.73–18.87	15.65–15.69	38.75–39.02	**MIRT**
		S*	***Stromboli, Vulcanello***	Leucite-tephrite	0.20–0.0	0.7050–0.7075	0.5124–0.5127	18.93–19.20	15.64–15.70	39.01–39.16	**MIRT**
		AI*	Aeolian Islands	Calc-alkaline basalt, leucite-tephr.	0.8–0.0	0.7034–0.7075	0.5124–0.5129	18.93–19.78	15.60–15.73	39.01–39.55	**MIRT**
		E*	***Etna***	Alkali basalt	0.5–0.0	0.7033–0.7037	0.5129–0.5130	19.46–20.01	15.63–15.68	39.11–39.50	**MIRT? FE?**
		U	*Ustica*	Alkali basalt	0.72–0.66	0.7031–0.7033	0.5129–0.5131	18.84–19.56	15.62–15.66	38.61–39.19	**MIRT? FE?**
NARROW RIFT	Sicily and Sardinia occurrences Late Miocene-Quaternary	H*	Hyblean Plateau	Alkali basalt, nephelinites	8–1.2	0.7028–0.7036	0.5129–0.5132	18.87–19.86	15.59–15.69	38.60–39.50	**FH#**
		NCS*	Northern-central Sardinia (UPV)	Alkali basalt	4–0.12	0.7043–0.7051	0.5123–0.5126	17.40–18.01	15.55–15.61	37.68–38.33	**FE**
		SS*	Southern Sardinia (RPV)	Alkali basalt	6.6–5	0.7031–0.7049	0.5127–0.5130	18.84–19.42	15.64–15.66	38.98–39.14	**FH#**
		SC*	Sicily Channel	Alkali basalt	1.18–0.0	0.7030–0.7048	0.5129–0.5131	18.30–19.94	15.55–15.70	38.04–39.60	**FH#**

Summary of Sr, Nd and Pb isotope data for the Italian igneous provinces and/or individual centres, along with major tectonic phases, magmatic affinity, age, range of isotopic values and mixing trends. The occurrences range in age from late Cretaceous to present, and are listed from oldest to youngest. Names of individual volcanic complexes given in italics and active ones in bold. Unpublished isotope data from Carleton University, Ottawa, Canada; for the outcrops highlighted with an asterisk in the abbreviation (abb.) column, data have been implemented with others from the literature (Lustrino et al., 2000; Gasperini et al., 2002, Conticelli et al., 2002, 2007 and 2009a,b; Peccerillo and Martinotti, 2006; Rotolo et al., 2006; Lustrino and Wilson, 2007; Beccaluva et al., 2007; Cadoux et al., 2007; Owens, 2008; Macera et al., 2008; Boari et al., 2009a,b; Lustrino et al., 2011; Avanzinelli et al., 2011; plus GEROC database at http://georoc.mpch-mainz.gwdg.de/georoc). The ages are derived from the literature (Savelli, 2001; Lavecchia et al., 2002; Vichi et al., 2005; Rosenbaum & Lister, 2005 and references therein; Conticelli et al., 2009a,b and references therein; Lustrino and Wilson., 2007; Lustrino et al., 2011 and references therein). The final column highlights the main mixing trends identified in Figures 4,6–8. Other mixing trends (FE = FOZO-EM1-like and FH = FOZO-HIMU-like) are derived from the literature; ? marks some degree of uncertainty in the mixing trends; the symbol # refers to a possible HIMU component proposed by Lustrino et al, 2000; Beccaluva et al., 2007; Rotolo et al., 2006; Bianchini et al., 2008. More detailed references for the data used to compile this table can be obtained from the authors. Key: Eastern Alps 1 includes Corvara in Badia and Calceranica; Eastern Alps 2 includes Val Fiscalina; Veneto Province 1 includes Val D'Adige and Lessini West; Veneto Province 2 includes Lessini East and Marostica; Tuscan Cretaceous Province includes Fosso Ripiglio, Castiglioncello, Senna River and Murci in western central Italy; Tuscan Pliocenic Province includes Montecatini, Val di Cecina and Orciatico; Tuscan Quaternary Province includes Radicofani, Torre Alfina plus Cimini and Amiata; Campanian Province includes Vesuvius, Phlagraean Fields, Ischia; Roman Province includes Vulsini, Vico, Sabatini and Albani; Aeolian Islands includes Alicudi Panarea, Salina and Vulcano. Sicily Channel includes Graham Bank, Linosa, Pantelleria; IUP includes Collefabri, Cuppaello, Grotta del Cervo, Polino, Oricola, and San Venanzo; northern-central Sardinia includes Logudoro, Montiferro, Monte Arci and Orosei Dorgali (UPV = unradiogenic Pb volcanics, Lustrino et al., 2000); southern Sardinia includes the Campidano graben (Guspini and Rio Girone) and Capo Ferrato (RPV = radiogenic Pb volcanics in Lustrino et al., 2000); the Tyrrhenian Sea includes samples from ODP Leg 107.

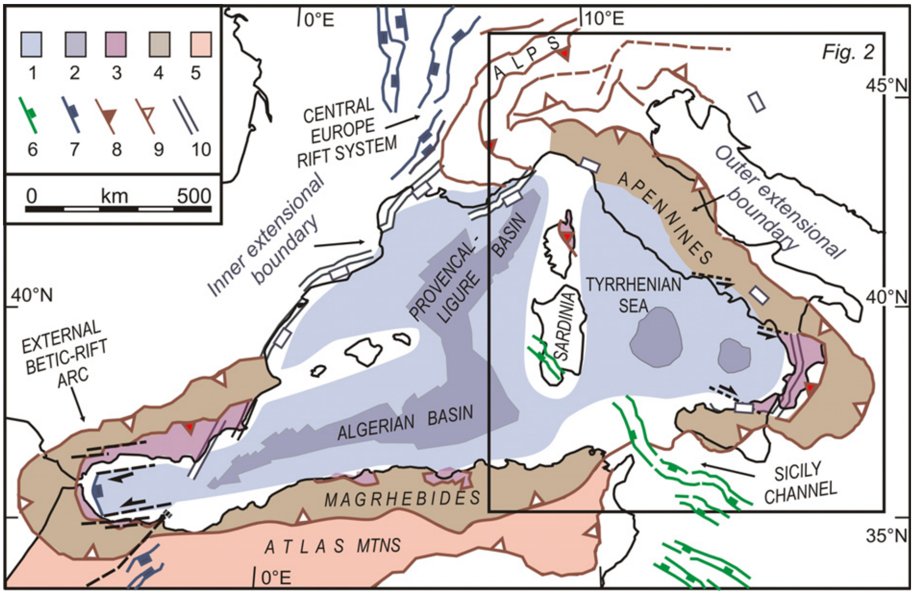

Fig. 1. Simplified map showing the western and central Mediterranean wide-rift basins and the surrounding compressional chains plus the central European and the Sicily Channel narrow rift systems. Key: 1. Oceanic and ultra-thinned continental crust ($< \sim 10$ km); 2. Thinned continental crust ($< \sim 25$ km); 3. Internal units of the Alpine-Betic chain of prevalent late Cretaceous–Paleocene age; 4. External units of the Alpine-Betic chain and Apennine-Maghrebian fold-and-thrust belt of prevalent Oligocene–Holocene age; 5. Atlas fold-and-thrust belt domain; 6. Sicily Channel rift system (after Corti et al., 2006) mainly Plio-Pleistocene in age; 7. Central Europe rift system mainly Oligocene–early Miocene in age; 8. Alpine-Betic thrust fronts; 9. Apennine-Maghrebide thrust fronts; 10. Inner and outer extensional boundaries of the Mediterranean micro-plate.

reader is referred to Beccaluva et al. (2004), Harangi et al. (2006), Conticelli et al. (2007), Lustrino and Wilson (2007), Macera et al. (2008), Conticelli et al. (2009a,b), Lustrino et al. (2011), Avanzinelli et al. (2011), among many others.

In Fig. 3, a compositional overview of the Italian igneous rocks is given using the semi-modal de La Roche diagram (Fig. 3d, de La Roche et al., 1980). More convenient than the conventional TAS (Total Alkalies vs. Silica) diagram, it emphasizes the wide compositional ranges, as well as the degree of silica-undersaturation. Use of the TAS diagram (e.g. Peccerillo, 2003) unrealistically shows that about 90% of the rock compositions from Italy plot in, or near, the basaltic andesite, basaltic trachyandesite, trachyandesite and trachyte fields at odds with the well-known leucite and other foid-bearing Italian igneous rocks (e.g. Washington, 1906).

Separation into three different groups in Fig. 3 is based on geographic/tectonic distribution, age, and/or relationship to distinct magmatic provinces. The Tyrrhenian, Sicily and Veneto rocks are dominated by basalts and alkaline basalts (Fig. 3a). The data from the Roman and Campanian co-magmatic province lie in the SiO_2-undersaturated, cafemic parts of the diagram, situated up and to the left of the 45° line (Fig. 3b). Interestingly, the ultramafic and alkaline rocks, along with the IUP carbonatites, lie in the negative *x* axes region, along with data from some of the Roman and Campanian Provinces and Vulture. The Aeolian and Tuscan volcanic rocks show the largest spread, and the data trend towards the SiO_2-saturated fields and extend past the 45° line (Fig. 3b and c). Two Sardinian cycles are clearly recognizable, one similar to foiditic rocks of the Roman Region and one similar to the Tuscan rocks (Fig. 3a and c).

3. Isotope geochemistry

3.1. Radiogenic isotopes

The range in isotopic ratios shown by Cenozoic igneous rocks from Italy is probably greater than any other part of the Earth's surface, with values similar to those of mantle and those typical of upper continental crust. Such variations have been discussed at length, especially the systematic variation in isotopic ratios along the length of peninsular Italy (northerly increase in $^{87}Sr/^{86}Sr$, $\delta^{18}O$, $\delta^{13}C$ and $^{3}He/^{4}He$ ratios, southerly increase in $^{143}Nd/^{144}Nd$ and $^{206}Pb/^{204}Pb$ ratios (e.g. Vollmer, 1976; Hawkesworth and Vollmer, 1979; Vollmer and Hawkesworth, 1980; Rogers et al., 1985; Ellam et al., 1989; Tedesco, 1997; Bell et al., 2003; Hoernle et al., 1995; Bell et al., 2005; Peccerillo and Lustrino, 2005; Harangi et al., 2006; Lustrino and Wilson, 2007; Avanzinelli et al., 2011; Lustrino et al., 2011)).

The isotopic ratio patterns that emerged were attributed to binary mixing of depleted and enriched end-members (e.g. Vollmer, 1976; Hawkesworth and Vollmer, 1979; Vollmer and Hawkesworth, 1980), occurring either at shallow levels by assimilation of continental crust (e.g. Turi and Taylor, 1976; Taylor et al., 1984) or at greater depths involving interaction with fluids with high $^{87}Sr/^{86}Sr$, low $^{143}Nd/^{144}Nd$ ratios and high K, Rb and LREEs released from subducted sediments (e.g. Holm and Munksgaard, 1982; Rogers et al., 1985; Peccerillo and Manetti, 1985; Peccerillo, 2003).

We have compiled an isotopic data base of Sr, Nd and Pb analyses (see summary in Table 1) for the Italian volcanic occurrences that range in age from late Cretaceous–early Paleocene (Alpine lamprophyres) to the present (Etna, Stromboli and Vesuvius). Data are presented in a series of two-, and three-dimensional isotope ratio diagrams along with some of the world-wide and European mantle end-member/component/reservoir compositions (Figs. 4–8). Our main aims are to identify the smallest number of isotopic end-members needed to explain the observed isotopic compositional ranges, to find an explanation for their regional distribution in terms of different mantle sources, and to propose the simplest geodynamic interpretation of the isotopic data.

3.2. Isotope ratio diagrams

Our data base consists of almost 300 samples each complete for $^{87}Sr/^{86}Sr$, $^{143}Nd/^{144}Nd$, $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$. Analyses from the literature (e.g. Rotolo et al., 2006; Beccaluva

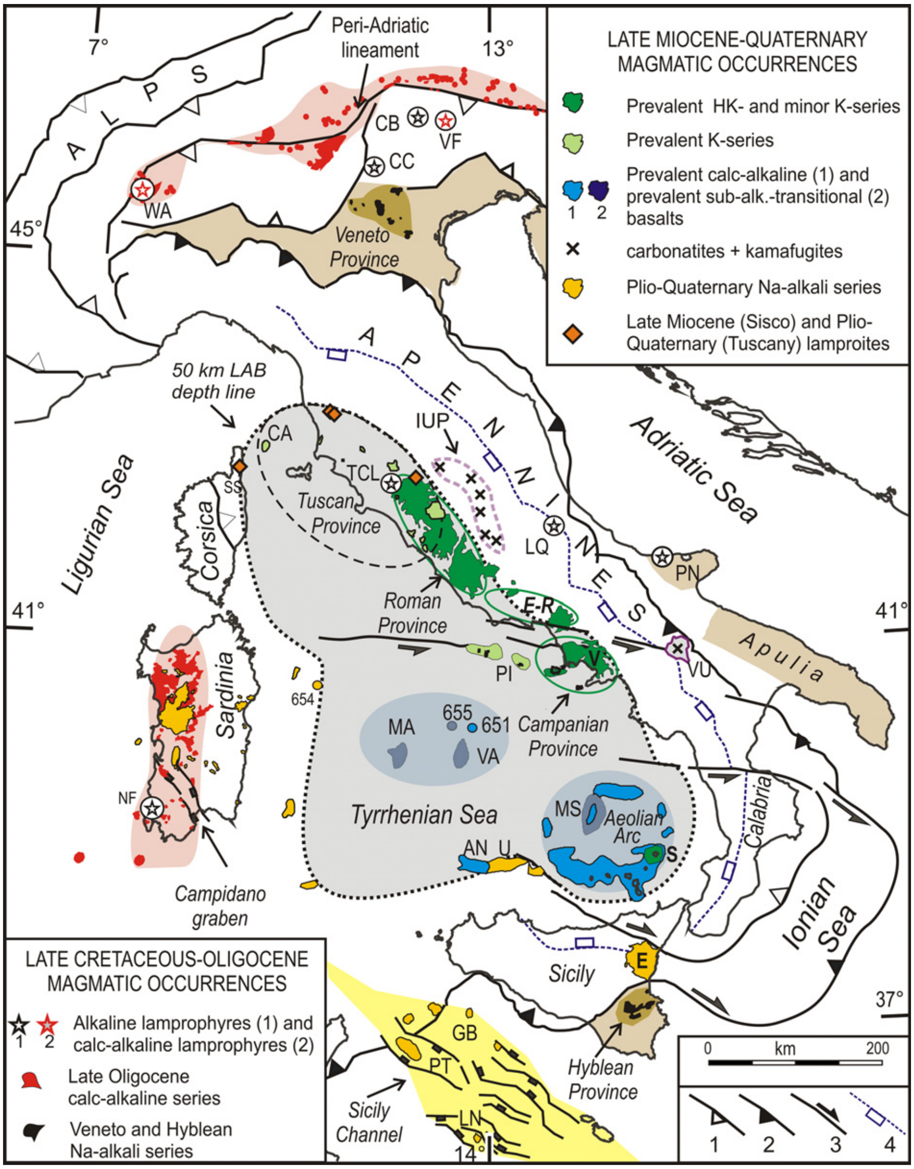

Fig. 2. Distribution of the Cenozoic igneous activity in Italy. Note the active volcanoes are V = Vesuvius, E = Etna, and S = Stromboli. Other location abbreviations as follow: AN, Anchise; CA, Capraia; CB, Corvara in Badia; CC, Calceranica; E–R, Ernici–Roccamonfina; GB, Graham Banks; IUP, Intramontane Ultra-alkaline Province; LN, Linosa; LQ, La Queglia; MA, Magnaghi; MS, Marsili; PN, Punta delle Pietre Nere; PI, Pontine Islands; PT, Pantelleria; NF, Nuraxi Figus; SS, Sisco, Corsica; TCL, Tuscan Cretaceous lamprophyres; U, Ustica; VA, Vavilov; VF, Val Fiscalina; WA, western Alps lamprophyres. Numbers in bottom, right hand corner are as follow: 1. Major Alpine thrusts, 2. Outer Quaternary front of the Apennine-Maghrebide thrust belt, 3. Major transfer faults, and 4. Outer Quaternary front of the intra-Apennine extensional belt. Additional abbreviations: LAB = lithosphere–asthenosphere boundary. Numbers in the Tyrrhenian Sea refer to ODP sampling sites (Ocean Drilling Project, leg 107).

et al., 2007; Conticelli et al., 2007; Lustrino and Wilson, 2007; Owen, 2008; Conticelli et al., 2009a,b; Avanzinelli et al., 2011 and many others) have been integrated with some new, as yet unpublished, analyses from Sardinia, Vulture and Oricola (Abruzzo).

The volcanic occurrences and provinces summarized in Table 1 not only include the ranges of isotopic values for the various sites but also some schematic petrological and tectonic information. Sr, Nd, Pb data are presented in a number of conventional binary isotope ratio diagrams (Figs. 4–6), as well as two tetrahedral (Fig. 7), and two triangular plots ($^{87}Sr/^{86}Sr_N$ vs. $^{143}Nd/^{144}Nd_N$ vs. $^{208}Pb/^{204}Pb_N$ and $^{87}Sr/^{86}Sr_N$ vs. $^{143}Nd/^{144}Nd_N$ vs. $^{206}Pb/^{204}Pb_N$; Fig. 8). Although some of the data from rocks >30 Ma remain uncorrected for *in situ* decay, the relatively low parent–daughter ratios for many of the samples along with the overall fit of the data to the main Italian trend suggest that the measured ratios are reasonable approximations to initial values.

We have made comparison of the Italian data with some of the mantle components found in oceanic basalts, in particular FOZO1 (Hart et al., 1992), HIMU, EM1, EM2, and DMM (Zindler and Hart, 1986). Our estimated values based on published information for the oceanic end-members are given in the caption to Fig. 4. For a more detailed review of isotopes in the context of oceanic volcanism and mantle components the reader is referred to Hofmann (1997).

The original definition of FOZO (FOcus ZOne) as proposed by Hart and co-workers was based on the point of convergence of linear arrays from oceanic basalts and associated rocks in three-dimensional isotope ratio diagrams involving EM1, EM2, HIMU and DMM, but various estimates of this common OIB component show considerable differences, e.g. FOZO1 (Hart et al., 1992), FOZO2 (Hauri et al., 1994), FOZO3 (Stracke et al., 2005). Although FOZO is traditionally interpreted as a widespread plume component

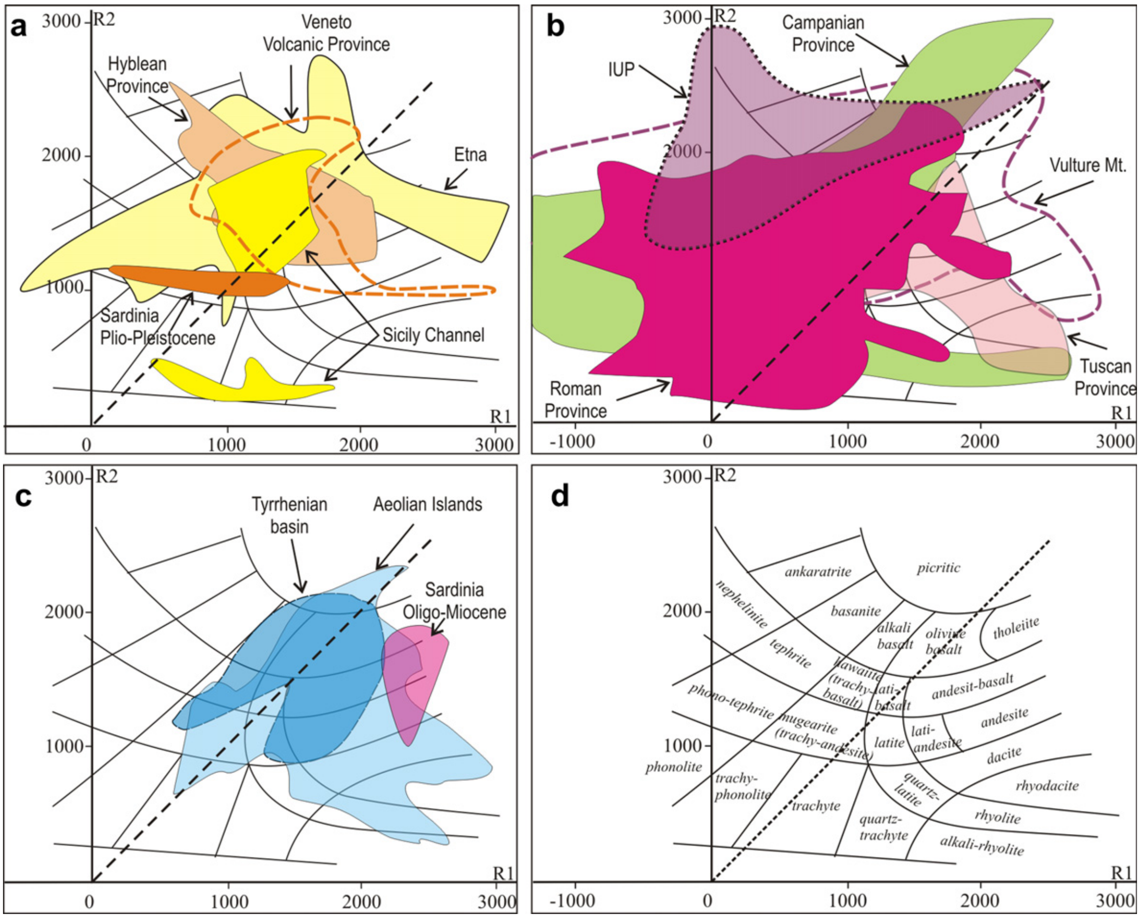

Fig. 3. Classification of igneous rocks from Italy using the de La Roche diagram (de La Roche et al., 1980). $R_1 = 4\text{Si} - 11(\text{Na} + \text{K}) - 2(\text{Fe} + \text{Ti})$; $R_2 = 6\text{Ca} + 2\text{Mg} + \text{Al}$. The data base consists of more than 900 analyses, separated into three different groups shown in (a, b and c) based on geographic/tectonic distribution, age, and/or relationship to distinct magmatic provinces. Note the wide scatter of the data shown by the individual fields. (d) shows the distribution of the representative rock-types within the de La Roche diagram. The 45° degree dashed line marks the line of critical silica saturation.

common in OIBs and located in the lower mantle (Hart et al., 1992; Hauri et al., 1994), a more recent interpretation considers FOZO to be a ubiquitous component in the source of MORB and OIB produced by the continuous recycling and ageing of unmodified, oceanic crust (Stracke et al., 2005). A common component, virtually identical to FOZO, is "C", which has been defined on the basis of the convergence of MORB isotopic arrays (Hanan and Graham, 1996). However, because of the continuous morphing nature of FOZO and for saneness, simplicity and consistency with our published papers, we will use as a reference point the values of FOZO1 as defined by Hart et al. (1992). For high ^{3}He/^{4}He mantle two quite different FOZOs of hemispheric proportions are recognized, FOZO A (Austral) situated in the southern hemisphere and FOZO B (Boreal) in the northern latitudes (Jackson et al., 2007a). The evidence from oceanic plateaus (Ontong Java, Caribbean), flood basalts, and OIBs suggests that FOZO is a major, primitive component in the lower mantle brought to upper levels by plume entrainment (Campbell and O'Neill, 2012, and references therein). We therefore assume in this paper that FOZO is plume-related.

The large spread of Nd and Sr isotopic data and its distribution seen in Fig. 4 reflects, as a first-order approximation, a binary mixing curve involving two end-members, one depleted (FOZO-like) and the other enriched (ITEM) (Bell et al., 2005). This line is defined by data from the Hyblean Province, the Tyrrhenian Sea floor, the Aeolian arc, Vulture, the Campanian and Roman Provinces, the Intra-montane Ultra-Alkaline Province, the Tuscan Lamproitic province, and the eastern and western Alps. A subordinate group of data from the Plio-Quaternary samples of Sardinia approaches EM1. End-member compositions are approximated by data from basalts of the Hyblean Province (depleted) and lamprophyres from the western Alps (enriched). Of particular note is the large spread of ^{87}Sr/^{86}Sr ratios (0.7059–7022) shown by the Oligocene lamprophyres from the western Alps.

The systematic isotopic variation in Fig. 4 is also accompanied by a change of major element abundances along the MIRT, from Na-alkaline to sub-alkaline-transitional basalts, calc-alkaline, K-alkaline, and HK-alkaline rocks to kamafugites, and carbonatites, consistent with Conticelli et al.'s (2009b) observation that different isotopic ranges characterize different magmatic provinces and tectonic environments. A decrease in K_2O and K/Na ratios with ^{87}Sr/^{86}Sr is shown by all of the rock types other than the lamprophyres, some of which show an extreme FOZO signature (e.g. Punta delle Pietre Nere, ~60 Ma) and others an extreme ITEM signature (western Alps lamprophyres, ~30 Ma) (see Table 1 for isotopic range values).

Although no distinct trends emerge from the isotopic lead diagrams, there is a vague linear array in Fig. 5b. In both Fig. 5a and b, most of the data, with the exception of some Sicilian occurrences (Etna, Hyblean Plateau, Sicily Channel), lie above the Northern Hemisphere Reference Line (NHRL), defined by Pb–Pb values of MORB and OIB from the northern hemisphere (Hart, 1988), and to the right of the 4.55 Ga geochron, indicating a multi-stage model for Pb evolution. In both of these diagrams data from Veneto, Vulture, Tuscany, and the IUP and Roman Provinces, are tightly clustered

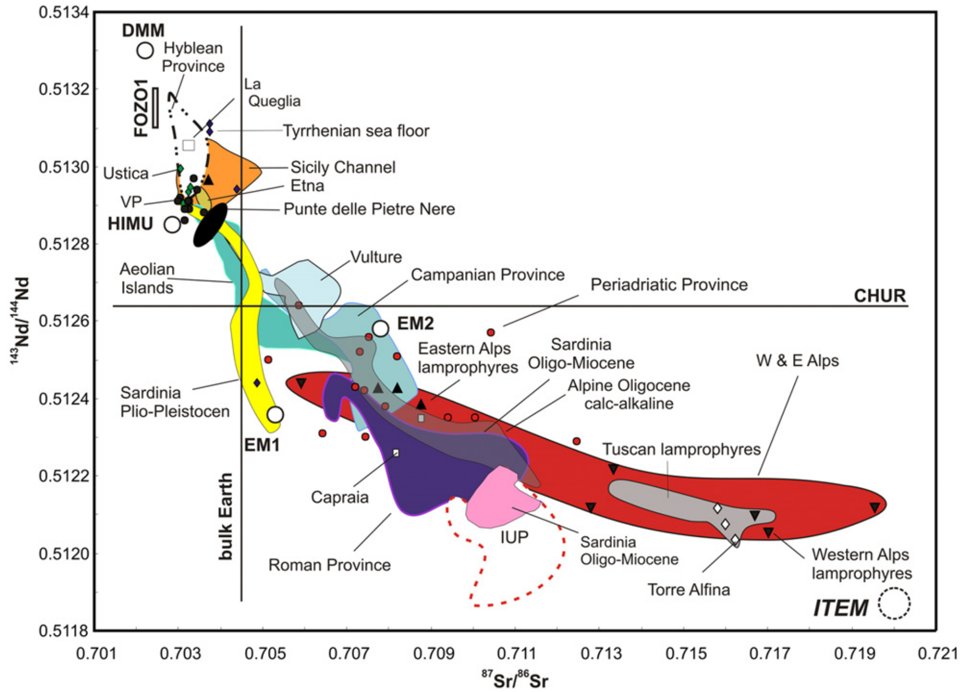

Fig. 4. $^{143}Nd/^{144}Nd$ vs. $^{87}Sr/^{86}Sr$ ratios for the Cenozoic rocks of Italy compared with the mantle components HIMU, EM1, EM2, DMM (after Zindler and Hart, 1986); FOZO1 (after Hart et al., 1992) and ITEM (after Bell et al., 2004); present-day Bulk Earth and CHUR (CHondritic Uniform Reservoir) are also shown. Source of data and acronyms as in Table 1. Most of the data reflect binary mixing between FOZO1 and ITEM. The greatest spread of data is shown by lamprophyres from the Alps. Estimated values used for mantle components for $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ used in this study are: DMM – 0.7020 and 0.5133; FOZO1 – 0.7024, and 0.5131; HIMU – 0.7029, and 0.5128; EM1 – 0.7053, and 0.5124; EM2 – 0.7078 and 0.5126; ITEM – 0.7220, and 0.5120; CHUR – 0.512638, bulk Earth – 0.7045 (see Hart et al., 1992; Bell et al., 2004 and references therein). Note that end-member compositions are only estimated average values and hence associated with some degree of uncertainty.

whereas the data from Etna, the Hyblean Plateau, the Sicily Channel, the Tyrrhenian Basin and Vulture, in particular, show crude, sub-parallel linear arrays to the NHRL, probably reflecting sources with similar Th/Pb ratios. The mantle end-member compositions that lie closest to the main data clusters are FOZO1 and EM2. Two groupings emerge from the Sardinian data, one corresponding to data from southern Sardinia and the Campidano graben with data lying within the main data cluster (see Fig. 5), and a second from northern and central Sardinia with relatively unradiogenic leads ($^{206}Pb/^{204}Pb < 18.0$), that lie close to the geochron and EM1.

When Pb is combined with Nd and Sr (see Fig. 6) a much clearer picture emerges confirming the prevalent FOZO–ITEM mixing line (i.e. MIRT) evidenced in Fig. 4. Two other linear arrays may be present involving a common FOZO end-member and HIMU and the other involving EM1 reflected by the very unradiogenic leads from the northern and central Sardinia Plio-Pleistocene groups. None of the data overlap with HIMU or DMM, although there may be some overlap with Atlantic E-MORB (not shown in Fig.4).

The entire data set plus the individual end-members can be further assessed using tetrahedral plots (Fig. 5a and b), an approach that has been used before (e.g. Hart et al., 1992; Hanan and Graham, 1996) that brings out features not apparent in some of the two-dimensional diagrams. Such tetrahedral diagrams are better able to separate out different components such as EM1, HIMU, ITEM and FOZO than many of the x–y plots. The rotation of Fig. 7a in three-dimensional space confirms that most of the data points from peninsular Italy and the Alps lie within and along MIRT, and that data from the same province tend to cluster together on or near the same part of the mixing line. Examples include Tuscany, the IUP, and the Campanian region. Two other possible linear arrays can be seen, one marked by the Plio-Pleistocene alkaline rocks from northern and central rocks from Sardinia (Fig. 7b) trending towards an EM1-like end-member, and an average data point from La Queglia, pointing towards HIMU (see Fig. 7a). Substituting $^{207}Pb/^{204}Pb$ for $^{206}Pb/^{204}Pb$ or $^{207}Pb/^{204}Pb$ for $^{208}Pb/^{204}Pb$ as one of the apices in the tetrahedron has little effect on the overall trends and the relative distribution of the data points.

The orientation of the tetrahedron shown in Fig. 7a is one of many, but we have deliberately chosen this particular view since it best shows the relationship of the Italian data to the oceanic components, and the DMM reservoir. More details about our approach using three-dimensional diagrams will appear in another paper.

The isotopic trends in the three-dimensional plots are also seen in two-dimensional triangular diagrams involving $^{87}Sr/^{86}Sr_N$ vs. $^{143}Nd/^{144}Nd_N$ vs. $^{208}Pb/^{204}Pb_N$ and $^{87}Sr/^{86}Sr_N$ vs. $^{143}Nd/^{144}Nd_N$ vs. $^{206}Pb/^{204}Pb_N$ (Fig. 8b and d). The distribution of the data re-emphasizes the MIRT, and the trend shown by the Sardinian data towards an EM1-like end-member. A possible FOZO–HIMU array might be envisioned using data from La Queglia in Fig. 7, and possibly the Sicily Channel, the Hyblean Plateau, the Veneto province and Punta delle Pietre Nere, although such an array can just as easily be accommodated within the FOZO–ITEM trend.

None of the identified isotope end-member compositions from Italy are known to be associated with present-day subduction-related magmatism. Given that almost all of the currently favoured models for Italian magmatism involve subduction this is surprising. All of the components established in this study are similar to those from OIBs, even the highly radiogenic end-member (ITEM) with an equivalence in the high $^{87}Sr/^{86}Sr$ values from Samoa (Jackson et al., 2007b). Even if subduction had played such an important role in Italian magmatism, DMM should feature prominently during consumption of ocean floor during subduction. Because of the sparsity of isotopic data from ophiolitic sequences in Italy, ophiolites from the Tethyan suture zone of Eurasia (Zhang et al., 2005) have been used as a proxy. The data are shown in Fig. 8 and, as

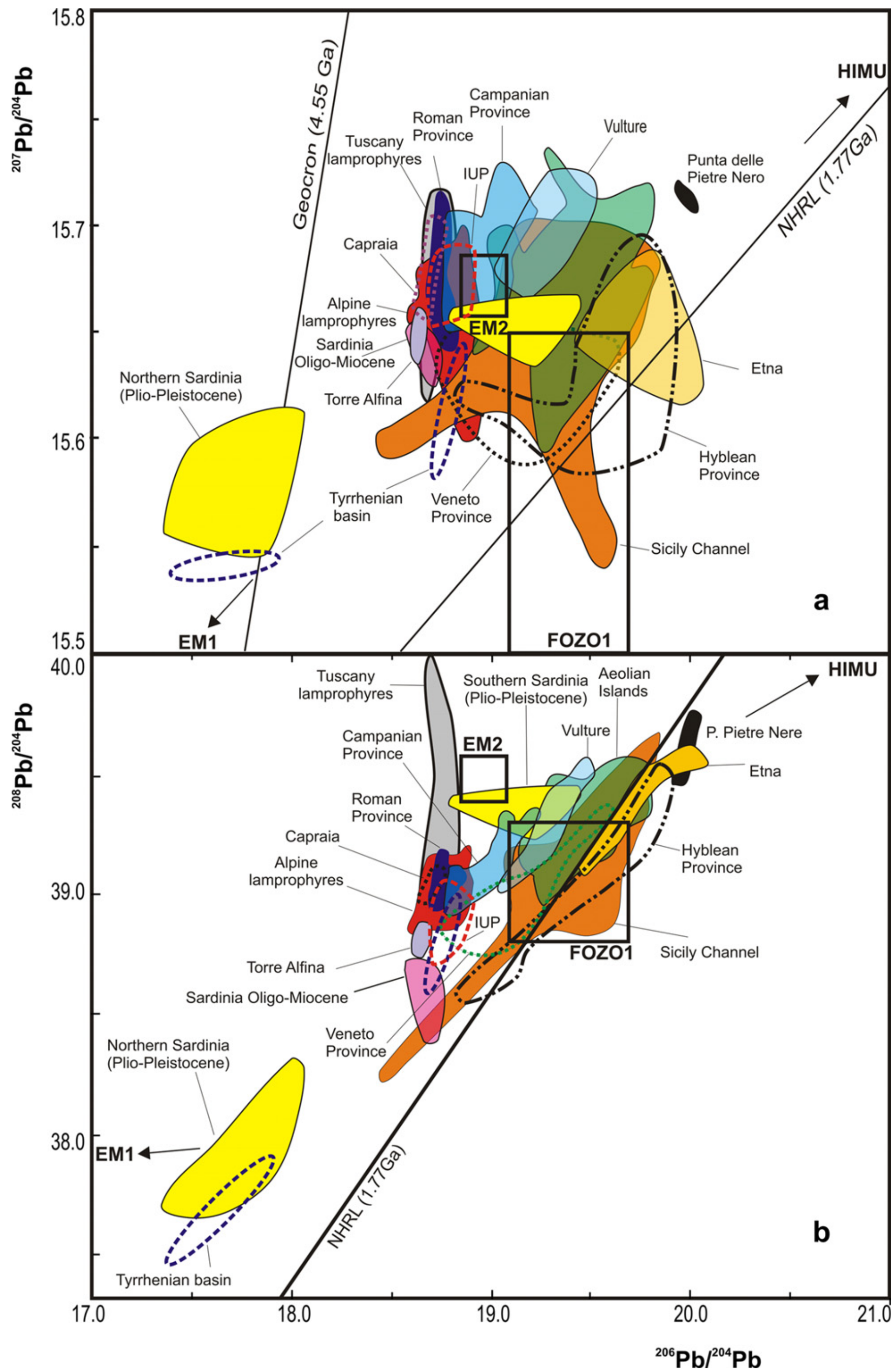

Fig. 5. Lead isotopic ratios for the Cenozoic rocks of Italy compared with other mantle components. (**a**) ^{207}Pb/^{204}Pb vs. ^{206}Pb/^{204}Pb. The 4.55 Ga geochron and NHRL (1.77 Ga) (Northern Hemisphere Reference Line) are used as reference lines. EM1 and EM2, along with FOZO1, are shown for comparison. Note the low Pb isotopic data from Plio-Pleistocene rocks from Sardinia and samples from the Tyrrhenian Basin have the lowest Pb values from Italy (Lustrino et al., 2000). That most of the data lie to the right of the geochron implies a heterogeneous mantle with different U/Pb ratios, and shows that the leads have had multi-stage histories. The two distinct fields for the Tyrrhenian data correspond to the sodic alkaline suite of the westernmost Tyrrhenian Basin close to Sardinia (ODP 654) and those from the Vavilov plain (ODP 651, and 655). (**b**) ^{208}Pb/^{204}Pb vs. ^{206}Pb/^{204}Pb. NHRL, EM1 and EM2, along with FOZO, shown for comparison. Our estimated values used for mantle components for ^{206}Pb/^{204}Pb, ^{207}Pb/^{204}Pb, and ^{208}Pb/^{204}Pb used in this study are: FOZO1 − 19.34,15.56, 39.00; HIMU − 22.00,15.85, 40.70; EM1 − 17.65, 15.47, 38.10; EM2 − 19.00, 15.85, 39.50; ITEM − 18.70, 15.80, 39.26. Estimated values for DMM (not plotted) − 17.50, 15.35, 37.00 (based on data from Hart et al., 1992; Bell and Tilton, 2001; Stracke et al., 2005). The linear arrays shown by data from Etna, the Hyblean Plateau, Vulture, and most of the data from the Tyrrhenian Seafloor lie sub-parallel to the NHRL indicating either binary mixing or sources with similar Th/Pb ratios. Location and abbreviations as in the text of Fig. 1.

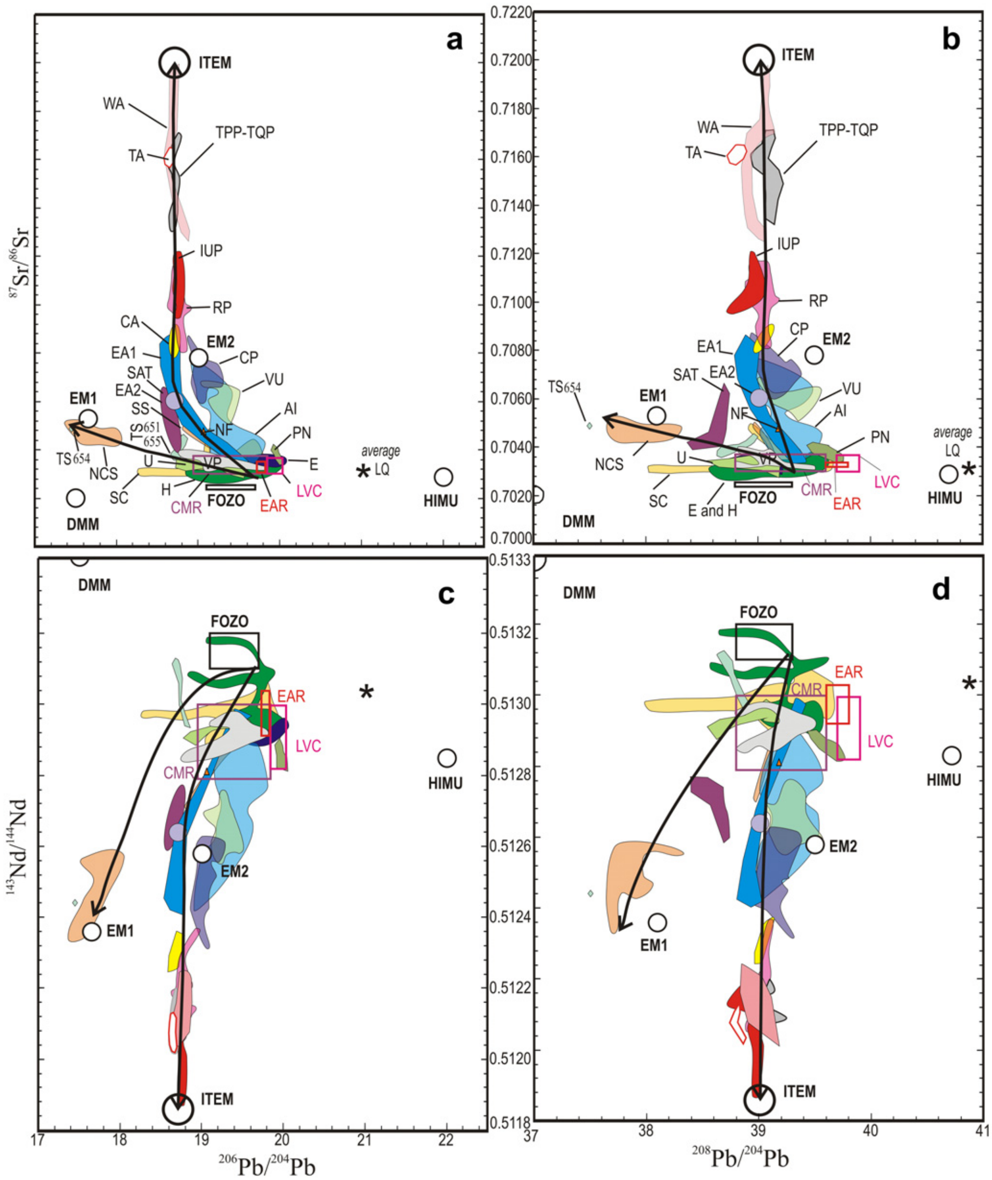

Fig. 6. Sr, Nd and Pb isotopic ratios of volcanic rocks from Italy. (**a**) $^{87}Sr/^{86}Sr$ vs. $^{206}Pb/^{204}Pb$; (**b**) $^{87}Sr/^{86}Sr$ vs. $^{208}Pb/^{204}Pb$; (**c**) $^{143}Nd/^{144}Nd$ vs. $^{206}Pb/^{204}Pb$; and (**d**) $^{143}Nd/^{144}Nd$ vs. $^{208}Pb/^{204}Pb$. Source of Italian data and acronyms as in Table 1. Fields shown contain at least 95% of the isotopic data from a given region. The Italian isotopic distribution is compared with oceanic-island basalt mantle end-members: EM1, EM2, HIMU, and FOZO1 (Hart et al., 1992) with European and Mediterranean end-members EAR (European Asthenospheric Reservoir, Wilson and Patterson, 2001), LVC (Low Velocity Component, by Hoernle et al., 1995) and CMR (Common Mantle Reservoir, by Lustrino and Wilson, 2007). Note the convergence of data in all diagrams towards a common FOZO end-member. Deviations of $^{87}Sr/^{86}Sr$ ratios (a and b) from the main mixing trends may result from secondary processes involved during emplacement, including contamination. Note that the average data point (asterisk) from La Queglia lies closer to HIMU than any of the other data. Most of the fields shown cover at least 95% of the data points for any given geographic region.

expected, trend from DMM towards HIMU, skirting the main ITEM–FOZO mixing line.

The involvement of DMM from the mantle melts appears to have been minimal. Although it might be argued that the absence of DMM is somehow related to the low degrees of partial melting needed to generate most of the magma types from Italy, some of the basalts, especially those from Sardinia, have isotopic compositions that fall well away from DMM and close to EM1.

3.3. Stable isotopes

The progressive increase from south to north along the length of Italy of C, O and He isotopic values mimics the patterns shown by the radiogenic isotope data. Carbon and O isotopic data, especially, are consistent with binary mixing, one end-member with values similar to continental crust, the other to mantle, and both show a general increase in values towards the north. The marked increase in $\delta^{18}O$ has been attributed by some to progressively greater degrees of contamination between mantle-derived melts and sedimentary and metasedimentary rocks (Turi and Taylor, 1976; Taylor et al., 1984). However, high Mg#, Ni and Cr contents, the presence of forsteritic olivine and the degree of silica under-saturation in many of the Cenozoic igneous rocks, as well the thermodynamic constraints imposed in assimilating crust, argue strongly against some of these models (Stoppa, 2008 and references therein). An alternative model proposed interaction between hydrous fluids, enriched in LILE (Large Ione Lithophile Elements) and high $^{87}Sr/^{86}Sr$ and $\delta^{18}O$ values and normal mantle (Holm and Munksgaard, 1982). An estimate of $\delta^{18}O$ of $+6.5 \pm 1.0‰$ for the mantle source beneath the Alban Hills volcanic rocks (Ferrara et al.,

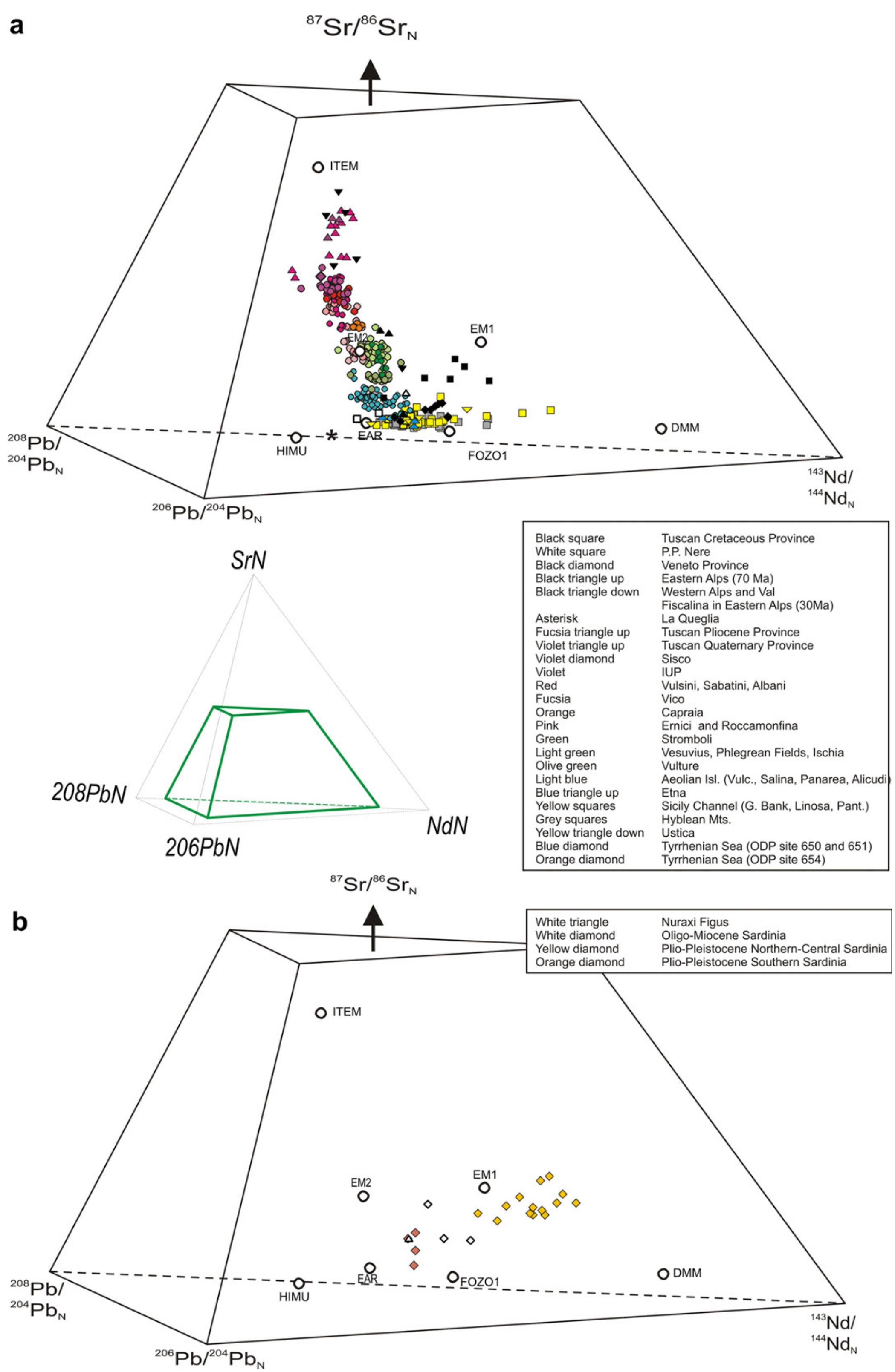

Fig. 7. Tetrahedral diagrams using $^{87}Sr/^{86}Sr_N$, $^{143}Nd/^{144}Nd_N$, $^{206}Pb/^{204}Pb_N$ and $^{208}Pb/^{204}Pb_N$. Source of Italian data and acronyms as in Table 1. Measured radiogenic isotope ratios are normalized and recalculated to a common magnitude and variation range. The measured (and age-corrected for rocks older than 30 Ma) isotopic ratios have been calculated using the following formulae: $Sr_N = (^{87}Sr/^{86}Sr\text{-}0.7)/0.0002$, $Nd_N = (^{143}Nd/^{144}Nd\text{-}0.511)/0.000018$, $^{206}Pb_N = (^{206}Pb/^{204}Pb\text{-}16)/0.045$, $^{207}Pb_N = (^{207}Pb/^{204}Pb\text{-}15)/0.01$, $^{208}Pb_N = (^{208}Pb/^{204}Pb\text{-}37)/0.02$. The normalized isotopic ratios are projected using Cspace software (http://www.ugr.es/~cspace/). The bulk rock database has been established using unpublished and published data and integrated with the database of GEOROC. (**a**) Tetrahedron showing the main ITEM–FOZO trend, and the average La Queglia data point (asterisk) showing a possible FOZO-HIMU trend; and (**b**) tetrahedron showing FOZO–EM1-like trend based on data from Sardinia and Nuraxi Figus.

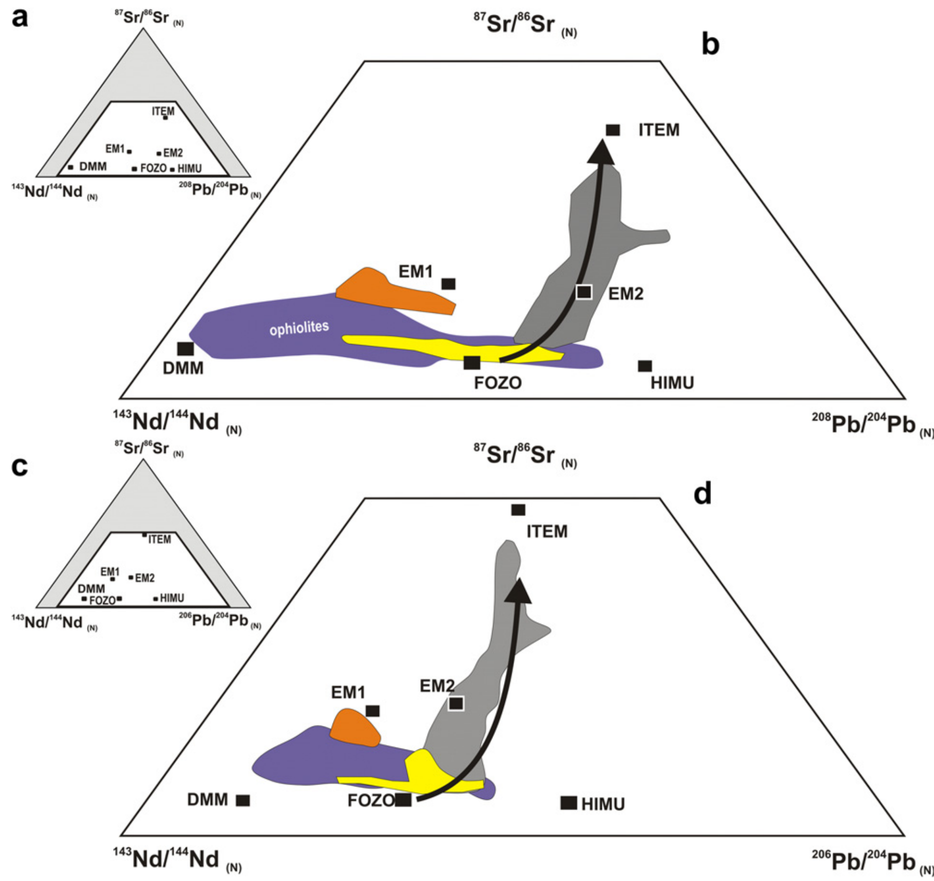

Fig. 8. (a and b) Triangular plots of $^{87}Sr/^{86}Sr_N$ vs. $^{143}Nd/^{144}Nd$ vs. $^{208}Pb/^{204}Pb$; (c and d) plots of $^{87}Sr/^{86}Sr_N$ vs. $^{143}Nd/^{144}Nd$ vs. $^{206}Pb/^{204}Pb$. Source of Italian data and acronyms as in Table 1. Shown are the distribution of FOZO, EM1, EM2, HIMU, DMM and ITEM. In (b and d) note the main binary mixing array between ITEM and FOZO (grey area), the isolation of DMM and HIMU away from the main array, the trend of the Tethyan ophiolites (purple area) towards HIMU, and the isolated array of data (orange) from Sardinia (b). Yellow area = data from the Sicily Channel, the Hyblean Plateau, Etna, Ustica, Punta delle Pietre Nere, and La Queglia. Note, however, that most of the data can be accommodated into the FOZO–ITEM trend. The Tethyan ophiolite data are from samples from the eastern Mediterranean. No data are available from the Ligurian ophiolites.

1985) lies close to the upper limit of mantle-derived material. Examples of binary mixing between $^{87}Sr/^{86}Sr$ and $\delta^{18}O$ include Alicudi (Peccerillo et al., 2004) and the Alban Hills (Ferrara et al., 1985). A north–south increase in $^{3}He/^{4}He$ from values lower than MORB to near crustal values, accompanied by increases in U and C, has been attributed to incursions of material rich in U and Th progressively subducted as the African plate moved beneath the Tyrrhenian Sea (Tedesco, 1997). However, in spite of this similarity, the data could also indicate an anomalous mantle enriched in radiogenic ^{4}He (Tedesco and Nagao, 1996). In addition, slightly lower than atmospheric $^{20}Ne/^{22}Ne$ ratios reflect an excess of ^{22}Ne atypical of any established terrestrial reservoir, while $^{21}Ne/^{22}Ne$ ratios are higher than both atmospheric values, and the ranges found in MORB and OIB (e.g. Kurz, 2005).

In spite of the variations observed in Italian rocks, extensive parts of the sub-continental, European mantle are now known to have relatively uniform O and He values (Marty et al., 1994), based on relatively constant $\delta^{18}O$ (+5.4‰), and $^{3}He/^{4}He$ (+6.7) ratios from olivine phenocrysts from Etna lavas, and European mantle xenoliths. Oxygen isotope data from representative whole-rock samples of the three end-members (EM1, FOZO, and ITEM) defined in the present study have been analysed at the Geological Survey of Canada (analytical details given in Mirnejad and Bell, 2006). A sample from Sardinia with an EM1-like signature has a $\delta^{18}O_{SMOW}$ of +6.14‰, a sample from Punta delle Pietre Nere yields the most primitive value of +4.67‰, and a sample from the Alps with an ITEM signature gives a much higher value of +9.58‰. Although these are only preliminary estimates, the spread of almost 5‰ is certainly greater than that shown by typical mantle $\delta^{18}O$ values of +4.7 to +6.1‰ from glass and olivine phenocrysts from MORBs (Eiler et al., 1997, 2000) and much higher than the maximum difference between MORB and OIB of about 0.6‰, and the overall range shown by basalts (Harmon and Hoefs, 1995). Our $\delta^{18}O$ value from Sardinia is the same as the lowest value of +6.15‰ obtained from clinopyroxene phenocrysts from lavas from Mt. Arcuentu in Sardinia (Downes et al., 2001), and lies close to normal mantle values.

Although few stable isotope measurements other than C and O and some noble gas data are available from Italy, these nonetheless point to unusual mantle sources, e.g. the high $\delta^{34}S$ value coupled with high S concentrations of undersaturated alkaline magmas from Vulture (Marini et al., 1994).

4. The geodynamic models for the central Mediterranean

The central Mediterranean, i.e. the Tyrrhenian Sea, is commonly considered to be a back-arc extensional basin resulting from slab retreat of the north-westerly subducting Ionian and African lithosphere (Doglioni et al., 1997; Carminati et al., 1998; Faccenna et al., 2004; Wortel et al., 2003 among many others). Evidence cited in favour of this includes deep-focus earthquakes off Calabria, tomographic imaging of a dismembered high velocity body dipping to the north-west (Selvaggi and Chiarabba, 1995; Chiarabba et al., 2005, 2008; Piromallo and Morelli, 2003) together with "shoshonitic" rocks in the Aeolian arc region (Keller, 1976; Trua et al., 2004). Most of these models consider magmatism as being orogenic, generated from an unusual mantle source produced by metasomatism, i.e. the addition of light elements released from a subducting plate (e.g. Conticelli and Peccerillo, 1992; Serri et al., 1993; Wilson and Bianchini, 1999; Lustrino et al., 2000; Conticelli et al., 2002; Peccerillo, 2003; Santacroce et al., 2003; Beccaluva et al., 2004).

In spite of the widespread acceptance of subduction as an explanation for much of what is seen in the central Mediterranean there are several features that are inconsistent with what is known about present-day, consuming plate margins. Concerns about the subduction model (see review in Lavecchia and Creati, 2006; Bell et al., 2004, 2006; Lavecchia and Bell, 2011) include: i) the lateral extent of the slab off Calabria which is only 250 km wide vs. the much longer extent of the Apennine-Maghrebide chain (about 1500 km from northern Italy to Sicily), ii) the kinematics of the deep focal mechanisms that show that the slab is in down-dip compression, implying that slab-pull mechanisms are not significant, iii) the ring shape of the Aeolian insular arc which has no correspondence with the linear shape of the seismic slab, iv) the lack of a typical accretionary prism along the Apennine thrust front, coupled with the prevalence of thick-skinned, compressional geometries, v) the presence within the Apennine mountain belt of ultra-alkaline magmatic association with carbonatites, and vi) the unnecessary equation that shoshonites = subduction.

Plumes/hotspots/diapiric upwellings might well be an alternative to subduction and we explore this possibility further. The involvement of plume activity in Italy has been proposed by several workers (Ayuso et al., 1998; Civetta et al., 1998; Gasperini et al., 2000; Schiano et al., 2001; Macera et al., 2003; Zaccarini et al., 2004; Montelli et al., 2004; Rotolo et al., 2006; Stoppa, 2007; Beccaluva et al., 2007; Piromallo et al., 2008). Mantle upwellings (plumes?) were considered completely independent of subduction by some (Wezel, 1981; Lavecchia, 1988; Locardi and Nicolich, 1988; Stoppa and Lavecchia, 1992; Lavecchia et al., 1995; Lavecchia and Stoppa, 1996), whereas others invoked a combination of subduction and plume activity. Proposed models include mantle upwellings involving asthenospheric migration through slab windows (Gasperini et al., 2002; Macera et al., 2003; Trua et al., 2003, 2004), plume truncation by subduction (Owen, 2008), melting of trapped plume heads (Gasperini et al., 2000; Rotolo et al., 2006; Owen, 2008) and progressive change of dip of the Alpine subduction plane, from SE to NW, due to the eastward plume growth (Lavecchia and Creati, 2006). Even individual centres have been attributed to plume-related activity, including those in the Veneto region (Gasperini et al., 2002; Piromallo and Morelli, 2003; Macera et al., 2003; Beccaluva et al., 2007), Etna (Montelli et al., 2004), Sardinia (Gasperini et al., 2000), Graham and Nameless Banks, the Hyblean Plateau, Ustica, and Alicudi (Rotolo et al., 2006). Other models related mantle upwellings to slab detachment (e.g. Macera et al., 2008).

5. Italian end-members and implications

The distribution of the isotopic data from Italy, as reassessed in this paper, involves a limited number of end-members (Figs. 6–8). In order of decreasing importance these are: one that is FOZO-like, ITEM and possibly HIMU and EM1.

The common Italian depleted end-member (FOZO in our diagrams) has been previously interpreted as E-MORB (Rogers et al., 1985), a mixture of OIB + MORB plus sediment (Ellam et al., 1989), DMM–HIMU mixing (e.g. D'Antonio et al., 1996; Gasperini et al., 2002; Rotolo et al., 2006; Beccaluva et al., 2007) and, more recently, to a FOZO-like end-member, first introduced into the Italian scene by Bell et al. (2003) and afterwards reported by others (Bell et al., 2005, 2006; Peccerillo et al., 2004; Peccerillo and Martinotti, 2006; Cadoux et al., 2007).

FOZO's spatial extension from southern Sicily to the Alps and in time from the Cretaceous to the present, marks a regional mantle source throughout the whole of the central Mediterranean area, that is not too different from the asthenospheric Low Velocity Component (LVC) of Hoernle et al. (1995), the European Asthenospheric Reservoir (EAR) of Wilson and Patterson (2001), and the Common Mantle Reservoir (CMR) of Lustrino and Wilson (2007). Principal component analysis of data from Sicily (Etna and Hyblean Mountains) also led to the conclusion that "C" (~FOZO) is the best representative of mantle composition, involving magmatic upwellings from a unique, lower mantle, source at the 670 km Transition Zone (Cadoux et al., 2007).

All of these components/end-members (Italian FOZO, LVC, EAR, and CMR) may reflect a relatively uniform isotopic end-member, other than Sr, perhaps a single mantle reservoir underlying both oceanic and continental areas. Average compositions from these sources are given in Table 2. The FOZO-like signatures are associated with different styles of magma incursions. Hoernle et al.'s (1995) and Duggen et al.'s (2009) models involving an inclined, sheet-like low-velocity anomaly (LVA) extending from the Atlantic to the Mediterranean and Africa, contrasts markedly with those of Granet et al. (1995), Goes et al. (1999), Wilson and Downes (1991), and Wilson and Patterson (2001). Upwellings proposed for the central Europe rift system (Granet et al., 1995; Goes et al., 1999; Wilson and Patterson, 2001) take the form of hot fingers derived from a much larger, parent plume located within the upper mantle. In Wilson and Patterson's (2001) model, hot fingers from the 670 km discontinuity are introduced into the thermal boundary layer at the base of the upper mantle, perhaps augmented by incursions from the present Icelandic plume. Variations in the isotopic compositions of these plume-related melts may be caused by interaction between an enriched asthenosphere and depleted lithospheric (Granet et al., 1995; Wilson and Patterson, 2001; Macera et al., 2003; Lustrino and Wilson, 2007) or heterogeneous mantle sources, e.g. the presence of FOZO and HIMU signatures in the carbonatite-alkaline rock association at Fuerteventura in the Canary Islands (de Ignacio et al., 2006).

Given the relatively shallow depths of the Italian parental melts, assumed to be generated close to the local lithosphere–

Table 2
Average compositions of proposed European reservoirs.

End-member	$^{87}Sr/^{86}Sr$	$^{143}Nd/^{144}Nd$	$^{206}Pb/^{204}Pb$	$^{207}Pb/^{204}Pb$	$^{208}Pb/^{204}Pb$
LVC – Low Velocity Component[a]	0.7032	0.51288	20.00	15.65	39.10
EAR – European Asthenospheric Reservoir[b]	0.7032	0.51292	19.80	15.63	39.80
CMR – Common Mantle Reservoir[c]	0.7034	0.51290	19.40	15.60	39.40
FOZO-like – Italian Common Mantle Reservoir[d]	0.7030	0.51287	20.50	15.70	39.00

[a] Hoernle et al., 1995.
[b] Granet et al., 1995; Wilson and Patterson, 2001.
[c] Lustrino and Wilson, 2007.
[d] Bell et al., 2005, 2006 and this work.

asthenosphere boundary (e.g. Peccerillo and Manetti, 1985; Beccaluva et al., 2007) and the control played on the locus of focussing of the volcanic activity by the geometry of the lithospheric tectonic structures (see Lavecchia and Stoppa, 1996; Panza et al., 2007), we consider that the Italian FOZO component, however, does not directly derive from a plume active beneath the Mediterranean region, but rather it represents the result of melting plume-modified lithosphere/asthenosphere.

Plume–lithosphere interaction in the southern hemisphere has been tied into a possible Jurassic plume prior to the mid Cretaceous fragmentation of the eastern margin of Gondwanaland in the mid-late Cretaceous (Panter et al., 2000, 2006). Hart et al. (1997) even suggested that a large, two-component (HIMU + FOZO), mantle plume metasomatized and enriched the Gondwanaland lithosphere. Given the ubiquitous presence of the FOZO component on both the European and Adria continental sides of the Alpine Tethys domain, we similarly propose that in late Triassic–early Jurassic times, an extensive FOZO-type mantle plume might have modified the Africa–Eurasia lithosphere/asthenosphere, prior to the late Jurassic–early Cretaceous phase of continental break-up and the opening of the Alpine Tethys oceanic domain. As an alternative explanation, the FOZO component presently underlying the Mediterranean might have been added to the mantle by secondary plumes/hot fingers from a deeper plume head perhaps at 100 Ma.

The widespread extension of ITEM across the eastern Tyrrhenian rift border, peninsular Italy and the Alps covering an interval of at least 70 Ma, is seen reflected in data from the late Cretaceous eastern Alps lamprophyres, the early Oligocene western Alps lamprophyres, the Pliocene Tuscan lamproites and the middle Pleistocene IUP carbonatites in central Italy. The highly enriched ITEM is isotopically similar to marine pelagic sediments and upper crust (Turi and Taylor, 1976; Vollmer, 1976; Hawkesworth and Vollmer, 1979; Holm and Munksgaard, 1982; Taylor et al., 1984; Ben Othman et al., 1989; Plank and Langmuir, 1998; Gasperini et al., 2002), but isotopic equivalents are rare in oceanic basalts, or in subduction-related products. Samoa is the only oceanic island with such high $^{87}Sr/^{86}Sr$ values (up to 0.720; Jackson et al., 2007b). Potential sources for ITEM (see Owen, 2008) include ancient and/or recently metasomatized mantle, continental crust subducted during the Apennine and/or Alpine orogenies or even earlier, and mantle plumes connecting the uppermost mantle with a relatively primitive reservoir at the CMB (core-mantle boundary). Problems incurred in recycling oceanic crust as a means of generating OIB components are discussed by Stracke et al. (2003).

As the lithospheric regions of the Apennines and Alps are approached, ITEM becomes increasingly more involved during magma generation. From Figs. 6–8, it is evident that the ITEM component has been contiguous with FOZO since late Cretaceous times and the absence of any mixing between ITEM and other possible end-members implies spatially-unrelated mantle volumes unable to communicate with one another, perhaps marking major discontinuities.

There is no doubt that sediment subduction accompanied by melts, and/or fluids generated during slab decarbonation or dehydration is an efficient way of introducing crustal components into the mantle (e.g. Tommasini et al., 2007), but it becomes complicated because crust of appropriate composition needs to be introduced into the mantle at different times (e.g. Peccerillo, 1999). Even high $^{187}Os/^{188}Os$ ratios in Neogene lamproites from the Tuscan magmatic province indicative of crustal material (Conticelli et al., 2007) require that tens of weight percent of a continental crustal component has to be recycled and added to mantle peridotite in order to obtain the appropriate ratios during partial melting. The uniform nature of ITEM, the lack of crustal material with appropriate isotopic signatures from peninsular Italy, the presence of ITEM in late Cretaceous Alpine lamprophyres, and the absence of ITEM in present-day, world-wide, subduction-related environments, better supports an event independent of any recent crustal subduction.

Long-term storage of high Rb/Sr, U/Pb and Nd/Sm material isolated from convection might generate an enriched mantle source similar to ITEM, although a similar signature could also be attributed to melting of crustal sediments more recently (but >70 Ma) transported into the mantle (e.g. Schaefer et al., 2002; Tolstikhin and Hofmann, 2005; Hutko et al., 2006; Jackson et al., 2007b). Some diamond-bearing lamproites, kimberlites and ultrapotassic rocks in cratonic areas have isotopic ratios consistent with these models (e.g. Nelson et al., 1986; Murphy et al., 2002). Alternatively, an enriched source of K and hence Rb in the deep mantle could derive from the Earth's core possibly containing a reasonable amount of K (between 60 and 130 ppm) that could be easily mobilized by fluids (Gessmann and Wood, 2002; Murthy et al., 2003). An enrichment of radioactive elements in the deep mantle is predicted by the transition-zone water filter model of Bercovici and Karato (2003). Lavecchia and Creati (2006) consider that the Italian highly radiogenic metasomatic component might be derived by the progressive addition to the Mediterranean mantle asthenosphere of a highly enriched, relatively primitive, part of the deep mantle, originating from the "D" layer, that served as an isolated rare-gas and incompatible-element-bearing radiogenic reservoir.

The presence of FOZO and ITEM might also reflect derivation of melts/fluids from a heterogeneous plume head such as those proposed by Nakamura and Tatsumoto (1988), Hart et al. (1992) and Kogiso (2007), but in this scenario ITEM is only sampled during periods of low degrees of partial melting, a feature consistent with the observed increase in K/Na ratios and K contents with a more pronounced ITEM signature. Although a heterogeneous mantle may pose problems in generating distinct end-member compositions, materials with highly heterogeneous compositions can still generate distinct end-members providing that the length scale of melting is larger than the length scale of source heterogeneity (Kogiso, 2007).

A highly radiogenic Sr component, similar to ITEM, has been found in many lamproites in other parts of the Mediterranean, and the mantle associated with the whole of the Alpine–Himalayan orogeny (e.g. Prelević et al., 2008; Prelević et al., 2012). Although this component has been attributed to the involvement of a subduction-related, crustal component (e.g. Prelević et al., 2010; Tommasini et al., 2011), we cannot exclude other origins similar to those advanced here. No matter which of the models is accepted, the highly radiogenic material on the basis of our findings would have had to have been introduced into the mantle prior to the onset of the Alpine–Himalayan orogeny.

It is difficult to assess the role that HIMU has played in Italian magmatism. If it has, then it is volumetrically subordinate, although it may have played a role at La Queglia and it may be present in other igneous rocks from the Adria foreland (Lavecchia and Bell, 2011). Likewise, a pure EM1 component is comparatively rare. In fact, the EM1-like component is restricted only to the Plio-Quaternary alkaline lavas from central and northern Sardinia which have the least radiogenic Pb in igneous rocks found in the circum-Mediterranean area (Lustrino et al., 2000; Lustrino and Wilson, 2007). In Fig. 7b a linear array containing the central-southern Sardinia data points towards FOZO at one end and on the other skirts EMI and continues towards a yet unknown end-member with a higher $^{143}Nd/^{144}Nd$ than EM1.

The isotopic signature now recognized as FOZO in Italy had previously been attributed to mixing between HIMU and DMM, e.g. Etna, Sicily Channel, Hyblean Plateau and Ustica, as well as the

Veneto region (e.g. Rotolo et al., 2006: Macera et al., 2003; Beccaluva et al., 2007), but now that FOZO appears as an end-member in its own right, there is no reason to involve either HIMU or DMM. Most of the data in our isotope diagrams neither trend towards nor attain a pure HIMU signature. If ratios >20.5 reflect HIMU, then the only true HIMU signature in Italy is only found at La Queglia ($^{206}Pb/^{204}Pb = 21.5$); relatively high $^{206}Pb/^{204}Pb$ values are also recorded at Punta delle Pietre Nere ($^{206}Pb/^{204}Pb \sim 20$) and less so in the Veneto Volcanic Province ($^{206}Pb/^{204}Pb$ up to 19.8).

A pure EM1 component proposed by several workers has yet to emerge. The component that resembles EM1 in the Plio-Pleistocene Na-alkaline basalts of northern and central Sardinia disappears in three-dimensional, isotopic space (Fig. 7b) and a new end-member emerges with a much higher $^{143}Nd/^{144}Nd$ than that normally associated with EM1.

In summary, FOZO and ITEM are important and ubiquitous Italian isotopic components and any linkage of FOZO or ITEM with the Apennine orogeny, or even the Alpine, subduction phase can therefore be ruled out. Of the two components, ITEM is spatially more restricted and seems to be related only to magmatism that occurred along the eastern margin of the Tyrrhenian Sea and the length of Italy from Sicily to the Alps. ITEM does not characterize the magmatic occurrences lying within the Veneto, Apulia, Hyblean areas of the Adria foreland. Nor do we find it associated with magmatic occurrences within the Campidano and the Sicily Channel grabens which involve FOZO and perhaps a HIMU-like component although we do not see it as a pure end-member in any of our isotope ratio diagrams. EM1 is very subordinate and, if present, is geographically limited to northern and central Sardinia.

6. Models

The isotopic similarity of many of the igneous rocks in Italy to some of the mantle components found in OIBs, especially FOZO, strongly favours plume activity in the central Mediterranean region and, although speculative, presents an alternative model to subduction. The major criticisms against any model involving a large plume beneath the Mediterranean and Europe (see Lustrino and Wilson, 2007) are the absence of abnormally high mantle temperatures, topographic upwellings such as swell structures, and basaltic melts commonly associated with LIPs (see Davies, 1998; Campbell, 2001a,b; Ernst and Bell, 2010). Compositional heterogeneities, however, in the lowermost mantle favour the coexistence of a great variety of plume shapes and sizes that can interact with the mantle, depending on size, temperature, shape and depth (e.g. Davies, 1998; Farnetani and Samuel, 2005). Plumes can bring both source and entrained material to upper levels, they can contaminate the asthenosphere, metasomatize the lithosphere and produce melts with different viscosities (e.g. Campbell, 1998). If a plume head is deep enough within the mantle, many of the problems involving a plume under Italy can be resolved (Griffiths and Campbell, 1991; Brunet and Yuen, 2000). Following Bell et al. (2004) and Lavecchia and Creati (2006), we thus propose a plume head trapped within the Transition Zone (410–670 km depth) beneath the western and central Mediterranean, and fed from deeper parts of the mantle. Such a plume, although not capable of producing thermal anomalies at lithosphere–upper asthenosphere depths would, nevertheless, be capable of causing metasomatism due to volatile/fluid loss. The progressive injection of plume-material within the Transition Zone would cause an eastward-migrating increase in volume of the asthenosphere (expansion), which in turn, would drive stretching of the overlying lithosphere.

One of the major requirements for Italian magmatism involves the development of an isotopically heterogeneous mantle source, raising the question as to how such a mantle came into being and the role, if any, played by subduction or plume activity. The main findings from the isotopic data of the ubiquitous presence of FOZO, the origin of a highly enriched component (ITEM) and the mixing curve between FOZO and ITEM (i.e. MIRT) form the basis for generating any model.

We have already discussed the origin of ITEM. Models can be divided into two, one in which ITEM was initially deep-seated, perhaps located at the "D" layer, while the other involves entrained sediments/continental crust in the sub-lithospheric mantle. In the latter scenario, ITEM could reside at any depth from "D" up to the base of the lithosphere, although estimated melting temperatures require that ITEM has to be relatively shallow, restricted to at least the upper mantle.

The widespread nature of ITEM signature in the sub-lithospheric mantle, especially under deep peninsular Italy, reveals a mantle that was either metasomatized by deep fluids/melts, or a mantle that contains a highly radiogenic component such as continental material introduced prior to 70 Ma and entrained in a FOZO-like mantle similar to the European Asthenospheric Reservoir. A FOZO-like mantle containing slabs of entrained sediments/upper continental crust with a present day ITEM signature would generate a series of mixtures with variable isotopic compositions depending on the degree of partial melting. Low degrees of partial melting would generate an initial melt fraction with an ITEM signature and rich in potassium, whereas much higher degrees of melting would generate a melt similar in composition to FOZO but more sodic than ITEM. Different degrees of partial melting of a heterogeneous source is certainly consistent with the variation in chemical composition shown by the different rock types assessed by their position along the MIRT, especially the variation in K/Na ratios (see Fig. 5).

The compositional variation within the Italian mantle could be either vertical, e.g. between a depleted lithosphere and an ITEM-enriched asthenosphere, or a chemically and physically heterogeneous mantle containing entrained sedimentary enclaves. Mixing of ITEM and FOZO during melting we think has little to do with recent subduction and for the most part is related to mantle expansion during Cenozoic plume activity.

Given the late Cretaceous age of the oldest Italian occurrences carrying the ITEM signature, such material had to have been incorporated into the mantle prior to the onset of the Mediterranean extensional phase. The chronology of the various phases of Italian magmatism and the geodynamic history of the central Mediterranean since the Oligocene have been attributed to lithospheric stretching associated with expansion of the asthenosphere driven by the eastward migration of a trapped plume head within the Transition Zone (Lavecchia and Creati, 2006). During the compressional Alpine phase melting was relatively limited with only low viscosity melts escaping to upper levels represented by isolated lamprophyric occurrences on both sides of the Alpine orogen. The bulk of magmatism in the central Mediterranean mainly starting in the late Miocene still involved the same two components, implying that ITEM and FOZO retained their isotopic compositions over a considerable period of time.

Although for many authors the entrained sedimentary model is attractive, a number of problems arise concerning the enclaves themselves. Among these are their age, their primary source, their chemical composition, along with the extremely uniform isotopic composition of ITEM.

Fig. 9 summarizes an alternative model. The shape of the inferred Mediterranean plume is based on the geometry of plumes trapped within the Transition Zone and numerically modelled by Brunet and Yuen (2000). This plume model might also be reconciled with some of the Mediterranean tomographic data (Piromallo et al., 2008) if the mantle P-wave velocity anomalies are considered in terms of chemical rather than thermal variations. The large-scale, high-velocity zones mostly confined within the Transition Zone and extending from the eastern North Atlantic to North Africa, central Europe and the western Mediterranean area might represent portions of a plume head now dehydrated and highly depleted through loss of volatiles and fluids. The overlying low velocity layer results from the effects of metasomatized fluids/melts containing CO_2–H_2O–K (Mei and Kohlstedt, 2000), which were carried from the deep mantle and subsequently released into the upper mantle. This is also consistent with Wyllie and Ryabchikov's (2000) suggestion that mantle plumes can generate interstitial volatile-rich liquids at levels determined by the thermal structure of the plume and the oxygen fugacity. The net effect is redistribution of mobile elements in the mantle, and "preparing sources capable of providing the geochemical signatures from kimberlites, lamproites and other types of alkaline primary magmas during subsequent melting events" (Wyllie and Ryabchikov, 2000). For a more detailed discussion as to how chemical-induced anomalies can affect seismic data in the western Mediterranean we refer the reader to Frezzotti et al. (2009).

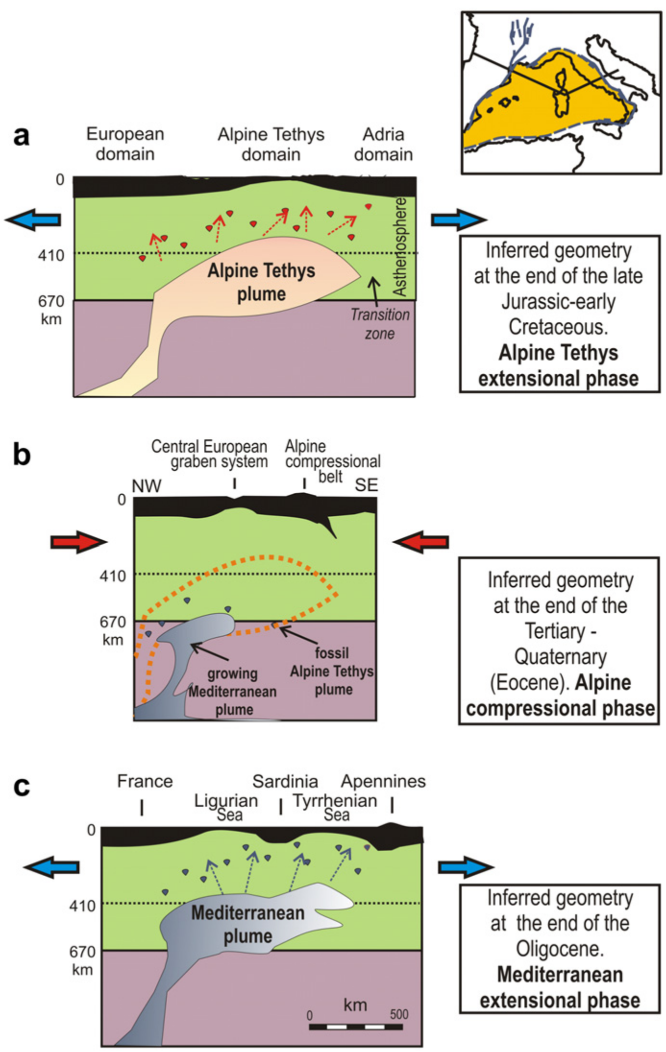

Fig. 9. Sketches of the Mediterranean plume along a transect from the Gulf of Lyon to Campania and Apulia foreland (modified from Lavecchia and Creati, 2006). Three snapshots correspond to events during the late Jurassic – early Cretaceous (a), the early Oligocene (b), and the present (c). Shown are the lithospheric mantle and the overlying crust (black), the upper mantle (green) and a part of the lower mantle (purple); low-viscosity fluids released from the plume head are shown by blue and red arrows. The thickness of the present-day lithosphere is from Suhadolc et al. (1990); the shape of the plumes is highly speculative and largely derived from Fig. 6 in Brunet and Yuen (2000).

The Mediterranean plume during the last 30–35 Ma might represent the present stage of a long-lasting and transient plume activity which involved several phases of plume incursions of differing scales into the upper mantle. We hypothesize that an extensive late Triassic–early Jurassic plume activity might have accompanied the rifting phase of the Alpine Tethys domain. The growth of an asymmetric plume head within the Transition Zone might have controlled the opening of the Alpine Tethys during the late Jurassic–early Cretaceous drifting phase (see Fig. 9a). The Alpine Tethys plume could have had several cycles of activity, remaining relatively quiet during the late Cretaceous–Paleocene Alpine compression (Fig. 9b), producing low viscosity fingers as isolated lamprophyres, as well as magmatism seen in the Veneto region. Renewed, plume-head growth within the Transition Zone since the late Oligocene would have led to mantle expansion and lithospheric thinning that led to the opening of the Mediterranean and widespread magmatism (Fig. 9c).

ITEM was clearly in existence prior to Alpine subduction. It could reflect the involvement of an unusual, highly radiogenic plume similar to the one associated with magmatic activity in Samoa (Jackson et al., 2007b) that led to metasomatism of the asthenosphere. Subsequent expansion of the asthenosphere during plume migration led to decompression melting and hence magmas with high $^{87}Sr/^{86}Sr$ ratios. Yet another alternative is the melting of continental crustal fragments caught up in the mantle long before Alpine subduction. Whatever the model, ITEM has been involved in Italian magmatism over a period extending from at least 70 Ma to the present.

During the Oligocene, plume activity initiated a new eastward growth within the Transition Zone giving birth to the western Mediterranean Basins. The opening of the Ligurian and Balearic Basins between ~26 and 16 Ma ago and of the Tyrrhenian Sea between ~15 Ma and recent, possibly represent two sub-stages of the same plume. The possible marginal players among the mantle end-members, i.e. the HIMU-like and the EM1-like components, are restricted to more peripheral magmatotectonic domains i.e. the Campidano graben, Etna, the Hyblean Mountains, and the south-western Tyrrhenian Sea and form distinct mantle domains physically separated from the FOZO–ITEM dominated mantle.

If the FOZO-like component is lithosphere that has been metasomatized by plume-driven melts and fluids during the late Triassic–early Jurassic rift phase, the possible HIMU-like component in the undeformed Adriatic region and the EM1-like component in Sardinia and Sicily may represent older inputs from independent pulsing plumes, perhaps associated with the opening of the Neotethys or two separate plumes of different age.

7. Conclusions

In this paper we have assessed and updated a regional data set of Sr, Nd and Pb isotope analyses. These have provided some insights into delineating different mantle sources beneath the central Mediterranean, their interaction with one another, and the role that they have played during Cenozoic magmatism. The isotopic data viewed in both two- and three-dimensional diagrams are far from random, but reflect quite distinct, different mixing trends. Of these, the main Italian radiogenic trend involves mixing between FOZO and a well-defined, highly radiogenic end-member (ITEM) that can be traced along the entire length of Italy from the Aeolian Island to the Alps. Data from the Adria foreland, Sicily and Sardinia, deviate from the main trend suggesting mixing with other components, perhaps HIMU and EM1. Significantly, DMM is absent and this along with other end-members not recognized in present-day consuming plate margins are incompatible with subduction-relate models. We consider one of the main findings in our paper to be the generation of most melts from an OIB-type mantle.

The geodynamic context of the central and western Mediterranean region can be interpreted in terms of a series of major tectonic events associated with transient plume activity. We distinguish three major extensional phases:

1. a late Triassic–early Jurassic rift phase, possibly controlled by a plume impingement at the base of the lithosphere that led to the impregnation of the overall Eurasia–Africa upper mantle with a FOZO-like signature.
2. a late Jurassic–early Cretaceous rift phase associated with the Alpine Tethys opening, possibly above a trapped plume head (Fig. 9a).
3. a late Oligocene to Holocene rift phase, responsible for the opening of the western and central Mediterranean wide-rift basins and associated with an expanded, ITEM-rich mantle lying above a plume head, trapped within the Transition Zone (Fig. 9c).

We propose that release of fluids/melts from a heterogeneous mantle plume, containing both source and entrained material, contributed CO_2, H_2O, perhaps Ca and K into the surrounding mantle, thus further enriching a source potentially capable of producing the diversity of rock types seen in Italy, including carbonated and silica-undersaturated magmas. Furthermore, the progressive injection of plume-related material within the Transition Zone would cause an increase in volume of the metasomatized asthenosphere which, in turn, would drive stretching of the overlying lithosphere. As the head of the Mediterranean plume progressively migrated to the east, its growth triggered lithospheric stretching and unloading with consequent decompression melting (Lavecchia and Bell, 2011 and references therein).

The dehydrated and decarbonated plume head is possibly now reflected by the high velocity anomaly found within the Transition Zone, while the overlying low velocity zone reflects metasomatized mantle. Easterly migration of the plume head along with lithospheric stretching and thinning led to mantle melting and the progressive generation of a series of melts whose compositions were controlled by the degree of partial melting. Because the proposed Mediterranean plume is trapped well beneath the lithosphere, it is not associated with any major thermal anomalies at lithosphere-upper mantle depths, major topographic upwellings and major outpourings of high-degree partial melts.

The avoidance of subduction in formulating our model has been deliberate. Our attempt to establish whether the magmatic and tectonic complexities in the central Mediterranean can be explained by plume processes has been reasonably successful, largely due to the difficulties encountered in explaining the Sr, Nd and Pb isotopic data by subduction-related magmatism. We agree that it is possible to construct other models, but the ones we have proposed best fits the data in terms of models involving only plume magmatism. Although models invoking plume-related magmatism may have their shortcomings they have, nevertheless, stimulated a great deal of discussion. Models have been modified, assumptions have been re-assessed, and some of the basic concepts that relate to Italian magmatism and its geodynamic setting are presently being re-evaluated. The growing number of recent papers relating plume activity, in one form or another, to magmatism in Italy has led to critical re-assessments of the role of subduction in the central Mediterranean region and can only be taken as a positive outcome for helping resolve some of the many complexities surrounding Italian magmatism and geodynamics.

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