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CHAPTER 2
Miocene – Quaternary magmatism in central-southern Italy

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2.1 BASIC PETROLOGICAL CHARACTERISTICS AND GEOGRAPHIC DISTRIBUTION OF MAGMA TYPES

The Miocene-Quaternary magmatism in central and southern Italy occurs along a NWSE trending distension zone parallel to the Apennine chain and to the Tyrrhenian sea border, in western Sicily, in the Sicily Channel and on the Tyrrhenian Sea floor and Sardinia (Fig. 1). It shows a large compositional variability, which is best illustrated by the Total Alkali vs. Silica diagram (TAS) (Le Bas *et al.*, 1986) reported in Fig. 2. Here, rock compositions from most, though not all, the Italian Miocene-Quaternary volcanic centres have been plotted; it is evident that the magmatism covers almost entirely the compositional field of igneous rocks occurring world-wide. Large variations are also observed for other key petrological parameters, such as the degree of silica saturation. Fig. 3 plots ΔQ vs. K_2O/Na_2O values for some Italian volcanoes. ΔQ is the algebraic sum of normative quartz (q), minus nepheline (ne), leucite (lc), kalsilite (kal) and olivine (ol); it quantifies the degree of silica saturation: undersaturated magmas have ΔQ < 0, whereas oversaturated magmas have ΔQ > 0 identify silica oversaturated magmas. From figure 2 and 3, it is evident that the Italian volcanic rocks range in composition from mafic to acid, from strongly undersaturated to oversarturated in silica, from tholeiitic, calcalkaline and shoshonitic to K- and Na-alkaline. There is a continuum in the increase in potassium and K/Na from tholeiitic, calcalcaline, high-K calcalkaline (HKCA) to shoshonitic, potassic and ultrapotassic rocks. Among K-alkaline rocks, various groups can be recognised; these include potassic series (KS), lamproites, kamafugites, and Roman-type highly potassic series (HKS) (Conticelli and Peccerillo, 1992; Peccerillo, 2001a). Potassic Series (KS) are slightly more enriched in potassium than shoshonites and are here defined as mildly alkaline rocks with K_2O/Na_2O = 1.5 – 2.5 at MgO > 3 wt%. KS are formed by trachybasalts, latites, trachites. Ultrapotassic rocks have K_2O > 3wt% and K_2O/Na_2O > 2.5 at MgO > 3 wt%. They are divided into Roman-type, lamproites and kamafugites. Roman-type ultrapotassic rocks (also known as High-Potassium Series, HKS) consist of silica undersaturated leucite tephrites, leucite phonolites and leucitites, which contain high Al_2O_3 and CaO (see table 1). Lamproites are from slightly undersaturated to oversaturated in silica and have lower Al_2O_3, CaO and Na_2O and higher K_2O/Na_2O than Roman-type rocks. Kamafugites are strongly undersaturated in silica and have low Al_2O_3

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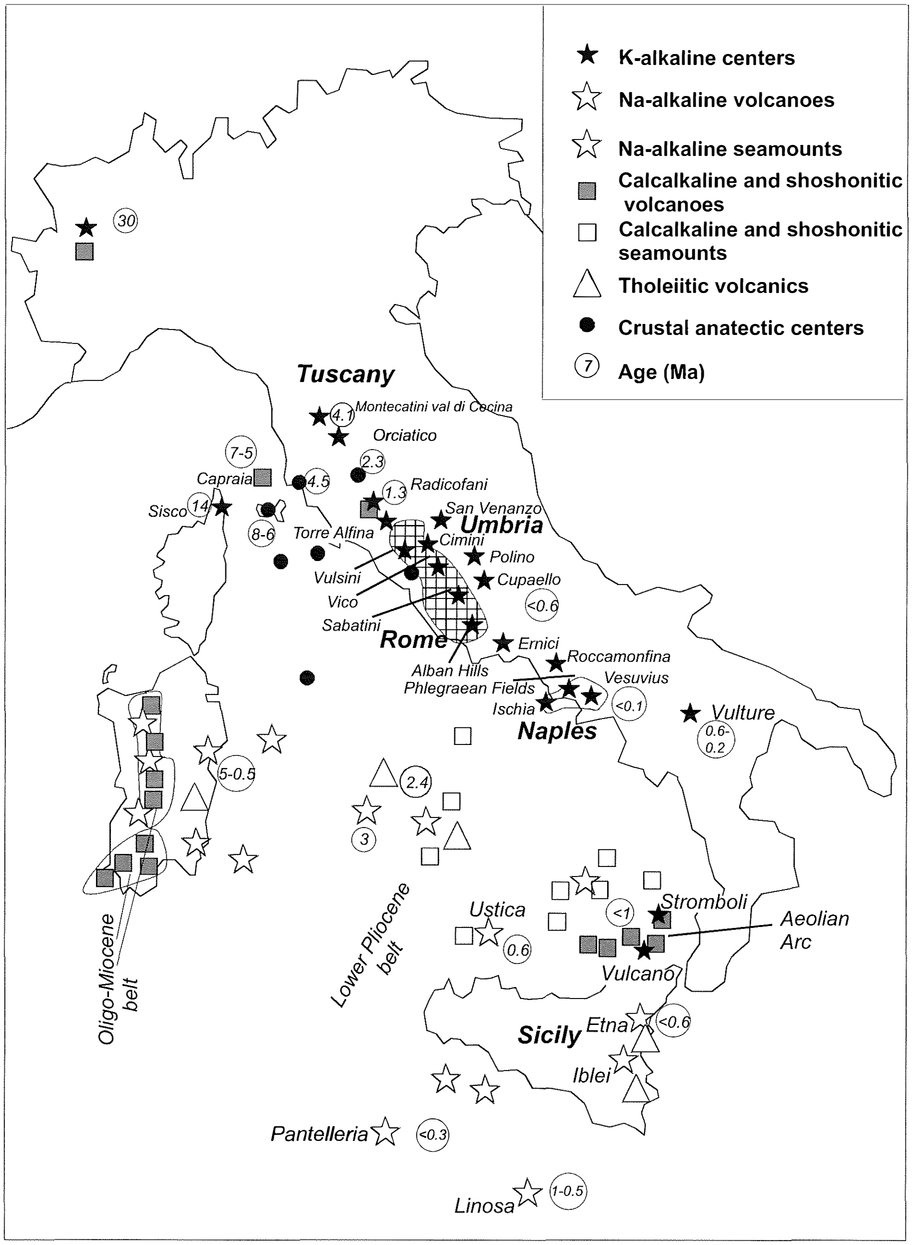

Fig. 1 – Schematic distribution of recent volcanism in Italy. The Oligo-Miocene orogenic volcanism of Sardinia and Western Alps is also indicated.

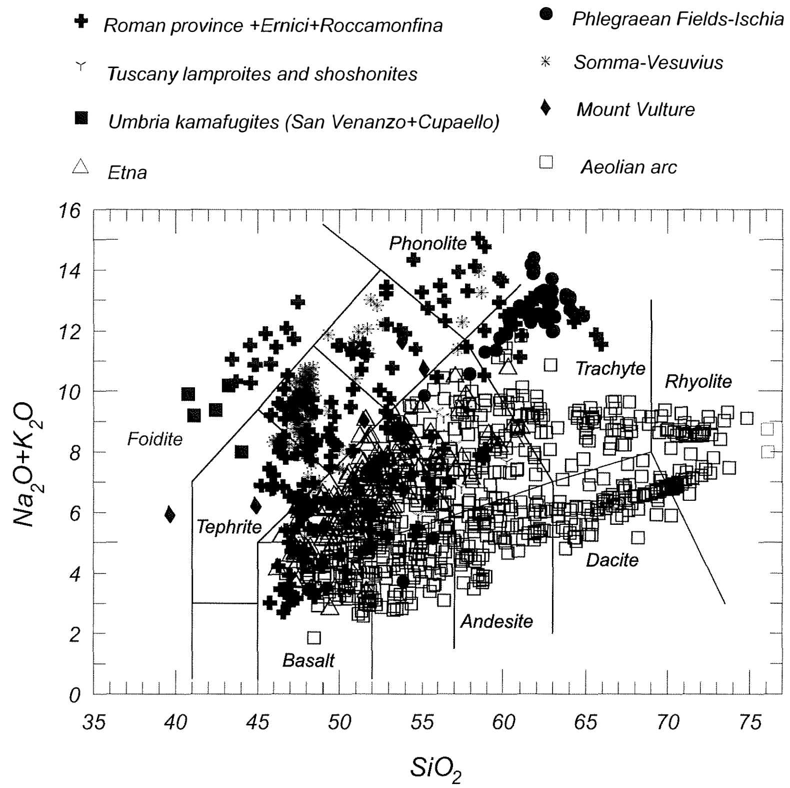

Fig. 2 – Total alkali vs. silica classification diagram of Le Bas *et al.* (1986) for Plio-Quaternary volcanic rocks from Central-Southern Italy. Note the extreme compositional variability. For source of data see Peccerillo (2001a).

and Na_2O, and high CaO and K_2O/Na_2O (Foley *et al.*, 1987; Peccerillo, 1992) (see also Fig. 3). Major, trace element and isotopic compositions of mafc samples are given in Table 1.

2.1.1 Geographic Distribution

Tholeiitic rocks occur in western Sicily (e.g. continental tholeiites from older Etna, Iblei) and Sardinia and forms some seamounts in the central and southern Tyrrhenian sea (MORB and island arc tholeiites). Calcalkaline and shoshonitic rocks are concentrated in the Aeolian arc, but also occur in the Neaples area (Di Girolamo, 1978) and in Tuscany (e.g. Capraia, Radicofani; D'Orazio *et al.*, 1991; Peccerillo *et al.* 2001 and references therein). Calcalkaline and shoshonitic seamounts occur in the Tyrrhenian sea, where they show an age which increases going westward (e.g. Locardi, 1988, 1993; Beccaluva *et al.*, 1989) (Fig. 1).

Na-alkaline rocks occur at Etna, Iblei in the Sicily Channel (Pantelleria, Linosa) in the Tyrrhenian Sea (Ustica and some seamounts) and extends to Sardinia.

Potassic and ultrapotassic rocks represent the most typical rocks in central Italy. KS and HKS rocks occur over a large area, including Vulsini, Vico, Sabatini, Alban Hills, Ernici, Roccamonfina and the Neaples area (Vesuvius, Ischia, Phlegraean Fields). Some

TABLE 1

Composition of some representative mafic rocks from central-southern Italy. For source of data see Peccerillo (2001a).

	Western Aeolian arc CA basalt	Stromboli KS	Vesuvius HKS	Vulture KS	Ernici HKS	Ernici	S.Venanzo kamafugite	Vulsini HKS	Vulsin KS	Tuscany shoshonite	Tuscany lamproite	Tuscany trachyte	Tuscany rhyolite
SiO_2	51.73	52.24	47.45	44.3	48.18	46.46	41.88	46.61	53.22	52.95	57.68	66.4	71.66
TiO_2	0.65	0.89	0.91	1.13	0.77	0.82	0.69	0.77	0.7	0.93	1.43	0.53	0.39
Al_2O_3	15.74	17.33	18.13	15.8	16.41	16.62	12.28	17.64	16	16.43	12.14	15.7	14.5
Fe_2O_3	2.16	2.51	4.41	6.1	2.6	5.86	1.95	8.39	2.17	2.33	2.17	0.72	2.18
FeO	6.11	5.8	2.81	3.3	4.86	1.77	4.45	0	4.2	3.89	3.12	2.52	0.25
MnO	0.16	0.15	0.13	0.2	0.15	0.15	0.11	0.14	0.12	0.12	0.09	0.06	0.03
MgO	8.78	5.8	5.46	5.3	8.68	6.04	12.78	5.87	7.12	8.51	8.34	1.32	0.31
CaO	10.55	8.94	10.32	12.83	11.98	10.87	15.21	11.59	8.76	7.92	3.5	2.99	1.51
Na_2O	2.23	2.19	2.63	3.17	2.82	2.6	1.06	2.09	8.76	1.9	1.34	2.37	3.28
K_2O	0.93	4.24	6.49	3.2	2.63	6.94	8.36	6.42	4.4	3.26	8.05	5.91	4.99
P_2O_5	0.2	0.59	0.94	1.22	0.27	0.45	0.39	0.47	0.21	0.27	0.85	0.16	0.03
L.O.I.	0.68	0.16	0.31	1.89	0.66	1.56	0.83	0.29	0.46	1.2	1.22	1.25	0.81
Ba	263	1748	1867	2379	539	1213	501	1016	462	610	1210	279	231
Rb	31	149	265	98	112	421	432	407	113	201	601	380	385
Sr	547	757	844	1709	841	1666	1706	1461	595	335	604	444	91
Y	14	29	27	44	19	32	27	33	29		30		35
Zr	81	187	232	282	91	227	319	242	285	211	859	286	214
Nb	6	28	27	59	8	12	18	13	19		42		10
Ni	114	36	40	37	89	63	141	45		97	288		
La	19	49	49	222	30	93	77	81	71	46	140	80	71

Table 1 continued

	Western Aeolian arc CA basalt	Stromboli KS	Vesuvius HKS	Vulture KS	Ernici HKS	Ernici	S.Venanzo kamafugite	Vulsini HKS	Vulsin KS	Tuscany shoshonite	Tuscany lamproite	Tuscany trachyte	Tuscany rhyolite
Ce	39.6	105	94	390	65	173	176	165	100	105	365	164	133
Nd	16.9	46		144	26	87	94	74		50	181	70	50
Sm	3	10	9.5	34	5.8	15.7	16.6	13.2	9.7	7.4	27.1	9.9	9.40
Eu	1.04	2.3	2.46	6	1.42	2.9	3	2.84	1.13	1.81	3.88	1.21	0.82
Tb	0.52	1.1	0.94	2.4	0.8	1.4	1.4	0	0.53	0.8	1.2	1.2	
Yb	1.67	2.3	1.97	2.5	1.9	2.7	2.4	2.29	1.91	1.94	1.68	3.1	3.40
Lu	0.3	0.4		0.51	0.23	0.4	0.45	0.33	0.34	0.36	0.43	49	0.63
Ta	0.26	1.7	1.63	5.1	0.53	0.69	0.92	0.9	0.71	1	2.9	1.6	
Hf	1.84	4.5	4.6	7.9	2.7	5.9	8.8		4.6	7.2	20	6.6	
Sc	42.8		23	24	37	24	21.4	14	17.3	26	18.5	11	
Cs	0.85			13			33			13	15		
Th	3.8	20.8	18.6	49	8	30	36	33	41	35	119	36	53
U	1.34		6.7										
Co	37		28		38	29	42	31	21	33	31	9	
Pb		28	28					27					
$^{87}Sr/^{86}Sr$	0.70407	0.7075	0.707	0.7059	0.7065	0.7104	0.7104	0.7135	0.70991	0.7158	0.7158	0.7129	0.71308
$^{143}Nd/^{144}Nd$	0.51278	0.5124	0.5126	0.5127	0.5124	0.5121	0.5121	0.5122		0.5121	0.5121	0.51211	
$^{206}Pb/^{204}Pb$	19.2	18.93	19.01	19.15	18.9	18.75	18.73	18.69		18.73	18.73		18.723
$^{207}Pb/^{204}Pb$	15.67	15.64	15.66	15.67	15.68	15.7	15.66	15.67		15.71	15.71		15.663
$^{208}Pb/^{204}Pb$	39.1	39.01	39.04	39.11	39.03	39.03	38.93	38.98		39.19	39.19		38.859

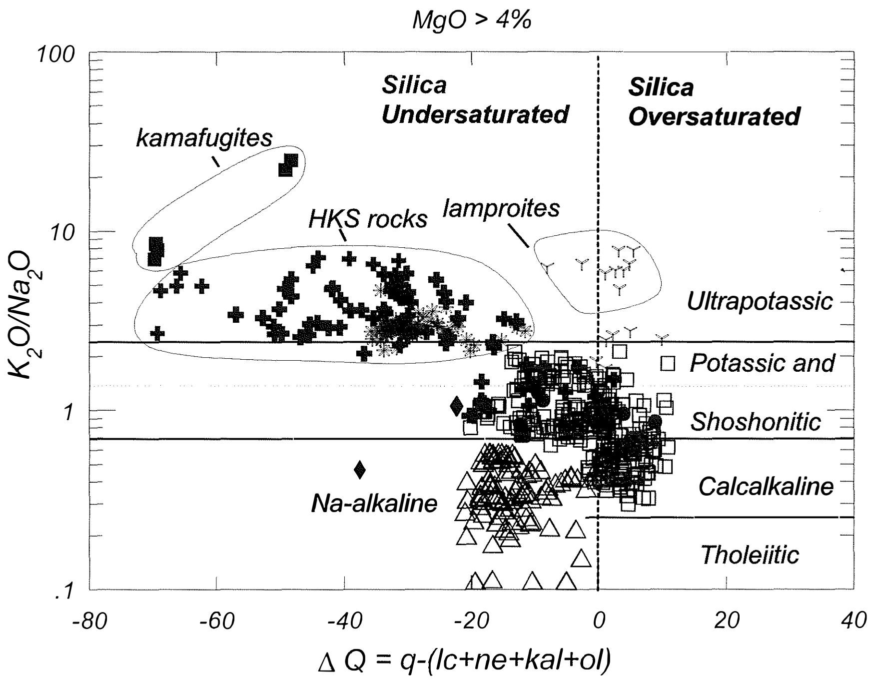

Fig. 3 – ΔQ vs. K_2O/Na_2O classification diagram for mafic (MgO > 4%) volcanic rocks from central-southern Italy. ΔQ is the algebraic sum of normative quartz (Q), minus leucite (lc), nepheline (ne), kalsilite (kal) and olivine (ol). ΔQ measures the degree of silica saturation of rocks: silica oversaturated rocks have ΔQ >0, whereas silica undersaturated rocks have ΔQ < 0. Symbols and source of data as in figure 2. Calc-alkaline (CA) rocks are saturated to oversaturated and have K_2O/Na_2O less than 0.7. Shoshonites (SHO), potassic series (KS) and high-potassium series (HKS) are characterised by increasing K_2O/Na_2O ratio and degree of silica undersaturation. Lamproites (LMP) are ultrapotassic (K_2O/Na_2O > 2.5) slightly undersaturated to oversaturated in silica. Kamafugites (KAM) have the highest K/Na ratio at the lowest ΔQ value. Na-alkaline mafic rocks are undersaturated and have K_2O/Na_2O less then unity. Tholeiites have the lowest alkalies and K_2O/Na_2O ratios.

KS occur in the Aeolian arc, at Vulcano and Stromboli.

Lamproites occur in southern Tuscany (Montecatini val di Cecina, Orciatico, Torre Alfina) and represent the northernmost occurrences of Miocene-Quaternary K-alkaline magmas. Similar but older rocks (14 Ma) occur at Sisco (Corsica; Peccerillo *et al.*, 1988 and references therein) and in the western Alps (30 Ma) (Venturelli *et al.*, 1984) (Fig. 1).

Kamafugites occur in the internal zones of central Apennines (i.e. San Venanzo and Cupaello, in Umbria) (Gallo *et al.*, 1984; Peccerillo *et al.*, 1988).

A particular volcano is Mount Vulture, east of Vesuvius; this is composed of undersaturated alkaline rocks, which are rich in both Na and K, with K_2O/Na_2O not far from unity (De Fino *et al.*, 1986).

2.2 REGIONAL VARIATION OF TRACE ELEMENTS AND SR-ND-PB-OXYGEN ISOTOPE COMPOSITION FOR MAFIC ROCKS

The magmatic rocks from central-southern Italy, including the most mafic ones, display variable abundances and ratios of incompatible elements. The rocks occurring in the Italian peninsula and in the Aeolian arc have variable abundances of Large Ion Lithophile Elements (LILE, e.g. K, Rb, Ba, Th, U) and Light REE, but display moderate to low concentration of High Field Strength Elements (HFSE, e.g. Ta, Nb, Zr, Ti) (e.g. Peccerillo *et al.*, 1988; Beccaluva *et al.*, 1991; Conticelli and Peccerillo, 1992). Mafic rocks (MgO > 4 wt%) give the maximum of the information on composition of mantle sources and processes. If these rocks are considered, one can distinguish various trends of LILE/LILE and LILE/HFSE ratios (Fig. 4). These appear to be related to the geographic position of volcanoes rather than to the petrological characteristics of rocks. For instance, HKS mafic rocks from the Roman area (i.e. Vulsini, Vico, Alban Hills) define different trends as rocks from Vesuvius, in spite of the similar major element chemistry. Moreover, calcalkaline and shoshonitic rocks from Tuscany plot in distinct fields than the analogous rocks from the Aeolian arc, for many trace elements and isotopes.

Variation of $^{87}Sr/^{86}Sr$ vs. $^{143}Nd/^{144}Nd$ of mafic rocks are shown in figure 5. The Italian volcanics define a curved trend between typical mantle compositions (Etna, western Aeolian arc, etc.) and upper crust values, with an overall increase of $^{87}Sr/^{86}Sr$ and a decrease of $^{143}Nd/^{144}Nd$ and $^{206}Pb/^{204}Pb$ from south to the north (Vollmer, 1976; Hawkesworth and Vollmer, 1979; Conticelli *et al.*, 2001a).

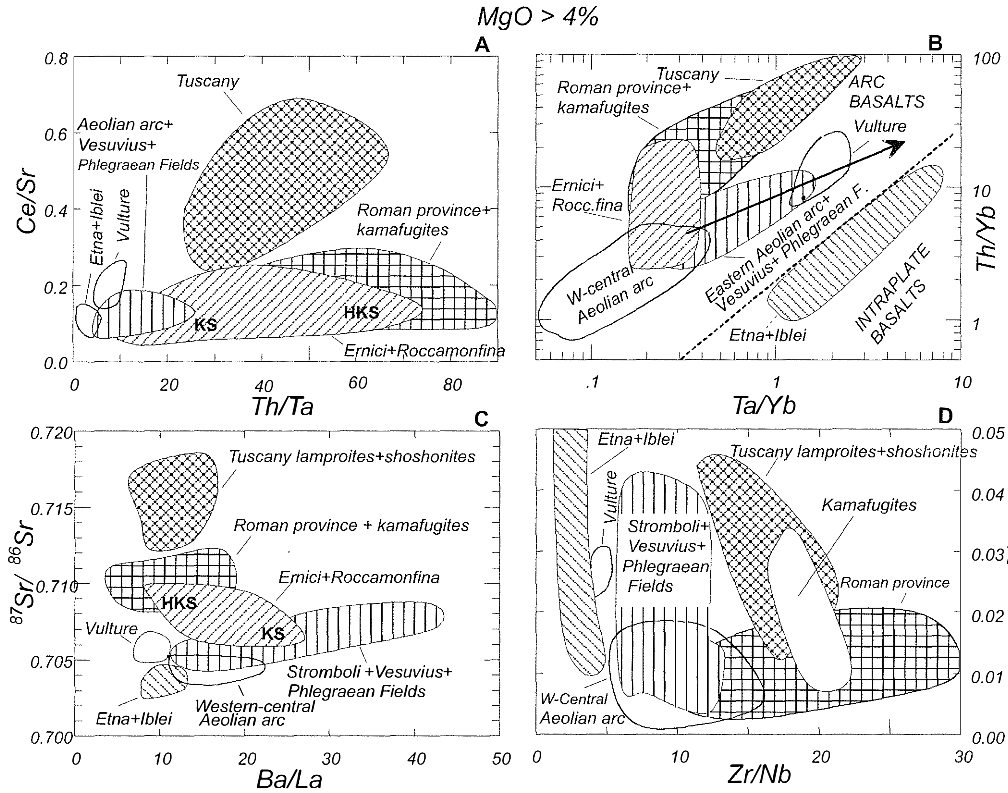

Fig. 4 – Variation diagrams of incompatible trace element ratios and $^{87}Sr/^{86}Sr$ for mafic (MgO > 4%) volcanic rocks from central-southern Italy. Rocks from different regions define distinct trends; Stromboli, Vesuvius and Phlegraean Fields define a single trend. For source of data see Peccerillo (2001a).

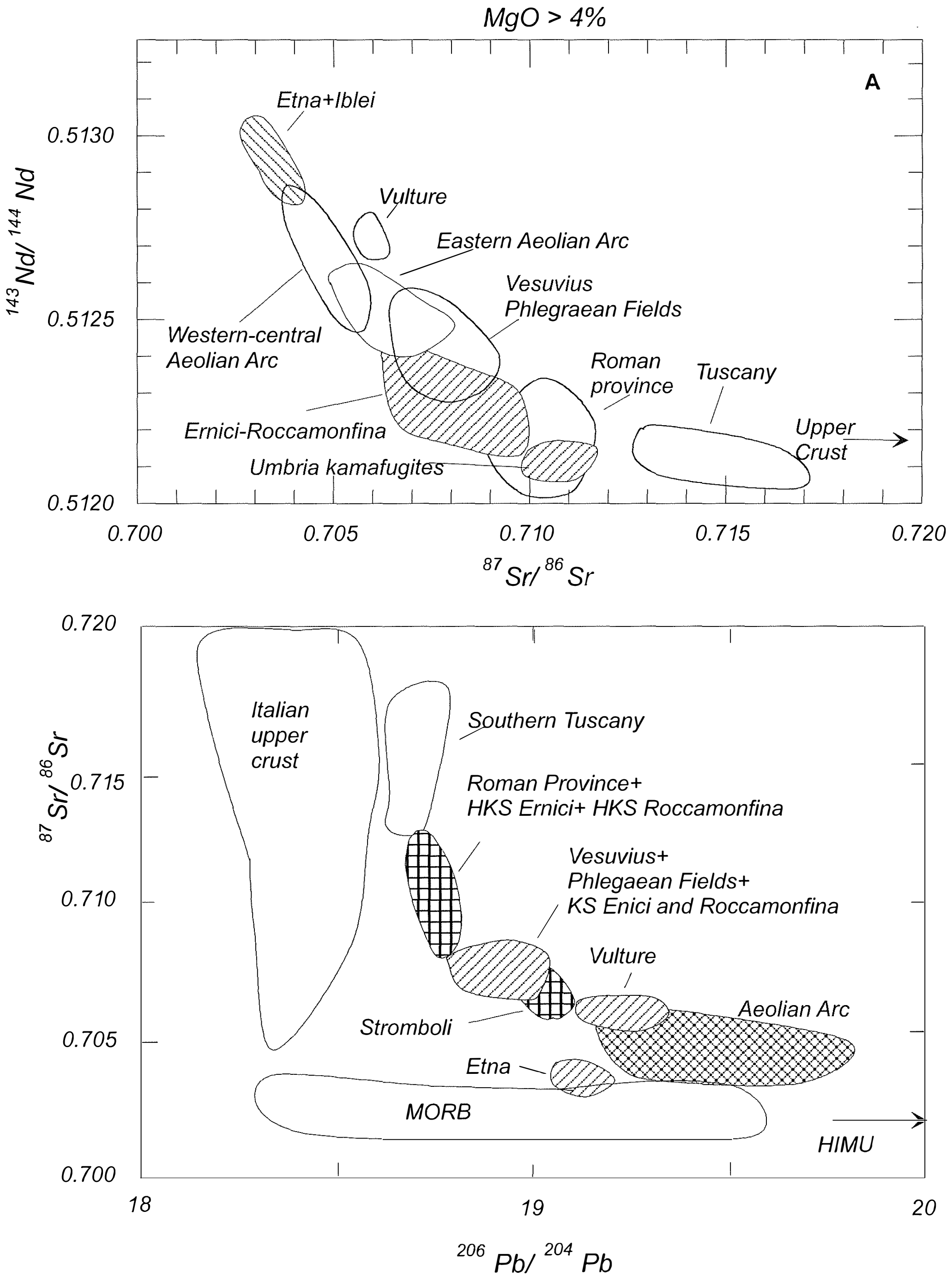

Fig. 5 – Sr vs. Nd and Pb isotope diagrams for mafic (MgO > 4%) volcanic rocks from central-southern Italy.

Oxygen isotopic data are also variable in the volcanic rocks from central-southern Italy (e.g. Turi and Taylor, 1976; Turi *et al.*, 1986; Holm and Munksgaard, 1982; Ellam and Harmon, 1990). The lowest values are found in the south (e.g., $\delta^{18}O \approx +5.5$ to +6, in the mafic rocks from the Aolian arc; Ellam and Harmon, 1990; Peccerillo *et al.*, 1993). Higher values ($\delta^{18}O \approx +7$ to +8) are found on mafic potassic and ultrapotassic rocks and separated minerals from central Italy (Harmon and Hoefs, 1995; Barnekow *et al.*, 1998).

2.3 Magmatic provinces in Central-Southern Italy

Miocene-Quaternary magmatism of central-southern Italy has been classically subdivided into five magmatic provinces, represented by Tuscany, the Roman-Neapolitan area (the so-called Roman Comagmatic Province, Washington, 1906), the Aeolian arc, the Sicily Na-alkaline province (Etna, Ustica, Iblei, Pantelleria, Linosa), and Sardinia. Major, trace element and isotopic data reported above provide evidence for a much more varied setting and allow to subdivide the Italian volcanism into several magmatic provinces that show distinct major element composition and/or incompatible trace element ratios and/or radiogenic isotope signatures. The newly established magmatic provinces also differ for several geophysical features such as crustal thickness, mechanical characteristics of the lid, etc. (Peccerillo and Panza, 1999).

The newly established magmatic provinces are (Fig. 6):

Tuscany province. This complex area consists of both volcanic and plutonic mafic and acid rocks. Acid rocks are either of crustal anatectic origin (e.g., Roccastrada) or, in most cases (e.g. San Vincenzo, Cimini, Elba, Giglio), represent mixtures between crustal magmas and various types of mantle-derived melts (Feldstein *et al.*, 1994; Poli, 1992). Mafic rocks range from High-K calcalkaline (HKCA) and shoshonitic, to KS and lamproitic compositions (Peccerillo *et al.*, 2001). All the Tuscany mafic rocks plot along the same trend on diagrams of incompatible element ratios, in spite of the differences in the main petrological characteristics; moreover, all have crustal-like geochemical and isotopic signatures (e.g. high $^{87}Sr/^{86}Sr$ around 0.712-0.717; Poli *et al.*, 1984; Conticelli and Peccerillo, 1992). Acid rocks associated with mafic magmas are likely related to anatexis induced by isotherm uprise during emplacement of mafic magmas (Peccerillo *et al.*, 2001 and references therein).

Roman province. It extends from Vulsini to the Alban Hills. It is formed by KS and HKS rocks with variable degrees of evolution (trachybasalt to trachytes; leucite tephrites to leucitites and phonolites). Evolved rocks largely prevail over mafic one, and mainly occur as large ignimbritic sheets and plinian fallouts. Isotope compositions are less extreme than in Tuscany (e.g. $^{87}Sr/^{86}Sr$ is around 0.708-0.711; Hawkesworth and Vollmer, 1979; Conticelli *et al.*, 2001a and references therein). Incompatible element ratios define distinct trends as the Tuscany mafic potassic rocks (Fig. 4).

Umbria ultra-alkaline province. This is formed by small monogenic centres, such as San Venanzo and Cupaello. Volcanic rocks consist of ultrapotassic pyroxene and olivine melilitites with a kamafugitic affinity and of pyroclastic rocks with a melilitite to phonolite compositions (Stoppa and La Vecchia, 1992). Incompatible element ratios and isotopic signatures are similar as to the Roman province; however, petrological characteristics are distinctively different (lower Al_2O_3 and Na_2O, higher CaO and K_2O/Na_2O, and stronger degree of silica undersaturation in the kmafugites than in the Roman-type HKS rocks). Kamafugites are associated with carbonate-rich pyroclastic rocks, which have been suggested to represent carbonatitic magmas by Stoppa and Woolley (1997). However, geochemical data show that the carbonate fractions in these rocks is geochemically barren and acts as a diluent over silicate magma. In fact, the degree of enrichment in incompatible elements of

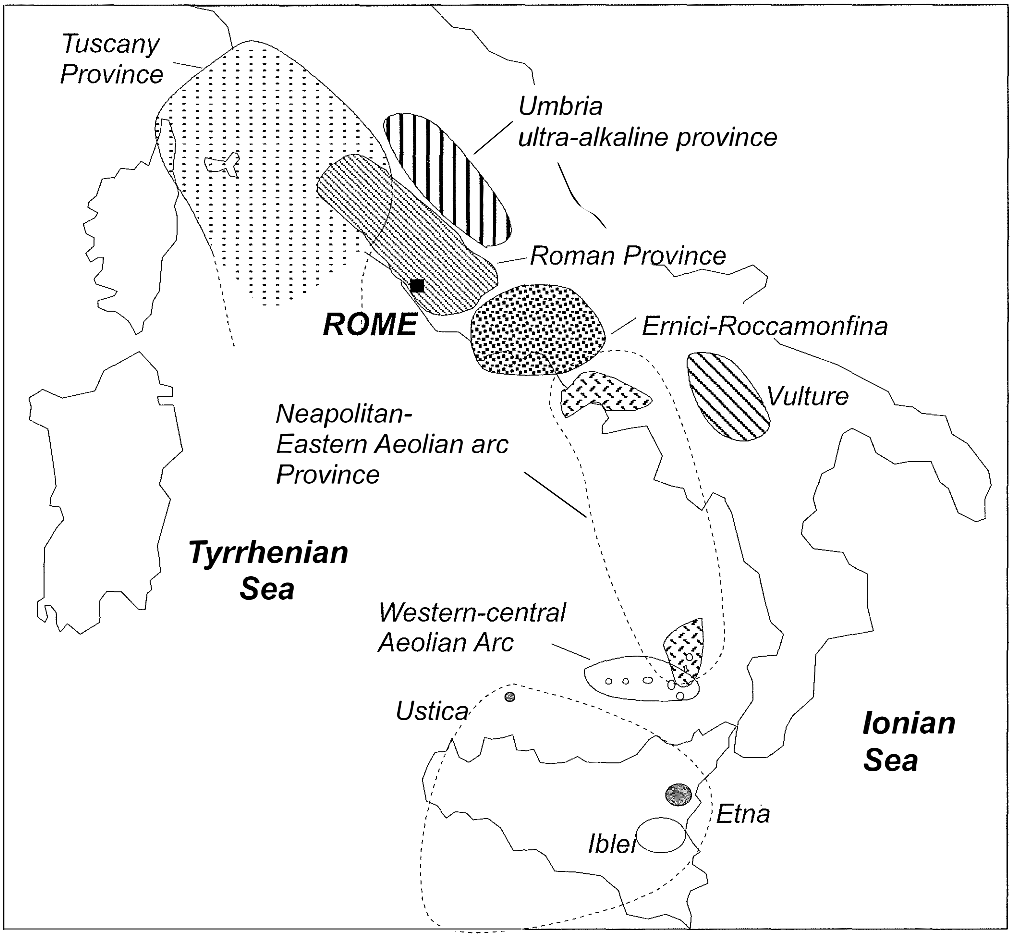

Fig. 6 – The new classification scheme for volcanic provinces in central-southern Italy, as inferred from major, trace element and isotopic characteristics of mafic volcanic rocks.

carbonate-bearing rocks decreases linearly with increasing carbonate fraction. This does not agree with a carbonatitic nature and strongly suggests a secondary origin for carbonate.

Ernici-Roccamonfina province. This is characterised by the close association of Roman-type HKS and KS. KS display incompatible trace element ratios and Sr-Nd-Pb isotopic signatures that are close to those of the Neapolitan volcanoes. On the contrary, HKS resemble the Alban Hills and other Roman volcanoes. Therefore, the Ernici-Roccamonfina zone displays transitional characteristics between the Roman and Neapolitan provinces.

Neapolitan province-Eastern Aeolian Arc. Somma-Vesuvius, Phlegraean Fields and Ischia are the largest centres in the Neaples area. The composition of volcanic rocks is variable, from KS to HKS; calcalkaline rocks are found by borehole drillings (Di Girolamo, 1978; Santacroce, 1987; Ayuso *et al.*, 1997; Pappalardo *et al.*, 1999, and rerefences therein). The mafic volcanic rocks show trends of trace element ratios and isotopes that are basically coincident with the rocks from Stromboli in the eastern Aeolian arc. Stromboli consists of rocks ranging from calcalkaline to shoshonitic and potassic. This leads to conclude that Vesuvius and adjoining volcanoes do not represent the southern end of the Roman province but rather the northern extension of the eastern Aeolian arc (Peccerillo, 2001b).

Aeolian arc province. Here, two sectors can be recognised. The western arc consists of calcalkaline rocks with typical island arc signatures. Sr isotope ratios in the mafic rocks mostly range between 0.7035 to 0.7045. The eastern arc (i.e. Stromboli) resembles the Neapolitan volcanoes, as mentioned earlier (De Astis *et al.*, 2000; Peccerillo, 2001b). The island of Panarea, which is sited between Stromboli and Lipari-Vulcano has intermediate characteristics between the two systems (Calanchi *et al.*, 2002). Lipari and Vulcano have similar isotopic signatures as the western arc, but contain shoshonitic and KS magmas, as in the east.

Mount Vulture. This volcano rises east of Vesuvius, in the internal zones of southern Apennines. It is composed of alkaline rocks that are enriched in both Na and K (De Fino *et al.*, 1986). Hauyne is the most typical foid of these rocks. Vulture is petrologically and geochemically different from any other Italian volcano, including those in Umbria, which also occur in the internal zones of Apennines. The latest activity at Vulture is characterized by an explosive eruption that emitted carbonate rich material again interpreted as carbonatite (Stoppa and Woolley, 1997).

Na-alkaline volcanoes of Etna, Iblei, Ustica and the Sicily channel (Linosa, Pantelleria). These centres have typical intraplate Na-alkaline composition, with some tholeiites at Etna and Iblei. Linosa consists almost entirely of mafic rocks, whereas peralkaline rhyolites (pantellerites) are abundant at Pantelleria. Etna and Ustica show similar compositions and display some arc-like geochemical signatures (e.g., low TiO_2) (e.g., Cristofolini *et al.*, 1987; Cinque *et al.*, 1988).

Finally, there is a large quantity of volcanoes hidden below the Tyrrhenian sea-level. These have MORB, arc tholeiitic, calcalkaline, shoshonitic, and Na-alkaline compositions. Some acid seamounts are also present. Ages range from Miocene to Quaternary. Plio-Quaternary tholeiitic to Na-alkaline volcanism occurs in Sardinia. This complex magmatism is the result of the SE migration of subduction processes and of deep-mantle uprise during opening of the southern Tyrrhenian sea (see Locardi, 1988, 1993; Beccaluva *et al.*, 1989; Lustrino *et al.*, 2000).

2.4 Petrogenesis

2.4.1 Role of low-pressure evolution processes and genesis of mafic magmas

Isotopic variations (Fig. 5) clearly suggest that the magmatism in central-southern Italy results from the interaction between mantle and crustal reservoirs, with crustal signatures increasing from south (Etna, western Aeolian arc, etc.) to the north (Roman province and Tuscany). One of the main problems is that of understanding to what an extent the crustal-like geochemical and isotopic signatures reflect source characteristics and how much they have been modified by magma contamination during ascent to the surface.

There is a general agreement that AFC played an important role during formation of evolved magmas such as rhyolites, trachytes and phonolites. However, it is unlikely that such a process is responsible for the range of isotopic variations encountered through the Italian peninsula.

Several studies demonstrated that, except in a few cases, evolutionary processes, including contamination, did not modify the first order compositional characteristics of mafic rocks. For instance, LILE/HFSE ratios change very little with crustal assimilation and AFC (Conticelli, 1998). Moreover, simple mass balance calculations show that some 70-90% of upper crust should be added to isotopically most primitive magmas (e.g., Etna, western

Aeolian arc) in order to have Sr-Nd-Pb isotopic compositions as the Roman and Tuscany rocks. Yet these rocks are mafic (sometimes with Mg# > 70) and most of them are undersaturated in silica, which strongly limits the role of magma contamination by upper crust. Note also that all the magmas in central-southern Italy are enriched in Sr, REE and Pb, which strongly buffer isotopic variations during assimilation. Therefore, the curved trends hown by isotopic data can be only explaining by assuming that interaction between crustal and mantle end-members occurred in the mantle. About 15% upper crustal material added to peridotite can generate isotopic signatures as those observed in the Tuscany lamproites. Therefore, it has been suggested that various amounts and/or types of upper crustal material have been added to the upper mantle beneath southern Italy. This generated a heterogeneous peridotite whose melting gave compositionally variable mafic magmas. The increase of $^{87}Sr/^{86}Sr$ and the decrease of $^{143}Nd/^{144}Nd$ and $^{206}Pb/^{204}Pb$ from south to north suggest that an increasing role of upper crustal material going northward (Peccerillo *et al.*, 1988, and references therein).

Major element data of mafic rocks offer a further insight into petrogenetic processes. Major element abundances of primary or poorly evolved melts depend on the mineralogy of the mantle sources and on the proportions that each phase enters the melt. The variable potassium contents of magmas in central-southern Italy reflects melting of different amounts of a K-rich phase, such as phlogopite (e.g., Wendlandt and Eggler, 1980). This can depend on the different amount of phologopite available in the upper mantle, which in turn depends on different degrees of metasomatic modifications. Since the most potassium-rich rocks are in the north, it can be concluded that the degree of metasomatic modifications in the upper mantle increases northward, in agreement with isotopic data. Moreover, the low CaO, Al_2O_3 and Na_2O of lamproites reflect a source depleted in these components; an harzburgite composition has been proposed for these magmas (Peccerillo *et al.*, 1988; Peccerillo, 1992). Since lamproites crop out in Tuscany, such a source is probably restricted to that area. Finally, the variable degrees of silica saturation may reflect different pressure of melting (Wendlandt and Eggler 1980; Foley and Peccerillo, 1992; Melzer and Foley, 2000).

Various trends of incompatible element ratios in the various volcanic provinces, also reveal regional compositional variability of the mantle sources, This again has been related to various types and intensities of mantle metasomatism (Peccerillo, 1999).

In conclusion, petrological, geochemical and isotopic data on volcanic rocks from central-southern Italy suggest that:

- Mafic magmas derive from heterogeneous and anomalous upper mantle sources, which basically result from mixing between upper mantle and crustal end-members.
- Interaction between mantle and crust occurred within the upper mantle, by addition of upper crustal material (mantle metasomatism).
- Regional variations of isotopic signatures and incompatible trace element ratios suggest that different degrees and type of metasomatic modification affected various sectors of the upper mantle. In other words, the distinct trends of incompatible element variation suggest that metasomatic agents, though of upper crustal origin, had different compositions in the various sectors of the Italian peninsula.
- Southern Tuscany mafic rocks show the strongest crustal-like geochemical and isotopic signatures among Miocene-Quaternary mafic rocks in central-southern Italy
- The variable major element contents and degree of silica undersaturation of mafic magmas reveal that mantle sources had variable mineralogical compositions and that melting occurred at various depths beneath the Italian peninsula.

2.4.2 Age and geodynamic context of metasomatic events

The age of metasomatisms and the geodynamic setting of magmatism in Italy are still debated. Geochemical and isotopic evidence, however, strongly suggests that upper crustal rocks were added to the upper mantle, as discussed earlier. According to present knowledge of geological phenomena, subduction is the only process that can bring upper crust into the upper mantle. Therefore, the hypothesis of a subduction-related origin for the Italian recent magmatism is inescapable.

The timing of mantle contamination is uncertain. However, it is well known that the Mediterranean area has been interested by subduction processes, as a result of convergence between Europe and Africa (e.g. Doglioni *et al.*, 1999). It has been also suggested that upper crust was brought deep into the mantle during continental collision, as evidenced by very high-P metamorphism of Dora Maira Massif (Chopin, 1984). Therefore, the most simple explanation is that during subduction processes and continental collisions that generated the Alpine-Apennine orogen, upper crustal material of various compositions were introduced into the upper mantle. These generated heterogeneous mantle sources for the Miocene-Quaternary orogenic volcanism in central-southern Italy.