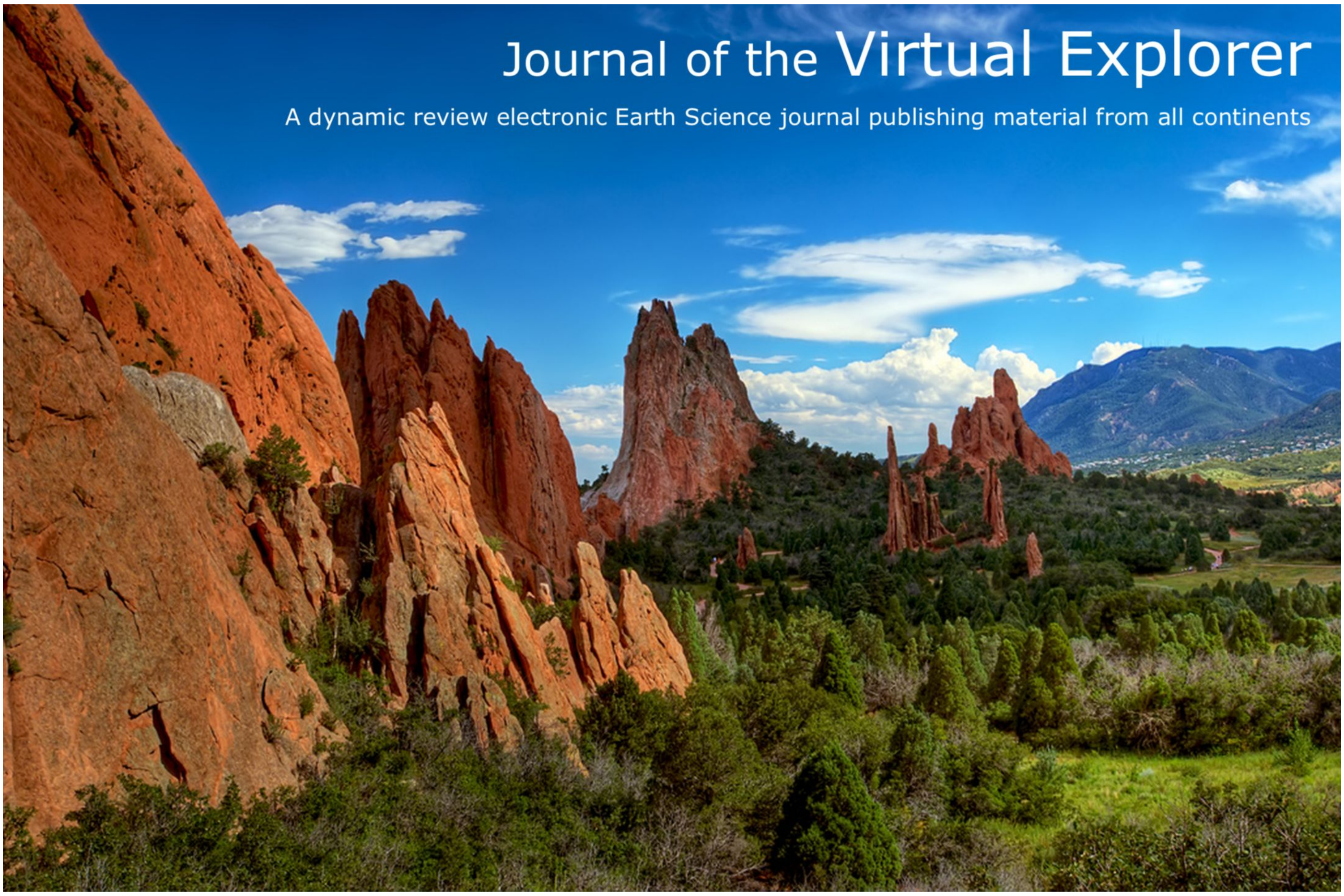

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Abstract: Tertiary to present magmatism in Italy is related to the convergence between the African and European plates. The Alpine orogeny and magmatism are the result of eastward and southward subduction of the Tethys ocean basin beneath the Adriatic continental plate and of the continental collision and post-collisional relaxation along the Alpine arc. The Apennine chain and associated magmatism developed as a result of west-directed subduction of the Adriatic plate beneath the southern European margin. The bulk of the magmatism during this complex geodynamic evolution is related to melting of mantle sources that were modified by subduction processes. These magmas, which are referred to as "orogenic", show high enrichments in Large Ion Lithophile Elements and relative depletion in High Field Strength Elements. A significant amount of magmas, however, are related to melting of mantle sources that were not contaminated by subduction. These magmas are referred to as "anorogenic" and have low LILE/HFSE ratios.

Eocene magmatism in Italy was concentrated in the Alpine area, with emplacement of both orogenic and anorogenic magmas. Orogenic igneous activity may have started also in Sardinia.

In the Oligocene, the climax of Alpine orogenic magmatism was reached. Compositions range from calcalkaline to ultra-potassic (lamproitic), the latter being restricted to the Western Alps, where subduction of upper continental crust is documented. Calcalkaline to shoshonitic activity in the Eastern Alps continues up to Late Oligocene.

Younger activity in Italy is essentially related to the Apennine subduction zone. In Sardinia, the bulk of calcalkaline and high-K calcalkaline activity started around ~28 Ma, and reached its climax at about 21-18 Ma, probably continuing until ~12 Ma. Successively, orogenic magmatism shifted eastward and southeastward forming several centres in the Tyrrhenian basin and in the Italian peninsula. At the same time anorogenic magmatism (tholeiitic to Na-alkaline) developed in several places behind the Apennine compression front (Sardinia and Tyrrhenian Sea basin), and along the northern margin of the Africa foreland (Eastern Sicily and Sicily Channel).

Relationships between magmatism and geodynamics in Italy are complex. Orogenic magmatism is sometimes coeval with subduction, suggesting mantle wedge melting under the effect of water-rich fluids released by the undergoing slabs. In other cases, magmatism is younger than subduction, resulting from post-collisional decompression melting of contaminated mantle wedge.

Petrological and geochemical compositions of orogenic magmatism suggests involvement of variable types of upper crustal material in its genesis. This was added to the mantle sources during subduction, and was particularly abundandant in the Tuscany and Roman provinces. Mantle components of deep origin were also involved in the orogenic magmatism especially along transversal lithospheric faults cutting the subduction front, or in backarc volcanoes. Asthenosphe and deep-mantle-plume have been suggested as possible sources for these components, but such an issue is poorly understood and still subject of debate.

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Introduction

The Italian territory occupies a central position in the Mediterranean area, one of the most complex geodynamic regions on Earth.

The present-day geological configuration of the central-western Mediterranean area and, in particular, of the Italian territory is the expression of two main orogenic phases, namely the Alpine and Apennine orogenesis. Both took place within the geodynamic framework of continuous convergence between Africa and Europe plates, a process which started in Cretaceous times and is still going on at present (e.g., Doglioni *et al.*, 1998).

The Alpine chain is the result of a first stage of Africa vs. Europe continental collision which followed the south-eastward immersion of the Alpine Tethys oceanic branches (i.e., Piemonte-Liguria and Valais) beneath the Adriatic continental plate, a promontory of the African plate (Handy *et al.*, 2010 for a review).

Starting from Eocene, the Apenninic subduction developed to the east of the former Alpine collision zone, in particular along its conjugated back-thrust belt, which should likely have been the southward prolongation of the Southern Alps. The former Alpine nappe stack was progressively buodinated and deformed by the back-arc extension behind the Apennine compression zone (e.g., Doglioni *et al.*, 1998). The compressional front and the associated backarc extension progressively migrated eastward and southward in response to slab-rollback-driven Apennine trench retreat. This determined diachronous rifting and opening of the Liguro-Provençal (~34-15 Ma) and Tyrrhenian (~15–0 Ma) sea basins and the counterclockwise rotation and eastward drifting of continental blocks rifted off the southern European margin (e.g., Corsica-Sardinia and Calabro-Peloritano blocks).

Such a complex succession of geodynamic events was accompanied by widespread magmatism. Compositions of magmas are variable and cover almost entirely the whole range of magmatic rocks occurring worldwide. Most of these magmas are of ultimate mantle origin, although they suffered important evolutionary processes during ascent to the surface, sometimes changing significantly their pristine petrological and geochemical features. A few magmas with a crustal anatectic origin are present in some places along the Alps and in Tuscany, central Italy.

According to many authors, the magmatism in Italy can be divided into two large groups, exhibiting distinct petrological, geochemical and isotopic signatures (e.g., Peccerillo, 2002; Lustrino & Wilson, 2007). One group ranges from arc tholeiitic (TH), calcalkaline (CA), high-K calcalkaline (HKCA) to shoshonitic (SHO) and potassic alkaline, is enriched in Large Ion Lithophile Elements (LILE: Rb, Cs, Th, U, Pb, LREE) relative to High Field Strength Elements (HFSE: Ta, Nb, Hf, Zr, Ti), and is believed to reflect a generation within mantle sources that were modified by addition of fluids or melts from the subducting oceanic or continental lithosphere (Peccerillo, 2005a and references therein). These rocks are generally referred to as “orogenic”, or also as “subduction-related”. They crop out over a wide area that includes the Alps, Sardinia, the Tyrrhenian Sea floor, the Aeolian Archipelago, and the Tyrrhenian border of the Italian peninsula, from the Naples area until Tuscany. Among orogenic rocks we also include the few crustal anatectic intrusive and extrusive bodies that are found along the Alps and in Tuscany.

Another group of rocks ranges from tholeiitic (TH) to Na-alkaline, is depleted in LILE relative to HFSE, and is believed to reveal a generation within mantle sources that did not suffer compositional modification by young subduction processes (Peccerillo, 2005a and references therein). These rocks are generally referred to as “anorogenic” and occur over a wide area, either related to back-arc extension or to melting of mantle sources of the foreland (see Bianchini & Beccaluva, this issue).

Such a twofold division of magmatism is overly simplistic, since there are several rocks which possess both “orogenic” and “anorogenic” compositional features (e.g., Plio-Pleistocene magmatism of Sardinia, Mount Vulture; Lustrino *et al.*, 2004; De Astis *et al.*, 2006). These were likely derived from mantle sources that had been affected by subduction-induced compositional modification, but preserved some signatures typical of intraplate magmas either for the scarce effect of subduction processes or/and for the involvement of other enriched sources, such as those that give OIB-type magmas.

In this paper, we review the main petrological, geochemical and isotopic characteristics of the Tertiary to present orogenic magmatism in Italy. A summary of occurrences, ages and compositions are reported in Table 1 (below) and Table 2 (available as a separate download - see note). We will briefly report on the most important data for various occurrences, discuss evolutionary processes occurred during magma emplacement, and explore implications for mantle source processes and the geodynamic setting in which they took place. This is a companion paper to those of Bianchini & Beccaluva and Conticelli *et al.*, which are respectively focused on anorogenic magmatism and on ultrapotassic volcanism of central Italy, one of the most intriguing issues of Italian geology. The ultrapotassic magmatism will be only briefly addressed in this paper.

Table 1. Sites, ages and petrological characteristics of Tertiary to Present orogenic magmatism in Italy

Magmatic Province	**Age**	**Main magmatic bodies**	**Rock composition**
Western Alps	34-29 Ma	Dioritic to granitic stocks (Traversella, Valle del Cervo, Miagliano), dykes, lavas and pyroclastics (Biella zone). Andesitic clasts in sandstones.	Mafic to felsic calcalkaline and shoshonitic intrusive and volcanic rocks. Ultrapotassic lamproitic dykes. Calcalkaline dominant basaltic andesite and andesite clasts in sandstones.
Central Alps	33-30 Ma (Bregaglia) 26-24 Ma (Novate)	Tonalite to granodiorite (Bregaglia-Bergel) and granitic (Novate) plutons plus mafic to felsic dykes.	Calcalkaline mafic to felsic compositions for both dykes and plutons. Some shoshonitic dykes.
Eastern Alps	Mostly 32 to 29 Ma. 43, 64-36, and 89-48 Ma at Adamello, Orobic Alps, SW Tyrol; 24-25 Ma at Molte Alto.	Numerous plutons (Adamello, Rensen, Monte Alto, Vedrette di Ries, Karavanke, Pohorje) of dominat tonalite and granodiorite plus minor gabbro, diorite and granite. Numerous dikes and small laccoliths and stocks.	Mafic to felsic rocks with dominant calcalkaline affinities. Mafic to felsic dikes with shoshonitic affinities.
Sardinia	38-12 Ma	Sequences of lava flows sometimes as pillows, domes and pyroclastic deposits running N-S along the Fossa Sarda, in the western sector of the island, and in Sulcis (SW Sardinia). Centres extending to southern Corsica, Ligurian-Provençal basin and Provence. Some clasts of possible Sardianian provenance found in sandstones in the Apennines.	Dominant dacites and rhyolites, minor andesite and scarce basalts with a calcalkaline affinity. Some peralkaline felsic rocks in Sulcis.
Tyrrhenian Sea Floor	12 Ma to Present	Cornacya, Anchise, Marsili, etc.	- Arc-tholeiitic, calc-alkaline, to potassic alkaline rocks, coexisting with intraplate (oceanic tholeiites, Na-transitional and alkaline) volcanics.
Tuscany	14 to 0.3 Ma	Acid intrusions (Elba, Montecristo, Giglio, Campiglia-Gavorrano), lavas and hypoabyssal bodies (San Vincenzo, Roccastrada, Amiata, Cimini, Tolfa-Cerite); mafic dikes and volcanics (Sisco,	Calcalkaline granitoid rocks plus aplites and pegmatites, rhyolite-trachydacite lava flows, domes, and polygenetic cones (Amiata, Cimini). Calcalkaline, shoshonitic and ultrapotassic (lamproites)

Magmatic Province	Age	Main magmatic bodies	Rock composition
		Capraia, Orciatico, Montecatini val di Cecina, Radicofani, Torre Alfina).	mafic to intermediate lavas and dykes.
Intra-Apennine	0.6 to 0.3 Ma	Monogenic pyroclastic centres with rare lavas (San Venanzo, Cupaello, Polino, Acquasparta, Oricola, etc.).	- Mafic undersaturated ultrapotassic melilitites (kamafugites). Dubious occurrence of carbonatitic pyroclastics.
Roman Province (Latium)	0.8 to 0.02 Ma	Large polycentric volcanic complexes (Vulsini, Vico, Sabatini, Colli Albani) with polygenetic calderas and volcano-tectonic collapses.	- Dominant pyroclastic rocks and minor lavas with potassic (trachybasalt to trachyte) and ultrapotassic (leucitite, leucite tephrite to phonolite) compositions.
Ernici - Roccamonfina	0.7 to 0.1 Ma	Monogenetic pyroclastic-lava centres at Ernici (Pofi, Ceccano, Patrica, etc.); stratovolcano with a central caldera and intracaldera lavas at Roccamonfina.	- Mafic to felsic ultrapotassic (leucitite, leucite tephrite to phonolite), shoshonitic (trachybasalt to trachyte) and calcalkaline (basalts and basaltic andesites) lavas and pyroclastics.
Campania and Eastern Pontine Islands	1 Ma to Present	Stratovolcanoes (Somma-Vesuvio, Ventotene), polycentric volcanic complexes (Campi Flegrei, Ischia), pyroclastic cones (Procida) etc.	- Shoshonitic (trachybasalt to trachyte) and ultrapotassic (leucite tephrite, leucitite to phonolite) rocks. Older calcalkaline lavas beneath Campi Flegrei.
Mount Vulture (Lucanian Province)	0.8 to 0.1 Ma	Stratovolcano with central caldera and intra-caldera explosive craters and a few parasitic centres (Melfi)	Dominant pyroclastic rocks and minor lavas with Na-K-rich tephrite and foidite (typically with haüyne) to phonolite compositions. Some carbonatites.
Aeolian Arc	0.4 Ma to Present	Large stratovolcanoes (Alicudi, Salina, Panarea, Stromboli) and polycentric volcanic complexes (Vulcano-Lipari), plus several seamounts.	Dominant calcalkaline lavas in the western islands (Alicudi, Filicudi, Salina), Lipari and Panarea; shoshonitic products in the central-western arc (Vulcano, Stromboli). Dominant mafic to intermediate lavas in the western and at Stromboli; abundant young acid lavas and pyroclastics in the central islands (Lipari, Vulcano).

Table 2

Click to download Table 2a - Alps - Sardinia

Click to download Table 2b - Aeolian arc

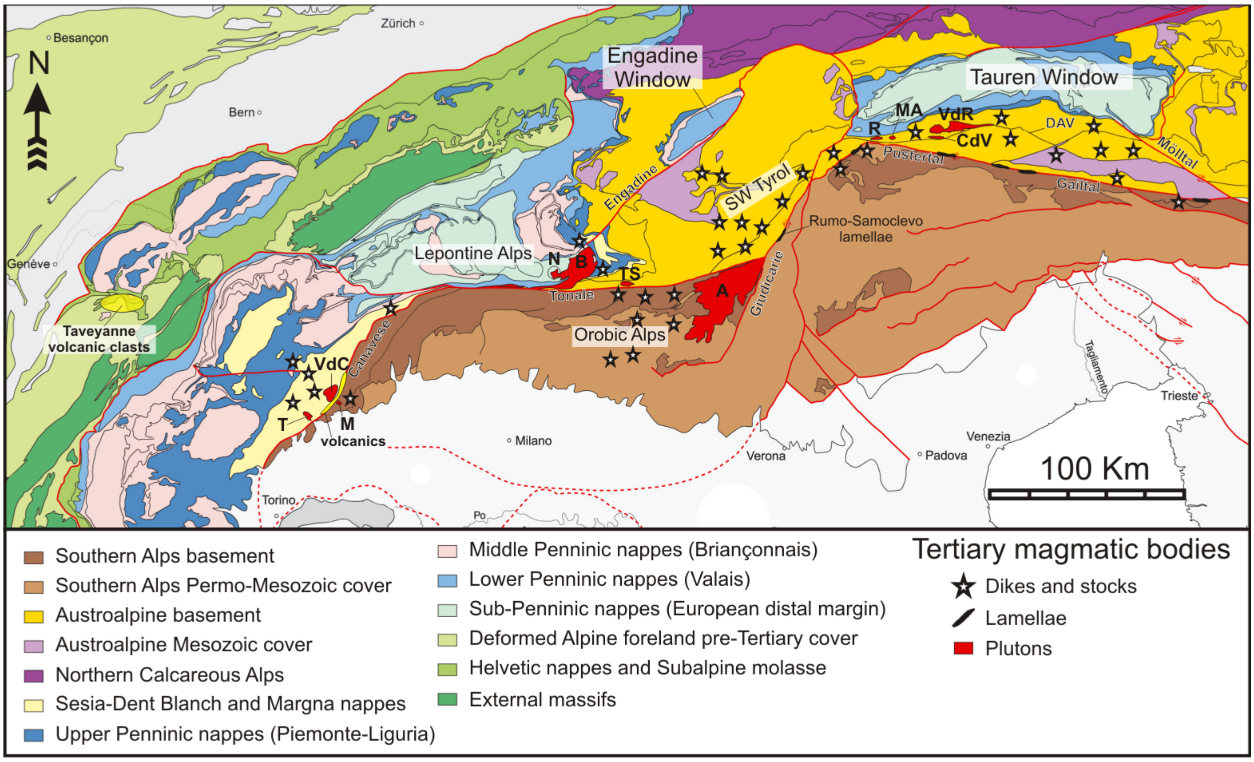
Click to download Table 2c - Central Italy

Alps

Introduction

Orogenic magmatism along the Alps took place during the Eocene and Oligocene (~ 43-24 Ma). The climax was reached around ~ 32-30 Ma, shortly after the final stages of the continental collision between the European and Adriatic continental margins, which was accomplished at ~ 35-32 Ma (e.g., Berger & Bousquet, 2008; Stampfli & Hochard, 2009; Handy *et al.*, 2010). Although subduction processes appear to have characterized Alpine geodynamics at least since the Upper Cretaceous (~ 90-80 Ma; Berger & Bousquet, 2008; Stampfli & Hochard, 2009; Handy *et al.*, 2010 for reviews), no convincing evidence exists for subduction-related magmatism prior to the middle Eocene. By contrast, collisional to post-collisional magmatism of late Eocene-Oligocene age is widespread in the Alps.

Figure 1. Tectonic map of the Alps



Tectonic map of the Alps (modified after Schmid *et al.*, 2004) with location of the main plutonic bodies (in red) and areas (stars) where small size intrusive bodies occur. T: Traversella; VdC: Valle del Cervo; M: Miagliano; N: Novate; B: Bregaglia (Bergell); TS: Triangia-Sondrio; A: Adamello; R: Rensen; MA: Monte Alto; VdR: Vedrette di Ries; CdV: Cima di Vila; DAV: Defereggér-Anterselva-Valles tectonic line.

The products of the Eocene-Oligocene magmatism are mainly exposed in the vicinity of the Periadriatic Fault System (PFS; Fig. 1), an orogen-parallel, crustal-scale transpressive mylonitic belt that extends from the Valle d'Aosta region in the West to the Pannonian Basin in the East (e.g., Schmid *et al.* 1989; Rosenberg, 2004). Bodies of variable size emplaced along the PFS from the Western to Eastern Alps mainly consist of plutonic and innumerable basic to acidic dikes. Minor volcanics and volcanoclastic sequences are restricted to the westernmost branch of the PFS (Canavese Line). Variable amounts of volcanic material also occur in clastic formations of the External Alps (Laubscher, 1983; Dal Piaz & Venturelli, 1983; Waibel, 1993).

Plutonic bodies are mainly composed of diorite-tonalite-granodiorite rock associations with calcalkaline (CA) to high-K calcalkaline (HKCA) compositions (according to the chemical nomenclature proposed by Peccerillo &

Taylor, 1976). Dikes are largely andesites belonging to the calcalkaline and shoshonitic (SHO) series. However, some important petrographic and geochemical variations occur along the Alpine arc. In particular, the Western Alps are the site of ultrapotassic igneous activity that is absent in the Central and Eastern Alps.

Different models have been proposed for the genesis of the Alpine magmatism, including subduction zone melting, lithospheric extension-related melting, thermal boundary layer detachment and melting of the Alpine crustal root, and slab breakoff (von Blanckenburg *et al.* 1998 for a review; Beltrando *et al.* 2010).

Western Alps

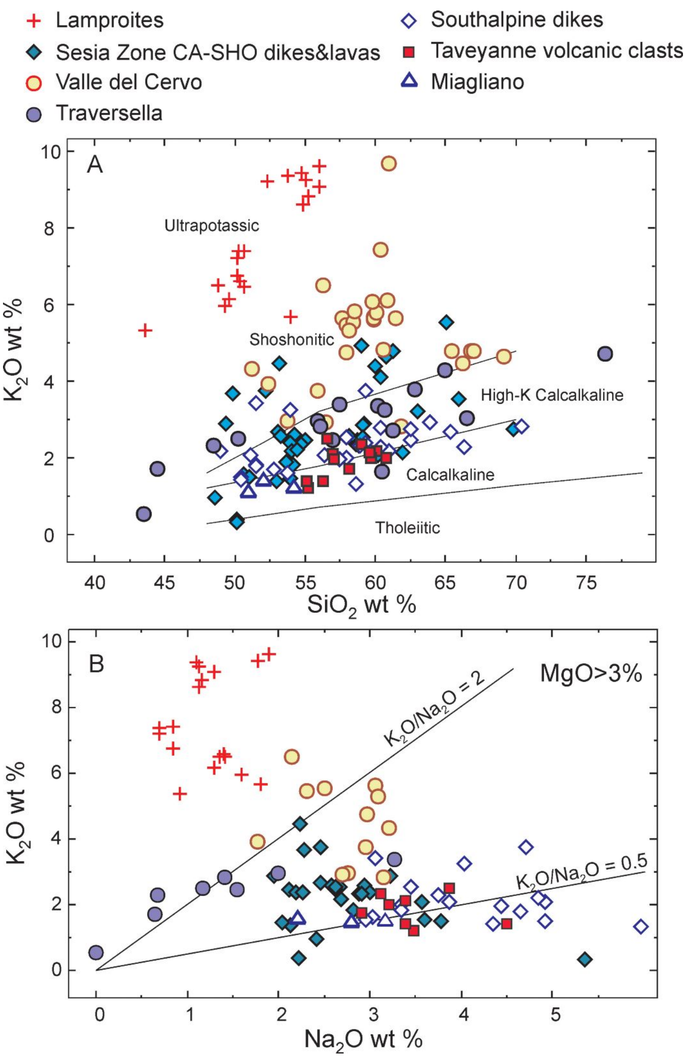
Tertiary magmatism in the Western Alps is mostly confined to the Sesia-Lanzo Zone of the Austroalpine domain, with only few dikes and stocks intruded into the Penninic and Southalpine units of the Internal Alps. Volcanic material occurs also in flysch deposits in the External Alps (Fig. 1).

Traversella pluton

The ~ 30 Ma old (biotite K/Ar age; Krummenacher & Evernden, 1960) Traversella pluton intrudes the “Micascisti Eclogitici” unit of the Sesia-Lanzo Zone. It is composed mostly of diorite to quartz-diorite with minor monzonite, formed by various proportions of biotite, augite, amphibole, plagioclase, quartz and K-feldspar. Mafic cumulates of biotite, augite, ilmenite and magnetite also occur, along with abundant inclusions of both igneous and metasedimentary origin. Various granitic and aplitic veins cross cut the main dioritic body (van Marcke de Lummen & Vander Auwera, 1990).

The Travesella plutonic rocks display a HKCA petrologic affinity with some mafic cumulates exhibiting a shoshonitic composition (Fig. 2a). TiO_2, FeO_{tot}, MgO, CaO decrease regularly with increasing SiO_2 whereas Al_2O_3, Na_2O and P_2O_5, and some trace elements (e.g., Sr, Ba, LREE) show bell-shaped trends, with an increase in the mafic range and a decrease in silicic compositions. K_2O and other incompatible trace elements (e.g., Rb, Th, U, Zr) are positively correlated with SiO_2, but aplites generally show the lowest concentrations for most of the trace elements.

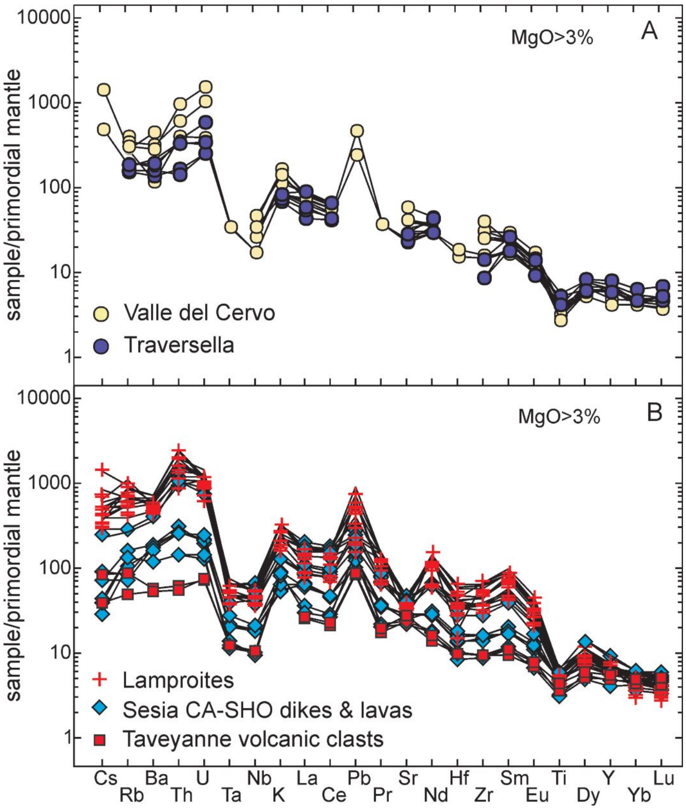
Figure 2. Alkali-silica classification diagrams, Western Alps



(A) - K_2O vs. SiO_2 classification diagram for the Western Alps Tertiary igneous rocks; (B) - K_2O vs. Na_2O diagram for mafic rocks (MgO > 3 wt%) from Western Alps.

Mafic rocks (MgO > 3%) exhibit always K_2O/Na_2O higher than unity, and have Na_2O contents generally lower than 2% (Fig. 2b). They display fractionated incompatible element patterns (Fig. 3) with high enrichments in Rb, Ba, Th, U, LREE, and positive spikes of Th and U anomalies and depletion in Ti and Zr. REE patterns for the mafic samples show variable fractionation (La_NYb_N ~ 6.3-13.8; chondrite normalizing values from Sun & McDonough, 1989) with small Eu anomalies.

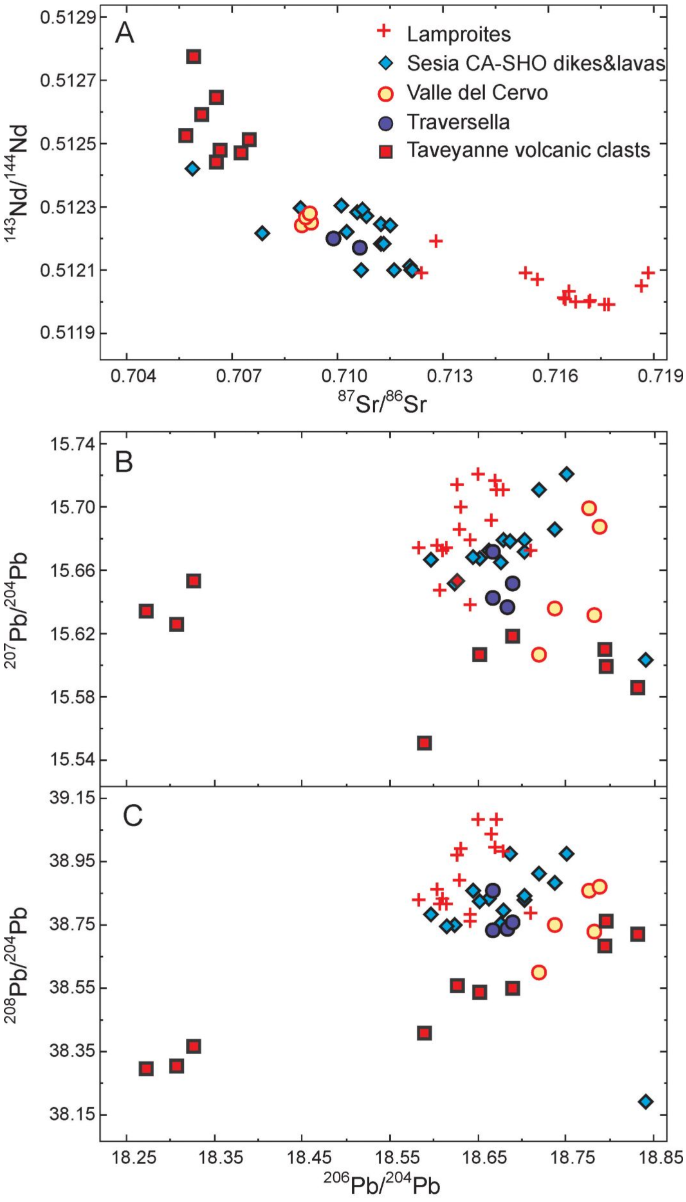
Figure 3. Spider-diagrams of mafic rocks, Western Alps



Incompatible element patterns normalized to primordial mantle composition for mafic igneous rocks (MgO > 3%) from the Western Alps.

Dioritic to monzonitic rocks have poorly variable initial $^{87}Sr/^{86}Sr$ (~ 0.7099-0.7107) and $^{143}Nd/^{144}Nd$ (~ 0.5122) (Fig. 4a). Their lead isotope ratios are rather homogeneous ($^{206}Pb/^{204}Pb$ ~ 18.67-18.69, $^{207}Pb/^{204}Pb$ ~ 15.64-15.67 and $^{208}Pb/^{204}Pb$ ~ 38.73-38.86) and coincide with upper crustal values (Fig. 4b,c). Oxygen isotope data have been determined for whole-rocks and some separated minerals. There is an increase of whole-rock $\delta^{18}O$ with SiO_2 from +5.9‰ of cumulates to +10.5‰ of granitic veins (Fig. 5; van Marcke de Lummen & Vander Auwera, 1990).

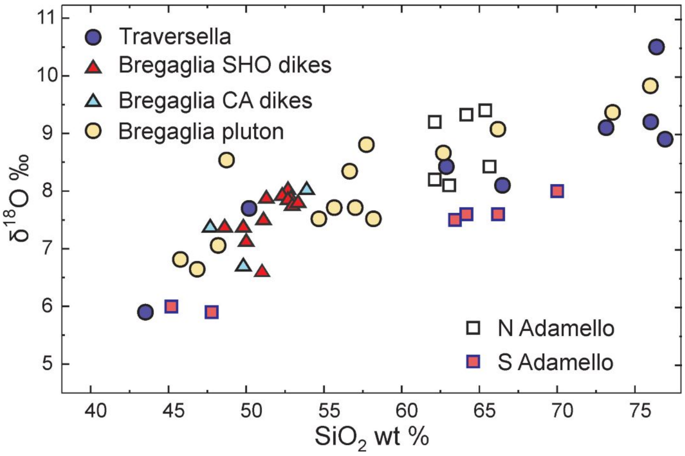
Figure 4. Radiogenic isotope compositions, Western Alps



Initial Sr-Nd-Pb isotopic compositions of Western Alps Tertiary igneous rocks.

On the basis of major, trace element and O and Sr isotope modelling, van Marcke de Lummen & Vander Auwera (1990) proposed that the most evolved rocks of the Traversella pluton derived form the less evolved ones by fractional crystallization and assimilation (AFC) processes. The geochemical characteristics of some granitic veins are compatible with an origin by AFC, whereas others are more likely derived by local partial melting of the country rocks. Low oxygen isotopic ratios of mafic cumulate, imply a crystallisation from uncontaminated mantle-derived melts, which were likely parents of the Traversella pluton

Figure 5. Oxygen isotope variation



Whole-rock $\delta^{18}O$ vs. SiO_2 diagram for the Traversella, Bregaglia (Bergell) and the Adamello intrusions.

Valle del Cervo pluton

The Valle del Cervo (Biella) pluton occurs north of Traversella intrusion. It emplaced into the "Micascisti Eclogitici" unit as a broadly concentric structure, with a granitoid complex at the core, surrounded by syenitic and monzonitic rocks. The granitoid complex consists of porphyritic monzogranite to quartz-poor granodiorites. The syenite complex consists of a clinopyroxene-bearing, biotite-hornblende syenite, locally including rounded enclaves of quartz-monzonites. The monzonite complex mainly consists of two-pyroxene-biotite-hornblende quartz-monzonite to mela-syenite, with porphyritic monzodiorite varieties at the contact with the country rocks. Mafic enclaves as well as aplitic and pegmatitic dikes occur in all the three complexes (Fiorentini Potenza, 1959; Bigioggero *et al.*, 1994; Rossetti *et al.*, 2007). Within the metamorphosed Sesia-Lanzo country rocks, several small satellite igneous bodies have been recognized. These include hornblende-biotite monzogabbro, gabbronorite to quartz-diorite, cordierite-bearing quartz-monzodiorite, syenite and plagioclase-quartz-tremolite-tourmaline orbicular rocks. Different types of hydrothermal mineralizations occur both within the Biella stock and at its roof zone (Rossetti *et al.*, 2007).

U-Pb zircon dating of the granodiorite indicates an age for the inner granitoid complex of ~ 31 Ma (Romer *et al.*, 1996). Bigioggero *et al.* (1994) published Rb/Sr biotite ages of 30-31 Ma for the monzonitic complex and 29-30 Ma for the granitoid complex.

The rocks of the Valle del Cervo pluton define a shoshonitic association, but some syenitic-monzonitic samples and mafic enclaves display an ultrapotassic affinity (Fig 2a). K_2O/Na_2O ratios for the mafic lithotypes (MgO > 3%) are generally comprised between 1 and 2 with some monzonites displaying $K_2O/Na_2O > 2$ (Fig. 2b).

Major element versus SiO_2 diagrams display negative correlations for all oxides, except for the alkalies. Incompatible trace element versus SiO_2 diagrams show wide scattering. Monzonitic and syenitic samples of the main plutonic mass generally exhibit the highest enrichments in incompatible trace elements (e.g., Rb, Ba, Th, U, Nb, Sr, Zr, LREE). The lowest abundances of incompatible trace elements are generally found in the diorite and monzogabbro satellite bodies.

Diorites to monzonites with MgO > 3% display fractionated incompatible element patterns with enrichments for some of the most incompatible elements (e.g., Cs, Th, U up to more than 1000 times Primordial Mantle values; Sun & McDonough, 1989), positive Th, U and Pb anomalies and pronounced negative spikes of Nb, Ta and Ti (Fig. 3). Ba and Rb are slightly depleted compared to elements with similar incompatibility (e.g., Cs, Th, U). Syenites and granites display incompatible element enrichments and patterns (not shown) that are comparable as the more mafic samples, but also have a distinct Ba negative anomaly. Overall, the Valle del Cervo pluton is significantly more enriched in most of the incompatible trace elements with respect to the Traversella pluton, in accordance also with the more potassic affinity of the former.

The initial $^{87}Sr/^{86}Sr$ isotopic ratios displayed by the Valle del Cervo pluton are similar in the granitoid and syenite complexes (~ 0.7089-0.7097), but are systematically higher in the monzonite complex (~ 0.7093-0.7113). Initial Nd isotope ratios are less variable and range between 0.51225 and 0.51228 with the lowest values observed in monzonitic samples (Fig. 4a). Pb isotopic ratios are rather homogenous ($^{206}Pb/^{204}Pb$ ratios = 18.72-18.79; $^{207}Pb/^{204}Pb$ = 15.61-15.70; $^{208}Pb/^{204}Pb$ = 38.6-38.87); samples from the granitoid complex show the least radiogenic compositions (Fig. 4b,c).

Mainly on the basis of Sr isotope data, Bigioggero *et al.* (1994) concluded that two different types of magmas with distinct petrochemical affinity were present at Valle del Cervo pluton, one forming the monzonite complex and the other forming the syenite and granitoid complexes. The two magma suites evolved from isotopically different parental melts by combined fractional crystallisation and assimilation processes. The parental magmas of both suites were generated in a heterogeneous upper mantle source, which had been variably metasomatised by subducted upper crustal material.

Miagliano stock

The Miagliano stock is intruded into the gabbroic rocks of the Southalpine Ivrea-Verbano Zone near the Valle del Cervo pluton, south-east of the Canavese Line. It is composed of a monzonitic core with some monzodiorite, surrounded by an outer zone of diorite (Carraro & Ferrara, 1968; Dal Piaz *et al.*, 1979). Carraro & Ferrara (1968) reported Rb/Sr and K/Ar biotite ages ranging between 29-33 Ma.

The few available data show that the Miagliano diorite-monzonite intrusion is calcalkaline in composition (Fig. 2a), with K_2O/Na_2O ratios around 0.5 (Fig. 2b). P_2O_5 and incompatible trace element (Rb, Sr, Zr, Nb) concentrations are lower than in similar rocks from the Taversella and Valle del Cervo plutons. Initial $^{87}Sr/^{86}Sr$ ratios (~ 0.7068-0.7075) are significantly lower than those measured for the Traversella and Valle del Cervo rocks (Fig. 4a).

Western Alps dikes and volcanic rocks

Dikes

Within the Sesia-Lanzo Zone, a large number of dikes occur around the Traversella and Valle del Cervo plutons and, more scarcely, northwards as far as the Ossola valley (Dal Piaz *et al.*, 1979; Beccaluva *et al.*, 1983). Dikes mainly include calc-alkaline to shoshonitic rocks ranging in composition from basalts and basaltic andesites to andesites and latites, with some ultrapotassic mafic dikes classified as lamproites. A few lamproitic dikes also cross cut the Combin unit of the Piemonte Ophiolite Nappe (Dal Piaz *et al.*, 1979; Diamond & Wiedenbeck, 1986), whereas granodiorite porphyritic dikes are reported in the north-eastern margin of the Sesia-Lanzo Zone, near the western margin of the Lepontine Gneiss Dome (Romer *et al.*, 1996). Basalts, basaltic andesites and andesites are variably porphyritic and contains various proportions of hornblende, clinopyroxene and plagioclase phenocrysts and minor biotite; in contrast, shoshonitic basalts have a phenocryst mineralogy dominated by biotite and clinopyroxene with minor hornblende phenocrysts set in a groundmass of K-feldspar and plagioclase. The latites have phenocryst assemblages of biotite, hornblende, plagioclase and K-feldspar. The lamproitic dikes contain abundant phlogopite, clinopyroxene and K-feldspar set in a groundmass mainly composed of K-feldspar and minor clinopyroxene. Some lamproites contain abundant riebeckite–arfvedsonite amphibole (Dal Piaz *et al.*, 1979; Venturelli *et al.*, 1984). Ages obtained for lamproitic dikes range between 30.3 and 32.7 Ma (K/Ar: Dal Piaz *et al.*, 1973; Diamond & Wiedenbeck, 1986; Rb/Sr: Pettke & Diamond, 1997); granodiorite porphyritic dikes from the north-eastern margin of the Sesia-Lanzo Zone gave U/Pb titanite ages of 31.7 and 32.4 Ma (Romer *et al.*, 1996). Recently, Babist *et al.* (2006) reported a poorly constrained plagioclase-amphibole Rb/Sr isochron age of ~ 44 Ma for an andesitic dike near the Traversella pluton, which would implicate an Eocene onset for the magmatic activity in the internal Western Alps.

A series of porphyritic dikes of uncertain age are found intruding the Southalpine Variscan basement and occasionally also cutting through Lower Jurassic sediments of the Southalpine cover series (Bigioggero *et al.* 1981). Some of these dikes have phenocryst assemblages of plagioclase and amphibole plus minor biotite and clinopyroxene. Others are characterised by phenocryst assemblages of plagioclase, biotite, minor hornblende and rare quartz set in a groundmass mainly composed of plagioclase and quartz

Volcanic rocks

Between the Sesia-Lanzo Zone and the Ivrea-Verbano Zone, along the Canavese Line (belonging to the PFS), a volcano-sedimentary unit is found laying unconformably on the “Micascisti Eclogitici” and representing part of the non-metamorphic Tertiary cover of the Sesia-Lanzo Zone. It is composed of lava flows, pyroclastic and epiclastic deposits, essentially agglomerates, tuffs, and breccias. Lava flows are represented by andesites and subordinated basaltic andesites with a high-K calc-alkaline affinity and trachyandesites and trachydacites with shoshonitic affinity (Callegari *et al.*, 2004). All rocks are porphyritic and show variable phenocryst mineralogy given by single pyroxene (orthopyroxene), two-pyroxene, two-pyroxene plus hornblende and two-pyroxene plus hornblende and biotite. Olivine occurs in basaltic andesites. Trachyandesites and trachydacites exhibit sanidine and phlogopite or biotite as phenocrystic phases together with plagioclase, augite, Fe-Ti oxides, apatite, and rare orthopyroxene, the latter being restricted to trachyandesites. Groundmass minerals consist of sanidine, quartz, clinopyroxene and opaque grains in a minute-microgranular matrix (Callegari *et al.*, 2004).

Hunziker (1974), Scheuring *et al.* (1974) and Zingg *et al.* (1976) found total rock K/Ar ages ranging between 33.3 and 29.5 Ma. These dates were recently confirmed by a precise U-Pb zircon age determination yielding a value of 32.6 Ma (Kapferer at al., 2009).

Geochemistry of dike and volcanic rocks

The dike and volcanic rocks in the Western Alps range from calcalkaline to shoshonitic and ultrapotassic (Fig. 2a). Mafic ultrapotassic dikes have a lamproitic affinity (Venturelli *et al.*, 1984; Peccerillo & Martinotti, 2006) and are variably enriched in silica (SiO_2 ~ 44-56%). As all lamproites, they are characterized by relatively low CaO (~ 3.1-8.4%), Al_2O_3 (~ 8.6-12.0%) and Na_2O (~ 0.7-1.9%), and high K_2O/Na_2O (~ 3.1-10.5) and K_2O/ Al_2O_3 (~ 0.4-1.1). They also show high MgO (~ 7.0-13.1%), Ni (~ 93-460 ppm) and Cr (~ 309-933 ppm) denoting a mantle origin. FeO_{tot}, MgO, CaO together with most of the compatible elements (e.g., Sc, V, Cr, Co) decrease markedly with increasing silica content, whereas TiO_2 and, to a lesser extent, Na_2O increase. Moreover, K_2O and several incompatible trace elements (e.g., Rb, Th, U, Nb, Pb, Zr) exhibit steep positive correlations with SiO_2. Incompatible trace element patterns normalized to primordial mantle compositions (Fig. 3) are strongly fractionated with very high enrichments in Cs, Rb, Th, U and Pb, distinct Ta, Nb, and Ti negative anomalies and slight depletion in Zr and Hf. Sr is depleted relative to the LREE. REE patterns show high enrichments in LREE (La ~ 200-600 times chondrite) relative to HREE (La_NYb_N ~ 18.9-48.2), small Eu negative anomalies and typically upward-convex LREE patterns.

The basaltic to latitic dikes and lavas associated with lamproites in the Sesia-Lanzo Zone, are less enriched in potassium and have a high-K calcalkaline to shoshonitic affinity, with only a few calcalkaline dikes (Fig. 2a). The dikes from the Southalpine domain mostly have HKCA affinity, with minor CA and SHO occurrences (Fig. 2a). Dikes and lavas from both areas generally exhibit comparable concentrations and trends for most major elements, with dikes from the Southalpine domain showing slightly higher Na_2O and lower FeO_{tot} compared to dikes and lavas from the Sesia-Lanzo zone.

Compared to lamproites, CA and SHO rocks have markedly higher Al_2O_3 and Na_2O and lower TiO_2, MgO and P_2O_5. Moreover, incompatible trace elements but also Ni, Cr are much more enriched in lamproites. Primordial mantle-normalized spider-diagrams for the most mafic rocks (MgO > 3%) display similar shape, but incompatible trace element abundances increase from CA to SHO and to lamproitic rocks.

In summary, available data show that there is an increase in incompatible element contents from calcalkaline to ultrapotassic rocks. However, the mantle-normalised pattern of all these rocks is remarkably similar.

Lamproitic dikes have extremely high and variable initial Sr isotope ratios (~ 0.7121-0.7216) and low initial Nd isotope ratios (~ 0.51199-0.51219; Fig. 4a). The calcalkaline to shoshonitic dikes display much lower $^{87}Sr/^{86}Sr$ (~ 0.7059-0.7122), and higher $^{143}Nd/^{144}Nd$ than lamproites (Fig. 4a). Granodioritic dikes from the northeastern part of the Sesia-Lanzo zone display initial $^{87}Sr/^{86}Sr$ around 0.7145.

Overall, Sr-Nd isotopic signatures are far away from typical mantle composition, suggesting an important though variable role of upper crustal components in the origin of these magmas. Lamproites exhibit a positive correlation between $^{87}Sr/^{86}Sr$ and SiO_2. However, it is unlikely that such a feature depends on shallow level evolution processes such as bulk assimilation of crustal rock or AFC. These processes should generate a sharp decrease of compatible elements, a feature that is not observed in the Western Alps lamproites. Therefore, it is likely that both the high values of $^{87}Sr/^{86}Sr$ and their increase with silica reflect pristine compositional characteristics of the primary melts.

Pb isotope ratios of lamproites and CA-SHO dikes and lavas show similar initial values (Fig. 4b,c). They are moderately radiogenic and close to upper crustal values ($^{206}Pb/^{204}Pb$ = 18.58-18.75; $^{207}Pb/^{204}Pb$ = 15.64-15.72; $^{208}Pb/^{204}Pb$ = 38.74-39.08). One basaltic calcalkaline dikes has been reported with distinct Pb isotope compositions ($^{206}Pb/^{204}Pb$=18.84, $^{207}Pb/^{204}Pb$=15.60, $^{208}Pb/$

^{204}Pb=38.19; Fig. 4b,c). This sample also displays the lowest ^{87}Sr/^{86}Sr (0.7059) and highest ^{143}Nd/^{144}Nd (~ 0.51242) as well very high MgO, Cr and Ni contents.

Volcanic clasts in flysch deposits

In the External Western and Central Alps, the Oligocene flysch deposits of the Helvetic-Dauphinois Zone, are characterized by volcanic clast-rich layers containing lava fragments mainly of basaltic andesitic and andesitic composition with minor dacites and rhyolites, as well as isolated igneous mineral fragments such as amphibole, clinopyroxene, plagioclase and biotite. Plagioclase, clinopyroxene and minor magnetite are the most common mineral assemblages found in the basaltic andesites. Andesites show phenocryst mineral assemblages dominated by plagioclase plus clino- and orthopyroxene some hornblende and magnetite. Dacites have phenocrysts of plagioclase, amphibole and biotite with subordinated clinopyroxene. Rhyolites are scarce and mainly represented by quartz-biotite-sanidine volcanic fragments with pumiceous textures (Ruffini *et al.*, 1997).

Ar/Ar analyses on amphiboles from the Champsaur Sandstone yielded two plateau ages of 32.5 Ma and 34.3 Ma (Boyet *et al.* 2001), while Ar/Ar dates from amphibole separates of the Taveyanne Sandstone cluster between 30.5 and 32.5 Ma (Fischer & Villa, 1990; Ruffini *et al.*, 1997; Boyet *et al.*, 2001).

The clasts have calcalkaline and high-K calcalkaline affinity (Fig. 2a). Variation trends of major elements versus SiO_2 mostly overlap with those of calcalkaline-shoshonitic rocks outcropping in the Internal Western Alps. The mafic samples (MgO > 3%) have low K_2O/ Na_2O ~ 0.3-0.6 (Fig. 2b). Incompatible element abundances plot generally close the lower limits of the calcalkaline and high-K calcalkaline rocks from the Southern Alps and Sesia-Lanzo Zone. Primordial mantle normalized diagrams (Fig. 3a) reveal fractionated incompatible trace element patterns, similar to the ones displayed by the calcalkaline rocks from the Internal Western Alps, with negative anomalies in Nb, Ta and Ti and positive spikes of Pb and Sr. Initial ^{87}Sr/^{86}Sr ratios (~ 0.7057-0.7075) are lower, whereas initial ^{143}Nd/^{144}Nd (~ 0.51277-0.51244) ratios are higher than other Western Alps Tertiary igneous rocks (Fig. 4a). Pb isotope composition are highly variable and include the lowest values reported for the whole Tertiary Alpine magmatism (^{206}Pb/^{204}Pb ~ 18.33-18.80, ^{207}Pb/^{204}Pb ~ 15.55-15.65 and ^{208}Pb/^{204}Pb ~ 38.29-38.79; Fig. 4b,c). δ^{18}O values measured on clinopyroxene separates range between +5.9-6.1‰ (Boyet *et al.*, 2001), close to typical mantle values.

Petrogenesis of Western Alps orogenic magmatism

Tertiary orogenic igneous rocks in the Western Alps have variable degrees of enrichment in potassium, ranging from calcalkaline to ultrapotassic lamproitic. Most of the occurrences consist of intrusive bodies of variable size, from dikes to small plutons. A few effusive products are found in the Sesia-Lanzo zone. Calcalkaline basaltic andesites, andesites to dacite and rhyolite are found as clasts in the external Alps flysch deposits, testifying to the occurrence of volcanic structures that have been dismantled by erosion.

Contents of incompatible elements increase from calcalkaline to lamproitic rocks. The same trend is also shown by Sr isotopic ratios, whereas ^{143}Nd/^{144}Nd has an opposite tendency. Lead isotopes are poorly variable. All radiogenic isotope ratios are intermediate between crust and mantle, and sometimes well within the range of typical upper crustal rocks. Yet, all the rocks are of ultimate mantle origin, inasmuch as the most mafic members have high to very high MgO, Mg# and ferromagnesian element contents. Finally, incompatible element patterns of Western Alps orogenic rocks are very similar in shape to each other, although absolute abundances of elements change strongly. These patterns are characterised by negative anomalies of HFSE, but also by a relative deficiency in Sr and, in some cases, Ba. Overall, they resemble patterns of some upper crustal rocks, such as metapelites and granites (Peccerillo & Martinotti, 2006). Therefore, the bulk of trace element and radiogenic isotope data clearly point to the contribution of both mantle and upper crustal components in the origin of these magmas (Venturelli *et al.*, 1984; Peccerillo & Martinotti, 2006; Owen, 2008; Prelević *et al.*, 2008; Conticelli *et al.*, 2009a). In principle, mantle-crust interaction may have occurred by assimilation of crustal rocks during of magma emplacement. However, this would imply some sort of increase of crustal-like signatures with decreasing MgO and other compatible elements, a feature that is not observed in the rocks. Therefore, there is a general agreement that, although magma contamination was occurring in several cases, the bulk of mantle-crust interaction occurred by addition of upper crustal material to the mantle wedge during the Cretaceous to Oligocene subduction of the

European plate beneath the northern African margin. The presence in the Western Alps of deeply subducted upper crustal rock (Dora Maira massif; Compagnoni 2003) represents a compelling evidence supporting this hypothesis.

The ultrapotassic dikes display the highest incompatible element abundances along with the highest Sr- and lowest Nd-isotope ratios. Therefore, these rocks reveal the strongest participation of upper crustal material to magma genesis. Shoshonitic and calcalkaline rocks have less extreme compositions than lamproites, testifying to a lesser contribution of crustal end-member to magma origin. This can be explained by assuming that different amounts of upper crustal material contaminated various sectors of the mantle wedge during subduction. Melting of such a heterogeneous source gave different types of magmas displaying similar patterns but variable incompatible trace element abundances and radiogenic isotope signatures (Peccerillo & Martinotti, 2006).

Data reported previously have shown that there are, however, also important differences in the abundances of some major elements among the Western Alps rocks. In general, lamproites have lower Al_2O_3, CaO and Na_2O than coexisting shoshonitic and calcalkaline rocks. Low abundances of these elements suggest that the source rocks were depleted in these components. This, in turn, suggests that the mantle source of lamproitic magma was represented by a harzburgite, i.e. a peridotite depleted in clinopyroxene. Such a composition might be determined by an older melting event and extraction of basaltic magma. In contrast, higher Al_2O_3, CaO and Na_2O of calcalkaline and shoshonitic rocks are consistent with partial melting of less depleted (higher Al_2O_3 and Na_2O) mantle peridotite (lherzolite), which had not been affected by previous melting events (Venturelli *et al.*, 1984). Therefore, a scenario for the origin of calcalkaline to lamproitic magmatism in the Western Alps would be the one in which a harzburgitic to lherzolitic mantle wedge was heterogeneously contaminated by upper crustal material from the subducting European plate. Melting of various proportions of these sources gave different types of orogenic magmas.

Another hypothesis, not necessarily alternative, could be that variable compositions are the effect of different degrees of partial melting of the metasomatic mantle wedge. According to this hypothesis, upper crustal material introduced into the upper mantle generated veins that infiltrated depleted mantle rocks. Low degrees of partial melting would preferentially affect the vein, giving ultrapotassic magmas with strong crustal signatures. Increasing partial melting would involve normal mantle rocks producing depleted liquids that dilute early formed melts to give calcalkaline and shoshonitic magmas (Conticelli *et al.*, 2009b).

The crustal material which was responsible for mantle modification was likely metapelitic s.l. in composition, as discussed earlier. This might be represented by 1) oceanic sediments brought down by subduction of European continental crust during the Alpine orogeny (Venturelli *et al.*, 1984); 2) crustal material eroded from the acretionary prism of the overriding Adria continental margin by the low-angle subducting European slab (Peccerillo & Martinotti, 2006); 3) fluids or melts derived from pelagic sediments subducted during the closure of the Alpine Tethys Ocean in the late Cretaceous to early Tertiary (Owen, 2008); and 4) more in general, subduction of siliciclastic sediments combined to variable proportions of sedimentary carbonate component (Prelevic *et al.*, 2008; Conticelli *et al.*, 2009a).

Melting was both coeval and younger than subduction processes. In particular, the bulk of dike magmatism took place during thinning of the underlying lithosphere and the resulting upwelling of asthenosphere, which may be related to slab breakoff or to episodic retreat of the subduction zone hinge, due to slab rollback (von Blanckenburg & Davies, 1995; Beltrando *et al.* 2010).

Central Alps

Magmatism in the Central Alps is mainly represented by the Bregaglia (Bergell) pluton, intruding Penninic and Austroalpine units at the eastern margin of the Lepontine Dome (Fig. 1). It is a composite structure consisting mainly of a biotite-hornblende-tonalite margin and a biotite-granodiorite core. Other rocks include some gabbros and ultramafic cumulates (hornblendites and pyroxenites), mafic dikes, aplites and some pegmatites. A separate peraluminous intrusion, the Novate granite, crosscuts fabrics of the Bregaglia tonalite (Gulson, 1973; Trommsdorff & Nievergelt, 1983; von Blanckenburg *et al.*, 1992). According to zircon, allanite and titanite U-Th-Pb dating, ages of the Bregaglia main plutonic body range between ~ 33 Ma and 30 Ma, and decrease from gabbros and tonalites to the inner granodiorite (von Blanckenburg *et al.*, 1992; Oberli *et al.*, 2004; Gregory *et al.*, 2009).

The Novate stock is a garnet-bearing two-mica granite apparently not genetically related to the main Bregaglia pluton. Monazite and zircon U-Pb dating gave ages of ~ 26-24 Ma (Köppel & Grünenfelder, 1975; Liati *et al.*, 2000).

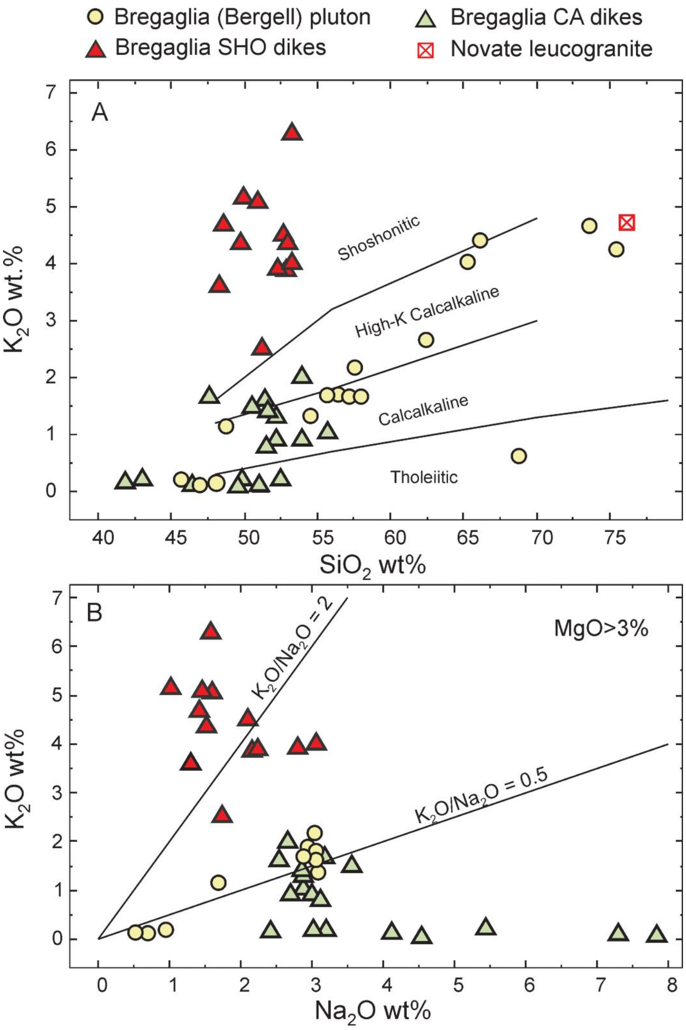
Swarms of mafic dikes crosscut both the Bregaglia intrusives and the regional metamorphic and folded country rocks (Suretta nappe, Margna nappe and Malenco ophiolitic serpentinite) to the north and southeast of the pluton (Nievergelt & Dietrich, 1977; Gautschi & Montrasio, 1978; Wenk, 1980; Diethelm, 1990). The dikes cutting the Bregaglia country rocks are mainly basalts and basaltic andesites. No radiometric ages have been published, but some dikes show thermal metamorphism when occurring within the Bregaglia contact aureole, and probably represent the first phase of magmatism in the region (Nievergelt & Dietrich, 1977; Gautschi & Montrasio, 1978; Wenk, 1980). Mafic dikes within the Bregaglia pluton were emplaced when the main plutonic body was only partially solidified (Diethelm, 1990). Some of these dikes are lamprophyres with hornblende, K-feldspar, plagioclase, clinopyroxene and biotite.

Granitic boulders from the Bregaglia massif have been recovered in the Oligocene-Miocene molasse of the Po Plane (Gonfolite Lombarda Group; Gulson, 1973; Oschidari & Ziegler, 1992), indicating that the exhumation and erosion of the intrusive massif must have been rapid.

Geochemistry and petrology

The Bregaglia plutonic rocks are calcalkaline and high-K calcalkaline. Mafic dykes range from tholeiitic to potassic alkaline (lamprophyres) (Fig. 6a). The gabbro-tonalite-granodiorite intrusives and the tholeiitic to high-K calcalkaline dikes display similar contents for several major elements, although alkalies show larger variations and scattering for dikes. K_2O/Na_2O ratios for the tholeiitic-HKCA mafic rocks (MgO > 3%) are frequently below 0.5 whereas shoshonitic lamprophyres have K_2O/Na_2O up to 5 (Fig. 6b). However, these high ratios in some lamprophyres could not indicate ultrapotassic affinities, but may be related to diffusion of alkalies into lamprophyric magmas from residual melts of partially crystallised intruded granitoids (e.g., Blundy & Sparks, 1992).

Figure 6. Alkali-silica classification diagrams, Central Alps

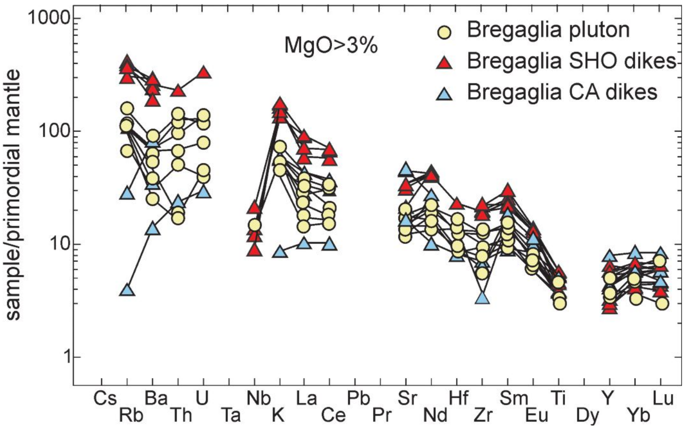


A - K_2O vs. SiO_2 classification diagram for the Bregaglia igneous complex and Novate granite; B and K_2O vs. Na_2O diagram for Bregaglia mafic rocks (MgO > 3%).

Incompatible element patterns normalized to primordial mantle composition of mafic plutonic rocks (Fig. 7) are fractionated with enrichments in Large Ion Lithophile Elements (LILE: Rb, Ba, LREE, etc.) with respect to High Field-Strength Elements (HFSE: Zr, Nb, Hf, etc.).

The tholeiitic to HKCA dikes display similar to somewhat less enriched incompatible element patterns as the mafic plutonic rocks (Fig. 7). Potassic dikes are moderately to strongly enriched in incompatible element in respect to other dikes and plutonic rocks. However, also MgO, FeO and ferromagnesian trace elements (Ni ~ 48-164 ppm; Cr ~ 193-612 ppm) are higher. Incompatible element patterns (Fig. 7) are fractionated, with Nb and Ti negative anomalies and slight depletion in Ba, Th and Sr.

Figure 7. Spider-diagrams, Central Alps



Incompatible element patterns normalized to primordial mantle composition for mafic rocks (MgO > 3%) from the Bregaglia igneous complex.

The Bregaglia pluton and associated dikes display a wide range of initial $^{87}Sr/^{86}Sr$ values, which increase with SiO_2 from ~ 0.7055 to ~ 0.7160. A smooth curved (mixing) trend between mantle and crust is defined in the Sr-Nd isotope space (Fig. 14a). All these feature clearly point to important contributions of mantle and crust to the origin of these magmas. Initial Sr, Nd and Hf istopic compositions reported for one shoshonitic dike ($^{87}Sr/^{86}Sr$ ~ 0.7073, $^{143}Nd/^{144}Nd$ ~ 0.51241 and $^{176}Hf/^{177}Hf$ ~ 0.28275; Stille *et al.*, 1989; von Blanckenburg *et al.*, 1992) also point to the same conclusion.

Pb isotope compositions for the Bregaglia tonalite-granodiorite suite define very small variations ($^{206}Pb/^{204}Pb$ ~ 18.72-18.80, $^{207}Pb/^{204}Pb$ ~ 15.68-15.72 and $^{208}Pb/^{204}Pb$ ~ 38.75-38.98; Fig. 14b,c), and fall close or within the field of upper crustal rocks. Slightly higher values have been measured in pegmatites.

Whole-rock oxygen isotope compositions for the plutonic and hypabyssal rocks area variable (Diethelm, 1990; von Blanckenburg *et al.*, 1992; Fig. 5). The cumulates and mafic dikes show $\delta^{18}O$ ranging between +6.6‰ and +8.0‰, with the lowest values displayed by the cumulates and tholeiitic dikes. Oxygen isotope compositions increase progressively from ~ +7.5‰ to +9.9‰ passing from tonalites to aplites.

The Novate leucogranite shows lower Nd-isotope ratios ($^{143}Nd/^{144}Nd$ ~ 0.51211-0.51215) than Bregaglia pluton (Fig. 14a), whereas initial $^{87}Sr/^{86}Sr$ (~ 0.7092-0.7106) and Pb isotopic signatures fall in the same range (Fig. 14b,c).

On the basis of Sr, Nd and O isotope geochemical data, von Blanckenburg *et al.* (1992) concluded that the Bregaglia magmas were formed by: (1) partial melting of an enriched lithospheric mantle that had been contaminated by crustal material, from which mafic magmas represented by mafic dikes, were extracted; and (2) subsequent simultaneous fractional crystallisation and contamination of the uprising magma. This second stage involved significant melting of the heterogeneous Alpine lower to middle crust to produce the main intermediate intrusive bodies, which typically show an increase in Sr-O isotopic signatures with increasing differentiation. From trace element data on brown amphibole and its clinopyroxene inclusions, Tiepolo *et al.* (2002) calculated that parental liquid compositions were characterized by marked enrichment of LILE, B, U and Th over HFSE and REE. Therefore, they proposed an origin for the Bregaglia parental melts by small degrees of batch melting of spinel-bearing MORB-type source metasomatized during Alpine and/or pre-Alpine times. Melting was triggered by B-rich fluids released by subducting oceanic or continental lithosphere. However, there was also open-system evolution dufing emplacement. This would explain the relatively high initial $^{87}Sr/^{86}Sr$ and $\delta^{18}O$ displayed by the mafic rocks.

According to von Blanckenburg *et al.* (1992), the shoshonitic lamprophyres that intruded the partly solidified granodiorite, originated instead by low degree partial melting of a deep garnet-lherzolitic mantle source, strongly contaminated by subducted sediments.

The ~ 25 Ma Novate granite is not cogenetic with the Bregaglia body, but rather derived by partial melting of crustal rocks during late-Alpine decompression (Gulson, 1973; von Blanckenburg *et al.*, 1992; Liati *et al.*, 2000).

In conclusion, geochemical and isotopic data on rocks from Central Alps, suggest strong interaction between mantle and crust. However, in this sector, the role of mantle contamination by uppper crustal material seems much less strong than in the Western Alps, as testified also by overall lower Sr isotopic ratios of mafic rocks in the central sector. In contrast, shallow level magma contamination appears strong, as suggested by a general increase of Sr and oxygen isotopic data with increasing magma evolution. The role of the crust during intrusion of magma in the Central Alps is also highlighted by the occurrence of peraluminous crustal anatectic melts, which are rare or absent in the West.

Eastern Alps

At the western margin of the Eastern Alps, orogenic magmatism occurred in a wide area both south and north of the PFS. In the Southern Alps, the Adamello batholith is found together with a series of dikes and stocks occurring more to the west in the Orobic Alps. In the southwestern Tyrol, numerous dikes and a few larger stocks are found intruding the Austroalpine units.

Moving east, the Tertiary magmatism is again localized along the Austroalpine-Southalpine boundary in the proximity of the PFS and most of the igneous activity occurred in the Austroalpine domain. South of the Tauren Window, the eats-west elongated plutonic bodies of Rensen, Monte Alto (Altenberg), Cima di Vila (Zinsnock) and Vedrette di Ries (Rieserferner) are found north of the Deferegger-Anterselva-Valles (DAV) tectonic line and very thin and elongated intrusive bodies occur along the northern sector of the Giudicarie line and along the Pusteria (Pustertal)-Gailtal line of the PFS. Numerous dikes also occur in a broad area to the south of the Tauren Window and volcanic to subvolcanic clasts are found in molasse deposits of the external Eastern Alps. Finally, intrusive magmatism continues in the easternmost Alps along the Periadriatic Zone, in Austria and Slovenia, or even more eastward, up to the Transdanubian Range (Kovács *et al.*, 2007). Here, only Pohorje Mts. and Karavanke plutons will be shortly described (Pamic & Palinkas, 2000; Bellieni *et al.*, 2010).

Adamello batholith

The Adamello batholith is the largest of the Tertiary intrusions along the PFS. It is located at the intersection between two important faults belonging to the PFS, i.e. the late- to post-magmatic Tonale Line and the Miocene Giudicarie Line (Fig. 1). The batholith intrudes the South Alpine Variscan basement and its non-metamorphic Permo-Triassic cover rocks and can be roughly subdivided into four individual plutons: Re di Castello, Adamello, Avio, and Presanella (Callegari, 1983). The individual plutons are composite bodies and were emplaced sequentially from the oldest units in the south (Re di Castello) to the youngest in the north (Presanella), from ~ 43 to 29 Ma (K/Ar and Rb/Sr ages: Del Moro *et al.*, 1983a; amphibole Ar/Ar ages: Villa, 1983; zircon U/Pb ages: Hansmann *et al.*, 1983; Hansmann & Oberli, 1991; Mayer *et al.*, 2003; Schaltegger *et al.* 2009). The plutons are composed of prevailing hornblende-biotite-bearing tonalite, sometimes grading to granodiorite, with minor amounts of ultramafic cumulates (wherlites, hornblendites), gabbro, diorite, quartz-diorite, trondhjemite and granite. A few garnet-bearing tonalites have also been reported. The mafic rocks are mainly found at the borders of the batholith and primarily in the oldest and southernmost Re di Castello plutonic unit (Ulmer *et al.*, 1983; Blundy & Sparks 1992; Tiepolo & Tribuzio, 2005). Microgranular mafic enclaves (MME) are ubiquitous (Blundy & Sparks, 1992) as well as swarms of different generations of dikes, which crosscut all the plutonic rocks. The mafic dikes are mainly represented by porphyritic to aphyric spessartites (phenocrysts of olivine, clinopyroxene and hornblende with a plagioclase-hornblende groundmass) grading to gabbroic porphyrites (Ulmer *et al.*, 1983). Crustal xenoliths are mainly observed in the felsic rock types and are more abundant in the northern intrusions.

Geochemistry and petrology

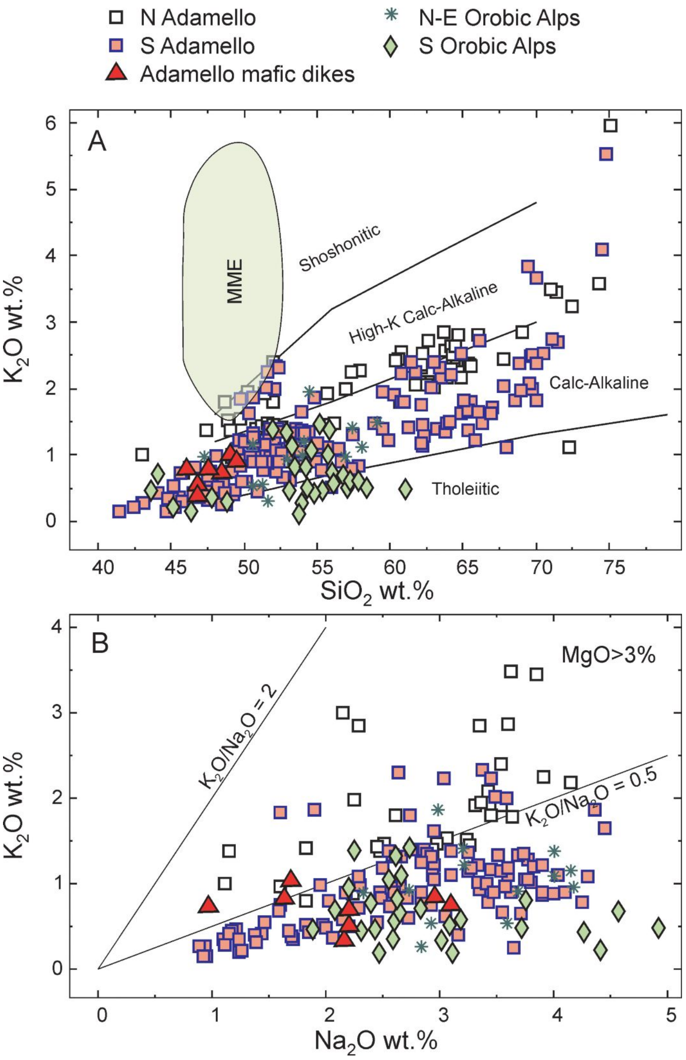
Magmas of the Adamello batholith range from calcalkaline to high-K calcalkaline, passing from mafic to evolved compositions (Fig. 8a). Microgranular Mafic Enclaves (MME) have more potassic compositions

Major element abundances are variable, with MgO rapidly decreasing in the range SiO_2 ~ 40-50%, from ultramafic cumulates to gabbros; CaO and FeO_{tot} define smooth negative trends with silica. Mafic dikes have higher MgO than gabbros suggesting they may represent near-primary magmas (Ulmer *et al.*, 1983).

K_2O and K_2O/Na_2O ratios for the most mafic samples (MgO > 3%; Fig. 8b) are generally lower for samples from the Re di Castello pluton, with K_2O/Na_2O mostly below ~ 0.5, whereas rocks from the northern plutons display ratios chiefly in the range ~ 0.5-1.2. The differences depend on higher K_2O in the northern plutons.

Compatible trace elements (e.g., Cr, Co, Ni) versus SiO_2 exhibit curved fractionation trends similar to MgO. Excluding the extremely differentiated aplitic and pegmatitic samples, most of the incompatible trace elements (e.g., Rb, Ba, Th, Nb, LREE) increase more or less regularly with SiO_2, whereas Sr, Zr and HREE show broadly bell-shaped trends. Samples form the southern Adamello show somewhat lower Rb and higher Sr, Ba and LREE concentrations than in he north. A number of mafic enclaves show pronounced enrichments in certain elements (e.g., K, Ba, Rb and Nb) relative to other Adamello rocks with similar SiO_2. This has been related to equilibration of the mafic inclusions with interstitial melts in the host granitoid (Blundy & Sparks, 1992).

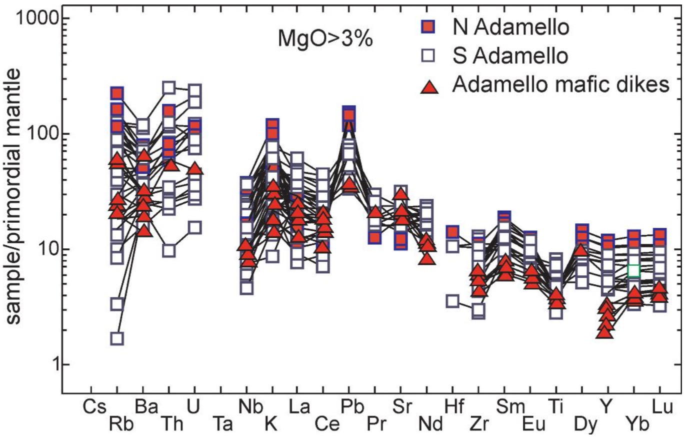
Figure 8. Alkali-silica diagrams for Adamello and Orobic Alps



A - K_2O vs. SiO_2 diagram for the Adamello plutonic rocks and microgranular mafic enclaves (MME), and for Orobic Alps; B - K_2O vs. Na_2O for mafic rocks.

Incompatible trace elements of mafic rocks (MgO > 3%; Fig. 9) exhibit fractionated patterns with high enrichments in Ba, Rb, Th and U, Pb spikes, troughs at Nb and minor depletion in Ti. REE patterns reveal variable enrichments and fractionation. The Blumone olivine-gabbros have almost flat patterns ($La_NYb_N < 5$) and show the lowest enrichments in LREE (La ~10 times chondrite), whereas other mafic rocks have La reaching ~100 time chondritic abundances.

Figure 9. Spider-diagrams of Adamello



Incompatible element patterns normalized to primordial mantle composition for mafic rocks (MgO > 3%) from the Adamello intrusions.

At the batholith scale, whole-rock initial Sr isotope ratios do not exhibit any particular correlation with SiO_2, but show a broad positive correlation with K and Rb. However, positive $^{87}Sr/^{86}Sr$ vs. SiO_2 correlations are sometimes observed for single plutonic units. In general, initial $^{87}Sr/^{86}Sr$ increases from south to north, with the Re di Castello pluton showing less radiogenic compositions ($^{87}Sr/^{86}Sr$ ~ 0.703-0.707) than the northern plutons (e.g., Adamello, Avio and Presanella; $^{87}Sr/^{86}Sr$ ~ 0.707-0.712). Northward increase of Sr isotope ratios is parallel to increase in some incompatible elements (e.g., K, Rb). The mafic dikes display initial $^{87}Sr/^{86}Sr$ ~ 0.7041-0.7064 (Cortecci *et al.*, 1979; Dupuy *et al.*, 1982).

Only a few whole-rock Nd and Pb isotope analyses have been published, mostly for southern Adamello rocks. $^{143}Nd/^{144}Nd$ for the Re di Castello pluton and one granodiorite from the Adamello pluton ranges from 0.51278 to 0.5121, showing a smooth negative trend with Sr isotopes, partly overlapping the mantle-crust mixing field of the Bregaglia complex (Fig. 14a). Pb isotope ratios of the Re di Castello pluton show relatively low $^{206}Pb/^{204}Pb$ (~ 18.47-18.58), with only extremely differentiated sample exhibiting more radiogenic values. $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ fall within the range displayed by the bulk of the Alpine magmatism (Fig. 14b,c) (Cortecci *et al.*, 1979; Dupuy *et al.*, 1982; Kagami *et al.*, 1991).

Oxygen isotope compositions increase from $\delta^{18}O$ ~ +5.9 to +8.0‰ values of the southern Re di Castello pluton to $\delta^{18}O$ ~ +8.1 to +9.4‰ of the northern plutons (Fig. 5).

The northward increase of initial $^{87}Sr/^{86}Sr$, $\delta^{18}O$ and some incompatible element abundances (Cortecci *et al.*, 1979; Dupuy *et al.*, 1982; Del Moro *et al.*, 1983a,b;Kagami *et al.*, 1991) has been interpreted as indicating assimilation plus fractional crystallization (AFC) as a main evolutionary process during evolution of the Adamello massif, with the amount of contamination becoming progressively larger from south to north, and with time. Mg-tholeiitic to picritic parental magmas similar to that forming the mafic dikes, were suggested on the basis of mineral and bulk rock chemistry (Ulmer *et al.*, 1983). These magmas were generated in a garnet-lherzolitic upper mantle, which had been metasomatically modified by fluids/ melts released from subducting oceanic crust (Ulmer *et al.*, 1983). However, the involvement of a sedimentary component during source metasomatism was suggested by Tiepolo & Tribuzio (2005). Finally, a metasomatized spinel-lherzolite source, similar to the one inferred for the Bregaglia parental melts suggested for Adamello by Tiepolo *et al.* (2002).

Orobic Alps magmatism

In the Southalpine domain west of the Adamello batholith (Orobic Alps; Fig. 1), several small bodies are intruded into the Southalpine crystalline basement and in the Permian to Lower Jurassic sedimentary cover (Crespi & Gandini, 1960; Casati *et al.*, 1976; De Michele & Zezza, 1978; De Michele *et al.*, 1983; Beccaluva *et al.*, 1983; Fantoni *et al.*, 1999). These consist of prevailing basaltic to andesitic dikes, some dacitic dikes, and minor gabbroic-dioritic laccoliths and stocks. In the central Valtellina area, immediately north of the Tonale line, the Triangia-Sondrio biotite-amphibole tonalite to granodioritie stock intrudes into Austroalpine basement rocks.

Basaltic-andesitic dikes, some bearing biotite, located in the northern (Valtellina area) and eastern (Val Camonica area) margins of the Orobic Alps, are probably genetically related to the Triangia-Sondrio and Adamello intrusions, respectively (Liborio & Mottana, 1969). However, no radiometric dating and very few geochemical studies have been undertaken on these dikes. Poorly constrained hornblende and whole rock K-Ar ages ranging between 64-36 Ma have been published by Zanchi *et al.* (1990) and Fantoni *et al.* (1999) for andesitic dikes and gabbro-diorite stocks from the Bergamo area, in the southern Orobic Alps. For the same rocks, more reliable middle to late Eocene U-Pb zircon ages have been recently reported by Zanchetta *et al.* (2009). These dates coincide with emplacement ages obtained for the oldest products of the Adamello massif.

Geochemistry and petrology

The few data on the Orobic Alps magmatism reveal predominant tholeiitic-calcalkaline affinities (Fig. 8a). Major and trace element variations showsome scattering, with MgO, TiO_2, FeO_{tot} and CaO decreasing more or less constantly with magma differentiation. Trace element data on rocks from the northern-eastern Orobic Alps display positive correlations for Ba, Rb and Zr with SiO_2, overlapping with values reported for the Adamello rocks. REE fractionation and LREE enrichments (La ~10-30 times chondrite) exhibited by dioritic rocks from the southern Orobic Alps is relatively higher (La_NYb_N ~ 21-30) than in similar rocks from the Adamello batholith.

South-Western Tyrol magmatism

North of the Adamello batholith, in the south-western Tyrol area (Fig. 1), numerous dikes and a few larger quartz-diorite stocks intrude the Austroalpine basement rocks (Ötztal-Stubai and Ortler-Campo nappes) or sometimes the Mesozoic sedimentary sequences (e.g., Ortler Group; Gatto *et al.* 1976, Beccaluva *et al.*, 1979; Dal Piaz *et al.*, 1988; Purtscheller & Mogessie, 1988; Mair & Purtscheller, 1995). Some dikes are also found intruding Southalpine rocks (e.g., Permian Bressanone, Brixen, granite; Purtscheller & Mogessie, 1988).

The dikes are mainly basaltic andesites and andesites with subordinate basalts, dacites and rhyolites. Basaltic andesites, andesites and the dioritic stocks contain hornblende, calcic plagioclase with minor biotite, clino- and orthopyroxene, K-feldspar and quartz. Most dikes contain also crustal xenoliths and mafic enclaves, sometimes showing cumulate texture (Mair & Purtscheller, 1995). Magmatic garnet is observed in some andesitic to rhyolitic dikes from the Merano area along the Periadriatic Line (Gatto *et al.*, 1976; Purtscheller & Mogessie, 1988). Dal Piaz *et al.* (1988) reported Rb/Sr biotite ages for the quartz-dioritic stocks in the range ~ 32-30 Ma. A similar U/Pb zircon age of ~ 31.9 Ma was obtained by Müller *et al.* (2001) for a garnet-muscovite-bearing granitic dike. However, Gatto *et al.* (1976) obtained for andesitic and dacitic dikes K/Ar total rock ages of ~ 89 Ma, ~ 48 Ma and ~ 32 Ma. If correct, these ages would represent the only evidence for Cretaceous subduction-related magmatism in the Alps.

Very thin and elongated dioritic-tonalitic bodies occur in the Eastern Alps along the Austroalpine-Southalpine boundary, in proximity of the northern Giudicarie and Pusteria-Gailtal lines of the PFS. These bodies have been traditionally reported as tonalite “lamellae” (Dal Piaz, 1926). They often display a foliated texture and contain mafic enclaves (Martin *et al.*, 1993 and reference therein). Rb/Sr ages obtained for the “lamellae” located along the northern Giudicarie Line (Rumo, Samoclevo and Mulles), north of the Adamello batholith, are in the range ~ 32-28 Ma (Sassi *et al.*, 1985; Martin *et al.*, 1993).

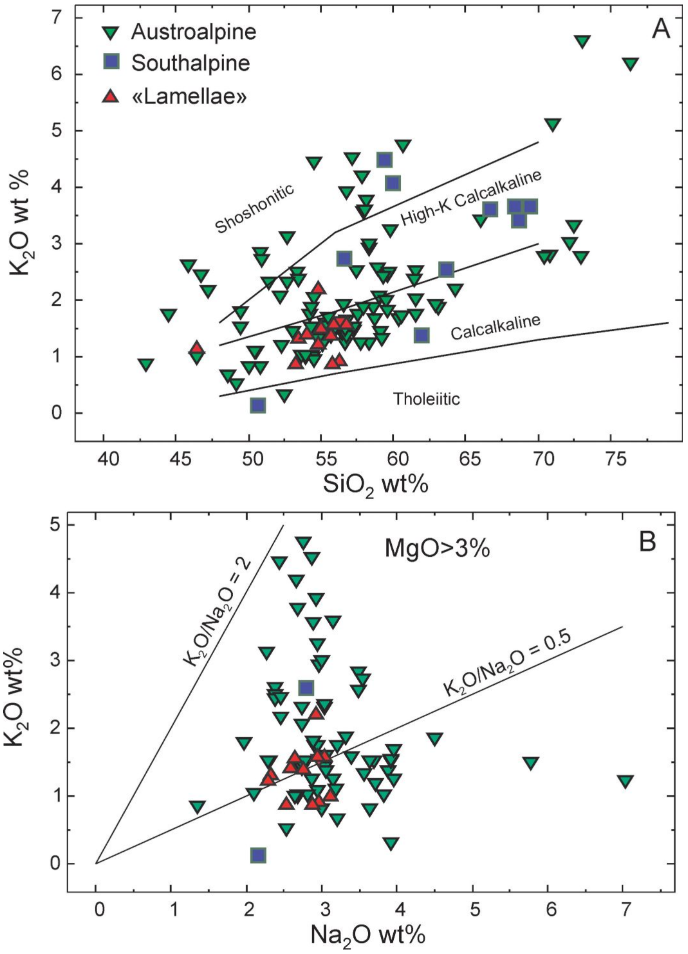
Geochemistry and petrology

Dikes and stocks form the south-western Tyrol display mainly calcalkaline to shoshonitic affinity. The “lamellae” are calc-alkaline (Fig. 10a).

Most of the Austroalpine calcalkaline and high-K calcalkaline dikes and stocks have low TiO_2 (<1%), whereas higher values (TiO_2 ~2.5 %) are displayed by some of the very mafic (MgO ~ 10-11%) high-K calcalkaline and shoshonitic rocks. The tonalite “lamellae” have intermediate Ti contents, similar to the tonalitic rocks from the Adamello. A few high-TiO_2 (~1.6-1.7%) andesitic-latitic dikes contain up to 7% Na_2O. The least evolved intrusives (MgO > 3%) have K_2O/Na_2O ratios increasing progressively from calcalkaline to shoshonitic samples, but never exceeding about 2 (Fig. 10b). The “lamellae” have ratios ~ 0.5 (Fig. 10b), similar to Adamello and Bregaglia tonalitic rocks.

Trace elements are rather scattered, with some of the highly incompatible elements (e.g., Rb) increasing constantly with SiO_2, and Cr and Ni showing an opposite trend. In general, shoshonitic rocks together with some HKCA samples exhibit the highest concentrations for several incompatible elements.

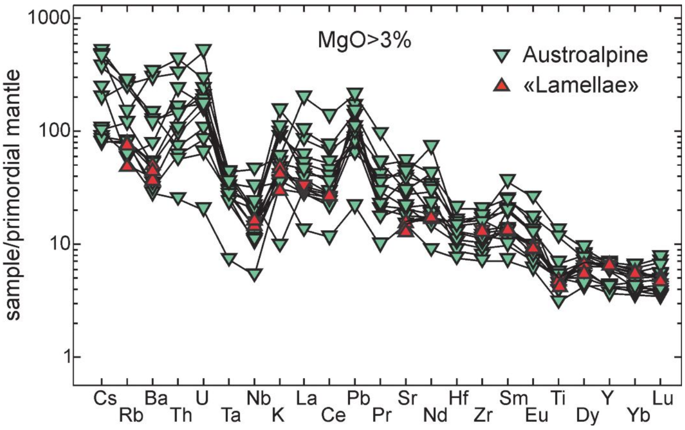
Figure 10. Alkali-silica diagrams of south-western Tyrol magmatism, Eastern Alps



A - K_2O vs. SiO_2 classification diagram, and B - K_2O vs. Na_2O diagram for south-western Tyrol Tertiary igneous rocks.

Primordial mantle normalized diagrams (Fig. 11) for calcalkaline-shoshonitic mafic rocks (MgO > 3%) reveal similar fractionated patterns with enrichments of LILE, Pb positive spikes and Nb, Ta and Ti negative anomalies. Moreover, they commonly show Ba negative anomalies. REE patterns show variable fractionation (La_NYb_N ~ 3.1-46.1), generally increasing from calcalkaline to shoshonitic rocks. The “lamellae” show REE patterns similar to the Adamello and Bregaglia calcalkaline rocks with relatively low fractionation (La_NYb_N ~ 5.4-6.0).

Figure 11. Spider-diagrams for south-western Tyrol, Eastern Alps

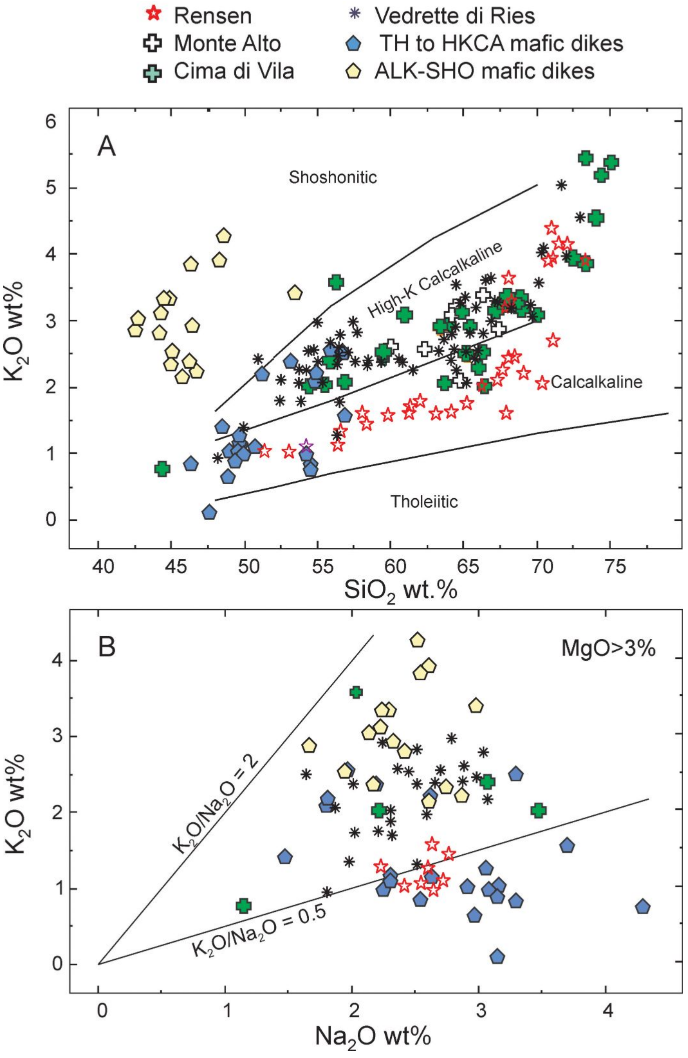


Incompatible element patterns normalized to primordial mantle composition for mafic rocks (MgO > 3%) from the south-western Tyrol area.

Initial Sr isotope ratios are extremely variable and show a rough tendency to increase with SiO_2. The Southalpine dikes have higher $^{87}Sr/^{86}Sr$ (~ 0.7148-0.7203) than the Austroalpine dikes and stocks ($^{87}Sr/^{86}Sr$ ~ 0.7051-0.7125) and display scattering in Sr-Nd isotope space (Fig. 14a). The “lamellae” have high initial $^{87}Sr/^{86}Sr$ ~ 0.7081-0.7109, comparable to values reported for tonalitic rocks from the northern Adamello plutons and Bregaglia massif.

Most authors agree that the widespread, mostly andesitic, magmatism occurring in the south-western Tyrol area is related to subduction processes (e.g., Gatto *et al.*, 1976; Beccaluva *et al.*, 1979; Dal Piaz *et al.*, 1988; Macera *et al.*, 2008). Based on geochemical and Sr isotopic constraints, Dal Piaz *et al.* (1988), proposed that at least two mantle derived parental magmas, respectively with calcalkaline and high-K calcalkaline-shoshonitic composition, were involved in the petrogenesis of dikes and stocks of the Austroalpine domain in the south-western Tyrol area. According to these authors, parental magma were generated in heterogeneous mantle sources, which were affected by different degrees of mantle metasomatism induced by fluid/melts released from an oceanic lithosphere during Cretaceous subduction. Mantle partial melting took place by thermal restoration occurred during Oligocene extensional processes. Magma evolution processes took place by fractional crystallisation and heterogeneous assimilation of various amounts and types of crustal material. These determined high initial $^{87}Sr/^{86}Sr$ of the igneous products as well as scattering of trace element and Sr isotope values, a feature that was increased by post-magmatic elemental transfer by fluid phases. According to Purtscheller & Mogessie (1988) the dikes found in the Southern Alps, just east of the Giudicarie line, could be cogenetic with the nearby calcalkaline-shoshonitic rocks from the Austroalpine domain, but suffered higher crustal contamination during differentiation.

Figure 12. Alkali-silica classification diagrams, Eastern Alps



A - K_2O vs. SiO_2 classification diagram; B - K_2O vs. Na_2O diagram for the plutons (Rensen, Monte Alto, Vedrette di Ries and Cima di Vila) and mafic dikes located south of the Tauren Window.

Rensen and Monte Alto (Altenberg) plutons

The Rensen pluton is mainly composed of granodiorites with minor tonalites. Quartz-diorites occur as small elongated bodies within the tonalites and granodiorites;

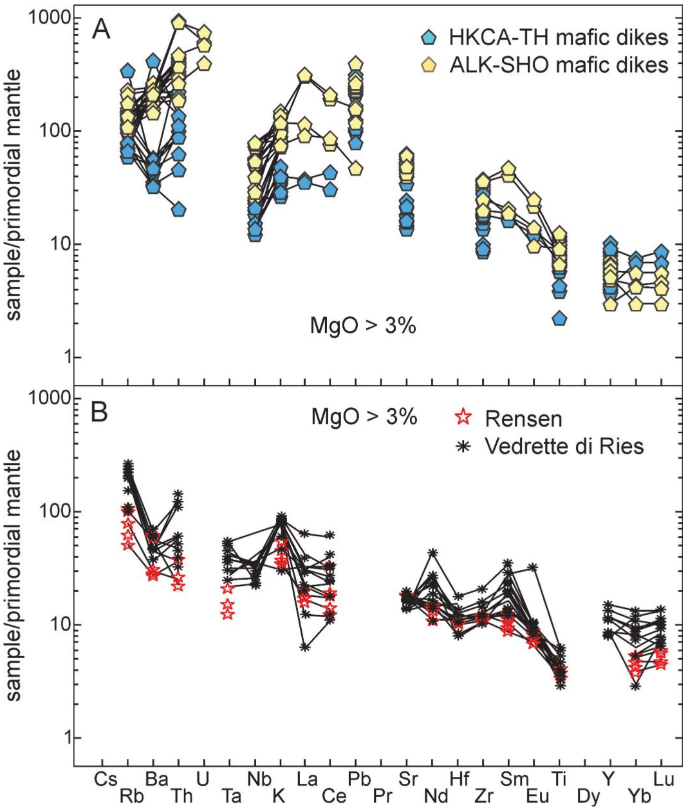
two-mica granites with a gneissic texture make up a small mass. Tonalites and granodiorites are made of plagioclase, biotite, epidote and quartz with minor amphibole, K-feldspar and rare muscovite. Garnet, typically enclosed in plagioclase, is rarely observed in quartz-diorites (Bellieni *et al.*, 1984; Barth *et al.*, 1989; Bellieni *et al.*, 1991). Allanite Th/Pb and zircon U/Pb age determinations for quartz-diorites, tonalites and leucogranites give similar ages of 31.7 to 30.8 Ma (Barth *et al.*, 1989).

The Monte Alto stock, located east of the Rensen massif (Fig. 1), is dominated by granodiorites with sporadic tonalites (Bellieni *et al.*, 1984). A Rb/Sr age determined by whole rock plus biotite isochron is around 24-25 Ma (Borsi *et al.*, 1979; recalculated by Sassi *et al.*, 1985).

Geochemistry and petrology

The Rensen plutonic rock association displays a smooth calcalkaline fractionation trend from quartz-diorite to granodiorite with the leucogranite showing a high-K calcalkaline affinity; the Monte Alto tonalites and granodiorites are mostly HKCA (Fig. 12a).

Figure 13. Spider-diagrams, Eastern Alps



Incompatible element patterns normalized to primordial mantle composition for mafic rocks (MgO > 3%) from the Rensen and Vedrette di Ries plutons and for alkaline (ALK)-shoshonitic (SHO) mafic dikes located south of the Tauren Window.

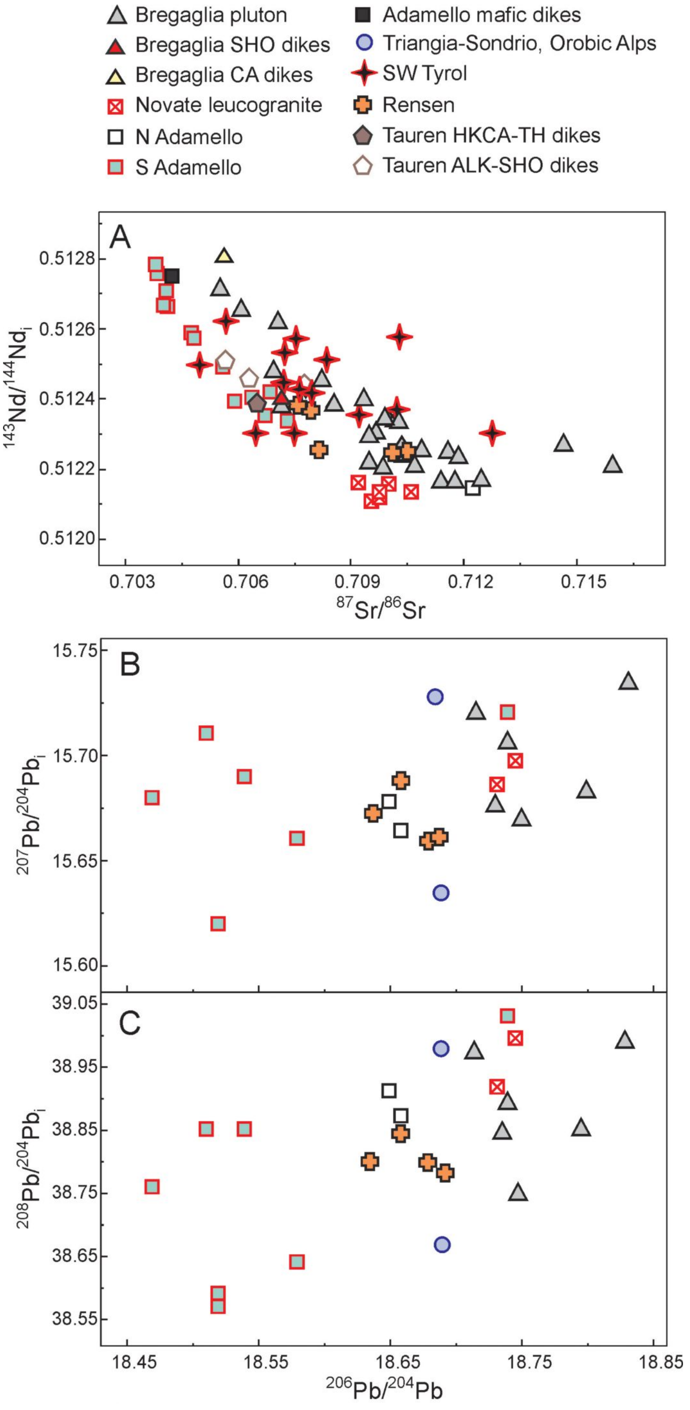
Rensen and Monte Alto display smooth negative trends of TiO_2, Al_2O_3, MgO, FeO_{tot} vs. silica, and positive trends for Na_2O. Monte Alto is more enriched in LILE (e.g., Rb, Sr, Th, LREE) with respect to the Rensen tonalites and granodiorites. Rensen exhibits positive trends for Rb, Ba and Ta vs. silica, with a marked increase in Rb and Ta passing from tonalite-granodiorite to leucogranite. Primordial mantle-normalized trace element diagrams for Rensen dioritic rocks with MgO > 3 % reveal fractionated patterns with moderate enrichments of LILE and Th over the REE and HFSE, troughs at Nb and Ti, small Sr positive anomalies and, frequently, Ba negative anomalies (Fig. 13). REE patterns for the Rensen mafic rocks show rather low LREE/HREE fractionation with La_NYb_N mostly ~ 3.7-5.5.

Quartz-diorites to granodiorites from Rensen show poorly variable and relatively high initial $^{87}Sr/^{86}Sr$ ~0.7075-0.7081, whereas an abrupt increase in the Sr isotope ratios is observed in leucogranites ($^{87}Sr/^{86}Sr$ ~0.7095-0.7110). Initial Nd isotope ratios decrease from 0.51236 to 0.51225, passing from quartz-diorite to leucogranite and some tonalites (Fig. 14a). Monte Alto displays initial $^{87}Sr/^{86}Sr$ similar or higher than the Rensen leucogranites (~ 0.7108-0.7113).

The different rocks from Rensen show rather homogeneous crustal-like Pb isotope compositions falling within the range defined by other Alpine plutonic rocks. The leucogranites show slightly higher $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ with respect to dioritic-tonalitic rocks (Fig. 14b,c).

Geochemical, isotopic and geochronological data suggest that Monte Alto and Rensen plutons are not comagmatic. According to Bellieni *et al.* (1984), high Sr contents and high HREE fractionation of Monte Alto rocks suggest an origin by melting of plagioclase-free, garnet-bearing deep crustal rocks, possibly followed by some degree of fractionation at shallower levels. An origin by crustal anatexis is also corroborated by the very high initial $^{87}Sr/^{86}Sr$ displayed by the Monte Alto tonalite-granodiorite. On the other hand, extensive interaction between mafic mantle-derived magmas and crustal material has been invoked in the genesis of the Rensen plutonic association (Barth *et al.*, 1989; Bellieni *et al.*, 1991). A multi-stage polybaric fractional crystallisation of a single type of dioritic magma, accompanied by variable interaction with the intruded crust, was suggested for the evolution of Rensen. This determined variable Sr isotopic signatures and different trends of compatible vs. incompatible elements (Bellieni *et al.*, 1991).

Figure 14. Radiogenic isotope compositions, Central and Eastern Alps



Sr-Nd-Pb isotopic compositions of Tertiary igneous rocks from Central and Eastern Alps.

The leucogranites show a strong crustal affinity both in terms of initial Sr-Nd isotopic compositions and occurrence of inherited pre-magmatic components in its zircon population. Accordingly, the bulk of this rock has been considered as crustal anatectic in origin (Barth *et al.*, 1989; Bellieni *et al.*, 1991).

Vedrette di Ries (Rieserferner) and Cima di Vila (Zinsnock) plutons

The Vedrette di Ries plutonic complex is composed mainly of granodiorite and tonalite consisting of various proportions of plagioclase, quartz, K-feldspar, hornblende and biotite. Garnet occurs in most tonalites and in some granodiorites. Small masses of granites and diorites, the latter containing some magmatic garnet, are distributed within granodiorites and tonalites. Dioritic to tonalitic microgranular enclaves, as well as metamorphic xenoliths are frequently found all over the pluton (Bellieni *et al.*, 1981; Cesare *et al.*, 2004). U-Pb ages of ~ 31.8-32.2 Ma were obtained on allanite by Romer & Siegesmund (2003), whereas a Rb-Sr whole-rock isochron yielded an age of ~ 31 Ma (Borsi *et al.*, 1979; recalculated by Sassi *et al.*, 1985).

The entire plutonic complex is cut by acidic (pegmatites and aplites) to basic lamprophyric dikes. The lamprophyres, cut both the plutonic rocks, including the aplite and pegmatite dikes, and the metamorphic country rocks and are probably not part of the Vedrette di Ries magmatic cycle (see below).

The Cima di Vila pluton is exposed along the DAV line (Fig. 1), close to the southern border of the larger Vedrette di Ries pluton and is mainly made up of biotite granodiorite surrounded by biotite-amphibole tonalite. Tonalites and granodiorites are cut by granitic and aplitic dikes and contain microgranular mafic enclaves and a few metamorphic xenoliths. Rare ultramafic enclaves with hornblenditic composition occur within the tonalitic rocks (Bellieni *et al.*, 1989; Bellieni *et al.*, 1996). A total rock and biotite isochron Rb/Sr age of ~ 29.5 Ma was published by Borsi *et al.* (1979).

Geochemistry and petrology

The Vedrette di Ries and Cima di Vila plutons display a common high-K calcalkaline affinity (Fig. 12a) and overlapping trends for major elements. The least evolved rocks (MgO > 3%) from both plutons, represented mostly by microgranular enclaves, exhibit variable but similar

K_2O/Na_2O ratios (~ 0.4-1.8; Fig. 12b). These values are overall much higher than the Resen pluton.

Despite the almost identical major element characteristics the Vedrette di Ries and Cima di Vila plutons display important differences in terms of some trace element and Sr isotope compositions. Incompatible trace element patterns (Fig. 13) for selected mafic rocks (MgO > 3%) from the Vedrette di Ries pluton reveal elevated enrichments in the highly incompatible elements with Nb, Ta, Ti and small Sr negative anomalies. Moreover, general depletion in Ba and Th relatively to Rb and high K/LREE are observed.

Vedrette di Ries exhibits poorly variable $^{87}Sr/^{86}Sr$ values (~ 0.709-0.711), with only some aplitic dikes reaching $^{87}Sr/^{86}Sr$ ~ 0.715.

Cima di Vila shows a positive $^{87}Sr/^{86}Sr$ vs. SiO_2 trend ($^{87}Sr/^{86}Sr$ ~ 0.7058-0.7113), and only the most evolved samples display $^{87}Sr/^{86}Sr$ values overlapping the Vedrette di Ries pluton.

Based on trace element modelling, Bellieni *et al.* (1981) ruled out the possibility that rock suite may be the product of crustal melting as previously was proposed by Borsi *et al.* (1979) on the basis of Sr isotopic data. It was suggest that a mantle-derived parental melts went through a two-stage fractional crystallization process, with high pressure separation of garnet+hornblende followed by lower pressures of hornblende+plagioclase. Crustal assimilation also took place during fractionation (Bellieni *et al.*, 1981).

Mixing between mafic mantle-derived melts and felsic crustal melts generated by melting within the deep crust was suggested as leading mechanism for Cima di Vila magmas by Bellieni *et al.* (1996). Granitic and aplitic derivative liquids were successively formed by fractional crystallisation and/or in situ separation of residual melt from an extensively crystallised body.

Dikes south of the Tauren Window

Numerous dikes occur in the area south of the Tauren Window and west of the Mölltal Line (Fig. 1). They are mostly intruded into the polymetamorphic Austroalpine basement, with a few also crosscutting the Austroalpine Mesozoic cover and the Southalpine basement along the Gailtal Line (Deutsch, 1984; Müller *et al.*, 1992; Müller *et al.*, 2000; Trepmann *et al.*, 2004). Ages (K/Ar and Rb/Sr) are scattered and mostly fall between about 40 and 24 Ma (Deutsch, 1984; Steenken *et al.*, 2000).

At least two generations of dikes have been distinguished: 1) porphyritic tonalitic (trondhjemitic) and granodioritic dikes that are not observed within the main Tertiary plutonic bodies; these are locally deformed and show a greenschist facies metamorphic overprint (Müller *et al.*, 2000; Trepmann *et al.*, 2004); 2) unfoliated and unmetamorphosed mafic dikes that locally cross-cut the main plutonic bodies as well as aplites and pegmatites (e.g., Vedrette di Ries; Deutsch, 1984; Steenken *et al.*, 2000; Müller *et al.*, 1992). Other dikes consist of aplites and pegmatites and are associated with intrusive rocks described above.

The tonalitic to granodioritic dikes are characterized by phenocrysts of magmatic garnet and/or muscovite (e.g., Trepmann *et al.*, 2004) and gave U/Pb zircon ages ~ 31-32.5 Ma (Müller *et al.*, 2000; Müller *et al.*, 2001) and slightly younger Rb/Sr ages in the range 29.9-30.9 Ma (Müller *et al.*, 2000). Among the mafic dikes, different groups have been distinguished. These include 1) porphyritic to aphyric CA-HKCA basaltic to andesitic dikes containing hornblende, plagioclase and minor augite and biotite; 2) amphibole-bearing and mica-bearing shoshonitic lamprophyres; 3) nepheline-normative to olivine-diopside-hyperstene-normative alkalibasaltic dikes containing kaersutite, Ti-pargasite/hastingsite, Ti-biotite, Ti-augite and alkalifeldspar (Deutsch, 1984; Müller *et al.*, 1992).

Limited geochemical studies have been undertaken for the deformed and slightly metamorphosed tonalitic-granodioritic dikes, whereas the mafic dikes were subjected to more comprehensive studies of major, trace element and Sr-Nd isotope compositions. Because of this data bias, attention will be focused on the mafic dikes in the following section.

Geochemistry and petrology

Major element abundances are variable, with alkaline (ALK) dikes showing the lowest silica and highest TiO_2 (~1.6-2.5%) and P_2O_5 (up to 1%). The subalkaline-transitional dikes range from tholeiitic to shoshonitic (Fig. 12a). A group of subalkaline samples is distinguished by high TiO_2 (~2%), similar to the alkaline ones, together with relatively high FeO_{tot} (~11%). K_2O/Na_2O ratios (Fig. 12b) are generally below 0.5 for the tholeiitic-calcalkaline products and comprised mostly between ~0.5-1.5 for the alkaline and high-K calcalkaline-shoshonitic dikes.

In general the mafic calcalkaline-shoshonitic dikes from south of the Tauren Window show major element compositions comparable with the basic magmatism from south-western Tyrol, except for slightly higher TiO_2 and lower Al_2O_3 for the former.

The Na-alkaline and high-K calcalkaline-shoshonitic products show commonly higher concentration in most of the incompatible elements with respect to the tholeiitic-calcalkaline dikes. Alkaline and shoshonitic dikes have similar fractionated incompatible trace element patterns (Fig. 13) with negative anomalies of Nb, and spikes in Th and U. Tholeiitic-calcalkaline and high-K calcalkaline samples generally show greater troughs at Nb and Ti and often display Ba negative anomalies. REE patterns are variably fractionated.

The alkaline dikes display lower whole-rock and amphibole $^{87}Sr/^{86}Sr$ (~ 0.7056-0.7069) compared to the subalkaline dikes ($^{87}Sr/^{86}Sr$ ~ 0.7065-0.7146). In the subalkaline rocks, the Sr isotope ratios determined an early crystallizing hornblende are generally lower (~ 0.7065-0.7080) compared to the whole-rock values (~ 0.7078-0.7145), suggesting magma contamination during crystallization. Initial Nd isotope ratios, only measured on amphibole, are higher for the alkaline samples (~ 0.51239-0.51245), but still away from typical mantle values.

According to Deutsch (1984), the mineralogical, geochemical and isotopic data displayed by the alkaline and subalkaline dikes are compatible with magma origin from an enriched sub-continental mantle variably metasomatized by LILE- and LREE-rich fluids. The high and variable $^{87}Sr/^{86}Sr$ particularly in the subalkaline dikes, indicates, a major contribution of crustal material in early evolutionary stages (Deutsch, 1984).

Müller *et al.* (1992), proposed that mantle metasomatism was achieved during Cretaceous subduction and melting occurred during a phase of extensional tectonics, post-dating continent-continent collision. Moreover, they suggested that the alkaline magma types may reflect a deeper mantle source due to asthenospheric upwelling.

Karavanke and Pohorje intrusions

The Pohorje Mts. and Karavanke plutons (Austria, Slovenia) represent the easternmost intrusions of the Periadriatic Zone. They are composed of dominant tonalites with subordinate granodiorites and rare diorites, showing CA and HKCA affinity (Pamic & Palinkas, 2000, with references; Bellieni *et al.*, 2010). Ages are 28-30 Ma (Kovács *et al.*, 2007). Major and trace element concentrations are not far from other intermediate to acid rocks of the Eastern Alps. Initial $^{87}Sr/^{86}Sr$ ratios range from 0.70656 to 0.70750 for Pohorje, whereas Karavanke rocks how values around 0.7075 (Pamic & Palinkas, 2000). Variation of major, trace element and Sr- and O-isotope data suggest that the rock suite of these plutons were formed by AFC processses starting from an olivine tholeiite parental magma. Based on element modelling, it has been suggested that parent magma were formed by melting of a slightly metasomatized garnet peridotite (Pamic & Palinkas, 2000).

External Eastern Alps flysch deposits

Fragments of volcanic or subvolcanic rocks occur as pebbles in alluvial conglomerates of late Oligocene to middle Miocene age in the Eastern Alps. According to Brügel *et al.* (2000), these clasts represent erosional products of volcanic edifices located in the vicinity of the PFS and genetically related to the widespread Oligocene plutonic activity of the Eastern Alps. They are porphyritic andesites and dacites composed mainly of plagioclase, amphibole, biotite and quartz, and showing high-K calcalkaline and shoshonitic affinity (Brügel *et al.*, 2000). Whole rock K/Ar ages in the range 24 to 40 Ma and a more precise amphibole Ar/Ar age of 32.3 Ma have been found (Brügel *et al.*, 2000).

Overview of Along-arc Variation of Magmatism

Tertiary orogenic activity shows important compositional variations along the Alpine chain, highlighting strong heterogeneities of mantle sources at a regional scale as well as various modalities of magma emplacement and evolution, as a consequence of variable structural setting along the Alps. The main compositional variations can be summarised as follows:

1 – Calcalkaline to shoshonitic magmatism occurs in all the sectors of the Alpine chain (Fig. 15a). Ultrapotassic alkaline rocks, however, are restricted to the Western Alps. In the Eastern Alps, some Na-alkaline rocks are found in association with calcalkaline and shoshonitic rocks. Moreover, CaO of mafic rocks increases from western to eastern Alps (Fig. 15b). Al_2O_3 also shows the same behaviour (Fig. 15d). Since major element abundances of mafic magmas basically depend on the

composition and proportions of mineral phases that enter into the melt during magma formation, major element variation along the Alps point to mineralogically heterogeneous mantle sources and/or different conditions of melting.

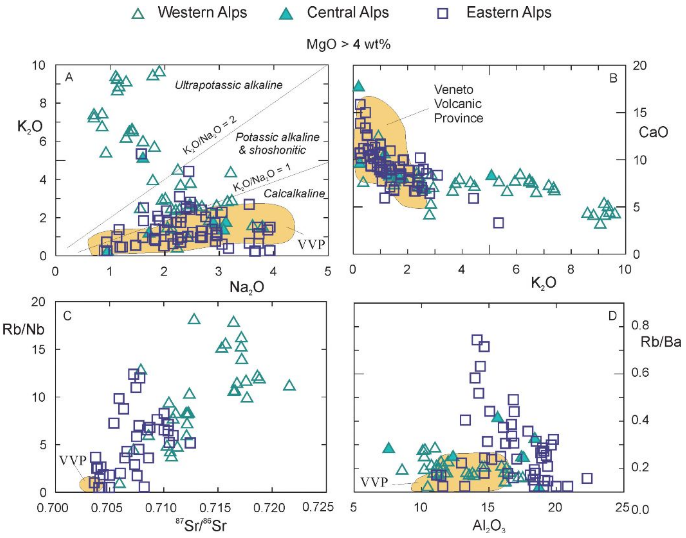
2 – Incompatible element ratios for mafic rocks (MgO > 4 wt%) also show large variations along the Alps (Fig. 15c,d), implying again important lateral variations of mantle compositions. Some element ratios (e.g., Rb/Ba) show different trends for Western and Eastern Alps (Fig. 15d), indicating different types of metasomatic modification in the upper mantle along the Alps. Finally, the mafic rocks from Eastern Alps exhibit incompatible element ratios (especially LILE/HFSE, such as Rb/Nb) that are similar or overlap with those of the intraplate rocks of the Veneto Volcanic Province (VVP). This supports a role of OIB-type components in the origin of orogenic magmatism of Eastern Alps. These components may represent composition of the popre-metasomatic mantle wedge or, alternatively, may derive from deep mantle components that are also responsible for the origin of VVP.

3 – Crustal anatectic melts apparently are more abundant in the Central and Eastern Alps than in the Western Alps. Moreover, magma volumes and, to a lesser extent, degrees of magma evolution are larger in the east. This suggests different thermal regimes, structural settings and/or type of intruded crust.

4 – There is a wide range of Sr-Nd isotopic compositions for the Alpine orogenic magmatism. The negative correlation in the Sr-Nd space suggests that both mantle and crustal end-members contributed to magmatism (Fig. 16a). Some of this interaction occurred by contamination of mantle-derived melts during magma ascent within the crust, as discussed earlier. However, if only the mafic rocks are considered one can see that there is still a very wide variation of Sr-Nd isotopes. Quantitative modelling clearly indicate that these variations cannot be due to intra-crustal processes and require mantle contamination by upper crust during subduction. Since the highest Sr and lowest Nd isotopic values are encountered in the Western Alps (Figs. 15c,16), it can be concluded that mantle contamination by subducted upper crust was stronger in the west.

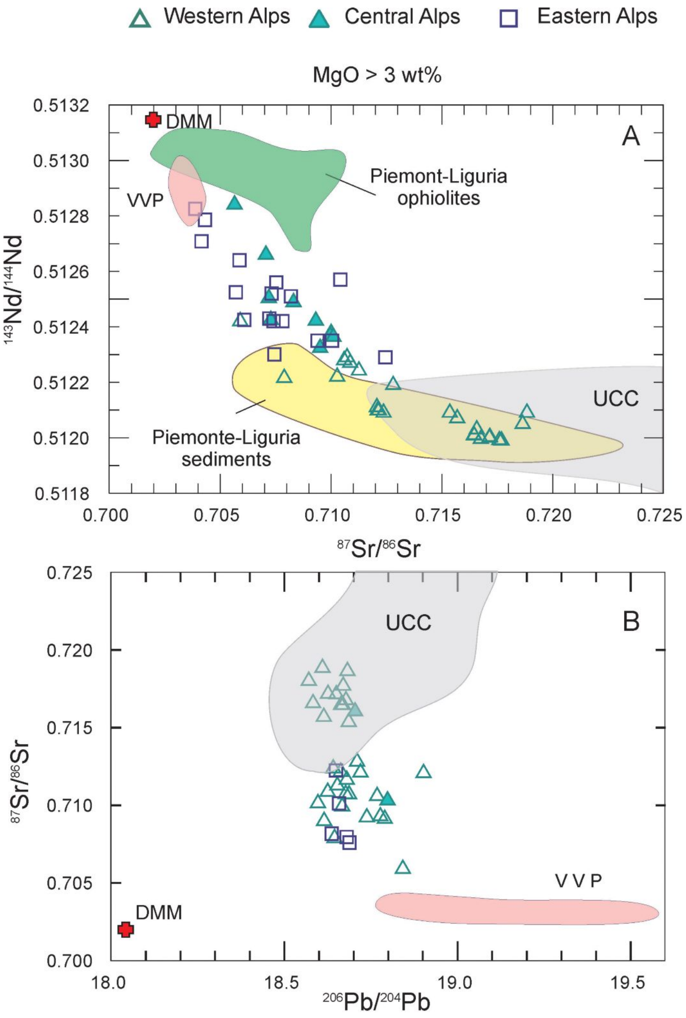
5 – In spite of the wide Sr-Nd isotopic variations summarised above, Pb isotopic compositions of orogenic rocks are remarkably similar all over the Alpine arc (Fig. 16b). In particular, $^{206}Pb/^{204}Pb$ values are mostly comprised between 18.6 and 18.8, a range that is much more narrow that crustal compositions (Fig. 16b). Variation of $^{206}Pb/^{204}Pb$ vs. $^{87}Sr/^{86}Sr$ shows that Alpine magmas define a vertical trend, which points towards upper continental crust. This supports the idea that the magmatism was the products of mantle-crust interaction, as concluded on the basis of Sr-Nd isotopic evidence. However, the narrow range of Pb isotope ratios would require that a single type of crustal composition, rather than different crustal rocks, was involved in the interaction with mantle. This corresponds roughly to an average of the crustal values reported in Fig. 16b. Alternatively, the narrow range of Pb isotope signatures may reveal a homogenisation of Pb isotopes in the crustal material during mantle contamination. Such a process could have not affected Sr-Nd isotopes, possible because of the lower mobility of these elements.

Figure 15. Compositional variations along the Alps



Variation of key major and trace element abundances and ratios, and $^{87}Sr/^{86}Sr$ for Tertiary mafic igneous rocks (MgO > 4%) from the Alps. The field of the anorogenic Veneto Volcanic Province (VVP) is also reported.

Figure 16. Radiogenic isotope variations, Alps



A - ^{143}Nd/^{144}Nd vs. ^{87}Sr/^{86}Sr diagram for Tertiary mafic igneous rocks (MgO > 3%) from the Alps. B - ^{87}Sr/^{86}Sr vs. ^{206}Pb/^{204}Pb for Tertiary igneous rocks from the Alps. The composition of depleted MORB mantle (DMM; Workman & Hart, 2005) and fields of continental upper-crustal rocks from the Alpine area (UCC) and anorogenic volcanic rocks from the Veneto Province (VVP) are also reported (Lustrino M. & Wilson M., 2007; Macera *et al.*, 2008 with references).

Sardinia

Introduction

During the Cenozoic, the island of Sardinia was the site of intense orogenic igneous activity, with a late Eocene-Middle Miocene phase of arc-tholeiitic to shoshonitic magmatism. Similar magmatism also took place during Eocene-Miocene in Corsica, in the Liguro-Provençal Sea basin, in Provence and in the Valencia Trough, and is apparently genetically related to the orogenic magmatism of Sardinia. Moreover, Oligo-Miocene volcaniclastic levels, linked to orogenic-type volcanism, occur in clastic formations of the Apennines, although their relation with the contemporaneous Sardinian volcanic activity is ambiguous (e.g., Mattioli *et al.*, 2002). The orogenic magmatism in Sardinia was followed by a middle Miocene-Pleistocene phase of anorogenic volcanism, showing a tholeiitic to Na-alkaline affinity (Lustrino *et al.*, 2004).

Geodynamic Framework

Sardinia and Corsica form a continental microplate, sited in the central Mediterranean Sea, between the Tyrrhenian Sea and the Liguro-Provençal-Balearic basin. This block was part of the southern European continental margin until late Oligocene, when backarc extension generated continental breackup, formation of the Liguro-Provençal- Balearic basin, separation of the Sardinia-Corsica microblock, and its eastward migration (e.g., Rollet *et al.*, 2002; Schettino & Turco, 2006; Lustrino *et al.*, 2009 with references). Rifting in the southern European paleomargin possibly started close to the Eocene/Oligocene boundary (~34 Ma), after the Eocene Pyrenean compressional phase (Cherchi *et al.*, 2008 with references). Spreading of the Liguro-Provençal basin and eastward drifting of the Sardina-Corsica microplate seems to have started around the Aquitanian/Burdigalian boundary (~20.5 Ma) and ceased not later than ~ 15 Ma (Gattacceca *et al.*, 2007; Cherchi *et al.*, 2008). According to Gattacceca *et al.* (2007), between 20.5 and 15 Ma the Sardinia-Corsica block rotated ~45° counterclockwise with respect to stable Europe, around a pole located north of Corsica. Most of the drifting occurred during the period 20.5–18 Ma, when ~ 30° of rotation was completed (Montigny *et al.*, 1981; Gattacceca *et al.*, 2007). In a recent paper, Lustrino *et al.* (2009) inferred the beginning of the westward Apennine subduction to have started between ~ 49–42 Ma.

Several authors (e.g., Malinverno & Ryan, 1986; Doglioni *et al.*, 1997; Carminati *et al.*, 1998; Gueguen *et al.*, 1998; Faccenna *et al.*, 2001) relate the opening of the Liguro-Provençal basin and drifting of the Sardinia-Corsica block to the south-eastward retreat and roll-back of an Adriatic/Ionian slab, subducting north-westward under the southern European paleomargin.

Age and occurrence

Orogenic magmatism occurred in Sardinia during a relative long period, from ~ 38 to ~12 Ma (K/Ar: Coulon *et al.*, 1974; Bellon *et al.*, 1977; Giraud *et al.*, 1979; Savelli *et al.*, 1979; Montigny *et al.*, 1981; Beccaluva *et al.*, 1985 for a review; Rb/Sr: Morra *et al.*, 1994; Ar/Ar: Deino *et al.*, 2001; Edel *et al.*, 2001; Speranza *et al.*, 2002; Gattacceca *et al.*, 2007; Lustrino *et al.*, 2009), even though most of the activity concentrated around ~ 21–18 Ma, almost contemporaneously with the main phase of rotation of the Sardinia-Corsica block.

Igneous activity occurred exclusively along and within the Sardinia Trough (Fossa Sarda), the Oligocene-Miocene rift system that crosses the western part of the island from north to south (Lustrino *et al.*, 2009 with references). The volcanic products were emplaced as pyroclastic flows and minor lava flows and domes, both in a subaerial and submarine environment. Rock compositions are dominated by dacites and rhyolites, with minor andesites and very scarce basalts. Plutonic rocks, mainly represented by gabbros and diorites, are very rare. In the Sulcis area of south-western Sardinia, peralkaline trachytes and rhyolites were also erupted (Morra *et al.*, 1994).

Igneous products with ages and petrological characteristics similar to the Oligocene-Miocene Sardinian magmatism, are also found 1) along the western Provençal margin of southern France, where ~ 34-18.7 Ma old microdiorites, basalts, andesites and dacites are found (Ivaldi *et al.*, 2003; Beccaluva *et al.*, 2004), 2) in southern Corsica, where rhyolitic and dacitic tuffs occur with ages comprised between ~17.8-21.2 Ma (Ottaviani-Spella *et al.*, 2001; Ferrandini *et al.*, 2003) and 3) south-west of the Corsican margin, where porphyric clinopyroxene basalt, amphibole-biotite andesite and pyroclastic breccia were dredged within the submarine prolongation of the Sardinia Trough (~16.0-17.2 Ma; Rossi *et al.*, 1998). Calcalkaline to shoshonitic basalts, andesites and dacites have also been recovered in other areas of the Ligurian-Provençal Sea, with K-Ar ages in the range 30-12 Ma (Beccaluva *et al.*, 2004).

Abundant Upper Oligocene volcanic material, including porphyritic to aphyric clasts and glass shards, ranging in composition from basalt to rhyolite, as well as isolated crystals, including mainly plagioclase with minor pyroxene, amphibole, biotite and opaque minerals, is found in the Sub-Ligurian sandstone formations of the Northern Apennines. These include the Ranzano Formation where the volcanic material is ~ 32-30 Ma old (Cibin *et al.*, 1998) and the Aveto-Petrignaccola Formation (Ar/Ar ages ~ 29-32.1 Ma; Mattioli *et al.*, 2002). Oligo-Miocene volcanoclastic levels are also found in the Bisciaro Formation of the Umbria-Marche sector of the Apennines (~ 26.8-17.1 Ma; Balogh *et al.*, 1993) and in several other localities of southern Italy (Critelli, 1993; De Capoa *et al.*, 2002). These volcanic clasts may have originated from Sardinia or also from volcanic centres located along the western part of the Alpine Periadriatic line and from volcanic edifices presently buried under a thick pile of the Po plane sediments (e.g., Mortara volcanic body) (e.g., Anelli *et al.*, 1994; Cibin *et al.*, 1998; Fantoni *et al.*, 1999; Mattioli *et al.*, 2002; Garzanti & Malusà, 2008).

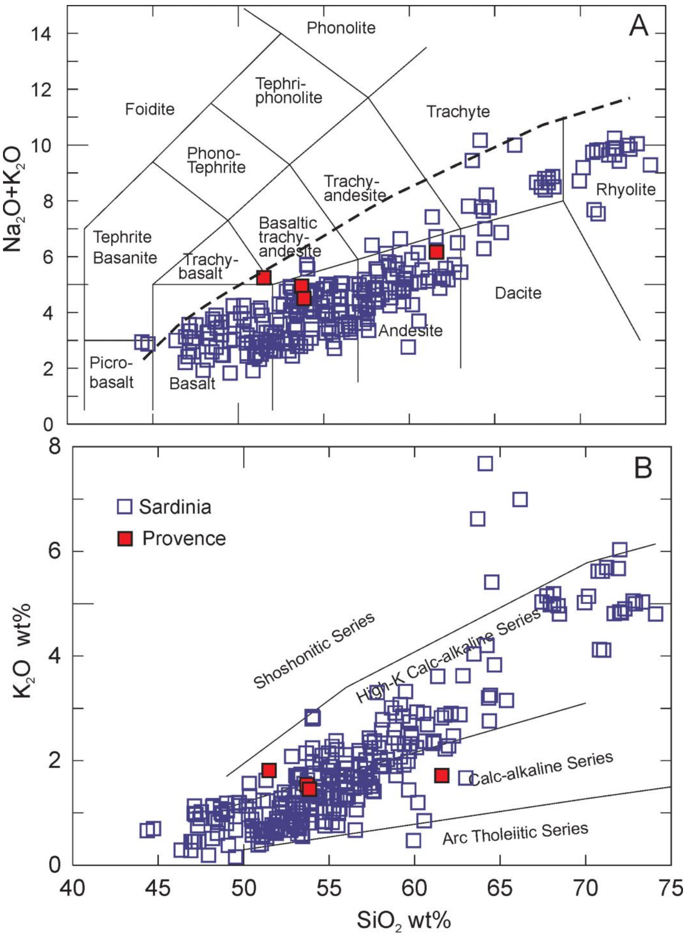
Geochemistry and petrology

The Eocene-Miocene volcanic and minor sub-volcanic rocks of Sardinia range in composition from basaltic to rhyolitic on the TAS diagram (Fig. 17a) and mainly have a CA and HKCA affinity (Fig. 17b). Some evolved rocks reach peralkaline, trachyte and rhyolite compositions. Although dacites and rhyolites are by far the most abundant lithologies, most of the whole-rock geochemical and isotopic studies have concentrated on basalt and andesites.

Major and trace elements show decrease in MgO, CaO, FeO_{tot}, Ni and Cr, and an increase in alkalies with SiO_2. TiO_2 and Al_2O_3 show more or less bell-shaped trends with much scattering among basalts (TiO_2 ~ 0.3-1.7% and Al_2O_3 ~ 12.3-21.0 %). Some mafic rocks are rich in MgO (~ 9.0-13.4 %), Ni and Cr and have lower SiO_2, Al_2O_3 and FeO_{tot} compared to the high-Al basalts, and are considered to represent primitive mantle compositions (e.g., Morra *et al.*, 1997; Mattioli *et al.*, 2000; Franciosi *et al.*, 2003). Major element variation from the high-Mg basalts to high-Al basalts are consistent with crystal/liquid fractionation dominated by olivine and clinopyroxene (Morra *et al.*, 1997).

K_2O/Na_2O ratios for samples with MgO > 3% are generally less than unity ad show positive correlations with SiO_2. Most of the incompatible trace elements (e.g., Rb, Th, U, HFSE, LREE) increase continuously with increasing SiO_2, whereas Sr generally decreases with magma evolution. Ba increases constantly up to SiO_2 ~ 70% and then drops abruptly passing to the peralkaline rhyolites. The last show also extreme enrichments in Nb (up to 140 ppm) and Zr (up to 1120 ppm).

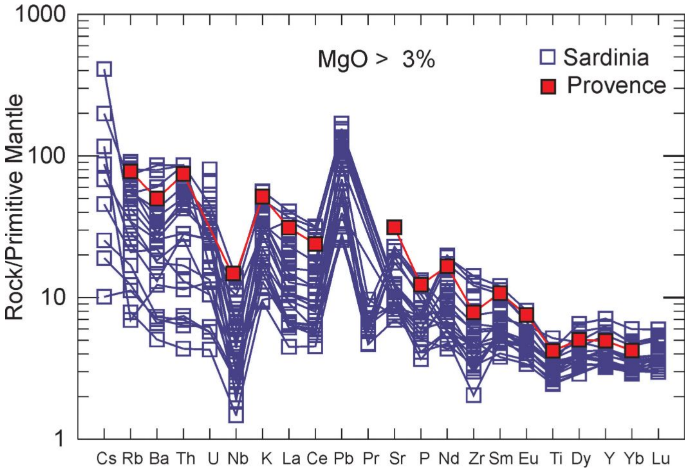
Figure 17. Alkali-silica diagrams of Oligo-Miocene rocks, Sardinia



A - TAS and B - K_2O vs. SiO_2 classification diagrams for Sardinian orogenic igneous rocks. Some data for southern France (Provence) are also reported. Dashed line is the divide between subalkaline and alkaline rocks (Irvine & Baragar, 1971).

Trace element features of the least differentiated samples (MgO > 3%) are typical of subduction-related magmas. Mantle-normalized trace element patterns (Fig. 18) exhibit enrichments of LILE over HFSE, with pronounced K, Pb and Sr positive anomalies. REE patterns of mafic rocks show variable and generally low LREE/HREE fractionation, with La_NYb_N mostly < 8 and La generally below 100 times chondrite. Eu negative anomalies are generally absent and when present are small.

Figure 18. Spider-diagrams of Oligo-Miocene rocks, Sardinia

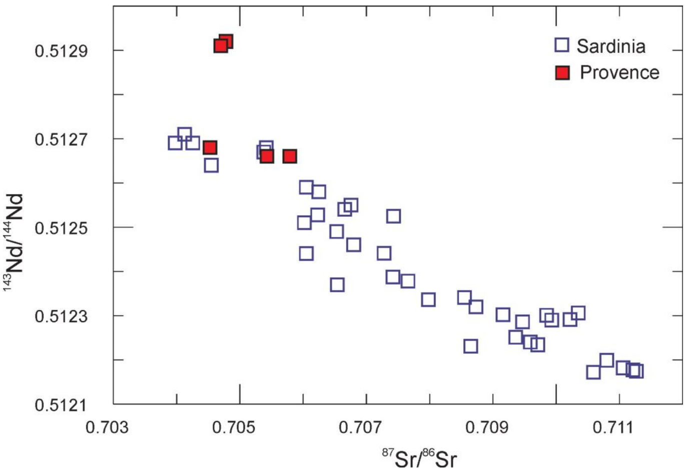


Incompatible element patterns normalized to primordial mantle composition for mafic rocks (MgO > 3%) from Sardinia and Provence (Southern France).

Sr isotope compositions are close to mantle values for the most basic rocks ($^{87}Sr/^{86}Sr$ ~ 0.704) and become progressively more radiogenic in the intermediate to felsic compositions. In particular, in a $^{87}Sr/^{86}Sr$ versus SiO_2 diagram (not shown) two distinct trends are evident, stemming from common relatively low $^{87}Sr/^{86}Sr$ (< 0.705) mafic compositions (SiO_2 < 50%). One trend is characterized by a steep increase of $^{87}Sr/^{86}Sr$ up to ~ 0.7113, whereas the other trend shows a sharp increase in the mafic to intermediate composition, and becomes flat in the acidic rocks, in which values of $^{87}Sr/^{86}Sr$, ~ 0.7065-0.7075 are observed. The peralkaline felsic samples plot at the high-SiO_2 end of this second trend while the steep section of the trend is defined by basaltic to andesitic lavas from the Mt. Arcuentu area in south-western Sardinia. The Mt. Arcuentu lavas have also high whole-rock $\delta^{18}O$ values, ranging from +6.4‰ in basalts to +12.4‰ in andesites. Clinopyroxene phenocrysts $\delta^{18}O$ values for the same lavas are generally lower and in the range +6.17 to +7.46‰ (Downes *et al.*, 2001). The differences between whole-rock and clinopyroxene $\delta^{18}O$ values are probably do to late stage alteration of the ground mass (Downes *et al.*, 2001).

Nd isotope ratios (= 0.51271-0.51217) exhibit the usual negative correlation with $^{87}Sr/^{86}Sr$ (Fig. 19). Pb isotopes for Sardinian orogenic magmas are moderately variable with $^{206}Pb/^{204}Pb$ ~ 18.53-18.75, $^{207}Pb/^{204}Pb$ ~ 15.62-15.68 and $^{208}Pb/^{204}Pb$ ~ 38.39-39.11.

Figure 19. Sr-Nd isotopes of Oligo-Miocene rocks, Sardinia



Sr-Nd isotopic compositions of Sardinian orogenic igneous rocks. Data for southern France (Provence) are also reported (bleu squares).

Modest fractionation of REE have been suggested to reflect a magma origin from a MORB-type spinel-bearing lherzolite mantle source metasomatized by fluids/ melts released from subducted oceanic crust (Morra *et al.*, 1997). Franciosi *et al.* (2003) modelled trace element and isotopic compositions of the basaltic magmas with about 15% partial melting of MORB-like mantle source metasomatized by 0.1-0.5% fluid derived from altered MORB and less than 0.1% fluid derived from sediment. Fluid-induced rather than melt-induced mantle metasomatism was inferred mainly on the basis of the low Th/ Pb and Th/Nd ratios displayed by the basaltic magmas (Franciosi *et al.*, 2003). On the other hand, Downes *et al.* (2001) attributed the strong correlation of radiogenic isotope ratios with SiO_2 displayed by Mt. Arcuentu lavas, to addition of variable large amounts (2-10%) of subducted siliceous sediment to a depleted MORB-source. However, other authors (e.g., Franciosi *et al.*, 2003) favour high degrees of crustal assimilation by ascending magmas.

In general, assimilation-fractional crystallization is considered to be the main process controlling the evolution of the Sardinian tertiary orogenic magmatism and responsible for the geochemical and isotopic characteristics (e.g., high $^{87}Sr/^{86}Sr$) of the prevailing dacitic to rhyolitic lavas, including the peralkaline trachytic-rhyolitic rocks (e.g., Morra *et al.*, 1994; Caron & Orgeval, 1996; Morra *et al.*, 1997; Franciosi *et al.*, 2003; Lustrino *et al.*, 2004). Regarding the peralkaline felsic lavas from the Sulcis region, these can be derived from the same parental subalkaline magma that gave the calcalkaline lavas. Crystal/liquid fractionation processes involved first separation of plagioclase-pyroxene and then separation of plagioclase plus K-feldspar, promoting the jump from subalkaline to peralkaline compositions (Morra *et al.*, 1994).

Summary

The geochemical and isotopic characteristics displayed by the Eocene-Miocene magmatism found in Sardinia are best explained by origin from a MORB-type mantle source variably metasomatized by fluids released from subducting oceanic lithosphere, with a minor contributions from sedimentary material. Magma differentiation was dominated by fractional crystallization and crustal assimilation processes.

The limited geochemical and isotopic data available for the volcanic and subvolcanic bodies outcropping in the neighbouring areas of Sardinia (e.g., southern France, Liguro-Provençal Sea and Corsica) do not allow to comprehensively infer source characteristics and magma differentiation processes for these igneous products. However, the close spatial distribution, the overlapping ages and the similar petrographic characteristics and calcalkaline affinities strongly suggests a common origin with the orogenic magmatism occurring in Sardinia.

The subduction-related geochemical characteristics of the Eocene-Miocene igneous rocks occurring in the areas surrounding and within the Liguro-Provençal basin are generally believed to be related to concomitant northwestward Apennine subduction (Lustrino *et al.*, 2009 and references therein). However, some authors (e.g., Schettino & Turco, 2006) have also proposed that the Tertiary orogenic magmatism of Sardinia and surrounding areas, including volcaniclastic deposits of the Apennines, was related to south-eastward subduction of the Valais ocean along the westernmost continuation of the Alpine orogenic system.

Tyrrhenian Sea and the Italian Peninsula

Introduction

Orogenic magmatic activity in the Tyrrhenian Sea and the Italian peninsula took place from the Miocene to the present. There is a temporal continuum from the Oligocene to Miocene magmatism of Sardinia to the orogenic magmatic cycle developed in the Tyrrhenian basin and the Italian peninsula, the all becoming younger southeastward (Table 1). Within single areas, orogenic magmatism is spatially associated with MORB-type to Na-alkaline anorogenic rocks (see Bianchini & Beccaluva, this issue), the latter being younger than orogenic activity. The orogenic magmas are directly related to the south-eastward rollback of the NW-dipping Adriatic-Ionian subduction zones, whereas anorogenic activity reflects backarc extension processes, which follow subduction hinge retreat and are responsible for the opening of the Tyrrhenian basin and the anticlockwise rotation of the Italian peninsula.

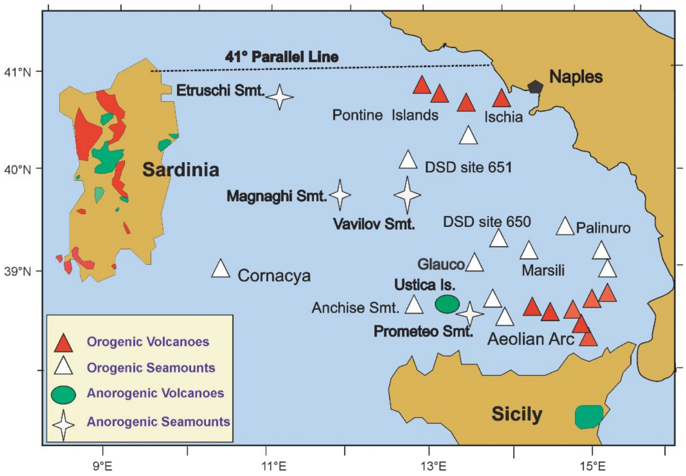
Orogenic magmatism in the Tyrrhenian Sea and the Italian peninsula shows extremely variable petrological and geochemical compositions, ranging from arc tholeiitic to calcalkaline, shoshonitic and potassic alkaline (Peccerillo, 2005a). Based on age of emplacement, petrological affinity, and geochemical characteristics of volcanic rocks (Tables 1, 2), several magmatic provinces or zone have been distinguished (see Fig. 41, 42; Peccerillo, 2002). These zones are:

1 – TYRRHENIAN SEA BASIN
a – Central Tyrrhenian Sea floor and seamounts
b – Aeolian Arc and associated seamounts
2 – ITALIAN PENINSULA
a – Mount Vulture, Campanian Province and the Pontine Islands
b – Ernici-Roccamonfina
c – Latium Province or Roman Province s.s.
d – Intra Apennine Province (IAP)
e - Tuscany Province

Tyrrhenian Sea Basin

The Tyrrhenian Sea is an extensional basin developed between about 15 Ma and present, between Corsica-Sardinia block and the Apennine-Maghrebide collisional chain (Carminati *et al.*, this volume). The triangular shape of the Tyrrhenian Sea is the result of a variable degree of extension, which increases from north to south. A major W-E trending lithospheric structural discontinuity crosses the Tyrrhenian Sea. This is known as the 41st Parallel Line (Fig. 20), and continues inland across the Italian peninsula (e.g., Serri, 1990; Bruno *et al.*, 2000). As a consequence of variable extension, the nature and thickness of the crust and the intensity of igneous activity are variable in the southern and in the northern Tyrrhenian Sea. Crustal thickness in the southern Tyrrhenian Sea ranges approximately between 20 to 25 km to less than 10 km, going from the basin margins to the Marsili and Vavilov basins. Moreover, magmatic activity is much more intense in the southern than in the northern Tyrrhenian Sea.

Figure 20. Tyrrhenian Sea magmatism



Distribution of orogenic volcanism in the Tyrrhenian Sea basin. Some anorogenic volcanoes and seamounts are also reported.

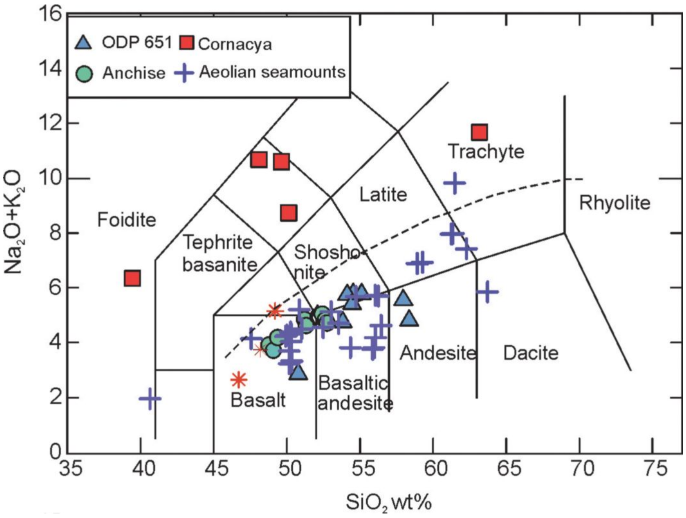
The upper mantle beneath the Tyrrhenian Sea basin is characterised by occurrence of a 20-30 km thick layer with relatively low values of S-wave velocity (Vs ~ 4.0 to 4.2 km/s). This extends westward beneath Sardinia and the Balearic Sea at a depth of about 80-120 km, and rises to shallower level in the southern and southeastern Tyrrhenian basin (Panza *et al.*, 2007; Peccerillo *et al.*, 2008a; Frezzotti *et al.*, 2009). The occurrence of such a layer has been interpreted as an effect of occurrence of compositionally anomalous mantle rocks, left behind the Ionian-Adriatic slab during its Oligocene to present southeastward retreat.

Igneous activity within the Tyrrhenian Sea basin is variable in age, intensity and composition. In the north, igneous rocks are scarce and belong to the Tuscany Magmatic Province, which will be described later in this paper. In the central-southern sectors, a wide variety of magmas were erupted from Miocene to present. These include three broad groups, which have MORB, OIB and island-arc geochemical signatures. The latter consist of several submarine centers plus the exposed volcanoes of the Aeolian Arc. Although treated separately, there is a continuum in the orogenic activity from Sardinia to the central Tyrrhenian basin and the Aeolian Arc, as a consequence of continuous retreat of the Ionian subduction zone toward the south-east.

Tyrrhenian Sea floor

Orogenic volcanic centres on the Tyrrhenian Sea floor have been found at several places. Older occurrences are Cornacya (12 Ma), Anchise seamount (5.2 to 3.6 Ma), ODP sites 650 and 651 (3 to 1.7 Ma). Marsili (0.8 to present) and other Aeolian seamounts (Sisifo, Enarete, Eolo, Lametini, Alcione, Palinuro) are located in the southeastern sector of the Tyrrhenian basin (Figs. 20, 22). There is a decreasing in age from west to southeastesrn Tyrrhenian basin, where active volcanoes are present.

Figure 21. TAS of Tyrrhenian Sea orogenic seamounts



Total Alkali vs. Silica (TAS) diagram for Tyrrhenian Sea floor orogenic volcanoes. Data have been recalculated on a water-free basis. The dashed line is the boundary between subalkaline and alkaline magmas (Irvine & Baragar, 1971).

The TAS diagram based on oxide concentrations recalculated on a water-free basis for some occurrences is shown in Fig. 21.

Cornacya is an about 12 Ma old volcano located SE of the southern Sardinian coast, and consisting of strongly altered (LOI up to about 23 wt %) lavas that contain enclaves of mica-rich lamprophyres. Lava textures are porphyritic with phenocrysts of plagioclase and biotite and minor amphibole and clinopyroxene, surrounded by an altered glassy matrix containing Na-rich plagioclase, anorthoclase, biotite, and secondary products. The lamprophyric enclaves are porphyritic with phenocrysts of altered olivine, amphibole and phlogopite. A shoshonitic to ultrapotassic lamproitic affinity is indicated by immobile element contents for lavas and enclaves, which respectively resemble shoshonites and lamproites from Tuscany (Mascle *et al.*, 2001).

ODP 651 Site is characterised by basaltic lava and sill associated with sediments and serpentinised peridotites (Bonatti *et al.*, 1990). $^{40}Ar/^{39}Ar$ dating indicates an age of approximately 3.0 to 2.6 Ma (Feraud, 1990). Volcanic rocks have a microcrystalline to moderately porphyritic texture with microphenocrysts of altered olivine, plagioclase, clinopyroxene and some biotite (Bertrand *et al.*, 1990). Secondary phases such as clay minerals, zeolites, Fe-hydroxides and carbonates are common. Incompatible element patterns of lavas and radiogenic isotope signatures show affinities with the calcalkaline (CA) and high-K calcalkaline (HKCA) rocks from Stromboli (Beccaluva *et al.*, 1990).

ODP 650 Site (Marsili basin) contains basaltic rocks beneath an approximately 600 m thick pile of sediments. Magnetostratigraphic and biostratigraphic age for the base of sedimentary pile is 1.9 to 1.7 Ma. Volcanic rocks consist of vesicular altered basalts, containing plagioclase, olivine, clinopyroxene and altered glass mesostasis. Petrogenetic affinity of these rocks is uncertain, because of severe alteration, although a similarity with Stromboli calcalkaline basaltic andesites has been recognised by Beccaluva *et al.* (1990) on the basis of incompatible element ratios.

Central Tyrrhenian arc. Volcanic occurrences forming a sort of arc crossing the entire central-eastern Tyrrhenian Sea, from offshore north-western Sicily to the western Pontine islands and the Neapolitan area, have been suggested to represent an unique structure (Locardi, 1986). Volcanic centres include the Anchise seamount in the south, some volcanoes in the central Tyrrhenian Sea (Site 650 and Glauco), the buried andesitic rocks of the Campanian plain (Parete-2 well), and the volcanic island of Ponza and surrounding islets. Data are available only for some occurrences. Compositions range from mafic to felsic, the latter being concentrated at Ponza and surrounding islets.

Anchise seamount is a 5.2 to 3.6 Ma volcano (Savelli, 1988) situated west of the Na-alkaline island of Ustica. Collected lavas have a vesicular porphyritic texture, with phenocrysts of clinopyroxene, plagioclase, and minor olivine surrounded by a groundmass of the same phases plus Fe-Ti oxides, sanidine and minor biotite and glass

(Calanchi *et al.*, 1984). Major element data indicate a mafic high-K calcalkaline to shoshonitic (SHO) composition, whereas the few available trace elements exhibit enrichment in Rb and depletion in Ti, Nb and Zr.

Ponza, Palmarola and Zannone make up the western sector of the Pontine Archipelago. Exposed products consist of rhyolitic to trachytic obsidian lava flows and domes, dikes, and pyroclastic deposits. K/Ar dating on sanidines indicates ages of 4.2 and 3.0 Ma for Ponza rhyolites, 1.0 Ma for trachytic activity from the same island, and 1.6 Ma for Palmarola (Cadoux *et al.*, 2005; Cadoux *et al.*, 2007). Rhyolites are calcalkaline in composition, although some late-erupted products are peralkaline (Conte & Dolfi, 2002).

Major, trace element and isotopic compositions of western Pontine islands are variable with peralkaline rhyolites strongly enriched in Rb, Th and other incompatible elements. REE patterns are fractionated, with negative Eu anomalies. ^{87}Sr/^{86}Sr are about 0.7085 to 0.7104 in the trachytes and about 0.7105 in the rhyolites. Nd isotopic ratio is higher in the trachytes (^{143}Nd/^{144}Nd ~ 0.51240) than in the rhyolites (^{143}Nd/^{144}Nd ~ 0.51225; Conte and Dolfi, 2002). Pb isotopic ratios are homogeneous (^{206}Pb/^{204}Pb ~ 18.80, ^{207}Pb/^{204}Pb ~ 16.80, and ^{208}Pb/^{204}Pb ~ 39.00; Cadoux *et al.*, 2007). Oxygen isotope composition from whole rocks and separated feldspars ranges from δ^{18}O ~ +7.3 to + 11.1, showing an increase from trachytes to rhyolites (Turi *et al.*, 1991). Rhyolites from the western Pontine Islands have a composition suggesting a derivation from a basalt or andesite parent by fractional crystallisation plus crustal assimilation (AFC). The same processes have been suggested for generation of trachytes, but a moderately potassic alkaline parents has been suggested (Conte & Dolfi, 2002; Cadoux *et al.*, 2005). This has led to conclusion that the western Pontine islands experienced a transition from calcalkaline to potassic alkaline volcanism from early to late exposed activity (Conte & Dolfi, 2002; Cadoux *et al.*, 2005).

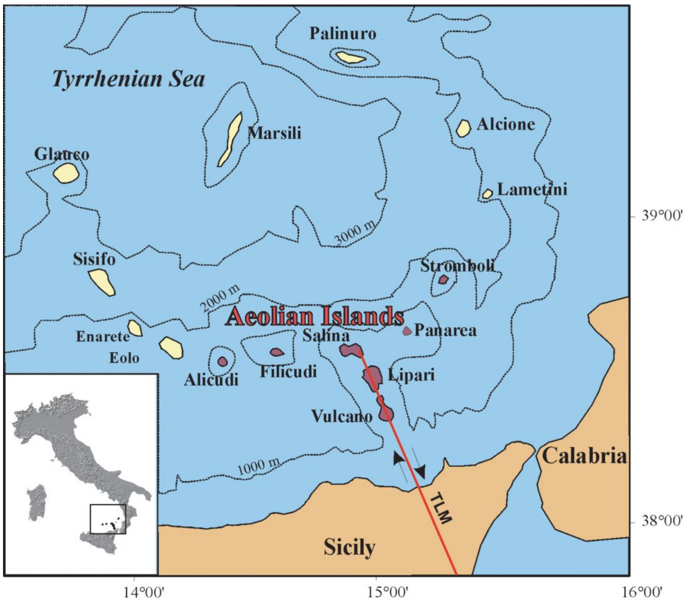
Parete-2 volcanics have been encountered by deep drilling in the Campanian Plain, north of the Campi Flegrei caldera. Here, a large calcalkaline basalt to andesite volcano occurs at depths of 300 to 1900 m, beneath the potassic alkaline suite of Campi Flegrei (Di Girolamo *et al.*, 1976; Barbieri *et al.*, 1979; Albini *et al.*, 1980). The lavas at the bottom of the drilled volcanic sequence have an age around 2 Ma. Rocks are porphyritic with phenocrysts of plagioclase, clino- and orthopyroxene and a few biotite. Sr isotopic ratios are relatively radiogenic and overlap the composition of Vesuvio and Campi Flegrei.

Overall, the Central Tyrrhenian arc could represent a remnant volcanic arc left behind by the retreating Ionian slab (Savelli, 1988, 2001; Argnani & Savelli, 1999). In the south, activity shifted toward the east and concentrated in the Marsili basin and the Aeolian Arc. In the northern end, activity also shifted partially to the east, but displacement was much smaller, because of the lower degree of extension of the Tyrrhenian basin. As a result the superimposition of subalkaline and potassic alkaline volcanism occurred in some areas, such as the western Pontine islands and especially in the Campi Flegrei area.

Aeolian Arc and related seamounts

The Aeolian Arc has developed over a continental crust of the Calabro-Peloritano basement, a fragment of the European plate, which detached from the Corsica-Sardinia block and migrated southeastward during the Miocene to Quaternary opening of the Tyrrhenian Sea. The Aeolian Arc consists of large volcanoes forming seven main islands and several seamounts (Fig. 22). Age of volcanic activity exposed at the surface goes from about 400 ka to the present (Gillot, 1987).

Figure 22. Aeolian arc and related seamounts

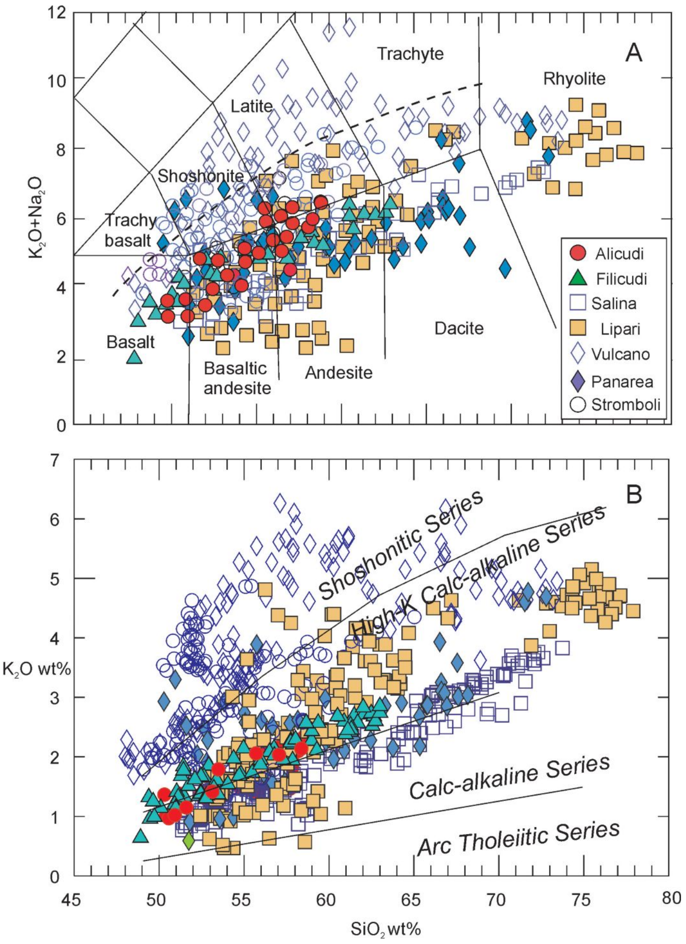


Distribution of Aeolian islands and seamounts. TLM is the Tindari-Letojanni-Malta fault, separating the western and eastern sectors of the arc.

Rocks show a wide range of compositions, from mafic to silicic with calcalkaline (CA) to shoshonitic (SHO) and potassic alkaline affinities (Fig. 23) (e.g., Keller, 1982; Francalanci *et al.*, 2004; Peccerillo, 2005a). A few rocks with an arc tholeiitic composition have been found among dredged samples along seamounts (Beccaluva *et al.*, 1982). Textures are generally porphyritic with ubiquitous plagioclase and clinopyroxene phenocrysts plus olivine in the mafic rocks and orthopyroxene in the calcalkaline intermediate lavas. Biotite and amphibole is present in some intermediate rocks, whereas sanidine appears in the rhyolites. Leucite is observed in some mafic to intermediate potassic rocks from Vulcano and Stromboli. Various types of xenoliths are found in the Aeolian Arc rocks, including fragments from the basement and cumulate igneous rocks. Small ultramafic xenoliths have been found at Alicudi and Stromboli (Peccerillo *et al.*, 2004; Laiolo & Cigolini, 2006).

Three main sectors have been distinguished in the Aeolian Archipelago, showing distinct compositions of volcanic products, ages and volcanological-structural features (Peccerillo, 2005a). The western sector is formed by the islands of Alicudi and Filicudi along a E-W trending fracture system, and has an age of about 0.4 Ma to 20 ka (Keller, 1980; Gillot, 1987). Volcanic rocks mostly consist of mafic to intermediate rocks with a calcalkaline to high-K calcalkaline affinity. A few dacites occur at Filicudi. Rocks show the most primitive compositions over the entire Aeolian Arc, and basalts from Alicudi have Mg#, Cr and Ni abundances not far from values of mantle equilibrated melts. Seismic activity is restricted to the upper 20 km in this sector, and no deep earthquakes have been detected.

Figure 23. Alkali-silica diagrams, Aeolian Arc



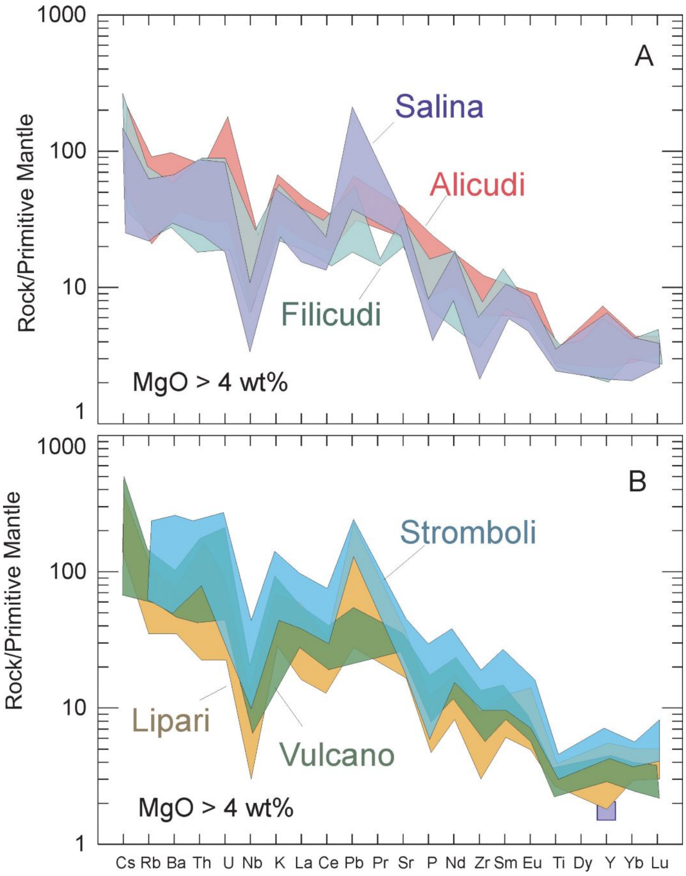
A - TAS and B - K_2O vs. SiO_2 classification diagrams for the Aeolian Arc volcanics. The dashed line on TAS diagram is the boundary between subalkaline and alkaline magmas (Irvine & Baragar, 1971).

The central sector is formed by the islands of Salina, Lipari and Vulcano. The latter islands are aligned along the NNW-SSE striking Tindari-Letojanni-Malta (TLM) fault system (Fig. 22), a major dextral strike-slip lithospheric fault cutting the Aeolian Arc and running until eastern Sicily and the Malta escarpment. Salina is at the intersection between TLM fault and the western arc tectonic structure. The exposed rocks in the central islands have an age between about 0.4 Ma to present, and have been erupted by both effusive and explosive activity. Youngest activity at Lipari took place at about 580 AD, whereas the latest eruption at Vulcano occurred from 1888 to 1890 AD (Mercalli & Silvestri, 1891). Volcanism developed within pull-apart basins along the main fault system. Rock composition ranges from basaltic to rhyolitic, with CA, HKCA and SHO affinity. Some leucite-bearing potassic alkaline rocks occur at Vulcano. Rhyolitic magmas are typical of central Aeolian islands and are very abundant at Lipari and Vulcano. Temporally, silicic magmas are restricted to the last 40 ka. Seismicity is still shallow and concentrated along the Tindari-Letojanni-Malta fault.

The eastern sector is formed by Panarea and Stromboli, developed along NE-SW faults. The exposed rocks have ages between about 0.2 Ma and present. Rock compositions range from mafic to silicic, and have a calcalkaline, shoshonitic to potassic alkaline affinity. Calcalkaline-shoshonitic intermediate to rhyolitic rocks form the bulk of the Panarea Island and surrounding islets. Stromboli rocks are mafic to intermediate in composition and range from calcalkaline to potassic alkaline, with an irregular increase of potassium with time. The present-day activity erupts shoshonitic basalt strombolian scoriae and lava flows. Deep seismic activity occurs beneath the eastern arc, with earthquake foci defining a narrow and steep NNW dipping Benioff plane that extends up to the Neapolitan area where about 500 km deep earthquakes have been detected (e.g., Falsaperla *et al.*, 1999; Panza *et al.*, 2003, 2004).

Alicudi consists of calcalkaline basalt, basaltic andesite and andesite lava flows and domes, and minor pyroclastics (Fig. 23a). Incompatible element patterns are fractionated and show negative anomalies of HFSE, and small positive spikes of Sr and Pb (Peccerillo *et al.*, 2004; Fig. 24a). Sr isotope compositions are the lowest in the Aeolian Arc ($^{87}Sr/^{86}Sr$ = 0.70343 to 0.70406), and decrease from basalt to andesites. Nd isotope ratios are the highest ($^{143}Nd/^{144}Nd$ = 0.51280 to 0.51290; Fig. 25a), and show the usual negative correlation with Sr isotopes. Pb-isotope ratios are moderately radiogenic ($^{206}Pb/^{204}Pb$ ~ 19.19 to 19.67; $^{207}Pb/^{204}Pb$ ~ 15.62 to 15.67; $^{208}Pb/^{204}Pb$ ~ 39.07 to 39.36; Fig. 25b), and slightly increase from basalts to andesites. Oxygen isotope ratios on separated clinopyroxenes range between $\delta^{18}O$ ~ +5.0 to +5.6, with a rough positive correlation with $^{87}Sr/^{86}Sr$ (Peccerillo *et al.*, 2004). He-isotope composition measured on olivine and pyroxene phenocrysts has R/R_A around 6.5 to 7.1 (Martelli *et al.*, 2008).

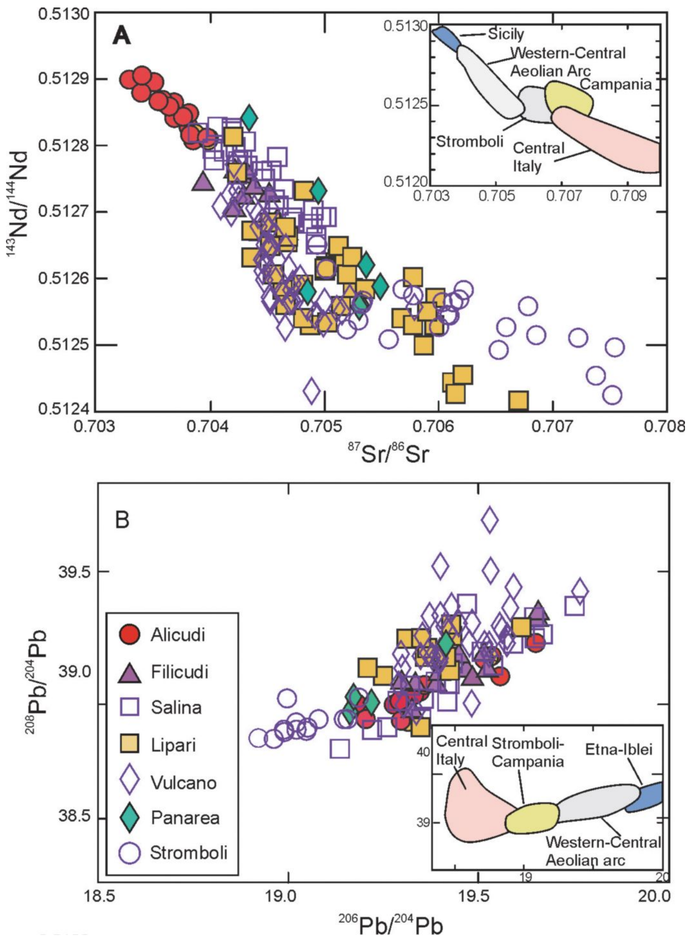
Figure 24. Spider-diagrams, Aeolian Arc



Incompatible element patterns normalized to primordial mantle composition for mafic rocks (MgO > 4%) from the Aeolian Arc.

Filicudi consists of calcalkaline basalt to high-K calcalkaline andesite and dacite lava flows, domes, and pyroclastic products. Mantle-normalised incompatible trace element patterns of mafic rocks are similar to Alicudi, whereas Sr-isotope ratios ($^{87}Sr/^{86}Sr$ ~ 0.70401 to 0.70474) are slightly higher and Nd-isotope ratios lower ($^{143}Nd/^{144}Nd$ = 0.51267 to 0.51276). Pb-isotope are in the range $^{206}Pb/^{204}Pb$ ~19.31 to 19.67; $^{207}Pb/^{204}Pb$ ~ 15.64 to 15.69; $^{208}Pb/^{204}Pb$ ~ 39.11 to 39.47 (Fig. 25; Santo *et al.*, 2004).

Figure 25. Radiogenic isotope variations, Aeolian Arc



Sr-Nd-Pb isotopic compositions of Aeolian Arc volcanics. Symbols as in Fig. 23.

Salina is sited at the intersection between the E-W trending Alicudi-Filicudi alignment and the Tindari-Letojanni-Malta fault system. The island is characterised by the two well-preserved symmetrical cones of Monte Felci and Monte Porri, which were constructed upon older products of the eroded Rivi, Capo and Corvo volcanoes. Age of the exposed products ranges between about 400 to 13 ka (Keller, 1980; Gillot, 1987).

Rocks range in composition from CA basalts to rhyolites (Fig. 23). Trace element abundances are variable, and LILE/HFSE ratios (e.g., Ba/Ta, La/Nb, Th/Ta) are generally higher than observed in other Aeolian magmas (Fig. 24a).

Sr-isotope ratios (0.70397 to 0.70507) and oxygen isotope ratios on whole rocks (δ^{18}O‰ = +6.4 to +8.5) increase slightly with decreasing MgO (Gertisser & Keller, 2000). Nd isotopes (0.51265 to 0.512815) and Pb isotopes are moderately radiogenic (^{206}Pb/^{204}Pb ~ 19.30 to 19.66, ^{207}Pb/^{204}Pb ~ 15.61 to 15.77, ^{208}Pb/^{204}Pb ~ 39.15 to 39.51) (Fig. 25).

Lipari is the largest of the Aeolian islands. Exposed products have an age ranging from about 220 ka to late Roman times (about 580 AD). Rock compositions range from CA basaltic andesite to rhyolite (Fig. 23). Early activity erupted basaltic andesitic and andesitic lavas and pyroclastic products. These were followed by high-K andesites and minor dacites. Strongly explosive eruptions from centres located between Lipari and Vulcano (70 to 13 ka) deposited high-K calcalkaline to shoshonitic pyroclastic products (the so-called Brown Tuffs). Younger activity gave acidic obsidian lava flows, domes and pumices.

Major and trace element variations show scattering, and distinct variation trends for some trace elements have been found (e.g., Crisci *et al.*, 1991). Incompatible element patterns are fractionated with negative anomalies of HFSE and positive spikes of Sr and Pb in the mafic rocks (Fig. 24b). Sr, Nd and Pb isotopic compositions (^{87}Sr/^{86}Sr = 0.7043 to 0.7067; ^{143}Nd/^{144}Nd = 0.51276 to 0.51242; ^{206}Pb/^{204}Pb = 18.46 to 19.63; ^{207}Pb/^{204}Pb = 15.61 to 15.71; ^{208}Pb/^{204}Pb = 39.05 to 39.43) exhibit strong variations indicating significant interaction with crust, a process that is testified by the occurrence of andesitic rocks containing xenocrysts of cordierite, garnet and sillimanite (Barker, 1987; Di Martino *et al.*, 2011).

Vulcano is the second largest island and one of the active centres of the archipelago. It consists of several superimposed volcanic centres, with two large intersecting calderas. Exposed activity started in the southern sector of the island where a stratovolcano (Primordial Vulcano) with a central caldera was constructed. Successively, the activity shifted northward where a second caldera collapse formed (Caldera della Fossa). Historical and present activity is concentrated in the centre (La Fossa Cone) and at the northern border (Vulcanello) of the Fossa caldera. The latest eruption took place at La Fossa Cone in 1888-1890 and was characterised by explosive emplacement of abundant juvenile and accessory pyroclastics. This eruption, later used to define “vulcanian” explosions was carefully described by Mercalli & Silvestri (1891) in a paper, which is considered as a milestone of descriptive volcanology.

Rock compositions at Vulcano range from mafic to felsic, with high-K calcalkaline to shoshonitic and potassic alkaline (Potassic Series: KS) affinities (Fig. 23b).

Calcalkaline rocks are lacking among the outcropping products. As at Lipari, there is an increase in silica with time. However, enrichments in potassium and incompatible elements are stronger at Vulcano and potassic alkaline rocks containing leucite are erupted especially during historical activity at Vulcanello, at the northern tip of the island.

HKCA rocks (Primordial Vulcano) have lower incompatible element abundances than younger shoshonitic and potassic products (De Astis *et al.*, 1997). Patterns of incompatible elements of mafic rocks show similar shape but overall higher element abundances than at Lipari (Fig. 24b). Sr-isotope ratios range from 0.7042 to 0.7059. When only the most primitive rocks are considered, HKCA rocks from Primordial Vulcano show less radiogenic Sr isotopic compositions than younger SHO and KS rocks (De Astis *et al.*, 1997). He-isotope composition measured on olivine and pyroxene phenocrysts gave values of $R/R_A \sim 2.3$ to 4.9 (Martelli *et al.*, 2008).

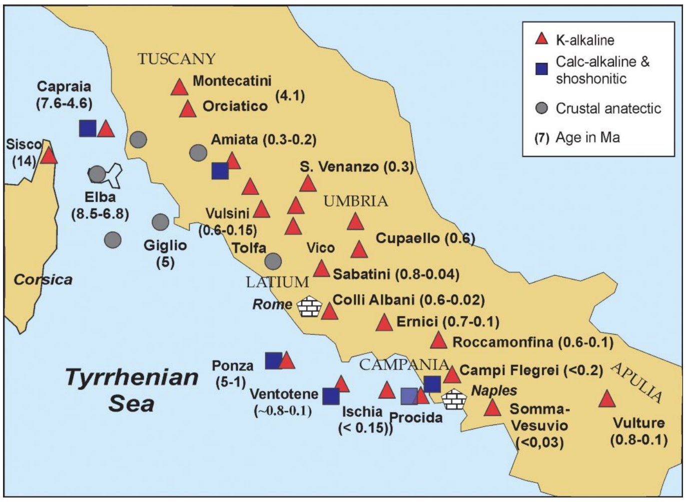
Panarea and surrounding islets are the emergent remnants of a large composite volcano rising about 1700 m above sea floor and forming a flat platform at a depth of about 100-150 m below sea level. Exposed rocks have a dominant CA to HKCA andesitic, dacitic and rhyolitic composition, but a larger range of magma types is evidenced by lithic clasts that reveal the occurrence of shoshonitic basalts and shoshonites. Ages range between about 150 and 45 ka.

Major and trace element compositions of Panarea volcanics show an increase of incompatible element contents from calcalkaline to HKCA and SHO rocks at comparable degree of evolution (Calanchi *et al.*, 2002). Mantle normalised incompatible element patterns show high LILE/HFSE ratios and a positive spike of Pb. Sr isotope ratios ($^{87}Sr/^{86}Sr$ = 0.7040 to 0.7057) increase from calcalkaline to shoshonitic rocks, whereas the few available Nd and Pb isotopic data do not show any significant trend ($^{143}Nd/^{144}Nd$ = 0.51284 to 0.51257; $^{206}Pb/^{204}Pb$ = 18.18 to 19.43; $^{207}Pb/^{204}Pb$ = 15.67-15.71; $^{208}Pb/^{204}Pb$ = 39.13-39.36). Overall, Panarea calcalkaline rocks have isotopic signatures and incompatible trace element ratios that are similar to those of the western Aeolian Arc. In contrast, geochemical and isotopic compositions of HKCA and SHO rocks are midway between the western arc and Stromboli.

Stromboli and the nearby islet of Strombolicchio represent the top of a structure that rises about 2000 m above the sea floor, and reaches 924 m above sea level. Age of the outcropping rocks is about 200 ka at Strombolicchio and between about 100 ka and present at Stromboli (Condomines & Allegre, 1980; Gillot, 1987; Gillot & Keller, 1993). Compositions range from mafic to intermediate, with calcalkaline and high-K calcalkaline to shoshonitic and potassic alkaline (KS) affinities (Francalanci *et al.*, 1993a). Calcalkaline rocks are minor with respect to dominant HKCA, SHO and KS products. KS rocks contain leucite. Overall, there is an increase in potassium with time, but with many irregularities. The present-day activity erupts shoshonitic basaltic lavas and scoriae by continuous "strombolian" mild explosions, and occasional outpouring of lava flows (Rosi, 1980; Francalanci *et al.*, 1989; Bertagnini *et al.*, 2003). Craters are located on a terrace at the top of a large depression bounded by parallel faults, known as Sciara del Fuoco.

In general there is an increase in incompatible element abundances from CA to HKCA, SHO and KS rocks, along with increase in potassium. Sr-isotope ratios ($^{87}Sr/^{86}Sr$ = 0.70500 -0.70757) also increase the same way, reaching the most radiogenic compositions in the KS. $^{143}Nd/^{144}Nd$ (= 0.51265 to 0.51243) decreases with increasing potassium. Pb isotopic compositions are less radiogenic than at other Aeolian islands ($^{206}Pb/^{204}Pb$ = 18.93 to 19.09; $^{207}Pb/^{204}Pb$ = 15.64 to 15.70; $^{208}Pb/^{204}Pb$ = 39.01 to 39.16; Fig. 25). Incompatible element patterns show moderate HFSE negative anomalies (Fig. 24). He-isotope compositions show R/R_A ratios of about 2.4 to 4.6, the lowest in the Aeolian Arc (Martelli *et al.*, 2008). In general, the Stromboli rocks have very similar radiogenic isotope compositions and ratios of several incompatible elements as those from the Campania volcanoes (Peccerillo, 2001a).

Figure 26. Central Italy volcanoes



Distribution of orogenic magmatism in central Italy. Note that ages, indicated in parentheses, decrease souteastward.

Aeolian Seamounts

There are several seamounts located to the northwest (Sisifo, Enarete, Eolo) and to the northeast (Lametini, Alcione, Palinuro) of the Aeolian Archipelago, defining a horseshoe-type pattern around the Marsili volcano and basin (Fig. 22). Another center has been recently discovered offshore Calabria (De Ritis *et al.*, 2010), and has been suggested to be the source of pyroclastic rocks commonly found in Callabria. Geochronological data of Beccaluva *et al.* (1985) and Trua *et al.* (2002, 2004) indicate ages from 1.3 to less than 0.1 Ma for Aeolian seamounts. Based on available data, compositions are mostly calcalkaline (Marsili, Sisifo, Eolo, Palinuro, Alcione) to shoshonitic (Enarete, Eolo, Sisifo), with a few arc tholeiitic basalts (Lametini and southern Marsili basin).

Marsili is the best studied of the Aeolian seamounts. It is huge (about 60 km long) NNE-SSW elongated structure, rising about 3000 m above the center of the Marsili basin, an area affected by extremely high degree of extension (Nicolosi *et al.* 2006). Rocks from Marsili seamount consist of calcalkaline basalts a few high-K andesites. Compositions of basalts reveal the occurrence of two types of primary magmas, exhibiting different enrichments in incompatible elements and LILE/HFSE ratios (Trua *et al.*, 2002, 2004 and references therein). Sr- and Nd-isotope ratios show a wide range of values (^{87}Sr/^{86}Sr ~ 0.7032 to 0.7052; ^{143}Nd/^{144}Nd ~ 0.5127 to 0.5129), with the most radiogenic-Sr compositions being found in the rocks with higher LILE/HFSE ratios (Trua *et al.*, 2004).

Petrogenesis of Aeolian Arc magmas

The Aeolian Arc volcanics have variable compositions both at local and regional scale. These can be summarised as follows:

1 – The islands of Alicudi, Filicudi and Stromboli, sited at the western and eastern ends of the arc, have compositions ranging from mafic to intermediate, with the absence of acid rocks. The islands of Panarea and Salina contain some rhyolites. Acid rocks become extremely abundant at Vulcano and Lipari, in the center of the archipelago. Rhyolitic activity starts during the latest stage of evolution of volcanism in all these islands.

2 – The western islands of Alicudi, Filicudi and Salina show a modest variation of potassium contents in mafic magmas, and are composed exclusively of calcalkaline to high-K calcalkaline rocks, with absence of shoshonites. At Lipari, Vulcano and the eastern islands of Panarea and Stromboli, shoshonitic magmatism is present along with calcalkaline and/or HKCA products. Leucite-bearing volcanics are found at Vulcano and Stromboli. Therefore, there is an increase in the range of potassium contents from west to east.

3 – Sr and Nd isotopic signatures respectively increase and decrease going from the western island of Alicudi to the central and eastern islands. At Stromboli, the highest Sr- and lowest-Nd isotopic ratios are observed. There is also decrease of He isotopic ratios from west to east, with R/R_A decreasing from about 7 at Alicudi to about 2 at Stromboli.

5 – Abundances of incompatible trace elements increase the same way as potassium. Instead, ratios of incompatible trace element have more complicated patterns. For instance, LILE/HFSE ratios (e.g., La/Ta) show lower values at the extreme islands of Alicudi and Stromboli, with respect the central islands, especially Salina (Francalanci *et al.*, 2004).

Increase in the amount of silicic rocks from external to central islands suggest that shallow level evolution processes of magmas had less intensity in the external islands. Occurrence of mafic to intermediate rocks at Alicudi, Filicudi and Stromboli suggests that magma evolution was modest and affected calcalkaline parental melts. Polybaric fractional crystallisation, accompanied by moderate interaction with the crust has been suggested for these two islands (Peccerillo *et al.* 2004; Santo *et al.* 2004; Bonelli *et al.* 2004).

Evolution processes in the central arc were more intensive that in the western islands, and rhyolitic compositions were reached. Acidic compositions were the result of complex processes dominated by fractional crystallisation plus mixing and crustal assimilation, starting from calcalkaline and shoshonitic magmas. Crustal contamination was more intense at Lipari, where some rocks contain significant amounts of crustal material (Barker, 1987; Di Martino *et al.*, 2011). Mixing-mingling processes also played an important role (De Astis *et al.*, 1997; Gioncada *et al.*, 2003).

When mafic magmas over the entire Aeolian Arc are considered, one can observe several important variations of key geochemical parameters. K_2O and LILE and $^{87}Sr/^{86}Sr$ in rocks with MgO > 5% increase from west to east, as mentioned earlier. However, a similar time-related increase of potassium and incompatible elements is also observed within single islands. It is unlikely that these variations depend only on crustal assimilation processes by the ascending magmas. This is excluded by the large amount of crust that would be necessary (more than 50-60%) to drive Sr isotopic compositions from values of about $^{87}Sr/^{86}Sr \sim 0.7035 - 0.704$ found in the western and central islands to values of $^{87}Sr/^{86}Sr \sim 0.706 - 0.707$ observed at Stromboli. Therefore, it has been concluded that the range of trace element and radiogenic isotopic compositions observed for mafic rocks both along the arc and within single islands, reflects those of the mantle sources. This points to strongly heterogeneous upper mantle both at regional scale and beneath some islands, especially Stromboli (e.g., Francalanci *et al.*, 1993a,b, 2007).

Compositional heterogeneities in the mantle source of Aeolian Arc relate to different amounts and types of upper crustal material carried into the mantle wedge by subduction processes (Ellam *et al.*, 1988; Francalanci *et al.*, 1993b, 2007). Regional isotopic (Sr, Nd, Pb, He) variations suggest that whereas the mantle sources of western-central islands underwent input of fluids or melts coming from an oceanic-type slab, upper crustal material (subducted sediments) were important mantle contaminants beneath eastern islands (Ellam *et al.*, 1988, 1989; Calanchi *et al.*, 2002; Francalanci *et al.*, 2007 and references therein). Variations of trace element and radiogenic isotope signatures within single islands, especially at Stromboli, would be related to vertical mantle heterogeneity, possibly generated by variable contamination of the peridotite column by sedimentary material from the Ionian subducted slab.

Francalanci *et al.* (1993b, 2007) highlighted significant along-arc variations of incompatible trace element ratios (e.g., Ba/Nb and La/Ta or other LILE/HFSE ratios). This was suggested to reveal a different role of transfer by fluid phases from slab to the mantle wedge. However, variable LILE/HFSE ratios may also indicate different types of pre-metasomatic mantle sources (Ellam *et al.*, 1989; Peccerillo, 2001b).

In conclusion, the bulk of geochemical and radiogenic isotope data for mafic Aeolian Arc magmas support an increased role of sediments with respect to basaltic slab as contaminant of the mantle sources, going from west to the east. Element transfer from slab to mantle wedge was accomplished by melts and fluids, with the two agents having different roles in the various sectors of the arc (Francalanci *et al.*, 1993b). It is still debated whether the pre-metasomatism mantle wedge had a OIB-type and MORB-type composition (Ellam *et al.*, 1989; Trua *et al.*, 2002, 2004, 2010; Francalanci *et al.*, 2007).

Italian Peninsula

Extensive Plio-Quaternary orogenic magmatism occurs along the western border of the Italian peninsula and some Tyrrhenian Sea islands (e.g., Ischia, Pontine Islands, Tuscan Archipelago). Ages range from about 8 Ma to present, and decrease from north-west to south-east (Fig. 26). Petrological features are extremely variable, from calcalkaline to alkaline potassic and ultrapotassic. Based on major, trace element and radiogenic isotope signatures, several magmatic provinces have been distinguished (Peccerillo, 2002, 2005a), each showing peculiar compositional characteristics (Figs. 41, 42) volcanological features and structural setting (Peccerillo, 2002). Geophysical investigation also evidences different structure of the lithosphere-asthenosphere system in the different regions (Peccerillo & Panza, 1999; Panza *et al.*, 2007). Staring from south, these provinces are:

1 – Mount Vulture

2 – Campania Province (SommaVesuvio, Campi Flegrei, Procida and Vivara, Ischia)

3 – Eastern Pontine islands (Ventotene and Santo Stefano)

4 – Ernici and Roccamonfina province

5 – Roman (Latium) Province s.s. (Alban Hills, Sabatini, Vico, Vulsini)

6 –Intra Apennine Province (IAP: San Venanzo, Cupaello and other minor centres)

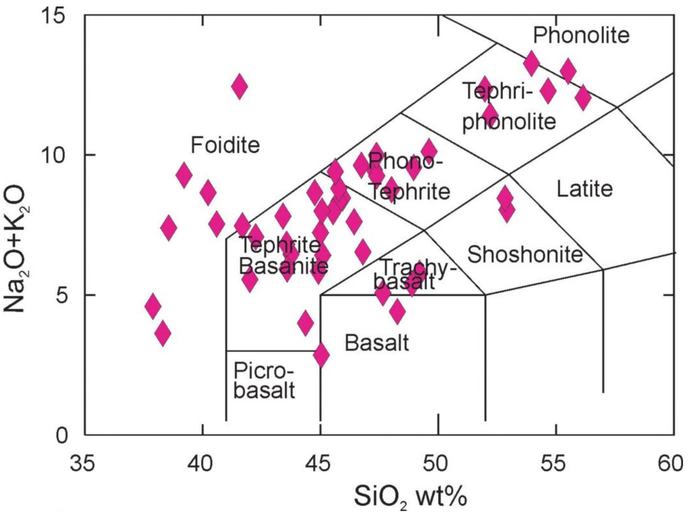
7 – Tuscany Province.

Potassic and ultrapotassic compositions are typical of most rocks occurring in the Italian peninsula. These are discussed by Conticelli *et al.* (this issue). Therefore, their characteristics, origin and geodynamic significance will be only briefly described in this paper.

Mount Vulture

Mount Vulture is an isolated volcano sited east of the Apennine compression front, at the border of the Apulia foreland, a promontory of the African-Adriatic plate. It has been formed by explosive and effusive activity between about 0.8 Ma and 0.1 Ma. The stratovolcano is cut by a summit collapse caldera, which hosts two explosion craters. Rocks are undersaturated in silica, and range from tephrite, foidite, melilitite, to phonolite (Fig. 27; De Fino *et al.*, 1984). Late carbonate-rich pyroclastics and lavas have been erupted (Stoppa & Principe, 1997; D'Orazio *et al.*, 2007). Rock textures are generally porphyritic with various types and abundances of phenocryst phases, including olivine, clinopyroxene, amphibole, feldspars, leucite and haüyne. Haüyne is the most common foid.

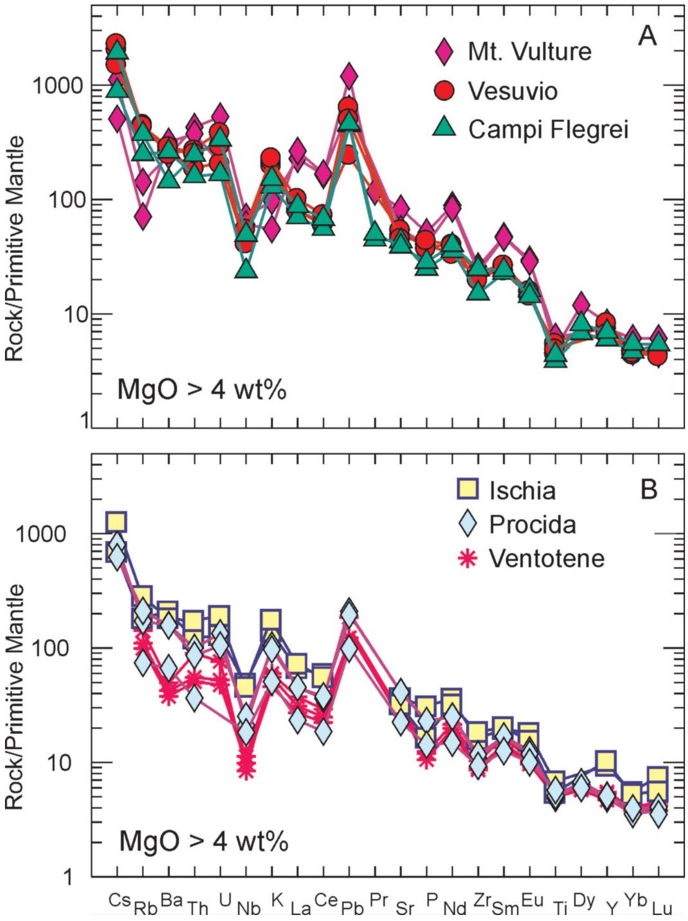
Figure 27. TAS diagram, Mount Vulture



Total Alkalies vs. Silica diagram for Mount Vulture volcano.

Vulture rocks are variably enriched in alkalies (Fig. 27) with K_2O/Na_2O ~ 0.1 to 1.6. Incompatible element patterns show HFSE negative anomalies, positive spikes of Pb, but also relative depletions in Rb and K, which are not observed in other alkaline rocks from the Italian peninsula (Fig. 28a), and are rather typical of OIB-type rocks such as those of Mt. Etna. Enrichment in volatile elements, especially sulfur and chlorine, are very high, up to percent values. Sr isotope ratios range form 0.7055 to 0.7070, and $^{143}Nd/^{144}Nd$ ~ 0.5126-0.5128. Lead isotopic ratios ($^{206}Pb/^{204}Pb$ = 19.13-19.48; $^{207}Pb/^{204}Pb$ = 15.68-15.72; $^{208}Pb/^{204}Pb$ = 39.16-39.55) show slightly more radiogenic compositions than other volcanic rocks from the Italian peninsula (Fig. 29; De Astis *et al.*, 2006).

Figure 28. Spider-diagrams for Vulture and Campania volcanoes



Incompatible element patterns normalized to primordial mantle composition for mafic rocks (MgO > 4%) from Mount Vulture and the Campania Province.

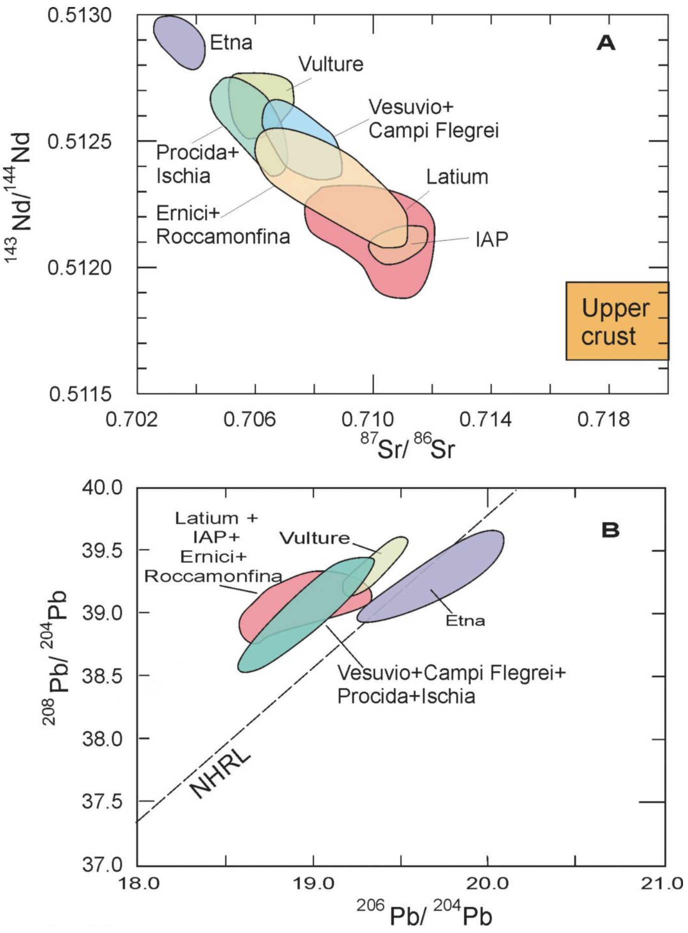
Campania Province and Eastern Pontine Islands

The Campania Province includes the active potassic and ultrapotassic volcanoes of Somma-Vesuvio, Campi Flegrei, Procida-Vivara, and Ischia. Ages range from about 0.2 Ma to present. The Pontine Islands (Ponza, Palmarola, Zannone, Ventotene and Santo Stefano) have variable ages and composition and only the eastern islands (Ventotene and Santo Stefano; age 0.8 to 0.13 Ma) and the younger rocks from Ponza (about 1 Ma) have compositional affinities with Campanian magmatism.

Volcanic rocks from Campania and Eastern Pontine islands range from mafic to felsic and exhibit variable degree of silica undersaturation and enrichment in potassium. Most rocks are moderately enriched in potassium, but reach ultrapotassic compositions at Vesuvio. Blocks of mafic rocks with K_2O contents close to calcalkaline compositions have been found at Ventotene and Procida-Vivara (De Astis *et al.*, 2006). As recalled earlier, 2 Ma old calcalkaline basalts to andesites have been found by borehole drilling beneath the Campanian Plain (Parete-2 drilling).

Somma-Vesuvio is a stratovolcano with a polygenic summit caldera, formed by an older cone (Somma) and by an intra-caldera cone (Vesuvio). Exposed activity ranges in age between 30 ka and present, although 0.4 Ma old ultrapotassic rocks have been found by drilling in the Vesuvius area (Brocchini *et al.*, 2001). Vesuvio was built up inside the caldera depression of Monte Somma, after the 79 AD eruption that destroyed Pompeii and Herculaneum (Santacroce, 1987; Rolandi *et al.*, 1998; Santacroce *et al.*, 2003). Three main rock series showing distinct ages and variation trends for alkalies and some trace elements have been distinguished at Somma-Vesuvio (Fig. 30; Joron *et al.*, 1987). The older rocks (> 8 ka) make up a slightly silica undersaturated potassic suite ranging from trachybasalt to trachyte. A second series (about 8 ka to 79 AD) is formed by moderately silica undersaturated phonotephrites, tephriphonolites and phonolites. The younger rocks (from 79 AD to present and forming the Vesuvio cone) are the most undersaturated in silica and range from leucite tephrite to leucitite, phonotephrite, tephriphonolite and phonolite. All rocks have variably porphyritic textures, with plagioclase and clinopyroxene as main phenocrysts. Leucite is more abundant in the younger than in the older rocks.

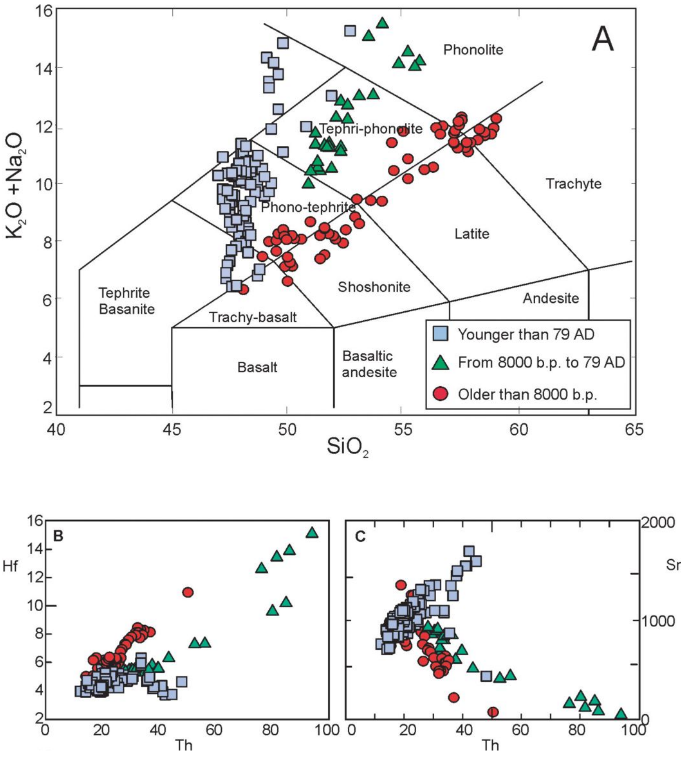
Figure 29. Radiogenic isotope compositions, central-southern Italy



Sr-Nd-Pb isotopic compositions of central Italy and Etna volcanic rocks.

Sr, Nd, Pb isotopic compositions are similar in the three series ($^{87}Sr/^{86}Sr$ ~ 0.7063 to 0.7080; $^{143}Nd/^{144}Nd$ ~ 0.5124 to 0.5125; $^{206}Pb/^{204}Pb$ ~ 18.90 to 19.10; $^{207}Pb/^{204}Pb$ ~ 15.61 to 15.71; $^{208}Pb/^{204}Pb$ ~ 38.90 to 39.30; Hawkesworth & Vollmer, 1979; Civetta *et al.*, 1991a; Fig. 29). $^{176}Hf/^{177}Hf$ isotopic ratios for a few samples are around 0.28278 (Gasperini *et al.*, 2002). Helium isotope studies on clinopyroxene and olivine from historical lavas gave values of R/R_A ~ 2.2 to 2.7 (Graham *et al.*, 1993). Oxygen isotope compositions determined on Vesuvio whole rocks (Ayuso *et al.*, 1998) range between $\delta^{18}O$ ~ +7.0 to +10.0, and are positively correlated with CaO. REE patterns of Somma-Vesuvio rocks (not shown) are fractionated for both LREE and HREE, with small negative Eu anomalies, which become stronger in trachytes and phonolites. Patterns of incompatible elements normalised to primordial mantle compositions for mafic rocks (Fig. 28a) show negative anomalies of HFSE and positive spikes of LILE and Pb.

Figure 30. TAS and trace element variations of Somma-Vesuvio

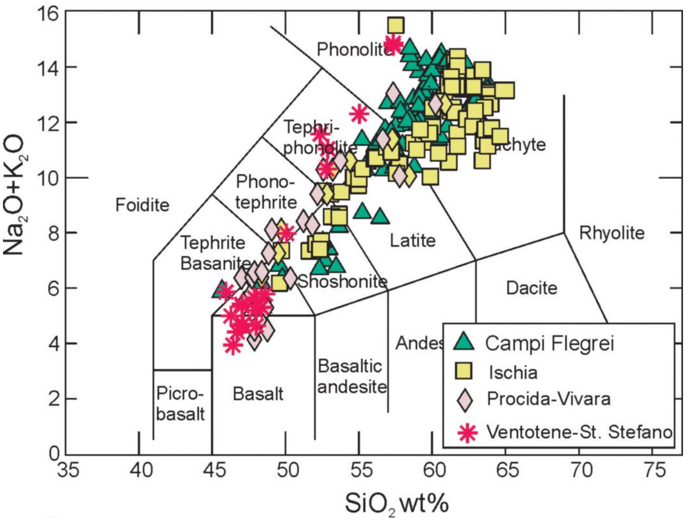


A – TAS diagram for Somma-Vesuvio volcanics. B, C – Th vs. Hf and Sr diagrams for Somma-Vesuvio volcanics.

Major and trace element variation at Somma-Vesuvio rocks suggest that fractional crystallisation was a leading evolution mechanism. Different trends of major and trace elements suggest that different types of phases were separated during fractionation, with a variable role being played by plagioclase. This may be related to polybaric fractional crystallisation and/or to a variable role of carbonate assimilation by potassic magmas, a process that destabilises plagioclase (Peccerillo, 2005b; Iacono-Marziano *et al.*, 2008). Primitive rocks from Somma-Vesuvio have many geochemical and isotopic signatures that are similar to KS rocks from Stromboli, a feature that suggests a similar source for the two volcanoes (Peccerillo, 2001a).

The *Campi Flegrei* is a volcanic complex formed by two calderas and by several monogenetic cones and craters. The latest activity took place in 1538 AD when the Monte Nuovo phonolitic cone was formed. The Campi Flegrei rocks consist of dominant pyroclastic deposits and minor lavas. Compositions range from trachybasalt to trachyte and phonolite (Fig. 31) and are moderately undersaturated to oversaturated in silica. Some phonolites are peralkaline. Intermediate and felsic rocks largely prevail over mafic compositions.

Figure 31. TAS diagram, Campania volcanoes



Total Alkalies vs. Silica (TAS) diagram for Campi Flegrei, Ischia, Procida-Vivara and Ventotene-Santo Stefano volcanoes.

Incompatible element patterns of mafic rocks normalised to primordial mantle composition (Fig. 28) show moderate negative anomalies of HFSE and Pb positive spikes. Sr isotopic ratios are similar to Somma-Vesuvio, although some larger range of compositions is observed (^{87}Sr/^{86}Sr ~ 0.7065 to 0.7086; ^{143}Nd/^{144}Nd ~ 0.5124 to 0.5128; ^{206}Pb/ ^{204}Pb ~ 18.90 to 19.25; ^{207}Pb/^{204}Pb ~ 15.65 to 15.77; ^{208}Pb/^{204}Pb ~ 38.95 to 39.38). Compositional variations at Campi Flegrei have been suggested to be related to fractional crystallisation plus come crustal assimilation and mixing, starting from a trachybasaltic parental magma (Pappalardo *et al.*, 2002). Selective enrichment by fluids has been also invoked to explain high abundances of some volatile elements (Cl, F, and alkalies; Villemant, 1988).

Ischia consists prevalently of moderately potassic pyroclastic rocks and minor lavas, slightly less enriched in alkalies than Campi Flegrei. Ages range from more than 150 ka to 1302 AD. Rocks are intermediate to felsic, ranging from shoshonite to trachyte (Fig. 31). Trace element abundances are similar to the equivalent rocks of Campi Flegrei, whereas radiogenic isotope signatures are slightly more primitive (^{87}Sr/^{86}Sr ~ 0.7061 to 0.7076,

^{143}Nd/^{144}Nd ~ 0.51246 to 0.51261, ^{206}Pb/^{204}Pb ~ 19.01-19.21, ^{207}Pb/^{204}Pb ~ 15.66-15.71, ^{208}Pb/^{204}Pb ~ 39.06-39.34; Cortini & Hermes, 1981; Hawkesworth & Vollmer, 1979; Civetta *et al.*, 1991b).

The islands of *Procida and Vivara*, sited between Campi Flegrei and Ischia, are formed by scoriae, lithic clasts, pumices, and hydrovolcanic ashes erupted between 55 ka and 17 ka (D'Antonio & Di Girolamo, 1994; D'Antonio *et al.*, 1999 and references therein). Rock compositions range from basalt to trachyte with moderate abundances in alkalies (Fig. 31). Some lithic ejecta that show a calcalkaline composition. Overall, the Procida and Vivara rocks have trace element compositions that resemble closely the equivalent rocks from Ischia. However, mafic compositions are more depleted in alkalies and fall in the subalkaline field of Irvine and Baragar (1971). Sr and Nd isotopic ratios are respectively lower and higher than other Campanian volcanoes; Pb isotope ratios are variable (^{87}Sr/^{86}Sr = 0.7051 to 0.7065; ^{143}Nd/^{144}Nd = 0.5125 to 0.5126; ^{206}Pb/^{204}Pb ~ 18.68 to 19.30; ^{206}Pb/^{204}Pb ~ 38.68 to 39.99).

The Eastern Pontine islands of *Ventotene and Santo Stefano* consists of basalt and trachybasalt to phonolites (Fig. 31; Mètrich *et al.*, 1988; D'Antonio & Di Girolamo 1994, D'Antonio *et al.* 1999). Mafic rocks are poorly enriched in potassium, but show a steep increase of alkalies with silica. Incompatible element patterns of mafic rocks (Fig. 28) are similar to other Campania potassic volcanics, but absolute abundances are lower. Radiogenic isotope compositions (^{87}Sr/^{86}Sr ~ 0.7070 to 0.7077; ^{143}Nd/^{144}Nd ~ 0.51228 to 0.51244; ^{206}Pb/^{204}Pb ~ 18.50 to 18.86; ^{207}Pb/^{204}Pb ~ 15.64 to 15.68; ^{208}Pb/^{204}Pb ~ 38.45 to 38.99; D'Antonio *et al.*, 1996, 1999; Frezzotti *et al.*, 2007; Conticelli *et al.*, 2009b) resemble Campanian volcanoes but are also close to the moderately potassic rocks (KS) from Ernici and Roccamonfina.

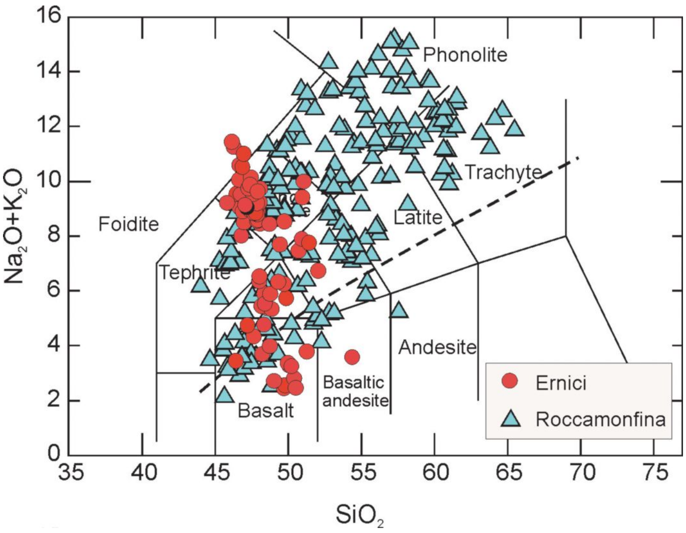
The rocks from the Eastern Pontine islands, Campania Province, and Vulture show a variety of compositions in terms of petrological affinity, enrichments in potassium and incompatible elements. All the mafic rocks show a negative anomaly of HFSE, typical of arc-related magmas. However, the magmas of the Campanian volcanoes have small negative spikes of HFSE and their LILE/HFSE is lower than in other orogenic volcanic suites from central-southern Italy (Peccerillo, 2005a and references therein). Low LILE/HFSE ratios are typical of OIB, and, therefore, it has been suggested that the rocks from Campania and Vulture have intermediate compositions between OIB and arc rocks (e.g., Beccaluva *et al.*, 1991, 2002; De Astis *et al.*, 2006).

Sr-Nd-Pb isotope ratios of Vulture, Campania and Eastern Pontine volcanics have similar range of values, and plot midway between the Aeolian Arc and the central Italy potassic volcanoes, along a trend connecting OIB-type volcanoes of southern Italy (Etna, Iblei) and the upper crust (Fig. 41). This suggests an overall mixing between OIB-type mantle material and upper crust. Such a process is believed to result from mantle source contamination by upper crustal material (Peccerillo 2005a and references therein). Origin of OIB-type mantle is controversial. Inflow of asthenospheric upper mantle from the Adriatic plate after slab breakoff has been suggested by Peccerillo (2001b). Alternatively, the OIB-type signatures may represent deep mantle material that was emplaced at shallow level along structural discontinuities of the slab (Rosenbaum *et al.*, 2008).

Ernici and Roccamonfina

The Monti Ernici volcanoes, consist of several pyroclastic and lava centres with an age of 0.7 to 0.1 Ma, sited in the Mid Latina Valley, about 70-80 km southeast of Rome. Roccamonfina is a stratovolcano with a central caldera and intra-caldera domes, formed between about 0.6 and 0.1 Ma. The peculiarity of this volcanic province is the occurrence of two contrasting series of rocks, showing distinct enrichments in potassium and incompatible elements, and radiogenic isotope signatures (e.g., Appleton, 1972; Civetta *et al.*, 1981; Frezzotti *et al.*, 2007; Rouchon *et al.*, 2008; Conticelli *et al.*, 2009b). A group of rocks showing ultrapotassic composition and classically indicated as the high-potassium series (HKS), ranges in composition from leucite tephrite to phonolite (Fig. 32). These are undersaturated in silica and display high enrichments in LILE and radiogenic Sr. Another group of rocks is less enriched in potassium, is saturated to poorly undersaturated in silica, and ranges in composition from calcalkaline basalt to moderately potassic trachybasalt, latite and trachyte. These latter are generally referred to as the potassic series or KS, and display a moderate enrichment in LILE and lower Sr isotopic signatures than HKS. A complete series of mafic to felsic KS and HKS rocks are found at Roccamonfina, whereas only mafic rocks occur at Monti Ernici.

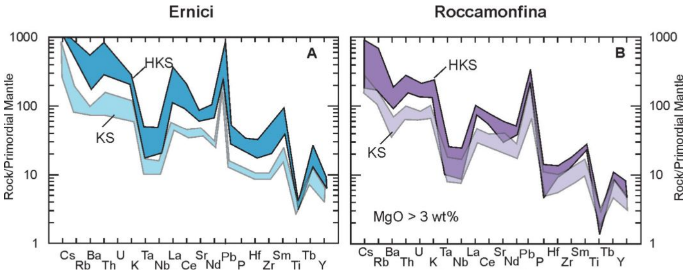
Figure 32. TAS, Ernici and Roccamonfina



TAS diagram for Ernici and Roccamonfina volcanics. The ashed line is the divide between subalkaline and alkaline magmas.

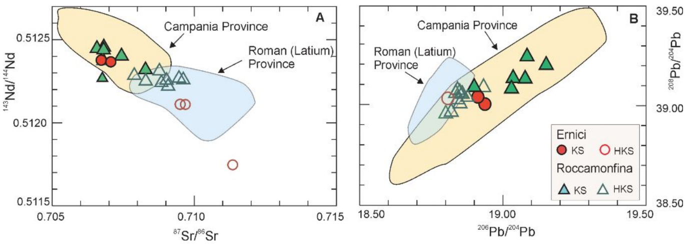
Abundances of incompatible elements increase from KS to HKS. However, the shape of mantle normalised element patterns are similar (Fig. 33). Sr-Nd isotopic compositions show wide range of values, with an increase of Sr- and a decrease of Nd-isotope ratios from KS to HKS rocks. Pb isotopic ratios are poorly variable and are slightly less radiogenic in the HKS than in the KS rocks (Fig. 34). Overall, radiogenic isotope signatures of Ernici and Roccamonfina cover a large compositional range, linking the Campanian and Aeolian Arc volcanics to those from Latium and Intra Apennine provinces (Figs. 41, 46).

Figure 33. Spider-diagrams, Ernici and Roccamonfina



Incompatible element patterns normalized to primordial mantle composition for mafic rocks (MgO > 4%) from Ernici and Roccamonfina volcanoes.

Figure 34. Radiogenic isotopes, Ernici and Roccamonfina



Sr-Nd-Pb isotopic compositions of Ernici and Roccamonfina volcanics.

There is a general agreement that the Ernici-Roccamonfina parental magmas were formed in an anomalous and heterogeneous mantle source that had undergone different amounts and types of metasomatic modifications. The variable compositions of the rocks erupted at the surface would reflect such a heterogeneity, but may also depend on variable degrees of partial melting (see Conticelli *et al.*, this issue). Mantle metasomatism is likely related to subduction of the Adriatic plate beneath central Italy, with a possible role of material coming from the Ionian slab.

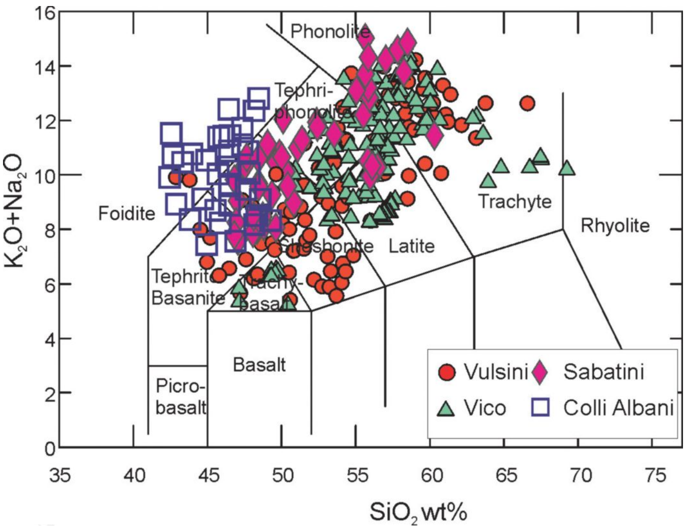
Roman Province

The Roman Province was early defined by Washington (1906) as the area of potassium-rich volcanism, extending from northern Latium (i.e., the Vulsini district) to the Campania area. A wealth of recent studies, however, have shown that the Campania volcanics have distinct petrological and geochemical characteristics as the Latium rocks, and that the Ernici-Roccamonfina magatism is somewhat transitional between the two (Peccerillo, 1999, 2002). Therefore, we here define the Roman Province s.s. (or Latium Province) as the region formed by the four large volcanic complexes of Vulsini, Vico, Sabatini and Colli Albani, sited between southern Tuscany to the city of Rome, along the border of the Tyrrhenian Sea (Fig. 26). These volcanoes erupted about 900 km^3 of dominant pyroclastic products and minor lavas, from about 800 ka to 20 Ka. Volcanism was prevailingly explosive, with numerous plinian eruptions that generated large calderas and volcano-tectonic collapses. The pyroclastic flow deposits generated by these eruptions form thick piles of mildly welded rocks, which have been extensively used as building material form early historical times. The volcanism took place along faults of extensional basins whose formation is related to the opening of the Tyrrhenian Sea.

The Roman Province s.s. mostly consist of felsic, generally phonolitic and trachytic, pyroclastic deposits. These are derivative melts of mafic parents, after some 70-80% fractional crystallisation. This implies that the total amount of potassium-rich melts generated in the Roman Province is much higher than the already huge volumes exposed at the surface.

Rock compositions in the Roman Province are variable and include mildly undersaturated KS trachybasalts to trachytes, and strongly silica undersaturated HKS leucite tephrites, leucitites to phonolites. KS rocks are especially abundant during the latest phases of activity of Vulsini, are less common at Vico and rare at Sabatini, whereas they are absent at Colli Albani (Fig. 35).

Figure 35. TAS, Roman volcanoes



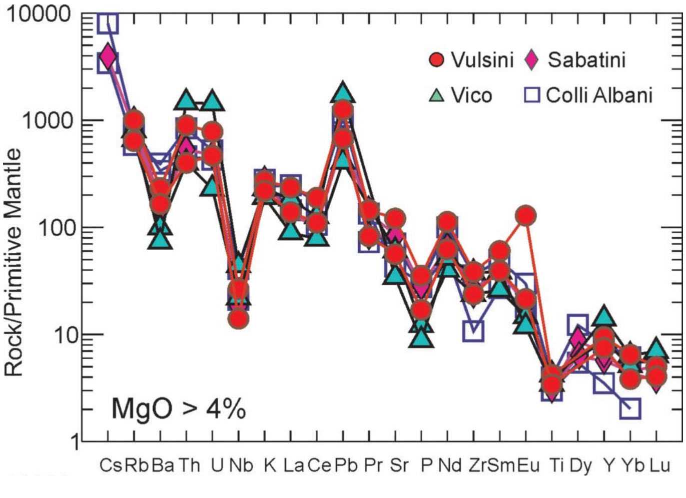
TAS diagram for volcanic rocks from Latium (Roman s.s.) Province.

Lava textures range from almost aphyric to strongly porphyritic. Pumices are glassy with a few phenocrysts. KS rocks generally contain phenocrysts of clinopyroxene, plagioclase and olivine in the mafic rocks, whereas sanidine and biotite appear in the felsic compositions. Leucite is often observed as phenocrysts and in the groundmass. The HKS rocks are also variably porphyritic with the same phenocrysts as the KS rocks, but with much higher leucite contents. Nepheline and haüyne are also observed. Clinopyroxene is often strongly zoned, a feature which is evident at the petrographic observation due to colour changes from green salite to colourless diopside.

Overall, the rock suites making up the KS and HKS of the Roman Province are formed by dominant fractional crystallisation processes, starting from different types of parental magmas showing distinct abundances of potassium and incompatible trace element, and radiogenic isotope compositions. Mixing and crustal assimilation also played important roles during magma evolution, and zoned clinopyroxenes commonly encountered in Roman rocks are considered as a main evidence of magma mixing. Assimilation of wall rocks is believed particularly abundant at Colli Albani. Here, extensive assimilation of limestones and dolostones strongly modified the evolution path of magmas, driving magma compositions from parent tephrite to foidite, instead of from tephrite to phonolite, as typically observed in other Roman centres (Gaeta *et al.*, 2009; Iacono-Marziano *et al.*, 2007; Peccerillo *et al.*, 2010 and references therein).

Patterns of incompatible elements normalised to primordial mantle of mafic KS and HKS rocks have different element abundances but similar shapes, with enrichments in LILE, positive spikes of Pb, and marked depletion in HFSE (Fig. 36), whose abundances are much lower than in the Campanian volcanoes and are close to MORB (Peccerillo, 2005a). Radiogenic isotopic compositions are moderately variable, with $^{87}Sr/^{86}Sr$ ~ 0.7090 to 7110, $^{143}Nd/^{144}Nd$ ~ 0.5121, and $^{206}Pb/^{204}Pb$ ~ 18.80; $^{176}Hf/^{177}Hf$ ~ 0.28258.

Figure 36. Spider-diagrams, Roman Province



Incompatible element patterns normalized to primordial mantle composition for mafic rocks (MgO > 4 wt %) from the Roman (Latium) volcanic Province.

The bulk of geochemical and petrological data suggest that the parental magmas of Roman volcanoes were generated by various degrees of partial melting of a lherzolitic upper mantle, which contained phlogopite, generated by metasomatic processes. Geochemical and radiogenic isotope data suggest that metasomatic modifications were accomplished by addition to the upper mantle of sedimentary material with a marly composition (Peccerillo *et al.*, 1988). This was related to subduction processes of the Adriatic slab beneath central Italy (e.g., Conticelli and Peccerillo, 1992; Conticelli *et al.*, this issue).

Ultrapotassic rocks are rare at a global scale, but are very abundant in central Italy. The reason of this anomaly is still unclear, and although representing a main petrological and geodynamic problem, has not received much attention. Ultrapotassic magmatism is particularly abundant in the Latium region, in which the four huge polycentric volcanic complexes of Vulsini, Vico, Sabatini and Colli Albani developed almost contemporaneously over a time span of less than 1 Ma. This area has been affected by strong extensional tectonic regime, connected with the opening of the Tyrrhenian basin. Moreover, the upper mantle beneath the Latium area was also affected by two stages of metasomatic modification (Peccerillo, 1999), as it will be discussed later. One occurred during Alpine subduction of the European plate beneath the northern African margin; a second stage occurred during subduction of the Adriatic plate beneath the Italian peninsula. Both metasomatic stages were accomplished by introduction of continental-type material into the upper mantle. The extensive mantle modification resulting from the two-stage metasomatism, along with strong regional extension, may represent the reasons for the generation and eruption of large amounts of ultrapotassic magmas in this region.

Intra Apennine Province

Volcanoes of the Intra-Apennine Province (IAP) consist of several small centres made of ultrapotassic pyroclastic rocks and minor lavas, scattered along the axial zone of Apennines. The main occurrences include San Venanzo, Cupaello, and Polino, in Umbria. Lavas are found only at San Venanzo and Cupaello.

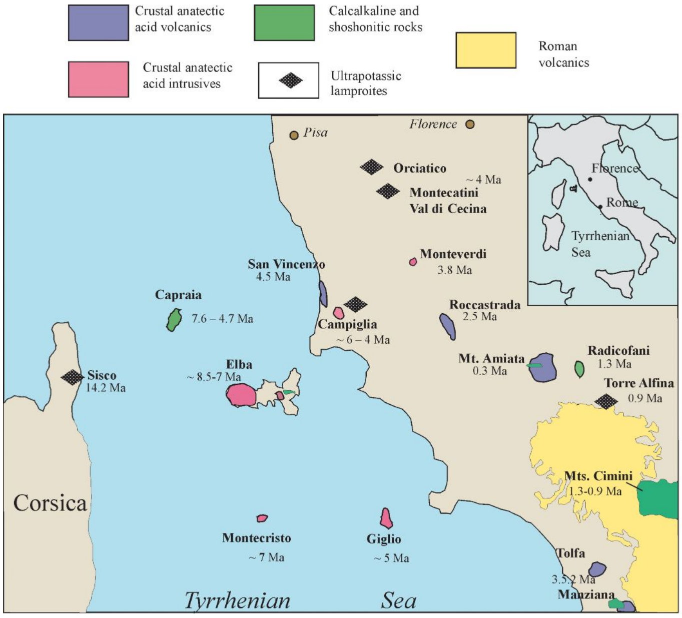
Lavas have olivine melilitite and kalsilite melilitite composition and show a typical ultrapotassic kamafugitic affinity, i.e. strong undersaturation in silica, lower SiO_2, Na_2O, Al_2O_3 and higher CaO and K_2O/Na_2O than Roman rocks. Carbonate-rich pyroclastic rocks are also present in this province. Kamafugitic lavas, especially those from San Venanzo, have incompatible element patterns and radiogenic isotope signatures that are similar to the mafic rocks of the Roman Province. This clearly suggests an origin in compositionally similar mantle sources that had undergone similar type of metasomatic modifications.

More controversial is the origin of carbonate rich pyroclastic rocks. Some authors suggest a carbonatitic nature (Stoppa & Woolley, 1997), whereas an interaction between kamafugitic magmas and sedimentary carbonates is suggested by other authors (Peccerillo, 1998; Barker, 2007). High oxygen isotopic compositions of silicate phases and of carbonates, with $\delta^{18}O‰ \sim + 14$ in olivine and pyroxene and $\delta^{18}O‰ \sim + 20$ to + 25 in calcite, support the latter hypothesis.

Tuscany Province

This is by far the most complex magmatic province in Italy. It includes both volcanic and intrusive rocks and extends from the Tuscan Archipelago to the Tolfa-Manziana area, a few km north of Rome (Fig. 37). Ages range from about 8 to 0.3 Ma. A small 14 Ma old ultrapotassic minette from Sisco, Corsica, is also included in the Tuscany Province.

Figure 37. Tuscany Magmatic Province

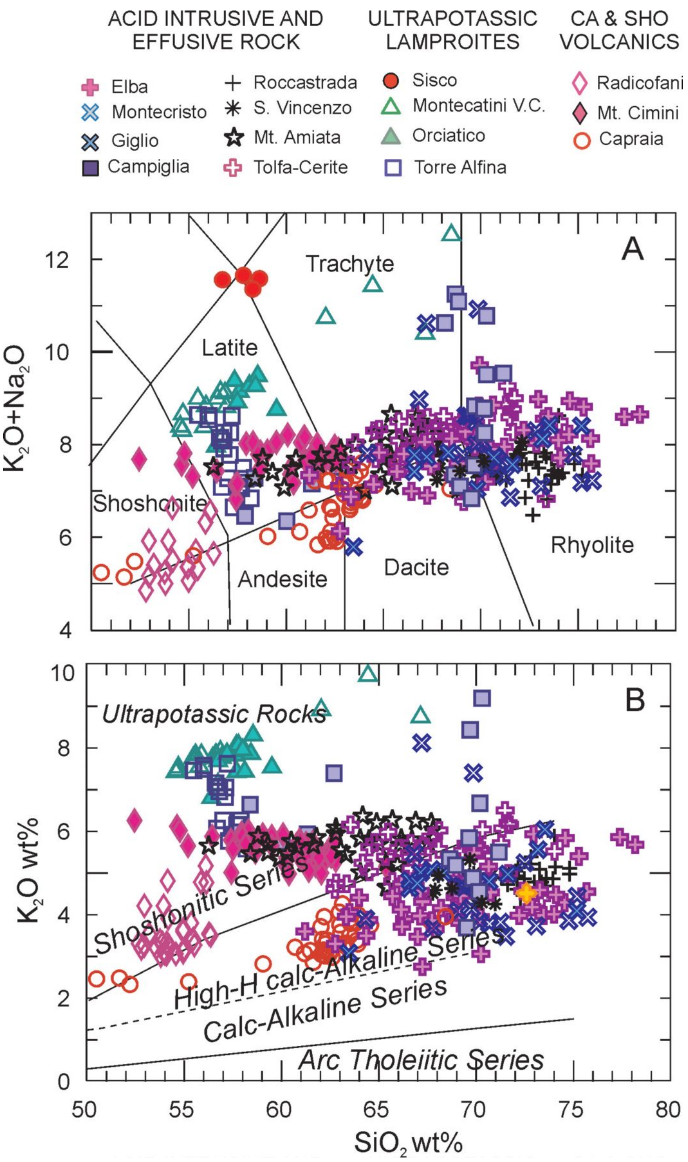


Distribution, composition and ages of magmatic rocks of the Tuscany Province. Note the overlap with the Roman (Latium) Province.

Rock compositions are variable from mafic to felsic (Fig. 38), and show calcalkaline, shoshonitic to ultrapotassic alkaline affinities. Ultrapotassic rocks in Tuscany have distinct petrological characteristics as the equivalent types in central Italy, and are classified as lamproites. These are oversaturated in silica and have high silica content (SiO_2 ~ 55-60), high MgO (~ 7-10%) and Mg# (70-75), low CaO (3-5%) and Na_2O (~ 1.5%). Many shoshonitic rocks, especially at Radicofani, result from mixing between lamproite and calcalkaline or Roman-type KS magmas (D'Orazio *et al.*, 1994; Peccerillo, 1994; Peccerillo *et al.*, 2008b).

Mafic rocks have high MgO and ferromagnesian element contents, and are of obvious mantle origin. Acid rocks are polygenic and may be generated by crustal anatexis, by fractional crystallisation of mafic-intermediate parents plus interaction with crustal rocks, and by mixing between different types of mantle-derived melts and crustal anatectic magmas (Poli, 1992; Poli *et al.*, 2003).

Figure 38. Alkali-silica diagrams, Tuscany Province

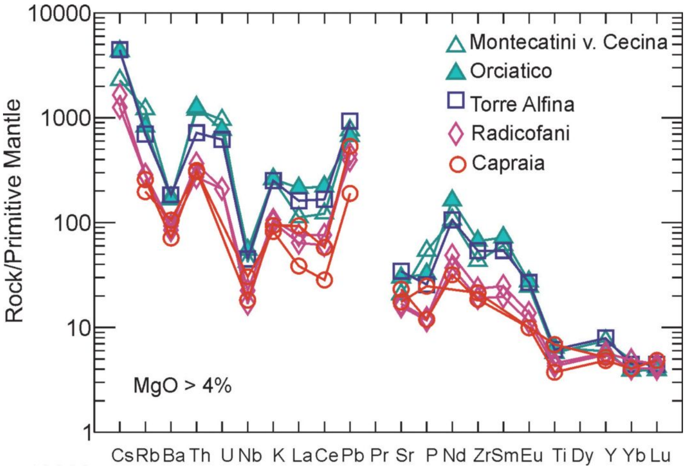


A - Total Alkalis vs. Silica, and B - K_2O vs. SiO_2 classification diagrams for volcanic rocks from the Tuscany Province.

Calcalkaline and HKCA to shoshonitic rocks in Tuscany mainly crop out at Capraia, but also occur as mafic enclaves in some granitoid intrusions and acidic lavas (e.g., Elba; Poli, 1992). Shoshonitic rocks occur at Radicofani and Cimini but are also found in minor amounts in other centres, such as the silicic volcano of Monte Amiata. Lamproitic rocks occur at Montecatini val di Cecina, Orciatico, Torre Alfina and Sisco (Corsica).

Incompatible element abundances of mafic rocks increase from CA to SHO and lamproitic magmas. Mantle normalized incompatible element patterns of all mafic rocks (Fig. 39) are fractionated and show evident negative anomalies of HFSE, Sr and Ba. These patterns are very similar to those of the Oligocene mafic rocks of the Western Alps, where a similar association of calcalkaline, shoshonitic and lamprotic magmas is observed (Peccerillo *et al.*, 1988; Peccerillo & Martinotti, 2006). Overall, these patterns resemble those of some upper crustal rocks, such as shale and gneiss.

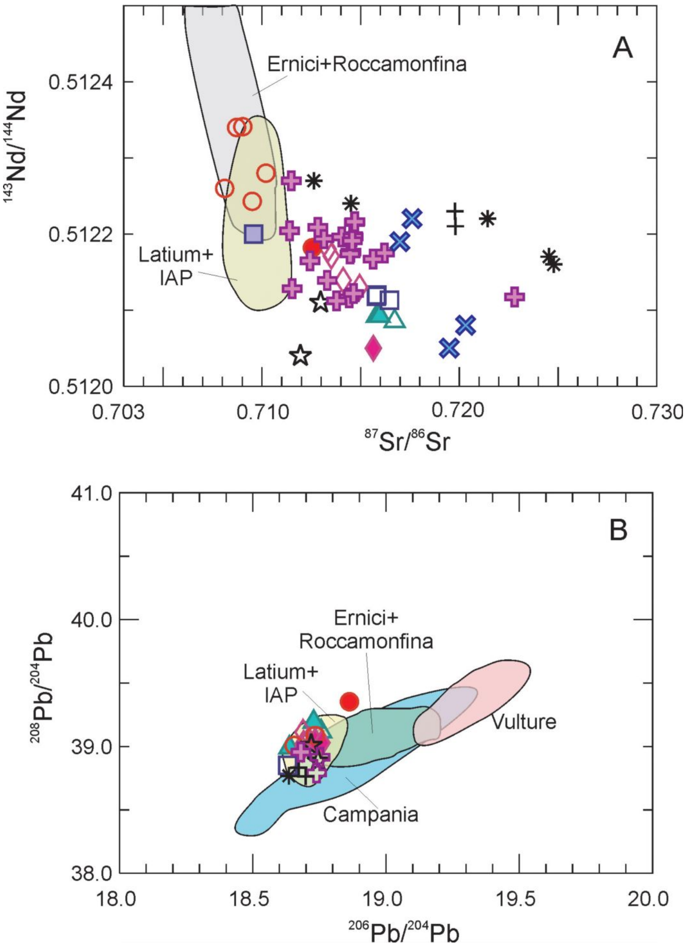
Figure 39. Spider-diagrams, Tuscany Province



Incompatible element patterns normalized to primordial mantle composition for mafic rocks (MgO > 4) from the Tuscany Province.

Sr-Nd isotope ratios of Tuscany mafic rocks are variable. Capraia shoshonitic basalts and HKCA andesites show the least radiogenic Sr and the highest Nd isotopic signatures in the Tuscany Province (^{87}Sr/^{86}Sr ~ 0.708-0.710), whereas more radiogenic Sr compositions are found at Radicofani (^{87}Sr/^{86}Sr = 0.713-0.716), Cimini and Amiata (Poli *et al.*, 1984; Conticelli *et al.*, 2002) (Fig. 40a). Lamproitic rocks have the highest ^{87}Sr/^{86}Sr (~ 0.713-0.717) and the lowest ^{143}Nd/^{144}Nd (~ 0.521-0.522) among mafic rocks. Pb isotopic ratios are poorly variable (Fig. 40b).

Figure 40. Radiogenic isotope compositions, Tuscany Province



Sr-Nd-Pb isotopic compositions of volcanic rocks from the Tuscany Province. Symbols as in Fig. 38.

Silicic rocks in Tuscany consist of lavas (San Vincenzo, Roccastrada, Monte Amiata and, at some extent, at Monti Cimini), and several intrusions occurring in the Tuscan archipelago (Elba, Giglio and Montecristo islands), the northern Tyrrhenian Sea floor (Vercelli seamount) and on the mainland (Campiglia). Other intrusive bodies occur at shallow depths beneath the Amiata and Larderello area. Pyroclastic rocks are only present at Mt. Cimini where rhyodacitic ignimbrites crop out. Intrusive rocks have similar major, trace element and radiogenic isotope compositions as extruve rocks.

Some silicic rocks (e.g., Roccastrada peraluminous rhyolites; Mazzuoli, 1967) represent pure crustal anatectic magmas, and were egenerated by partial melting of metapelites (Giraud *et al.*, 1986; Pinarelli *et al.*, 1989). Their Sr-isotope ratios are high (^{87}Sr/^{86}Sr ~ 0.718-0.720 ca) and Nd isotopes are low (^{143}Nd/^{144}Nd ~ 0.51222).

Other acid rocks (e.g., rhyolitic lavas of San Vincenzo, Cimini, Amiata, Tolfa-Cerveteri) are hybrids between crustal anatectic melts and subcrustal mafic-intermediate magmas (Vollmer, 1976; Giraud *et al.*, 1986; Pinarelli, 1991) Their $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ are variable and sometimes show disequilibrium between phenocrysts and groundmass (Ferrara *et al.*, 1989; Feldstein *et al.*, 1994).

Petrological and geochemical variability of magmas in the Tuscany Province suggests complex petrogeneitic processes, which are still debated. The large variety of mafic magmas calls for an origin in a heterogeneous mantle source. The low CaO, Na_2O and Al_2O_3 and the high MgO, Ni and Cr of lamproites suggest an origin in an upper mantle that was depleted in mineral phases that contain CaO, Na_2O and Al_2O_3 as major components (i.e., clinopyroxene). On the other hand, high potassium contents of lamproites points to the occurrence of phlogopite or other K-rich phases in the source. Therefore, a phlogopite harzburgite has been suggested as a source of lamproitic magmas in Tuscany (Peccerillo *et al.*, 1988; Conticelli & Peccerillo, 1992). Phlogopite was generated by metasomatic processes, which were also responsible for enrichments in incompatible elements and radiogenic Sr of mantle source. Upper crustal material with a pelitic composition is the best candidate for mantle contaminant in Tuscany (Peccerillo *et al.*, 1988). Calcalkaline and shoshonitic rocks have higher CaO and Na_2O and Al_2O_3, and lower K_2O and incompatible trace elements than lamproites. This suggests an origin in a mantle source that contained clinopyroxene but was less intensively metasomatised than the lamproite source. However, the similar shape of incompatible element patterns suggests that the nature of metasomatic contaminant was the same as for lamproites.

The geochemical evidence suggesting that the Tuscany upper mantle was contaminated by crustal material with a pelitic composition, led to infer a subduction-related origin for this magmatism (Peccerillo *et al.*, 1988; Conticelli & Peccerillo, 1992; Serri *et al.*, 1993). However, the age of the subduction event(s) is discussed. It has been noted that similar mafic rocks as in Tuscany, also occur in the Western Alps, where magmatism is Oligocene in age and has been associated to mantle contamination during subduction of the European plate beneath the western Alpine margin. Since Tuscany mafic rocks resemble closely those in the Western Alps, it has been suggested that also the Tuscany upper mantle was contaminated during Alpine subduction (Peccerillo & Martinotti, 2006 and references therein). This is supported by the hypothesis that Tuscany region represents a portion of the Alpine belt shifted eastward during opening of the Tyrrhenian basin (Doglioni *et al.*, 1998).

Tyrrhenian Sea and Italian Peninsula Orogenic Magmatism: A Summary of Compositional Features and Geodynamic Implications

The very wide petrological and geochemical variations of orogenic magmatism in and around the Tyrrhenian Sea, highlight complex origin and evolution processes for magmas and their sources. Parental magmas originated within the upper mantle and underwent various evolution processes, including fractional crystallisation, assimilation, and mixing, giving different types of derivative magmas. However, compositions of mafic rocks are believed to reflect rather closely those of mantle-equilibrated parents, and, therefore, are able to furnish important constraint on source composition and processes. The main compositional features can be summarised as follows:

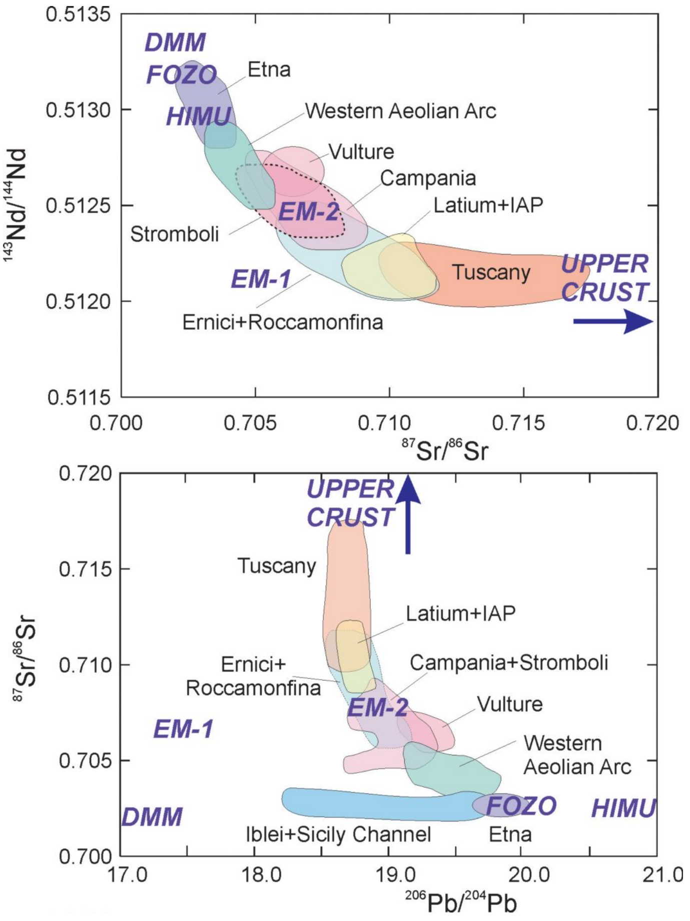
1 - Major, trace element ratios and radiogenic isotope signatures of mafic rocks are variable and reflect heterogeneous mantle sources with diverse modal mineralogy, trace element and isotopic compositions.

2 - Potassic alkaline composition are dominant in the Italian peninsula, and also occur in the central-eastern Aeolian Arc. This requires an origin of primary melts in phlogopite-bearing mantle sources. The presence of this mineral in the upper mantle demands metasomatic enrichment processes, a hypothesis strongly supported by high abundances of LIL element and the anomalous radiogenic isotope compositions of magmas. High ratios of LILE/HFSE, which are typical of island arc magmas, require that subduction processes are responsible for mantle metasomatism. However, this conclusion is not unanimously accepted, and alternative hypotheses invoking mantle plumes or deep mantle fluids have been suggested (e.g., Locardi, 1988; Bell *et al.*, 2004). Such an issue is discussed by Peccerillo & Lustrino (2005) and will not be reiterated here.

3 - Sr-Nd-Pb-He isotopic variations of Plio-Quaternary Italian orogenic volcanics define continuous trends between the OIB-type rocks of Etna and eastern Sicily, and the upper crust (Fig. 41). This points to an interaction between mantle and crustal end-members in the genesis of

Italian orogenic magmatism. Such an interaction occurred mainly in the upper mantle by addition of crustal material by subduction processes.

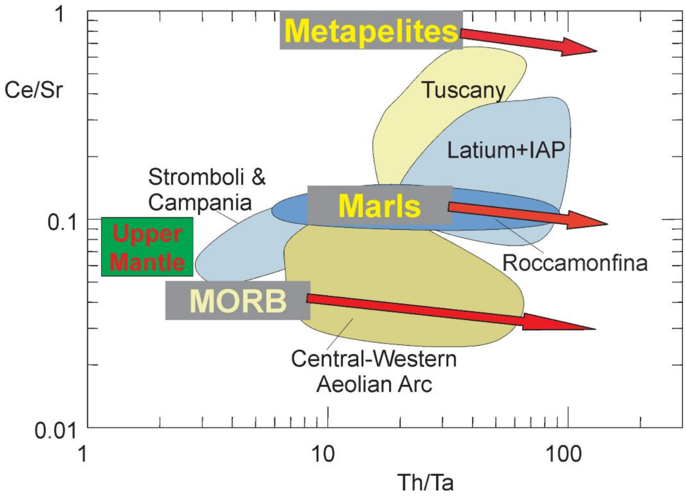
Figure 41. Sr-Pb isotopic variation in Italy



^{87}Sr/^{86}Sr vs. ^{143}Nd/^{144}Nd and ^{206}Pb/^{204}Pb for mafic (MgO > 4 wt%) orogenic rocks in central-southern Italy. Compositions of anorogenic of Etna and Sicily Channel are also shown. DMM (Depleted MORB-type Mantle), HIMU, FOZO, EM-1 and EM-2 are worldwide mantle end-member compositions.

4 - Variations of key trace elements ratios and radiogenic isotopes for orogenic mafic rocks in Italy (Figs. 41, 42) highlight different compositions for various volcanic provinces (Peccerillo, 1999). These have been explained as an effect of different compositions of crustal contaminants (i.e. MORB, MORB+sediments, marls, pelites) in different regions. However, some Italian volcanic rocks show higher incompatible trace element ratios (especially LILE/HFSE; e.g., Th/Ta) than any crustal rock. However, fluids released from subduction zones are able to transport more readily LILE (Rb, Th, U, K, etc.) than HFSE (Ta, Nb, Zr, etc.), and, therefore, have higher LILE/HFSE ratios with respect to the source crustal rocks. Such an increase is indicated by arrows in Fig. 42. Length of arrows signify the degree of LILE over HFSE enrichment, which appears stronger in the south. This supports a stronger role of aqueous fluids in the Aeolian Arc than in the magmatic province of central Italy.

Figure 42. Trace element ratios, central-southern Italy



Variations of LILE/LILE (Ce/Sr) and LILE/HFSE (Th/Ta) ratios in mafic (MgO > 3 wt%) orogenic rocks in central-southern Italy. Note strong regionality, which is explained by source contamination by different types of crustal rocks, i.e. MORB, marls, metapelites. Fluids transfer from slab to mantle wedge (arrows) produces small variation of LILE/LILE and a significant increase of LILE/HFSE. Length of arrows indicates the degree of LILE/HFSE enrichments operated by fluids. These are stronger in the Aeolian Arc, suggesting a stronger role of fluids in the mantle metasomatism of this region.

5 - Calcalkaline magmas are dominant in the Aeolian Arc and Tyrrhenian seamounts. This points to large degrees of partial melting in the presence of aqueous fluids, in agreement with evidence arising from LILE/HFSE ratios. Sr-irotope compositins of these magmas are poorly radiogenic, suggesting source contamination by a poorly radiogenic crust, such as MORB. Variations of isotopic compositions along the Aeolian Arc, require an increase in the role of upper crustal contaminants, most likely sediments from the Ionian slab, going from the western to the eastern islands. Similar trace element ratios and radiogenic isotopic signatures for Stromboli rocks and the Campania Province suggest a similar mantle contamination history, and have been interpreted as evidence that the Campania Province represents the northern end of the

Aeolian Arc rather than the southern extension of the Roman Province (Peccerillo, 2001a).

6 -The occurrence of dominant potassic alkaline rocks in central Italy reveal stronge degrees of mantle contamination by upper crust. Marly sediments have been suggested as contaminants of mantle wedge in the Roman, Intra Apennine, and Ernici-Roccamonfina provinces. In Tuscany, contaminants with pelitic composition are required by geochemical and isotopic data.

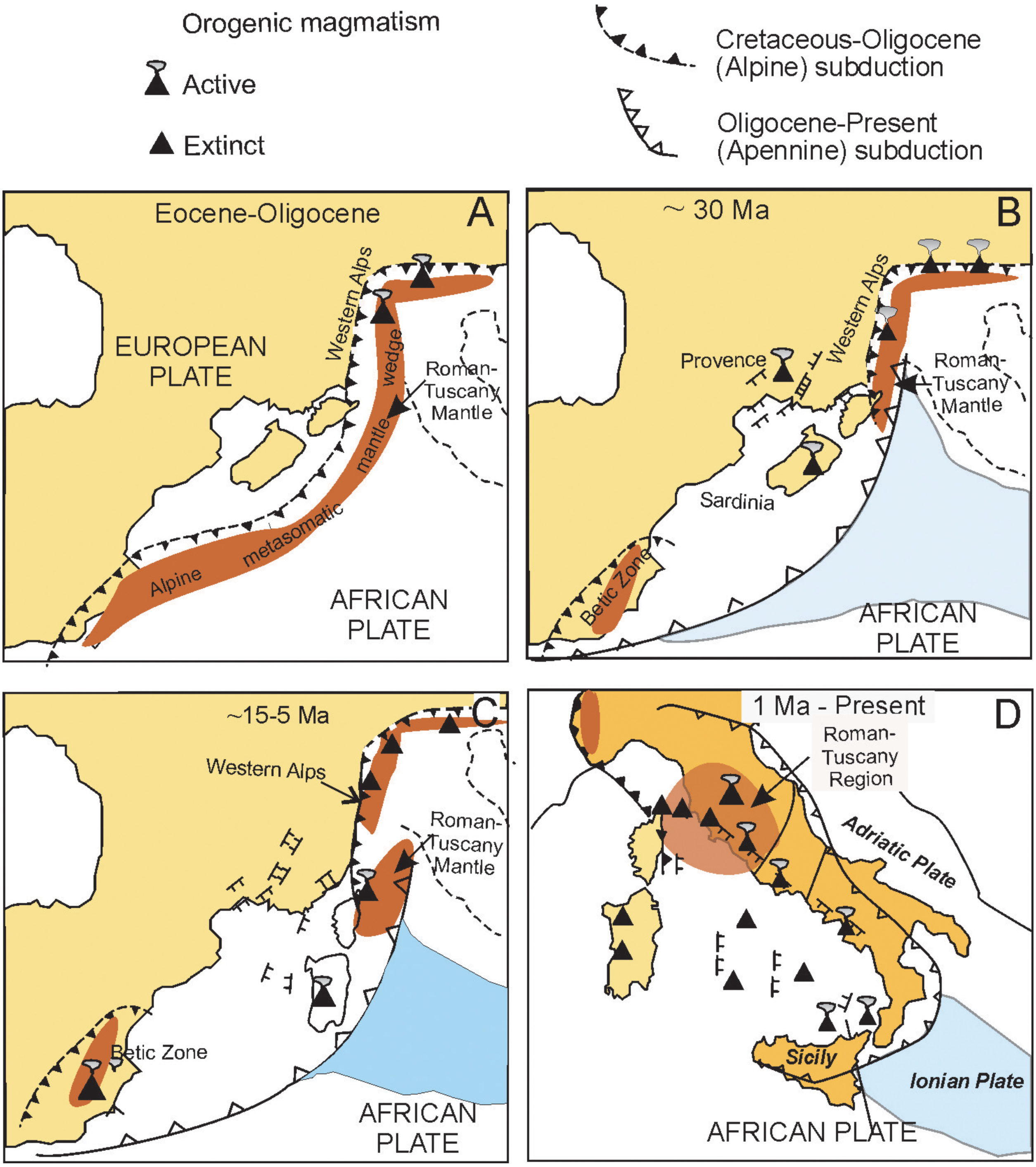
7 - Many compositional characteristics of mafic magmas were likely inherited from pre-metasomatic mantle sources. However, pristine nature of the upper mantle is difficult to constrain because of the intensive modification suffered by metasomatism. The single trend between Etna and the upper crust defined in the Sr-Nd-Pb isotope space by the bulk of orogenic magmas in Italy (Fig. 41) suggests a single type of composition for mantle endmember. This has a composition similar to Etna, which has isotopic signatures close to the so-called FOZO (Focus Zone) mantle composition. The physical significance of FOZO is a main problem of petrology and geochemistry at a global scale (Stracke *et al.*, 2005), and a deep mantle origin has been suggested for Italy (Gasperini *et al.*, 2002; Bell *et al.*, 2004). However, low contents of HFSE in several volcanoes, such as ultrapotassic rocks of the Roman Province, require mantle sources that are depleted in these elements, pointing to a MORB-type premetasomatic mantle, in most cases.

The complex history of mantle contamination suggested by petrological and geochemical data is related to several stages of metasomatic events occurred during the late Tertiary to present geodynamic evolution of the Mediterranean area. Such an issue is the focus of other papers in this volume.

Basically, two main subduction processes have been responsible for the origin of Alps and Apennine chain and associate magmatism (Fig. 43). Late Tertiary to Oligocene "Alpine" subduction of the European plate generated a belt of metasomatic mantle along the northern border of the African plate (Fig. 43a). Melting of this metasomatic mantle took place contemporaneously or later than subduction, and at different times in the various zones, depending on local modifications of tectonic and thermal regimes (Peccerillo & Martinotti, 2006; Beltrando *et al.*, 2010 and references therein). Significant contamination by the upper continenental crust affected the mantle wedge beneath the Western Alps and the region that will be later the site of the Tuscany and Roman provinces.

Successively, convergence between Africa and Europe took place by subduction of the Adriatic-Ionian plate beneath the southern European margin (Apennine subduction). This process also generated mantle contamination and magmatism, which initially affected Sardinia and Provence (Fig. 43b) and successively shifted eastward, during opening of the Balearic and Tyrrhenian basins and the rotation of the Italian peninsula (Fig. 43c,d) (e.g., Doglioni *et al.*, 1999). This second stage of orogenic magmatism also had a calcalkaline to ultrapotassic composition as along the Alps, but ultrapotassic magmatism dominating in central Italy (Roman-type magmas; see Peccerillo, 1992) has a distinct composition as the ultrapotassic lamproitic rocks from Western Alps. Roman-Tuscany area, which is a portion of the former Alpine collision zone that migrated eastward (Doglioni *et al.*, 1998), was affected by both Cretaceos-Oligocene "Alpine" and Oligocene to present "Apennine" subduction. Therefore, and its lithospheric upper mantle was subjected to two stages of metasomatism. These superimposed to each other generating a pervasively metasomatised mantle that originated abundant potassic and ultrapotassic magmatism. It is worth recalling that calcalkaline to lamproitic magmatism in Tuscany is different from the equivalent rocks occurring in other provinces of central Italy, and resembles closely to the Oligocene magmatism of Western Alps. The occurrence in the Tuscany-Roman area of two types of ultrapotassic magmatism is considered as an evidence of a two-stage metasomatic modification suffered by the upper mantle in this area (Peccerillo and Martinotti, 2006).

Figure 43. Geodynamic evolution of the Tyrrhenian Sea area



Schematic evolution of the Tyrrhenian Sea area from Eocene-Oligocene to present. For explanation, see text.

Summary and Conclusions

Tertiary to present magmatism in Italy is basically related to the convergence between the African and European plates, a process which has been going on since late Cretaceous and is still presently active. Cretaceous-Oligocene subduction of the European plate beneath the northern African margin and the following continental collision, have been the cause of Alpine orogenesis and associated magmatism. Tertiary orogenic magmatism along the Alpine chain is variable but overall indicates an origin within upper mantle sources that were contaminated by upper crustal material during subduction. Potassic rocks in the Western Alps show the strongest crustal-like geochemical and isotopic signatures, indicating a very important contribution by upper crustal material in the origin of magmatism. Note that deep subduction of continental crust (Dora Maira Massif) is documented in this region.

Mantle-originated melts along the Alps, underwent strong modification during emplacement, forming derivative magmas by combined processes of fractional crystallisation and crustal assimilation. Therefore, significant mantle-crust interaction in the Alpine magmatism occurred both in the source (mantle contamination), and during magma emplacement (magma contamination). The two processes superimposed to each other, making their respective effects difficult to recognise, in most cases. Amount of crustal melting seems stronger in the Central and Eastern Alps than in the west, suggesting different thermal regimes for various Alpine sectors.

Younger orogenic magmatism in Italy developed in and around the Tyrrhenian Sea basin and is essentially related to the subduction of the Adriatic-Ionian plate beneath the southern European margin. Ages range from Oligocene to present and become younger from west to south-east. This is the effect of migration of subduction processes.

Magmatic compositions vary very strongly and range from arc-tholeiitic and calcalkaline to shoshonitic and potassic-ultrapotassic alkaline. Overall, there is an increase in potassium with time and from west to east, the most potassium-rich rocks being found among the youngest products of central Italy. This time-related regional modification of magma compositions results from modification of the nature of the undergoing lithosphere from Oligocene to present during eastward migration of subduction. Subduction of an oceanic-type lithosphere is believed to be responsible for tholeiitic to calcalkaline magmatism in Sardinia, the Tyrrhenian Sea basin and the Aeolian Arc. Subduction of a continental-type lithosphere is believed to be the cause of extensive mantle contamination and generation of potassic and ultrapotassic volcanism in central Italy (Peccerillo, 2005a and references therein).

Some sectors of the upper mantle beneath the Italian peninsula also shows geochemical evidence of a previous contamination event, with compositional characteristics similar to the one which occurred in the Western Alps. This is particularly evident in Tuscany, where mafic rocks have major, trace element and radiogenic isotope compositions similar to those of the Western Alps. This is in agreement with hypotheses that the lithospheric sectors of the Tuscany-northern Latium area were part of the Oligocene Alpine overriding margin, which was successively dissected by extensional processes behind the subducting Adriatic plate, and shifted eastward to its present position.

Compositions of pre-metasomatic mantle sources are still poorly understood. Mantle components of both asthenospheric and lithospheric origin were subjected to contamination by subduction-related material. The role of deep mantle plume components is very hypothetical and poorly constrained and conflicts with a number of geochemical, geophysical and field evidence, as discussed by Peccerillo & Lustrino (2005).

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