Per. Mineral. (2007), 76, 49-66
SPECIAL ISSUE: From Petrogenesis to Orogenesis

doi:10.2451/2007PM0008
http://go.to/permin

PERIODICO di MINERALOGIA
established in 1930

An International Journal of
MINERALOGY, CRYSTALLOGRAPHY, GEOCHEMISTRY, ORE DEPOSITS, PETROLOGY, VOLCANOLOGY
and applied topics on *Environment*, *Archaeometry* and *Cultural Heritage*

Petrogenesis of post – orogenic Late Paleozoic andesite magmatism: a contribution from the Ligurian Alps (Italy)

Laura Buzzi and Laura Gaggero*

Dipartimento per lo Studio del Territorio e sue Risorse, Università degli Studi di Genova, Corso Europa 26, 16132 Genova, Italy.

Accepted, April 2007

Abstract. — The post-orogenic subalkaline andesite to K-andesite volcanism, developed within intramontane basins after the collapse of the Variscan orogen, originated in a geodynamic environment significantly different from that of continental or island arc settings. However, the major, trace and rare earth element compositions are not particularly effective in discriminating any clear affinity, and suggest a complex genetic hypothesis. In southwestern Europe, andesites are preserved in the Alpine units of the Ligurian Alps, and belong to successions characterised by the constant occurrence of a basal rhyolitic ignimbrite, followed by andesites, and conspicuous dacites-rhyodacites (or diorites), all intercalated within lacustrine sediments.

The trace element ratios and initial Sr and Nd isotopic compositions of the intermediate and outer Briançonnais andesites were compared with potential magma sources, and allowed to exclude Andean-type and OIBs magmas. The initial (290 Ma) $^{144}Nd/^{143}Nd$ and $^{87}Sr/^{86}Sr$ for the Ligurian Briançonnais andesite fitted the composition issuing from the assimilation-fractional crystallisation model, starting from a subcontinental, lithospheric mantle-type parental magma through the addition of ~80 wt% of a crustal metasedimentary component to the picrobasaltic composition. The fractionating assemblage for the SLM parental picrobasalt consisted of 40 wt% olivine, 10 wt% orthopyroxene, 40 wt% clinopyroxene and 10 wt% plagioclase. We assumed that such melt, generated at some 3 GPa and ≈1400 °C in equilibrium with a garnet lherzolite, was the parental liquid of the Briançonnais calc-alkaline magmatism.

A crust/mantle separation model age of 1.26 Ga was calculated from the Nd isotopic composition, possibly matching the Elzevirian Orogeny event (~1250-1190 Ma), at the southeastern margin of Laurentia.

Riassunto. — Il vulcanismo subalcalino da andesitico a K-andesitico, sviluppato in bacini intramontani a seguito del collasso dell'orogene Varisico, si è originato in un contesto geodinamico molto differente da quello degli archi continentali o di isole. Tuttavia, la composizione degli elementi maggiori, in traccia e delle terre rare non discrimina efficacemente l'affinità suggerendo piuttosto una genesi complessa. Nelle aree dell'Europa meridionale del Mediterraneo occidentale, tali andesiti sono preservate nelle unità Alpine delle Alpi Liguri, e appartengono a successioni caratterizzate dalla presenza di una ignimbrite riolitica basale, seguita da andesiti e quindi da cospicue effusioni dacitiche-riodacitiche (o intrusioni dioritiche), in sedimenti lacustri.

* Corresponding author, E-mail: gaggero@dipteris.unige.it

I rapporti tra gli elementi in traccia e le composizioni isotopiche di Sr e Nd (ricalcolati a 290 Ma) di andesiti del Brianzonese intermedio ed esterno, sono stati confrontati con possibili sorgenti, evidenziando la differenza dal contesto Andino e da *end-members* di tipo OIB. I rapporti isotopici iniziali $^{144}Nd/^{143}Nd$ e $^{87}Sr/^{86}Sr$ per l'andesite del Brianzonese corrispondono alle composizioni ottenute attraverso un modello di assimilazione e cristallizzazione frazionata, a partire da un liquido parentale di composizione picrobasaltica generato da un mantello litosferico sottocontinentale per addizione di ~80% di una componente crostale metasedimentaria. La paragenesi frazionata dal liquido parentale picrobasaltico è 40% olivina, 10% ortopirosseno, 40% clinopirosseno and 10% plagioclasio. Tale liquido, originato a circa 3 GPa e ~1400 °C, in equilibrio con una lherzolite a granato, può essere considerato un possibile magma parentale per le vulcanite calc-alcaline del Brianzonese Ligure.

L'età modello di separazione crosta/mantello a 1,26 Ga, calcolata sulla base della composizione isotopica del Nd, potrebbe corrispondere all'evento orogenico Elzeviriano (~1250-1190 Ma), alla periferia sudorientale della Laurenzia.

Introduction

It is well known that the petrogenetic heterogeneity of arc magmas over space and time is caused by many factors, firstly in their slab- or mantle-dominated or multisource origin (Green, 1982; Myers and Johnson, 1996; Kimura and Yoshida, 1999; Peacock, 1996), followed by the mechanism of slab-mantle mass transfer (Hanyu *et al.*, 2002), the quantity and nature of migrating fluids (Nichols *et al.*, 1996), the extent of crystal fractionation and of crustal assimilation (Tatsumi *et al.*, 2002; Zeck *et al.*, 1999).

In volcanic arc environments, the occurrence of intermediate volcanic rocks in orogenic belts or reworked in mélanges is generally assumed to be the marker of a past subduction (Gaggero *et al.*, 1997; Polat and Kerrich, 2002; Sandeman *et al.*, 2006). Interpreting an igneous event as a geodynamic indicator requires that all the geological data fit the petrogenetic model. In particular, the geological, stratigraphic, petrographic and geochemical evidence, suggests that andesites can also originate in other geodynamic contexts, characterised by an even more complex pattern of geochemical contributions than "orogenic" andesites (Bixel *et al.*, 1983; Innocent *et al.*, 1994; Gans *et al.*, 1989; De Larouzière *et al.*, 1988).

Permo-Carboniferous intermediate volcanic rocks are reported in all post-orogenic successions; their ubiquitous occurrence in the most complete stratigraphic sequences suggests that they can be assumed to be a lithological unit.

Andesitic volcanism is also reported from several regions in Southern Europe, such as the Southern Alps, Sardinia and the Ligurian Alps (Cortesogno *et al.*, 1998). An apparent stratigraphic convergence has been demonstrated, suggesting, as a whole, a post-Sakmarian age (<294.6 ± 0.8 Ma) for the volcanic activity.

Andesites are widespread in the Ligurian Alps from the eastern (inner) to the western (outer) Alpine tectonic units (Cortesogno *et al.*, 1982; 1984a; 1992; 1993). In the inner and intermediate sectors their composition ranges from rare basalt andesites to abundant andesites with subalkalic, calc-alkalic affinity. Trachy-andesites and dacites with shoshonitic affinity have instead been emplaced mostly in the outer sectors, likely related with increasing thickness of crust above the source (Cortesogno *et al.*, 1992). As a general feature, the andesitic volcanism occurs in a broad, though defined, zoneography with respect to the paleogeography of the exhumed and tectonically collapsing Variscan cordillera. The orogenic collapse, where extensional tectonics and subordinate compressional phases were alternating, suggests a regional transtensional regime, active along the Variscan suture of Pangaea (Cortesogno *et al.*, 1998, 2003; Cassinis, 1996; Cassinis *et al.*, 1997; Doblas *et al.*, 1994; Echtler and Malavieille, 1990).

In this study we have tried to quantify the possible source regions, the components that contributed to the origin of andesitic magmas and the processes encompassed during their ascent and emplacement using geochemical and petrological tools. We focused our attention on andesites of the Eze Formation in the Ligurian Alps (Cortesogno *et al.*, 1992; 1998) because of their widespread occurrence and the abundance and availability of an exhaustive set of stratigraphic and compositional data. The following paleogeographic distribution and stratigraphic descriptions are based on the successions inferred disregarding the dissection of the passive margin and the build-up in the Alpine edifice (Cortesogno *et al.*, 1992; 1993).

PALEOGEOGRAPHIC DISTRIBUTION

In the Ligurian Alps (Fig. 1), Lower-Upper Permian intermediate volcanic rocks (Eze Formation) occur in the inner, intermediate and outer Briançonnais tectonic units as: I) dykes across the polymetamorphic Lower Paleozoic basement, II) lava flows and tuffs interbedded in lacustrine shales (Gorra Schists) heteropic with continental quartzitic siltites (Viola Formation), III) scarce volcanic clasts in Carboniferous basal conglomerate (Ollano Formation; Cortesogno *et*

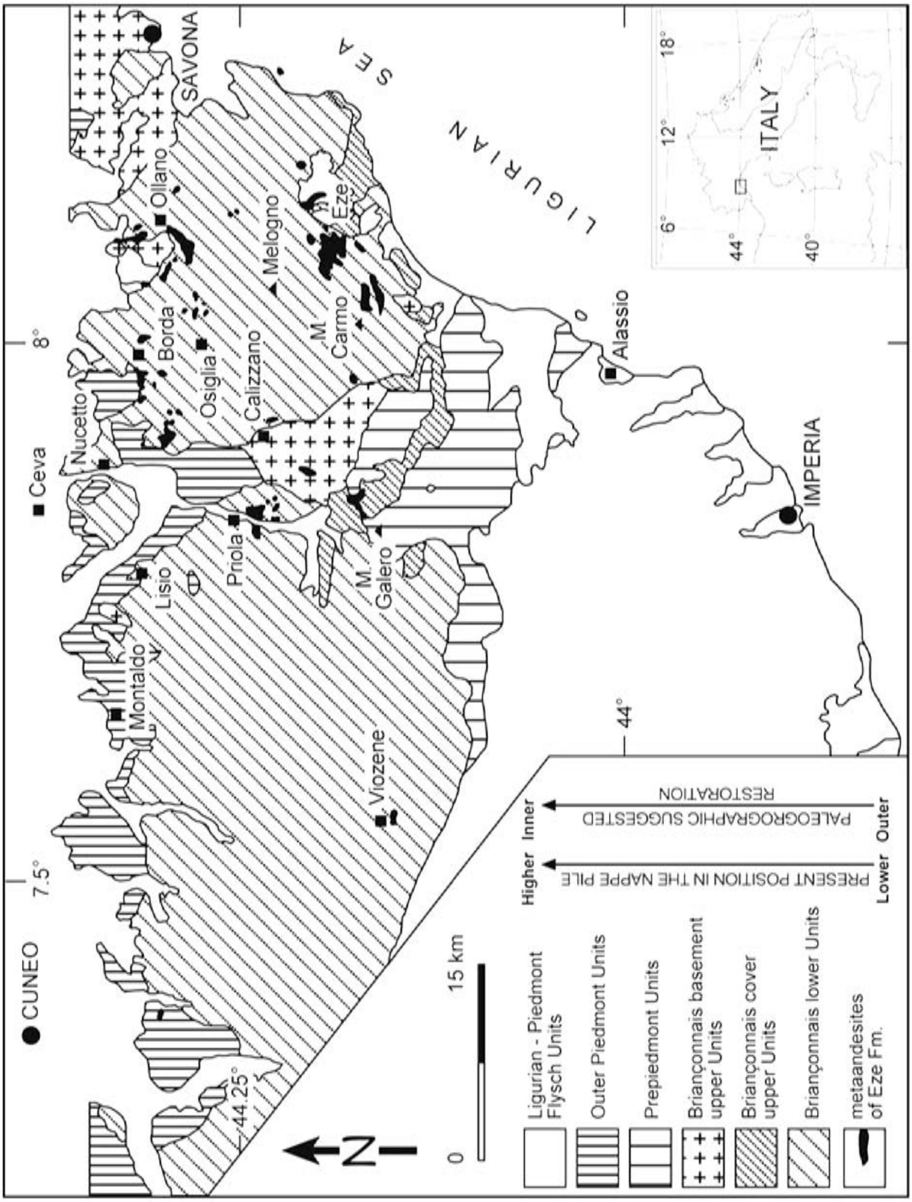

Fig. 1. Tectonic sketch-map of Western Liguria and distribution of andesitic rocks (modified after Cortesogno *et al.*, 1992).

al., 1984b; Cortesogno *et al.*, 1988), IV) volcanic clasts in Lower-Middle Jurassic breccias (Monte Galero) from the Prepiedmont domain, and V) volcanic clasts in Upper Jurassic breccias from a Piedmont unit (Cortesogno *et al.*, 1992). The most widespread products are lavas and tuffites.

In spite of the polyphase Alpine tectonics, several inferences can be made from detailed surveys and reconstructions (Fig. 2; Cortesogno *et al.*, 1992), in particular: I) in both the inner and outer zones an extensional tectonic regime controlled the mode and site of emplacement in thick vs. thin or

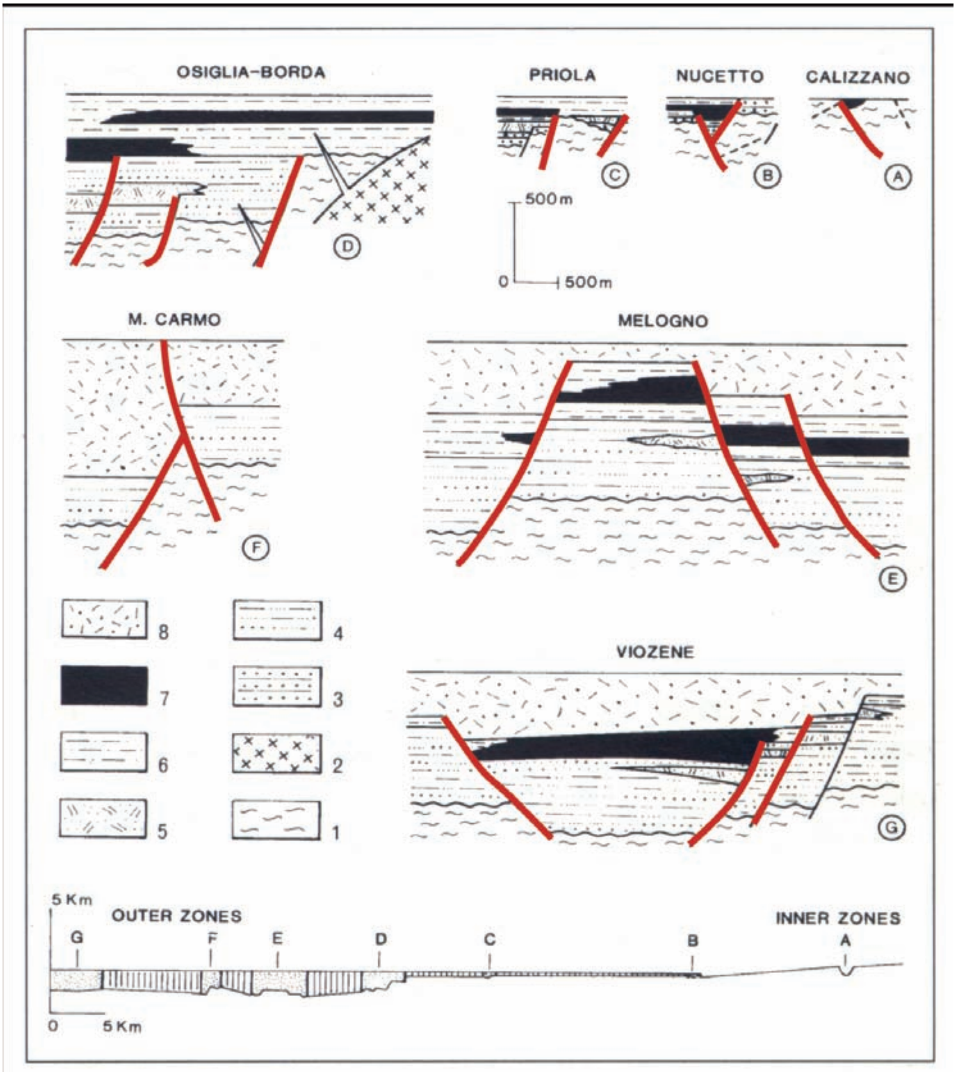

Fig. 2. Inferred paleogeographic setting of the Ligurian Briançonnais domain during the Lower Permian (modified after Cortesogno *et al.*, 1992). 1: Pre-Namurian basement; 2: Late Variscan granodiorites; 3: Lower Late Carboniferous coarse continental metasediments; 4: Upper Carboniferous coarse to fine continental metasediments; 5 Metarhyolitic ignimbrite, agglomerates and dykes; 6: Carboniferous fine to very fine continental metasediments; 7: Eze Formation; 8 Permian mainly rhyolitic metaignimbrites

reworked successions of the volcanic products, II) the volumes of the volcanic products increased significantly from the inner to the outer zones; the igneous activity was associated with subsidence that likely migrated from paleo E to paleo W between the Lower and Upper Permian.

Stratigraphic relevance

On the whole, the available radiometric dating of the post-Variscan successions of the Ligurian Alps tends to rejuvenate the stratigraphic record.

A Lower Permian igneous event is revealed by the intrusion of calc-alkaline, Al-saturated granitoid rocks (Borda granodiorites) between ~294 and ~300 Ma (U/Pb by isotopic dilution and SHRIMP methods respectively, Cortesogno *et al.*, 2003; Gaggero *et al.*, 2004), corresponding to the Asselian up to the Asselian–Sakmarian boundary.

In the intermediate Briançonnais unit of Mallare, a younger, though early acidic volcanic event is represented by a rhyolitic ignimbrite (Osiglia) heteropic with the basal Ollano conglomerate. The U/Pb dating of the ignimbrite by isotopic dilution yielded a concordia age of 279 +5-3 Ma (Cortesogno *et al.*, 2003), corresponding to the Artinskian. However, the Ollano conglomerate is generally ascribed to the Bashkirian according to the time scale of Gradstein *et al.* (2004), formerly Westphalian (i.e. the 315-305 Ma age interval), on the basis of plant remnants, which include *Senftenbergia (Pecopteris) elegans* CORDA, *Pecopteris nodosa* GOEPP and *Annularia longifolia* BRONGN (Portis, 1887).

A Lower Permian age is accordingly attributed to andesitic lavas and breccias in lacustrine environment from central and southeastern Sardinia, as well as to the rare andesites reported from the Collio and Tione basins in the Southern Alps (Cortesogno *et al.*, 1998).

At the scale of southwestern Europe, the constant occurrence of compositionally intermediate volcanics in the post-orogenic phase of the Variscan event has enabled us to consider it as a reliable lithostratigraphic marker. However, preliminary LAM-ICP-MS in situ U/Pb dating on zircon carried out on the andesites of the Eze Formation in the Ligurian Alps shows a complex inherited history recorded in zircon crystals, together with important Triassic re-equilibration (in prep.), both suggesting various overprinting events.

Petrography

In spite of the Alpine metamorphic overprint at the blueschist–greenschist facies boundary, primary mineralogical, textural and compositional features in Eze andesites are rather well preserved (Cortesogno *et al.*, 1992). In the Eze Formation volcanites are mainly andesites and minor basaltic andesites at the boundary with trachyandesites. Minor dacitic compositions occur. The primary textural features are preserved from inner and outer Briançonnais, whereas the inner Briançonnais outcrops (dykes across the polymetamorphic Lower Paleozoic basement) are more pervasively re-equilibrated under blueschist Alpine metamorphism.

The Eze Formation andesites from both the inner and intermediate Briançonnais units are porphyritic (Porphyritic Index, PI between 5 and 20) with seriate and glomeroporphyritic textures (Fig. 3). The phenocryst assemblage includes plagioclase, generally altered, and brown hornblende. Brown amphibole, rarely preserved, from the most conspicuous lava flows is idiomorphic, has an edenitic hornblende to Mg-hornblende composition and can include plagioclase. Plagioclase phenocrysts are altered to albite ± epidote ± pumpellyite ± lawsonite and the groundmass shows extensive recrystallisation under Alpine metamorphism.

In the basaltic andesites, augite clinopyroxene is the main phenocrystic phase; orthopyroxene is rare and inferred from amphibole + chlorite pseudomorphs. Ilmenite and Ti-magnetite, with rare allanite are accessory phases. The most common xenocrysts can be quartz and garnet; hydrothermal tourmaline can occur in pyroclastic levels.

The andesites from the outer Briançonnais unit are mainly volcanic breccias and pyroclastites, and are different from the inner and intermediate ones in that they have a more restricted PI range (20-30). The phenocryst assemblage is represented by plagioclase and biotite with rare hornblende (Cabella *et al.*, 1988; Cortesogno *et al.*, 1992). A low grade to very low grade Alpine metamorphic recrystallisation is widespread.

Analytical techniques

A reappraisal of the major-, trace- and rare earth elements abundances of 63 andesite analyses from Cortesogno *et al.* (1992) and 24 analyses from Cortesogno *et al.* (1983) was integrated with new data on the Sr and Nd isotopic compositions of 2 andesite samples of the intermediate and outer Briançonnais units respectively (Tab. 1).

Whole-rock major and trace element abundances for basalts were carried out with XRF techniques at the X-RAL Laboratories, Canada. Losses

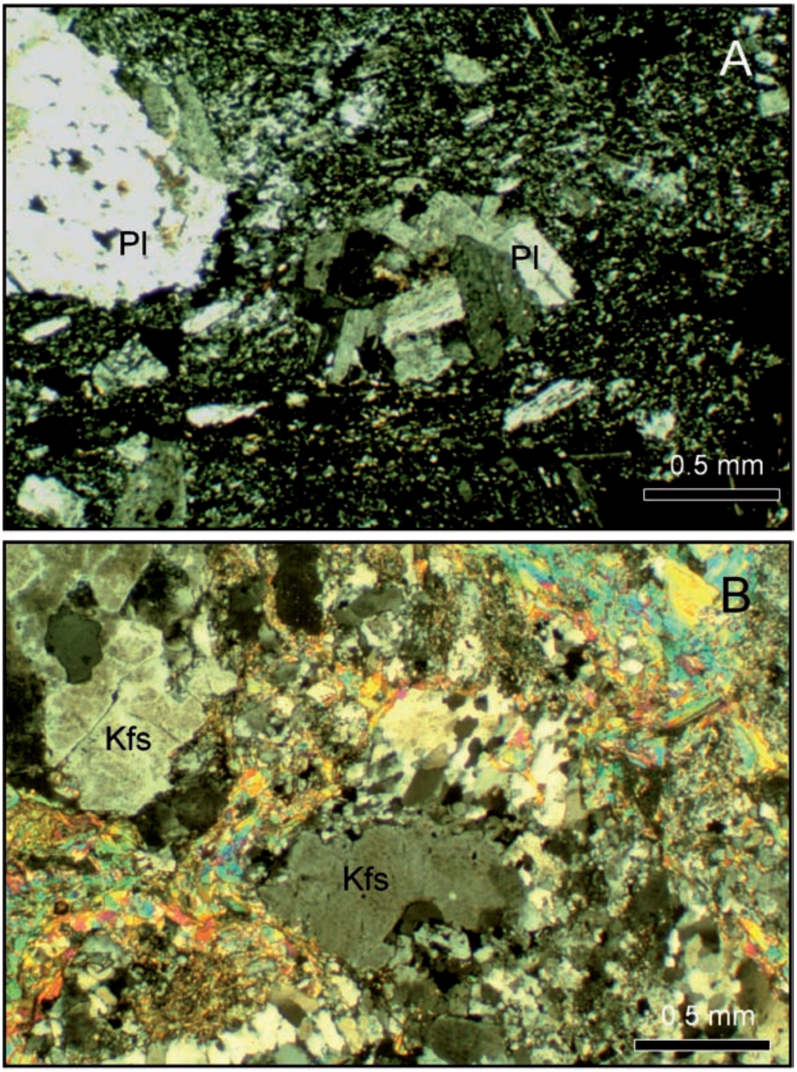

Fig. 3. Representative transmitted-light microphotographs of the Ligurian Briançonnais andesite textures and composition. Bar scale in photos. A) Crossed polars. Plagioclase phyric lava and isoriented mesostasis from the intermediate Briançonnais domain. B) Crossed polars. K-feldspar-phyric K-andesite from the outer Briançonnais domain.

TABLE 1

Sr and Nd isotope compositions of the outer and intermediate Briançonnais Lower Permian andesites; N-MORB (Hart el al., 1999), E-MORB (Cocherie et al., 1994), SLM (Kagami et al., 1991), felsic granulite (Montanini and Tribuzio, 2001), S-type granitoid and I-type granitoid (Liew and Hofmann, 1988)

Rock-type	Rb (ppm)	Sr (ppm)	$^{87}Sr/^{86}Sr_{meas} \pm 2\sigma$	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr_{(290\ Ma)}$	$\varepsilon Sr_{(290\ Ma)}$	Sm (ppm)	Nd (ppm)	$^{143}Nd/^{144}Nd_{meas} \pm 2\sigma$	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd_{(290\ Ma)}$	$\varepsilon Nd_{(290\ Ma)}$
Outer Briançonnais andesite	65	91	0.71250 ± 1	2.068	0.70397	-2.7	5.43	20.6	n.a.			
Intermediate Briançonnais andesite	104	170	0.71480 ± 2	1.771	0.7075	47.3	4.4	19.1	0.51237 ± 2	0.139	0.5121	-3.15
N-MORB	9	118	0.70464	0.223	0.70372	-6.3	2.55	6.8	0.51308	0.228	0.51264	7.4
E-MORB	10.8	335	0.70521	0.093	0.70483	9.4	4.05	16.6	0.51263	0.148	0.51235	1.8
SLM	20.7	205	0.70431	0.292	0.7031	-15	1.98	7.6	0.51279	0.158	0.51249	4.3
Felsic granulite	83	225	0.71577	1.073	0.71134	101.9	4.15	22.4	0.51218	0.112	0.51197	-5.7
S-type granite	224	165	0.7293	3.94	0.71304	126.1	5.55	30.2	0.51223	0.111	0.51202	-4.8
I-type granite	109	768	0.7081	0.411	0.7064	31.8	6.84	41.5	0.51226	0.1	0.51207	-3.7

on ignition (LOI) were determined with the gravimetric method. The RE elements were analysed with ICP-MS at the X-RAL Laboratories, Canada. Strontium and Nd isotopic concentrations were analysed at the Geochemistry Laboratory of Trieste University. Samples for isotopic analysis were dissolved in teflon vials using a mixture of HF-HNO_3 and HCl purified reagents. Sr and Nd were collected after ion exchange and reversed-phase chromatography, respectively; the total blank for Sr was less that 20 pg. The Sr and Nd isotopic composition were obtained using a VG 54E mass spectrometer and "Analyst" software (Ludwig, 1994) for data acquisition and reduction. The $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$ ratios were corrected for fractionation to $^{86}Sr/^{88}Sr$=0.1194 and $^{146}Nd/^{144}Nd$= 0.7219, respectively, and the measured ratios were corrected for instrumental bias to NBS 987 and La Jolla standard values of 0.71025 and 0.51186. The reported errors represent a 95% confidence level. Nd-model ages were calculated with respect to a depleted mantle evolution curve given by $\varepsilon Nd(T)= 0.25T^2-3T+8.5$ (T in Ga) as reported in Ludwig (1994).

Whole rock geochemistry

Secondary alkali mobilisation could have affected some of the andesites during diagenesis and/or metamorphism. Nevertheless poor correlations between LOI and major "mobile" elements suggest an overall low extent of alteration. The Eze andesites from the intermediate Briançonnais have on the whole high Al_2O_3 (15-22 wt%), low FeO_t (5-10 wt% on average), TiO_2 (0.6-1 wt%), and Zr (131-395 ppm). The highest Al_2O_3 contents not associated with positive Eu anomaly likely reflect plagioclase sericitisation. They mostly fall in the sub-alkaline calc-alkaline field (Fig. 4A); however basaltic trachy-andesites and trachy-andesites occur locally in the intermediate Briançonnais. The volcanic clasts in Lower-Middle Jurassic breccias were characterised by a wide spread in SiO_2 and K_2O (Fig. 4B).

On the whole, the andesites display a relatively low Ni (38-72 ppm) and lower Sc/Cr, Sc/Ni and trace element ratios than those of OIBs and CABs (Tab. 2).

The REE patterns (Cortesogno *et al.*, 1992) showed a positive LREE fractionation, a less pronounced HREE fractionation, and a significant negative Eu anomaly higher than OIBs and comparable to CABs and Andean andesites, suggesting that the andesites experienced significant plagioclase fractionation.

The composition and element ratios of the high-K andesites from the outer Briançonnais fall within the range of the intermediate Briançonnais andesites; they have significant chemical differences from the previous ones, due to the early precipitation of biotite and relative enrichment in the rock, and have relatively high ΣREE, higher Rb (67 ppm), Ba (346 ppm) and ΣLREE (90 ppm) (Tab. 2).

The MORB-normalised spiderdiagrams for the inner and intermediate Briançonnais andesites (Fig. 5 A, B) are characterised by average Sr, Ca enrichments, and wider Ti, Yb and P variations than those of the outer Briançonnais ones. These latter andesites specifically show higher average Rb and K (Fig. 5C), and an evident negative Nb spike in accordance with a calc-alkaline signature. Element/MORB ratios for the volcanic clasts in Lower-Middle Jurassic breccias (Fig. 5D), LILE enrichment and Sr depletion are consistent with the shoshonitic affinity already demonstrated by Cortesogno *et al.* (1992).

Different initial $^{87}Sr/^{86}Sr$ ratios for the outer and intermediate Briançonnais andesites (0.70397-0.70750 respectively), suggest (Fig. 6) internal heterogeneities of source and/or secondary processes (from source metasomatism to assimilation at shallower levels). Also Ba/Th and Ba/La ratios point to enrichments by possible assimilation. Potential MORB or OIB mantle sources are hardly acceptable due to the lack of Nb, Ta or Ba enrichments relative to other LILE elements; therefore other sources and possibly a multisource origin can be envisaged.

The intermediate Briançonnais andesite (0.512103 and 0.70750 for the $^{143}Nd/^{144}Nd$ and $^{87}Sr/^{86}Sr$ initial ratios, Tab. 1, Fig. 7) have a significantly lower Nd isotopic composition than the MORB-OIB mantle array and are close to the high-K calc-alkaline magmatism of the Southern Alps (Rottura *et al.*, 1998). Moreover, they do not show any overlap neither with the oceanic island arc field nor with the Andean volcanic rocks.

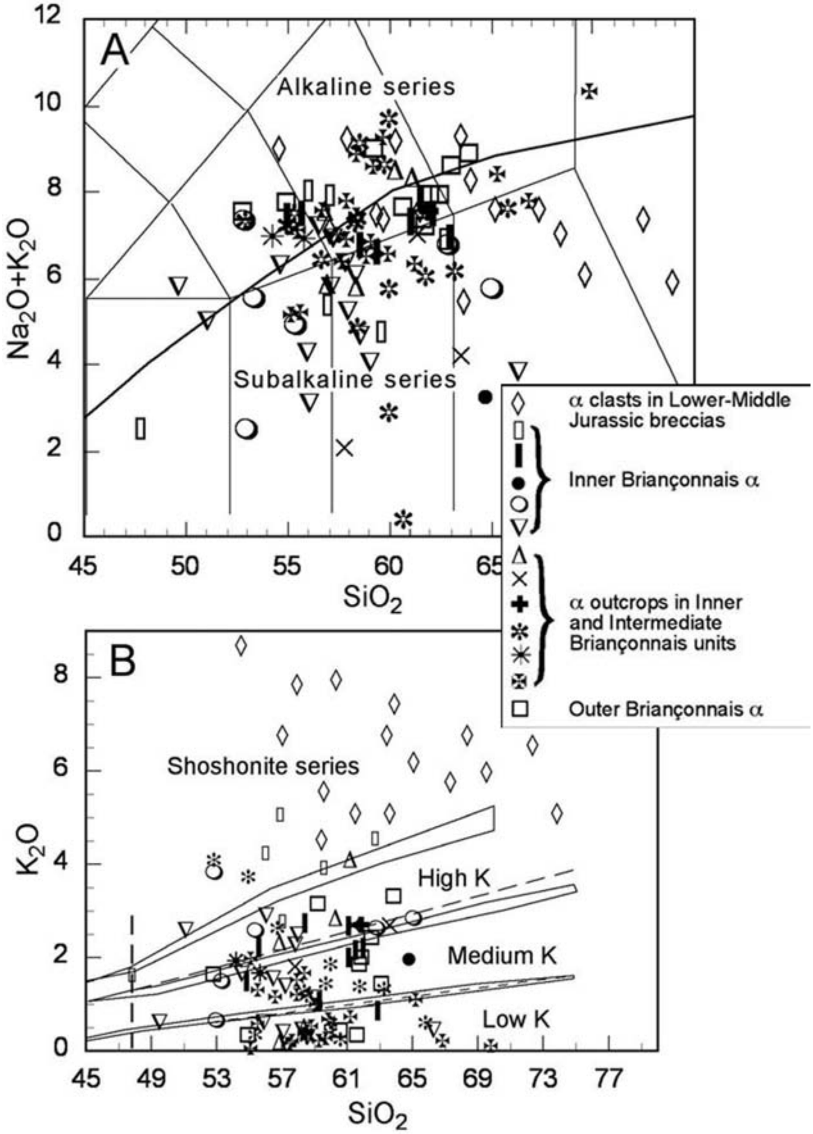

Fig. 4. A) Total Alkali-Silica (TAS, Le Maitre *et al.*, 1989) diagram showing the calc-alkaline and transitional character of the Lower Permian andesites in the Ligurian Briançonnais. B) SiO_2 vs. K_2O (Le Maitre *et al.*, 1989). The lowest values of K_2O values represent the effects of moderate alteration. The samples with the highest K_2O wt% reflect enrichments in K-feldspar and/or biotite and correspond to the shoshonitic compositions of Monte Galero volcanic clasts in Lower–Middle Jurassic breccias from the Prepiedmont domain.

Petrogenetic model and discussion

The subalkaline calc-alkalic affinity of the Briançonnais andesites has been recognised and assessed in analogy with other Lower Permian andesites from Sardinia (Cortesogno *et al.*, 1998) and Alto Adige (Di Battistini *et al.*, 1988; Rottura *et al.*, 1998). In particular, a K-andesitic character has been demonstrated in Alto Adige as well as in the Ligurian Briançonnais (Di Battistini *et al.*, 1988, Cortesogno *et al.*, 1992). In the present study, our initial (t=290 Ma) $^{87}Sr/^{86}Sr$ vs. initial $^{143}Nd/^{144}Nd$ (Tab. 1, Fig. 7) enabled us to exclude a similarity with OIBs, or calc-alkaline volcanic rocks from any segment of the Andean Belt calc-alkaline volcanics. Similar inferences are also possible for the basaltic andesite of the Atesina platform (Rottura *et al.*, 1998).

In the literature, the petrogenesis of Lower Permian andesitic magmatism in the investigated area of south-western Europe has been correlated with the interaction of mantle-derived melts and crust, acting through wall-rock assimilation and fractional crystallisation (Stille and Buletti, 1987). This model, envisaged for the Lugano area, can be extended with good approximation to the origin

TABLE 2

Diagnostic parameters and element ratios for the Ligurian Briançonnais andesites. Major element contents are normalised to anhydrous bulk compositions. RE elements are normalised according to Nakamura et al. (1974). Literature data are taken from the compilation at http://www.Geokem.com site

Andesite type-locality	Inner Briançonnais	Intermediate Briançonnais	Outer Briançonnais	Clasts Jurassic breccias	Central Amer	Andes	Mexican Arc	Cascades
Number of analyses	36	49	10	17	532	1597	1154	893
SiO_2	57.9	59.3	60.3	63.6	53.0	59.4	58.6	58.7
A/CNK	2.16	1.69	1.90	2.15	1.21	1.39	1.29	1.33
Mg#	33.5	36.2	29.1	47.2	38.6	37.6	41.4	40.1
Rb (ppm)	75	38	60	146	26	89	49	29
Ba (ppm)	390	209	297	447	553	521	701	419
Sr (ppm)	141	362	122	13	413	485	792	589
Th (ppm)	6.07	6.75	5.90	26.38	2.20	10.03	6.71	3.92
Ni (ppm)	43	31	23	19	90	40	83	70
Ni/Co	2.30	1.61	1.52	2.19	2.58	1.84	3.23	1.92
Sc/Cr	1.76	0.77	0.34	1.44	-	0.18	0.10	0.15
Sc/Ni	2.24	1.47	1.18	7.55	-	0.39	0.18	0.29
Zr/Y	7.60	9.45	6.00	8.75	3.94	7.28	7.47	6.77
Th/U	-	3.05	-	-	2.50	2.81	2.65	3.06
La (ppm)	27.8	24.5	20.6	10.8	15.7	26.4	31.1	16. 0
Ce (ppm)	57.5	52.0	42.6	23.3	27.3	55.1	64.7	32.7
ΣLREE	108	106	85	45	65	120	147	75
ΣREE	123	125	107	59	64	109	124	74
La/Y	0.98	1.44	0.67	0.64	0.65	1.20	1.12	0.77
K/La	705	390	664	3916	564	729	614	757
P/La	42	50	71	95	54	40	52	60
La_N/Yb_N	7.46	10.25	15.29	3.72	4.81	8.36	7.82	5.55
La_N/Lu_N	6.98	9.35	5.83	4.28	4.90	8.91	8.35	4.49
Tb_N/Yb_N	2.16	1.74	-	-	1.80	1.93	1.94	2.11
Eu/Eu*	0.92	0.82	0.74	0.58	0.76	0.81	1.95	0.96

of most post-Variscan intermediate volcanic rocks. In the Ligurian Briançonnais, the partial melting of lower crust, in equilibrium with garnet was demonstrated by Cortesogno *et al.* (1992). Therefore we tentatively modelled concurrent crustal assimilation and fractional crystallisation for the potential mantle sources of the andesite magmas.

In the present study, the isotopic content of the intermediate Briançonnais andesites (Fig. 8) falls along the vectors of fractional crystallisation calculated from a sublithospheric mantle (SLM) source towards crustal metasedimentary sources. The selected contaminants are: I) felsic granulites of the External Liguride Units issued from anhydrous anatectic melts extracted from restitic bodies of metasedimentary origin (Montanini and Tribuzio, 2001); II) S-type peraluminous granitoids of the Moldanubian zone, related to the dehydration melting of a metasedimentary protolith

TABLE 2 — *continued...*

Kamchatka	Kuriles	Indonesia	Izu Bonin	Marianas	Fiji-Lau Arc	Tongan Arc	Andesite type-locality
608	988	848	1356	881	312	122	**Number of analyses**
55.8	58.2	54.3	58.3	54.3	54.9	55.9	**SiO_2**
1.32	1.42	1.21	1.37	1.26	1.32	1.25	**A/CNK**
39.9	35.5	37.2	38.0	39.7	36.5	35.7	**Mg#**
24	33	109	11	11	27	7	**Rb (ppm)**
438	363	806	100	120	269	118	**Ba (ppm)**
440	332	635	193	235	420	198	**Sr (ppm)**
1.94	3.53	10.13	1.12	0.83	1.40	0.26	**Th (ppm)**
60	45	36	79	80	42	30	**Ni (ppm)**
2.01	1.96	1.25	2.75	2.19	1.59	0.78	**Ni/Co**
0.14	0.36	0.29	0.10	0.17	0.27	0.55	**Sc/Cr**
0.44	0.63	0.75	0.36	0.44	0.60	1.39	**Sc/Ni**
5.53	5.24	4.80	3.14	3.12	3.14	2.15	**Zr/Y**
2.35	2.79	6.79	1.70	2.41	2.24	1.48	**Th/U**
11.8	11.8	57.3	5.7	9.6	11.9	2.3	**La (ppm)**
27.4	28.4	100.1	11.8	17.7	25.0	5.6	**Ce (ppm)**
64	63	211	28	44	61	15	**ΣLREE**
61	62	137	33	55	52	23	**ΣREE**
0.54	0.49	1.99	0.31	0.43	0.36	0.15	**La/Y**
951	990	352	1134	678	1073	1685	**K/La**
97	71	27	84	74	104	224	**P/La**
3.93	2.69	7.28	1.82	2.53	2.92	0.97	**La_N/Yb_N**
4.09	2.77	13.32	1.76	2.51	2.62	0.95	**La_N/Lu_N**
1.82	1.51	0.95	1.36	1.60	1.65	1.33	**Tb_N/Yb_N**
1.07	0.65	0.87	0.96	0.95	1.20	1.43	**Eu/Eu***

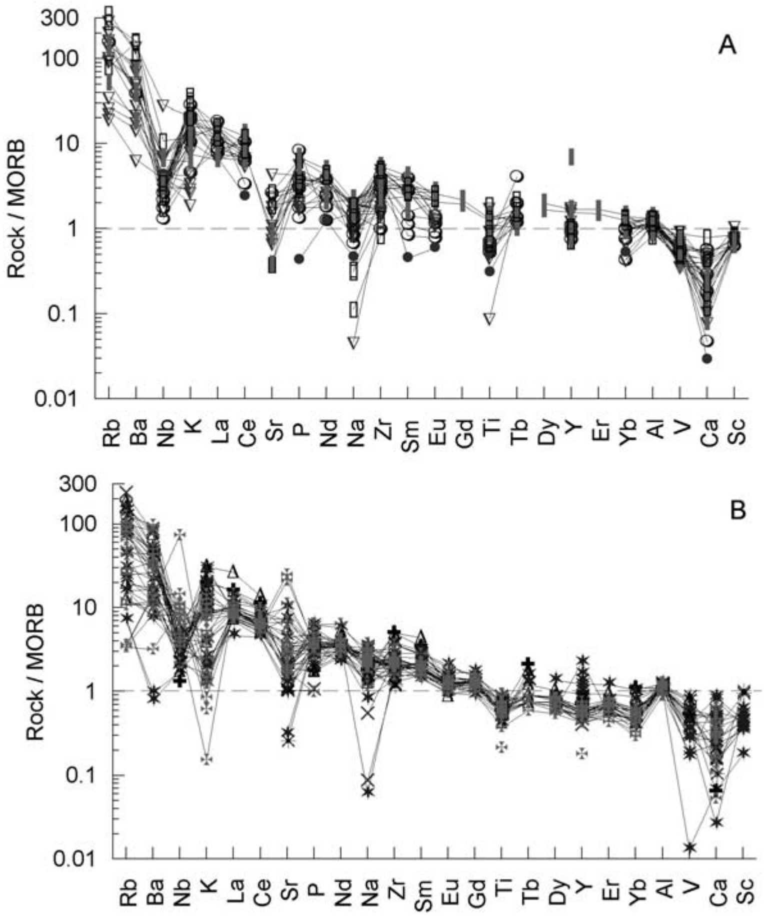

Fig. 5. Rock-MORB spiderdiagrams (normalised according to Pearce and Parkinson, 1993) for the Lower Permian andesites in the Ligurian Briançonnais. A) Dikes and lavas across Lower Paleozoic basement (Inner Briançonnais); B) Andesite lava flows and tuffs from inner and intermediate Briançonnais Lower Permian successions;

(Liew and Hofmann, 1988) with the production of peraluminous felsic melts in equilibrium with a garnet-bearing residuum (Rottura *et al.*, 1998) and used to define the isotopic signature of their deep crustal metasedimentary source; III) I-type metaluminous granitoids of the Saxothuringian zone, interpreted as the product of partial melting in a lower crustal source (White and Chappell, 1983) or in the high-grade metamorphic basement with a mantle component contribution (Liew and Hofmann, 1988).

A MORB-type signature of the parental magma has been reported for mafic rocks in Corsica and the Southalpine and Alpine domains (Cocherie *et al.*, 1994; Voshage *et al.*, 1990; Miller and Thöni, 1995). A picrobasaltic composition was inferred by Kagami *et al.* (1991) as potential parental magma of the calc-alkaline Adamello batholith (Southern Alps) and assumed to be an isotopic image of the related subcontinental lithospheric mantle (SLM). Taking all these potential mantle sources into account for the Briançonnais andesites we have used N-MORB, E-MORB and SLM isotopic

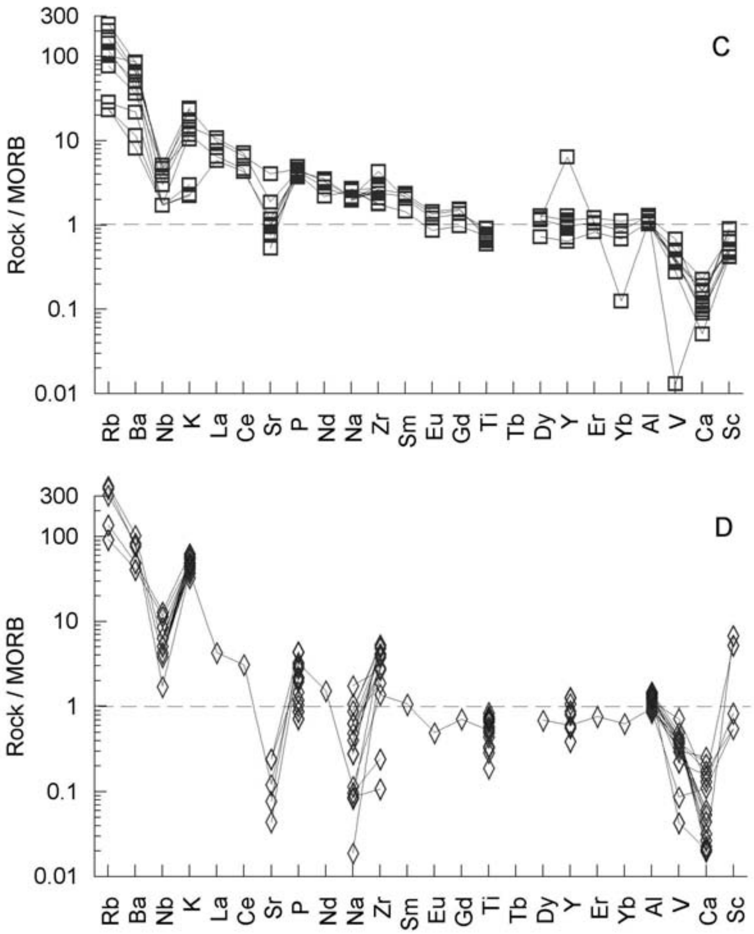

Fig. 5 C) Volcanic breccias, lavas and tuffs from the outer Briançonnais Lower Permian successions; D) Monte Galero volcanic clasts in the Lower–Middle Jurassic breccias (Prepiedmont domain).

compositions to model assimilation-fractional crystallization paths, calculated according to De Paolo (1981) equation.

Thompson *et al.* (2002) discussed the trends with r = 0.5 and r = 0.6 as derived from assimilation of less fertile crust (tonalite) by hotter hydrous picritic magma or alternatively assimilation by a more fertile magma or fertile crust preheated to near its solidus temperature. On the other hand, in the Ligurian Briançonnais Lower Paleozoic basement an Early Ordovician event with partial melting of lower crust under granulite facies metamorphism was discussed in Cortesogno *et al.* (1993), Gaggero *et al.* (2004). Thus, the regional evolution suggests to envisage a fertile contaminant with an assumed rate of crustal contamination relative to fractional crystallisation of r = 0.5, rather than a highly overheated contaminated magma to explain the high silica content of the Briançonnais andesite volcanism. For MORB-type parental magmas, the fractionating assemblage (paths a, b, c and d, Fig. 8) consists of 15 wt% olivine, 25 wt% clinopyroxene and 60 wt% plagioclase. These phases that co-crystallise between 0.6 and 0.8 GPa (Elthon, 1993) correspond to a bulk distribution coefficient > 1 for Sr and < 1 for Nd. The fractionating assemblage

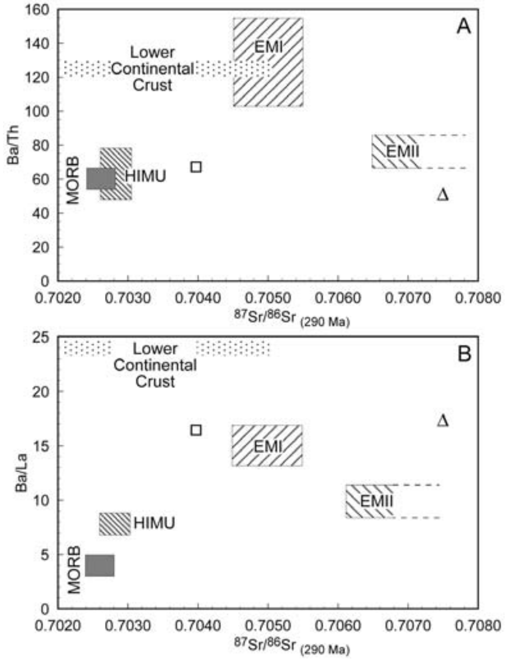

Fig. 6. A) Ba/Th vs. $^{87}Sr/^{86}Sr_{(290\ Ma)}$ and B) Ba/La vs. $^{87}Sr/^{86}Sr_{(290\ Ma)}$. Range of trace element ratios and Sr isotopic compositions of the MORB, HIMU, EMI, EMII and lower continental crust are taken from Hart *et al.* (1999); Weaver (1991); Rollinson (1993). All isotopic compositions have been recalculated for t = 290 Ma. Symbols. Empty triangle: intermediate Briançonnais Lower Permian andesite; square: outer Briançonnais Lower Permian andesite.

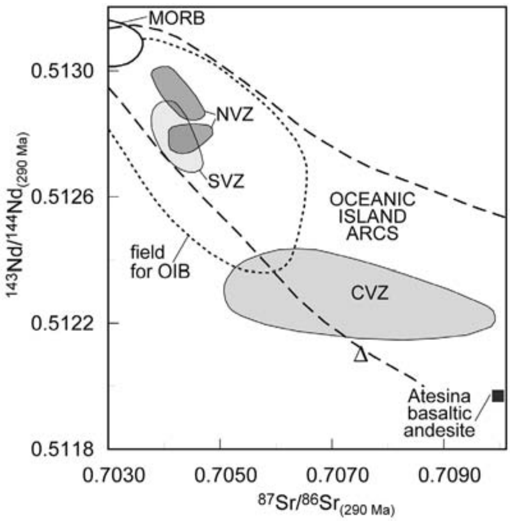

Fig. 7. Initial (290 Ma) $^{87}Sr/^{86}Sr$ (0.512103) vs. $^{143}Nd/^{144}Nd$ (0.707496), for intermediate Briançonnais andesite. MORBs, OIBs, oceanic island arcs volcanic rocks, volcanic rocks from the northern (NVZ), central (CVZ) and southern (SVZ) active volcanic zones of the Andes (Wilson, 1991) and the isotopic composition of a Permian basaltic andesite of the Southern Alps (Rottura *et al.*, 1998) are reported for comparison.

for SLM, represented by picrobasaltic parental magmas (paths e, f and g, Fig. 8; Kagami *et al.*, 1991), consists of 40 wt% olivine, 10 wt% orthopyroxene, 40 wt% clinopyroxene and 10 wt% plagioclase, with bulk distribution coefficients < 1 for Nd and Sr. Experimental works (Ulmer, 1987) confirm that picrobasaltic magmas are primary mantle partial melts in equilibrium with garnet lherzolites. We assumed that such melts generated at some 3 GPa and 1400 °C (Kagami *et al.*, 1991) were the parental magma of the Briançonnais calc-alkaline activity.

In our assimilation-fractional crystallisation model, starting with a subcontinental, lithospheric-mantle-type parental magma through the addition of about 80 wt% of metasedimentary component to the picrobasaltic composition, it is possible to reproduce the Sr and Nd isotopic composition observed in the Briançonnais andesites (Fig. 8). The modelling of MORB-type mantle sources contaminated by addition of an I-type metaluminous granitoid component yielded unsatisfactory results.

The crust/mantle separation T_{DM} age, calculated on the basis of Nd isotopic data for the Briançonnais andesites, resulted at 1.26 Ga (this work). This suggests that the crust where the Nd isotopic signature originated, was separated from the depleted mantle possibly during the Elzevirian Orogeny (~1250-1190 Ma), when the closure of the Central Metasedimentary Belt marginal back-arc basin occurred at the south-eastern margin of Laurentia. Comparable crust/mantle separation ages were also found for the Permian plutonic complexes of the Southern Alps (Rottura *et al.*, 1998), the Caledonian paragneisses of the Moldanubian zone and the Hercynian granitoids of the Bohemian Massif (Liew and Hofmann, 1988).

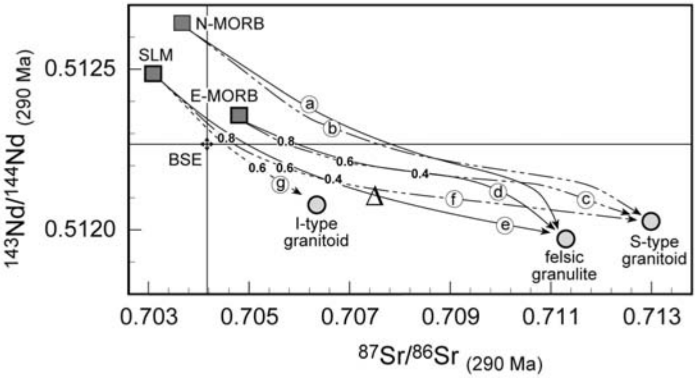

Fig. 8. Initial (290 Ma) $^{144}Nd/^{143}Nd$ vs. $^{87}Sr/^{86}Sr$ for the intermediate Briançonnais andesite. The model mixing fractional crystallisation vectors from the potential mantle and crustal sources of the Permian magmatism are reported. BSE: Bulk Silicate Earth from Faure (1986). N-MORB from Hart *et al.* (1999). E-MORB type magma from Cocherie *et al. (*1994). SLM: subcontinental lithospheric mantle from Kagami *et al.* (1991). Early Permian felsic granulite from Montanini and Tribuzio (2001). Carboniferous S-type peraluminous granitoid of the Moldanubian zone and I-type metaluminous granitoid of the Saxothuringian zone from Liew and Hofmann (1988). All compositions recalculated for *t* = 290 Ma. All paths calculated according to De Paolo's equation (1981), assuming a rate of crustal contamination relative to fractional crystallization r = 0.5. The mineral K_D values used for calculation of the bulk partition coefficients for Sr and Nd were taken from Rollinson (1993). Numbers on the paths 0.8, 0.6 and 0.4 represent proportions of residual magma.

Conclusions

Trace element variation and isotopic compositions of the analysed andesites evidenced the heterogeneity of calc-alkalic andesites to K-andesites magmas erupted during the Upper Permian in the intermediate and outer Briançonnais domains, as already demonstrated by Cortesogno *et al.* (1992) on the basis of petrography, trace and RE element patterns. As a consequence, we can confirm an E to W compositional zoneography for the post-orogenic volcanic products and envisage that in the collapse of the Ligurian segment of the Variscan cordillera the ridge was eroded to the amphibolite facies level between 327 Ma (Del Moro *et al.*, 1982) and the deposition of its conglomeratic covers (315-305 Ma; Gaggero *et al.*, 2004; Cortesogno *et al.*, 2003). The inner Briançonnais andesites thus poured out onto the Variscan basement; conversely, the intermediate and outer Briançonnais andesites, were emplaced in tectonically active basins belonging to volcano-sedimentary successions whose estimated thicknesses increases towards the W.

The parental magma of the Briançonnais andesites originated in a subcontinental, lithospheric mantle through the addition of a significant metasedimentary crustal component to a picrobasaltic composition; the assimilation was associated with fractional crystallisation up to 0.2 mole fraction of the residual magma.

The variegated isotopic composition revealed at the Ligurian Briançonnais scale, suggests a dynamic scenario between the Lower and Middle Permian. On the other hand, the high $^{87}Sr/^{86}Sr$ of the intermediate Briançonnais andesite supports significant lower crustal contribution to the parental magmas. The lower $^{87}Sr/^{86}Sr$ of the outer Briançonnais andesites supports that the system might have turned to tapping sublithospheric mantle sources. This would match the paleogeographic reconstruction of the surface, where the inner basement blocks were exhumed and eroded to the amphibolite facies level; conversely, the outer Briançonnais could represent the periphery of the collapsing Variscan range.

Acknowledgments

Luciano Cortesogno introduced us to the intriguing topic of post-Variscan volcanism and profused us his enlightening teaching. We wish to thank Francesca Slejko (University of Trieste) for help in acquisition of Sr and Nd data and acknowledge the constructive comments by Silvio Rotolo (Palermo) and Nasrrddine Youbi (Marrakech).

REFERENCES

BIXEL F., KORNPROBST J. and VINCENT P.M. (1983) - *Le massif du Pic du Midi d'Ossau: un "cauldron" calco-alcalin stéphano-permien dans la Zone Axiale des Pyrénées*. Rev. Géol Dyn. Géogr. Phys., **24**, 315-328.

CABELLA R., CORTESOGNO L., DALLAGIOVANNA G., VANNUCCI R. and VANOSSI M. (1988) — *Vulcanismo, sedimentazione e tettonica nel Brianzonese ligure esterno durante il Permo-Carbonifero*. Atti Tic. Sc. Terra, **31**, 269-326.

CASSINIS G. (1996) — *Upper Carboniferous to Permian stratigraphic framework of South-western Europe and its implications — An overview*. In: Moullade, B.M., Nairn, A.E.M. (Eds), The Phanerozoic Geology of the World: I. The Paleozoic, B. Elsevier, 110–167.

CASSINIS G., PEROTTI C.R. and VENTURINI C. (1997) — *Examples of late Hercynian transtensional tectonics in the Southern Alps, Italy*. In: Dickins, J. (Ed), Late Palaeozoic and Early Mesozoic Circum-Pacific Events and Their Global Correlation. Cambridge Univ. Press, 41–50.

COCHERIE A., ROSSI P., FOUILLAC A.M. and VIDAL P. (1994) — *Relative importance of recycled-and mantle-derived material in granitoid genesis: an example from the Variscan batholith of Corsica studied by trace element and Nd–Sr–O isotope systematics*. Chem. Geol., **115**, 137–211.

CORTESOGNO L., CASSINIS G., DALLAGIOVANNA G., GAGGERO L., OGGIANO G., RONCHI A., SENO S. and VANOSSI M. (1998) — *The Variscan post-collisional volcanism in Late Carboniferous-Permian sequences of Ligurian Alps, Southern Alps and Sardinia: a synthesis*. Lithos, **45**, 305-328.

CORTESOGNO L., GIANOTTI R., VANNUCCI R. and VANOSSI M. (1984 a) — *Le volcanisme permo-carbonifére du Briançonnais Ligure (Alpes Maritimes) dans le cadre des phases tardives de l'orogenése hercynienne*. Sci. Géol. Bull., **37**, 37-50.

CORTESOGNO L., GIANOTTI R., VANOSSI M., ODDONE M. and VANNUCCI R. (1984 b) — *Contributo alla conoscenza delle metavulcaniti tardo-erciniche del Brianzonese ligure Alpi Marittime: 1 I "Porfidi" di Osiglia ed i clasti di vulcaniti nella formazione di Ollano*. Rend. Soc. It. Mineral. Petrol., **39**, 575-592.

CORTESOGNO L., ODDONE M., OXILIA M., VANOSSI M. and VANNUCCI R. (1982) — *Le metavulcaniti a chimismo andesitico del Permo-Carbonifero Brianzonese (Alpi Marittime): Caratterizzazione petrografica e chimica e tentativo di interpretazione geodinamica*. Rend. Soc. It. Mineral. Petrol., **38**, 581-606.

CORTESOGNO L., DALLAGIOVANNA G., GAGGERO L. and VANOSSI M. (1992) — *Late Variscan intermediate volcanism in the Ligurian Alps*. IGCP N.276, Newsletter **5**, 241–262.

CORTESOGNO L., DALLAGIOVANNA G., GAGGERO L. and VANOSSI M. (1993) — *Elements of the Palaeozoic History of the Ligurian Alps*. In: von Raumer, J.F., Neubauer, F. (Eds), Pre-Mesozoic Geology in the Alps. Springer-Verlag, 257–277.

CORTESOGNO L., DALLAGIOVANNA G., VANNUCCI R. and VANOSSI M. (1988) — *Volcanisme, sedimentation et tectonique pendant le Permo-Carbonifere en Briançonnais ligure: une revue*. Ecl. Geol. Helv., **81**, 487–510.

CORTESOGNO L., GAGGERO L., MOLINA M., PAQUETTE J.L. and BERTRAND J.M. (2003) — *U/Pb dating of pre-alpine granitoid rocks in the Ligurian Briançonnais internal alpine basements: geochronological constraints on the metamorphic records*. AGU-EUG Joint Assembly, Nice, France, April 2003. Abstract Book CD-ROM Geophysical Research Abstracts, **5**, EAE03-A-10923.

DE LAROUZIÈRE F.D., BOLZE J., BORDET P., HERNANDEZ J., MONTENAT C. AND OTT D'ESTEVOU P. (1988) - *The betic segment of the lithospheric Trans-Alboran shear zone during the late Miocene*. Tectonophysics, **152**, 41-52.

DEL MORO A., PARDINI G., MESSIGA B. and POGGIO M. (1982) — *Dati petrologici e radiometric preliminary sui massicci cristallini della Liguria occidentale*. Rend. Soc. It. Mineral. Petrol., **38**, 73-87.

DE PAOLO D.J. (1981) — *Trace element and isotopic effects of combined wallrock assimilation and fractional crystallization*. Earth Planet. Sci. Lett., **53**, 189–202.

DI BATTISTINI G., BARGOSSI G.M., SPOTTI G. and TOSCANI L. (1988) — *Andesites of the Late Hercynian volcanic sequence in Trentino-Alto Adige northern Italy*. Rend. Soc. It. Mineral. Petrol., **43**, 1087–1100.

DOBLAS, M., LOPEZ-RUIZ, J., OYARZUN, R., MAHECHA, V., SANCHEZ MOYA, Y., HOYOS, M., CEBRIA, J.-M., CAPOTE, R., HERNANDEZ ENRILE, J.-L., LILLO, J., LUNAR, R., RAMOS, A. and SOPEÑA, A. (1994) — *Extensional tectonics in the central Iberian Peninsula during the Variscan to Alpine transition*. Tectonophysics, **238**, 95–116.

ECHTLER, H. and MALAVIEILLE, J. (1990) — *Extensional tectonics, basement uplift and Stephano-Permian collapse basin in a late Variscan metamorphic core complex Montagne Noire, Southern Massif Central*. Tectonophysics, **177**, 125–138.

FAURE G. (1986) — *Principles of isotope geology*., John Wiley and Sons, 589 pp.

GAGGERO L., CORTESOGNO L. and BERTRAND J.M. (2004) — *The Pre-Namurian basement of the Ligurian Alps: a review of the lithostratigraphy, pre-Alpine metamorphic evolution, and regional comparisons*.

Per. Mineral. Special Issue **73/2**, 85-96.

Gaggero L., Cortesogno L., Savelieva G., Spadea P. and Pertzev A. (1997) — *Petrology of igneous rocks from the Nurali Ophiolite Mélange Zone, Southern Urals*. Tectonophysics, **276**, 139-161.

Gans P. B., Mahood G. A. and Schermer E. (1989) - *Synextensional magmatism in the Basin and Range Province: a case study from the eastern Great Basin.* Geol. Soc. Am. (Boulder, Colo.) ISBN: 0813722330

Gradstein F.M., Ogg J.G., Smith A.G., Agterberg F.P., Bleeker W., Cooper R.A., Davydov V., Gibbard P., Hinnov L.A., House M.R., Lourens L., Luterbacher H.P., McArthur J., Melchin M.J., Robb L.J., Shergold J., Villeneuve M., Wardlaw B.R., Ali J., Brinkhuis H., Hilgen F.J., Hooker J., Howarth R.J., Knoll A.H., Laskar J., Monechi S., Plumb K.A., Powell J., Raffi I., Röhl U., Sadler P., Sanfilippo A., Schmitz B., Shackleton N.J., Shields G.A., Strauss H., Van Dam J., van Kolfschoten T., Veizer J., Wilson D., 2004. *A Geologic Time Scale 2004*. Cambridge University Press, 589 pp.

Green T.H. (1982) — *Anatexis of mafic crust and high-pressure crystallization of andesite*. In: Thorpe, R.S. Ed., Andesites, 465–487.

Hanyu T., Tatsumi Y. and Nakai S. (2002) — *A contribution of slab-melts to the formation of high-Mg andesite magmas; Hf isotopic evidence from SW Japan*. Geophys. Res. Lett., **29**, 2051-2051.

Hart S.R., Blusztajn J., Dick H.J.B., Meyer P.S. and Muehlenbachs K. (1999) — *The fingerprint of seawater circulation in a 500-meter section of ocean crust gabbros*. Geochim. Cosmochim. Acta, **63**, 4059-4080.

Innocent C., Briqueu L. and Cabanis B. (1994) - *Sr-Nd isotope and trace-element geochemistry of late Variscan volcanism in the Pyrenees: magmatism in post-orogenic extension?* Tectonophysics, **238**, 161-181.

Kagami H., Ulmer P., Hansmann W., Dietrich V. and Steiger R.H. (1991) — *Nd-Sr isotopic and geochemical characteristics of the Southern Adamello (Northern Italy) intrusives: implications for crustal versus mantle origin*. J. Geophys. Res., **96**, 14331-14346.

Kimura J.I. and Yoshida T. (1999) — *Mantle diapir-induced arc volcanism: The Ueno Basalts, Nomugi-Toge and Hida volcanic suites, central Japan*. Island Arc, **8**, 304-322.

Le Maitre R.W., Bateman P., Dudek A., Keller J., Lameyre J.. Le Bas M.J., Sabine P.A., Schmid R., Sorensen H., Streckeisen A., Wolley A.R. and Zanettin B. (1989) — *A classification of igneous rocks and glossary of terms*. Blackwell, Oxford.

Liew T.C. and Hofmann A.W. (1988) — *Precambrian crustal components, plutonic associations, plate environment of the Hercynian Fold Belt of central Europe: indications from a Nd and Sr isotopic study*. Contrib. Mineral. Petrol., **98**, 129-138.

Ludwig K.R. (1994) — *Analyst. A computer program for control of a thermal-ionization single-collector mass-spectrometer*. U.S.G.S. Open-file report 92-543.

Miller C. and Thöni M. (1995) — *Origin of eclogites from the Austroalpine Ötztal basement (Tirol, Austria): geochemistry and Sm–Nd vs. Rb–Sr systematics*. Chem. Geol., **122**, 199–225.

Montanini A. and Tribuzio, R. (2001) — *Gabbro-derived granulites from the Northern Apennines (Italy): evidence for lower-crustal emplacement of tholeiitic liquids in post-Variscan times.* J. Petrol., **42**, 2259-2277.

Myers J.D. and Johnson A.D. (1996) — *Phase equilibria constraints on models of subduction zone magmatism (overview).* In: Subduction: top to bottom, (Eds. Bebout G.E., Scholl D.W., Kirby S.H., Platt J.P.) AGU Geophys. Monogr., **96**, 119-133.

Nakamura N. (1974) — *Determination of REE, Ba, Fe, Mg, Na, and K in carbonaceous and ordinary chondrites*. Geochim. Cosmochim. Acta**, 38**, 757-775.

Nichols G.T., Wyllie P.J. and Stern C.R. (1996) — *Experimental melting of pelagic sediment, constraints relevant to subduction*. In: Subduction: top to bottom, (Eds. Bebout G.E., Scholl D.W., Kirby S.H., Platt J.P.) AGU Geophys. Monogr., **96**, 293-298.

Peacock S.M. (1996) — *Thermal and petrologic structure of subduction zones.* In: Subduction: top to bottom, (Eds. Bebout G.E., Scholl D.W., Kirby S.H., Platt J.P.) AGU Geophys. Monogr., **96**, 119-133.

Pearce J.A. and Parkinson I.J. (1993) — *Trace element models for mantle melting: application to volcanic arc petrogenesis.* In: Magmatic processes and plate tectonics. Prichard H.M., Alabaster T., Near C.R. (Eds.) Geol. Society Spec. Publ., **76**, 373-403.

Polat A. and Kerrich R. (2002) — *Nd-isotope systematics of similar to 2.7 Ga adakites, magnesian andesites, and arc basalts, Superior Province: evidence for shallow crustal recycling at Archean subduction zones.* Earth Planet. Sci. Lett., **202**, 345-360.

Portis A. (1887) — *Sulla scoperta delle piante fossili carbonifere di Viozene nell'alta valle del Tanaro*. Boll. R. Com. Geol. It., **18**, 417-420.

Rollinson H. (1993) — *Using geochemical data: evaluation, presentation, interpretation*. Longman, Harlow, 352 pp.

Rottura A., Bargossi G.M., Caggianelli A., Del Moro A., Visonà D. and Tranne C.A. (1998) — *Origin* *and significance of the Permian high K-calc-alkaline magmatism in the central-eastern Southern Alps, Italy*. Lithos, **45**, 329-348.

SANDEMAN H.A., HANMER S., TELLA S., ARMITAGE A.A., DAVIS W.J. and RYAN J.J. (2006) — *Petrogenesis of Neoarchaean volcanic rocks of the MacQuoid supracrustal belt: A back-arc setting for the northwestern Hearne subdomain, western Churchill Province, Canada.* Precambrian Res., **144**, 140-165.

STILLE P. and BULETTI M. (1987) — *Nd–Sr isotopic characteristics of the Lugano volcanic rocks and constraints on the continental crust formation in the South-Alpine domain N-Italy–Switzerland*. Contrib. Mineral. Petrol., **96**, 140–150.

TATSUMI Y., NAKASHIMA T. and TAMURA Y. (2002) — *The petrology and geochemistry of calc-alkaline andesites on Shodo-Shima Island, SW Japan*. J. Petrol., 43, 3-16.

THOMPSON A.B., MATILE L. AND ULMER P. (2002) — *Some thermal constraints on crustal assimilation during fractionation of hydrous, mantle-derived magmas with example from Central Alpine batholiths*. J. Petrol., 43, 403-422.

ULMER P. (1987) — *Picrobasalts: a possible parental magma for calc-alkaline rocks: experimental, field and geochemical observations from the Adamello (northern Italy).* Terra Cognita, **7**, 356.

VOSHAGE H., HOFMANN A.W., MAZZUCCHELLI M., RIVALENTI G., SINIGOI S., RACZEK I. and DEMARCHI G. (1990) — *Isotopic evidence from the Ivrea Zone for a hybrid lower crust formed by magmatic underplating*. Nature, **347**, 731–736.

WEAVER B.L. (1991) — *The origin of oceanic island basalt end-member compositions: trace element and isotopic constraints*. Earth Planet. Sci. Lett., **104**, 381-397.

WHITE A.J.R. and CHAPPELL B.W. (1983) — *Granitoid types and their distribution in the Lachlan Fold Belt, southeastern Australia*. Geol. Soc. Am. Mem., **159**, 21-34.

WILSON M. (1991) — *Igneous petrogenesis. A global tectonic approach*. Harper Collins, 466 pp.

ZECK H.P., KRISTENSEN A.B. and NAKAMURA E. (1999) — *Inherited Palaeozoic and Mesozoic Rb-Sr isotopic signatures in Neogene calc-alkaline volcanics, Alboran volcanic province, SE Spain*. J. Petrol., 40, 511-524.