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Do coeval mafic and felsic magmas in post-collisional to within-plate regimes necessarily imply two contrasting, mantle and crustal, sources? A review

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Abstract

The end of major orogenic episodes is marked by uplift and erosion, transcurrent to extensional tectonic regimes induced partly by gravitational collapse of the thickened crust, partly by delamination of the lithosphere, and emplacement of voluminous igneous formations. This period starts soon after the completion of the continent–continent collisional event. Contrasting igneous suites, regarding their nature, evolution and original sources, are emplaced. Two distinctive and successive igneous associations can be evidenced:

(i) The post-collisional association is the more complex. Peraluminous silicic rocks, bearing Al–Fe–Mg silicates, such as garnet, cordierite, and sillimanite, are coeval with metaluminous mafic–felsic igneous suites, ranging from medium-K to high-K calc-alkaline to shoshonitic to ultrapotassic.

(ii) The postorogenic association yields less potassic and more sodic compositions. The igneous suites, comprising mafic and felsic rocks, range from alkali-calcic metaluminous to alkaline and peralkaline. They evolve progressively into more markedly alkaline within-plate suites.

The post-collisional association identifies two contrasting sources. Peraluminous granitoids and related volcanic rocks contain frequently mafic enclaves corresponding to blobs of undercooled shoshonitic to ultrapotassic basic to intermediate magmas. The peraluminous suite originates by dehydration incongruent melting of muscovite ± biotite in the continental crust. Medium-K to high-K calc-alkaline suites originate in an amphibole–spinel peridotite metasomatised lithospheric source. Shoshonitic to ultrapotassic metaluminous suites are issued from partial melting involving phlogopite of a garnet-bearing depleted lithospheric upper mantle, metasomatised by subducted material. The onset of the successive short-lived magmatic episodes is induced by lithosphere stacking and slab breakoff. Mantle-derived magmas emplaced within lower crust provide enough heat to enhance crustal anatexis and, then, they are injected into and mix with the crustal-derived liquids.

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During postorogenic and within-plate episodes, commingling of mafic and felsic magmas is documented by synplutonic dykes and sills, and by mafic enclaves. Radiogenic isotope systematics suggest that coexisting mafic and felsic magmas come from the same mantle source yielding depleted but LILE-enriched compositions, with subsequent wall-rock crustal contamination. The onset of the magmatic episode is promoted by lithosphere delamination. The role played by continental crust, though still disputed, becomes increasingly minor with time to null.

The transition from post-collisional to within-plate geodynamic settings documents the waning role played by crustal anatexis in magma generation, with regard to the increasing role of enriched OIB mantle sources.

Keywords: Bimodal magmatism; Post-collision; Within-plate; Mantle sources; Crustal anatexis

1. Introduction: mafic magmatic enclaves in granitic systems—a brief review

All granitoid types contain varying quantities of enclaves (for comprehensive reviews, see Didier, 1973; Didier and Barbarin, 1991). The origin and significance of enclaves is still a matter of debate, especially with regard to the specific group of mafic microgranular enclaves (MME). Field evidence from many parts of the world, combined with a wealth of experimental data, show that MME in granitoid plutons and their volcanic counterparts result from dynamic interaction between two contrasting magma types (Didier, 1964; Blake et al., 1965).

It is now widely accepted that MME correspond to hot mafic basic to intermediate (45–55 wt.% SiO_2) liquids having intruded into cooler felsic acid (65–75 wt.% SiO_2) crystallising magmas. So far, three types of transfer, thermal, mechanical and chemical, are identified (Barbarin and Didier, 1992). Despite continued uncertainty over the exact role played by each process, most MME in exposed plutons exhibit some degree of interaction with their surrounding granite. This is equally true for mafic enclaves within volcanic rocks. There is, however, no consensus as to the extent of chemical and isotopic exchange that is possible between coexisting magmas and the mechanisms by which it occurs. The various features observed in MME–granitoid associations originate in contrasting values and continuous variations of thermodynamic parameters, such as temperature, composition, viscosity and crystallinity, of coeval magmas (Sparks and Marshall, 1986; Fernandez and Barbarin, 1991) that result into fractal objects displaying a chaotic behaviour (Bébien et al., 1987; Platevoet and Bonin, 1991; Flinders and Clemens, 1996; Perugini and Poli, 2000).

The ability of magmas of different chemical composition to mix and homogenise is largely controlled by the nature of the physical contact between the two complex systems. How hot mafic magmas can be put in contact with cooler crystallising felsic magmas is, therefore, a basic question to explore. The "synplutonic dyke" model (Blake et al., 1965; Pitcher and Bussell, 1985) provides an elegant solution to the great variety of features observed in granitoid plutons (Barbarin, 1989; Barbarin and Didier, 1992). Alternatively, Wiebe and Collins (1998) observe features, such as load-cast and compaction, suggesting that MME concentrations record a sequential deposition onto a crystal-laden mush and beneath a crystal-poor magma, both of granitic composition. Last, as MME in volcanic associations are highly vesiculated, they have, consequently, a slightly lower bulk density than their hosts, implying that they can follow common pathways at similar velocities (Eichelberger, 1980; Coombs et al., 2002; Phillips and Wood, 2002). The three models, albeit differing in their thermodynamic parameters, are not exclusive and can be combined in a sequence of events occurring within different reservoirs and conduits.

Origins of two coeval magmas constitute also a matter of discussion, with the most popular interpretation favouring mingling–mixing processes affecting magmas issued from contrasting sources. MME would be hybridised products derived from upper mantle or mafic lower crust, while enclosing granitoids as well as their volcanic counterparts would be issued from anatexis of supracrustal materials (e.g., Poli and Tommasini, 1991; Koyaguchi and Kaneko, 1999). Numerical simulations (Fountain et al., 1989; Petford and Gallagher, 2001; Annen and Sparks, 2002) evidence that repetitive, periodic influx of mafic magma could provide the heat input necessary to induce melt generation in lower crust.

However, the amounts of crustal liquids that could be generated by this process are a matter of debate (Blundy et al., 2003). In the subduction-related magmatic provinces of Japan, coeval mafic and felsic rocks have in general identical Sr–Nd–Pb–O isotopic compositions, which yield strong correlations with the convergence rates of subducted oceanic plates. The varying crustal-like signatures are ascribed mostly to subducted sediment assimilation in the upper mantle wedge (Tatsumi, 2003) and not to wall-rock assimilation in AFC processes (DePaolo et al., 1992). The same interpretation (Peccerillo, 1999) is suggested for the post-collisional lamproites of Tuscany, Italy. Though lamproites are mafic, silica-undersaturated and peralkaline rocks, their trace-element contents are very close the subducted European continental crust of Dora-Maira.

The dualistic interpretation in terms of mantle and crustal sources, though largely accepted, should be critically discussed by examining different continental terranes affected by recent and ancient orogenies. The aim of this paper is to provide a review of the available evidence in the case of the late stage regimes occurring after major orogenies, namely post-collisional and within-plate settings. Examples will be chosen in the Variscan and Alpine orogenic belts, as their geodynamic evolution is better known and constrained than in the Precambrian terranes, where the part of speculations remains relatively high. However, at least since the Paleoproterozoic, no significant changes in terms of magmatic suites have been evidenced (e.g., Liégeois (editor), 1998).

2. Magmatic suites in post-collisional to within-plate geodynamic contexts

Liégeois (1998) states that post-collisional geodynamic settings are not yet fully integrated in plate tectonics model, which is based on geological processes occurring at plate edges, mid-oceanic ridges, active margins and in intercontinental collisions. Post-collisional settings are often referred to as a 'relaxation' phase following collision. However, this period is also characterised by voluminous magmatism. The collision stage, a period of maximum convergence, is less favourable for ascent of magmas (Le Fort, 1981; Brown, 1994) and widespread, but sparse, magmatism characterises within-plate settings (Black et al., 1985). Magmatism from active subduction at a plate margin is to be modified during collisions that almost inevitably follow. Many magmatic bodies exposed on the surface of continents should, therefore, be related to a distinctive post-collisional period.

The post-collisional settings define a complex period that can include geological episodes such as large movements along transcurrent shear zones, docking (oblique collision), lithosphere delamination, subduction of small oceanic plates and rifting. As a result, various types of magmatic episodes can occur in such settings. Three main common characteristics are identified:

(1) The magmatic, volcanic and plutonic, formations are, in composition, mainly potassic and even ultrapotassic (Conticelli and Peccerillo, 1992; Liégeois et al., 1996). Supplementary strongly peraluminous granitoids generated by dehydration melting reactions of crustal formations (Nabelek et al., 1992; Sylvester, 1998) and more or less juvenile sodic alkaline–peralkaline granitoids (Bonin, 1986, 1990; Liégeois and Black, 1987) can be voluminous, but are more sporadic.
(2) The magmatic episodes are commonly linked to large horizontal movements along major transcurrent shear zones (Black et al., 1994; Liégeois et al., 1998). Thus, the term of 'post-tectonic' commonly assigned to post-collisional plutons should be avoided (Bonin et al., 1998).
(3) The sources have been generated during the previous subduction and collision periods, whether they lie within the crust, or within the lithospheric mantle. The isotopic record is ambiguous, as numerous cases of MME yielding 'crustal'-like signatures, i.e., high $^{87}Sr/^{86}Sr$ and low ε_{Nd}, suggest either crustal sources (Pin et al., 1990), or high rates of isotopic equilibration with their host rocks (Peccerillo et al., 1994; Rottura et al., 1998),

or anomalous mantle sources (Janousek et al., 2000).

The aim of this paper is to address the issue of possible origins of the mafic and felsic magmas that are emplaced at the end of a major orogenic event, namely during post-collisional and within-plate episodes. The regional examples are from the Alpine belt, in order to compare what happened at the end of the Variscan orogeny and presently within the belt itself. An attempt to reconcile the observations and to provide a possible explanation will follow.

3. The Late Paleozoic Variscan belt

Successive Paleozoic events were responsible for the progressive welding of almost all continental terranes present at the Earth's surface into the Pangea super-continent. Amalgamation was completed at the end of the Carboniferous, while incipient continental rifting and break-up took place during the Late Permian (Ziegler and Stampfli, 2001).

The Variscan belt is a 1000-km-wide and 8000-km-long orogen extending from the Appalachians in North America to the Caucasus and Urals at the Europe–Asia boundary. Evolution of the Variscan belt involved (i) the step-wise accretion of Gondwana-derived super-terranes fringed by cordilleras, successively the Avalonian group of terranes and the Hun super-terrane (Stampfli and Borel, 2002) to the southern margin of Laurussia and (ii) ultimately the Late Devonian–Early Carboniferous collision of the northwestern margin of Africa with Iberia, a part of the Hun terranes (Stampfli, 1996). During the Carboniferous, deformation propagated eastward and southwestward in conjunction with progressive closure of the Paleotethys and Proto-Atlantic oceans. By Westphalian time, ca. 310 Ma ago, corresponding to the Alleghanian event, Gondwana had collided with the Laurussia craton, whereas in the east, the Paleotethys was still open. Thus, the western parts of the Variscan orogen were characterised by Himalayan-type continent–continent collisional to post-collisional settings, whereas an Andean-type ocean–continent setting remained in its eastern parts (Matte, 2002).

The two following sections will focus on two discrete Variscan zones reworked during the Alpine orogeny: (i) the Western Mediterranean area with magmatic episodes since the Devonian–Carboniferous boundary up to the Early Triassic, (ii) the External Crystalline Massifs (ECM) of the Western Alps with magmatic episodes since the Devonian–Carboniferous up to the Early Permian. The general characteristics of the magmatic episodes are described elsewhere (Bonin et al., 1998). Special attention will be paid to the associations of coeval mafic and felsic magmas that are exposed in both zones.

4. The Western Mediterranean area

The Western Mediterranean sea was created by extension within the Alpine belt during the Mid-to Upper Tertiary (Fig. 1). The extensional tectonic episodes were contemporaneous with a period of slow convergence of Africa with respect to Europe (Rosenbaum et al., 2002). The onset of the event occurred 33–27 Ma ago (Oligocene) in Gulf of Lion, Valencia trough and Alboran Sea, as well as between Provence and Corsica. Then, extension propagated eastward and southward to form the Liguro–Provençal basin by counterclockwise rotation of the Corsica–Sardinia block 21–17.5 Ma ago (Lower Miocene) (Edel et al., 2001) and the Tyrrhenian Sea by rotation of the Italian Peninsula since the Upper Miocene (ca. 10 Ma ago) (Mantovani et al., 1996). The geological and geochronological data (Brunet et al., 2000) suggest an almost continuous process of extension (Jolivet and Faccenna, 2000), in variance with classical scenarios involving two discrete histories and possibly two different mechanisms (e.g., Alvarez et al., 1974).

Remnants of the Variscan belt, strongly deformed and reworked by the Alpine orogeny, are to be found along the Western Mediterranean coasts, such as the Provence and the Costa Brava of Catalonia, or on the continental islands, i.e., the Balearic Islands, Corsica and Sardinia. Pertinent examples will be taken in Corsica and Sardinia (Fig. 1). The two islands are partly occupied by one of the largest batholiths in Europe, 500 km long and 50 km wide, formed by multiple intrusions emplaced successively (Orsini, 1980; Poli et al., 1989).

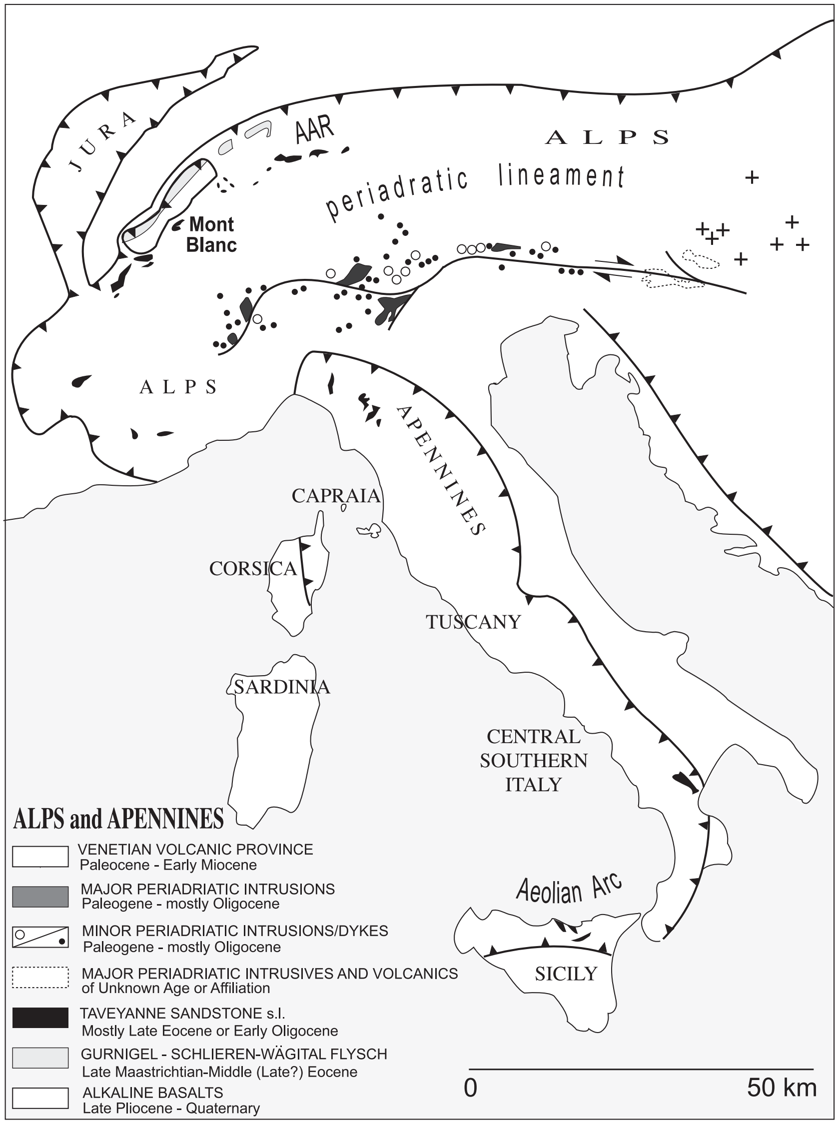

Fig. 1. Schematic map of the Alpine–Apenninic orogenic belt, with the post-collisional to within-plate igneous provinces discussed in the text (modified after Waibel, 1993).

4.1. The post-collisional Sardinia–Corsica batholith and associated formations

The magmatic episodes related to the Variscan event began by a poorly developed crustal anatectic episode yielding cordierite/garnet-bearing granitoids, which yield 347–345 Ma U–Pb zircon ages and bear an inherited component of about 1 Ga (Paquette et al., 2003). It was followed by a 338–337 Ma high-K to very high-K shoshonitic magmatic episode (U–Pb zircon ages, Paquette et al., 2003), forming the Mg–K U1 association of Rossi and Cocherie (1991), which is exposed only in northwest Corsica. The next and major episode occurred during the Upper Carboniferous and the Lower Permian. More than 80% of the exposed area of the Sardinia–Corsica batholith is occupied by dominantly high-K calc-alkaline magmatic units forming the U2 association of Rossi and

Cocherie (1991). Two suites are exposed: an older, yet not dated so far, medium-K to high-K calc-alkaline Cordilleran-type tonalitic to granodioritic units interpreted as the result of a possibly renewed subduction process (Finger and Steyrer, 1990), a younger 307–304 Ma high-K calc-alkaline units (U–Pb zircon ages, Paquette et al., 2003) having the latest massifs intruding their volcanic equivalents resting upon the largely unroofed U1 association (Rossi et al., 1993).

All the intrusives are crowded with MME that have been extensively studied (e.g., Zorpi et al., 1989; Poli and Tommasini, 1999). Coeval mafic complexes occur in all the associations, the U1 association comprising ultrapotassic mafic rocks akin to vaugnerite and durbachite (Rossi and Cocherie, 1991) and the U2 association being associated with gabbro-diorite (Tommasini and Poli, 1992).

Using the "sliding normalization" scheme of Liégeois et al. (1998), the two mafic–felsic U1 and U2 associations plot in the high-K calc-alkaline and shoshonitic field, characterised by high SNY (=mean [Rb–U–Th–Ta]NYTS) values and low SNX (=mean [Zr–Ce–Sm–Y–Yb]NYTS) values (Fig. 2). However, the behaviour of both suites differs strongly. In the compositionally expanded Mg–K U1 suite (Fig. 2A), high-Ni–Cr monzogabbros–monzodiorites yield the higher SNX–SNY values and evolved towards low-Ni–Cr monzodiorites having lower values, while

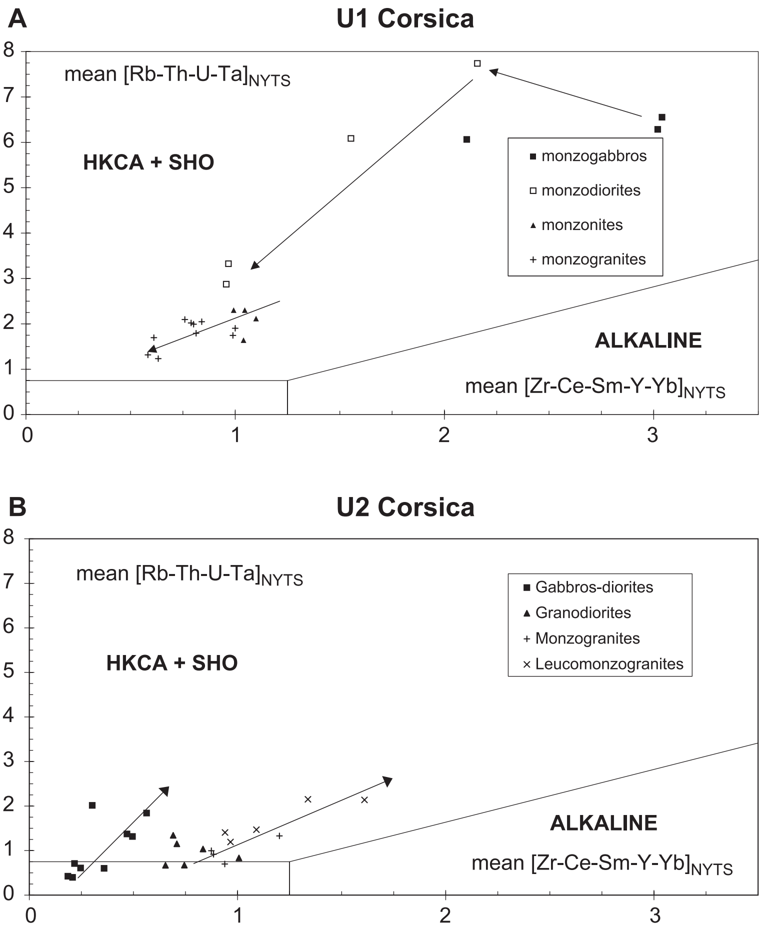

Fig. 2. SNY (=mean [Rb–U–Th–Ta]$_{NYTS}$)–SNX (=mean [Zr–Ce–Sm–Y–Yb]$_{NYTS}$) plot (Liégeois et al., 1998) for the Sardinia–Corsica batholith (data from Rossi and Cocherie, 1991; Cocherie et al., 1994). HKCA+SHO=high-K calc-alkaline and shoshonitic field, ALKALINE=alkaline–peralkaline field, as defined by Liégeois et al. (1998). (A) Mg–K U1 association, (B) medium-K to high-K calc-alkaline U2 association.

monzonites and monzogranites plot at the end of the trend with markedly low SNX–SNY values. The same behaviour is observed by Liégeois et al. (1998) on other potassic suites of various ages.

On the contrary, in the compositionally expanded high-K calc-alkaline U2 suite (Fig. 2B), the gabbro–diorite massifs and the granodiorite–monzogranite–leucomonzogranite associations plot at the very base of the field, corresponding to the syn-shear HKCA type (Liégeois et al., 1998), but evolved separately towards slightly higher SNX–SNY values. Such discrepant behaviours should be attributed to different processes in the source(s) and contrasting evolutionary trends in magma chambers.

Sr–Nd isotope systematics for mafic rocks of both associations (Cocherie et al., 1994; Tommasini et al., 1995) reveal a large and continuous range of values defining an "orogenic mantle array" starting from the depleted quadrant to the enriched quadrant, with $+0.7>\varepsilon_{Nd}(t)>-5.0$ and $0.7046<(^{87}Sr/^{86}Sr)i<0.708$, the isotopic ratios being calculated back to the time of emplacement of the associations (Fig. 3). The trends displayed by mafic rocks of the U1 and U2 associations are completely overlapping, implying that they define only one "orogenic mantle array" during the Carboniferous and the Early Permian. According to Cocherie et al. (1994), the U1 mafic potassic rocks originated in a deep source containing phlogopite ± garnet and suffered zone refining leading to a significant increase of incompatible element contents during the ascent of the magma. In the U2 suite, the mafic sequence was issued from a shallower spinel or amphibole garnet-free peridotite.

Granitoid host rocks have Sr–Nd isotopic ratios that plot along the same trend, with a range of values within the enriched quadrant, i.e. $-2.2>\varepsilon_{Nd}(t)>-4.3$ and $0.7044<(^{87}Sr/^{86}Sr)i<0.709$ (Fig. 3). The U1 felsic rocks yield a narrower range of values that those of the U2 association, but plot within the same field occupying the middle of the "orogenic mantle array".

As explicitly stated (Cocherie et al., 1994; Tommasini et al., 1995), gabbros are mantle-derived and granitoids should be generated in crustal sources, yielding either greywacke (Cocherie et al., 1994), or meta-igneous compositions (Tommasini et al., 1995). Geochemical modelling shows that a single protolith can yield the two felsic associations under different, anhydrous versus hydrous, melting conditions (Cocherie et al., 1994). Tommasini et al. (1995) insist on the role played by ~450 Ma (Ordovician) subducted sediments in the enrichment of mantle sources and the Variscan crustal growth

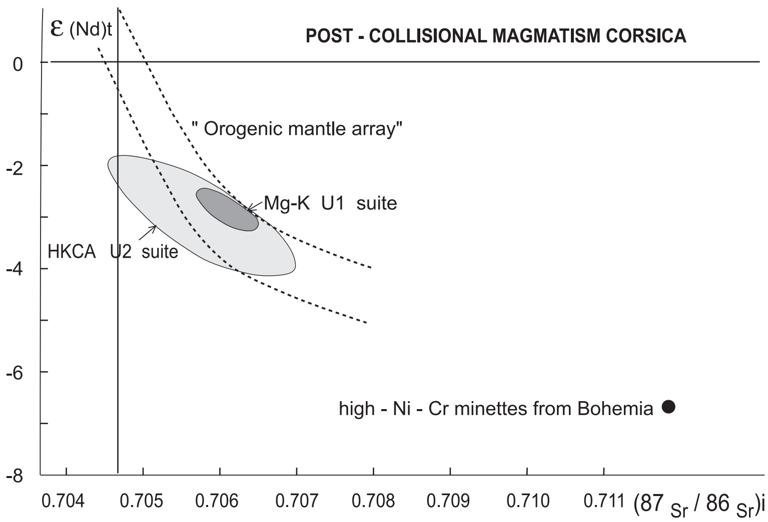

Fig. 3. Isotopic Sr–Nd plot for the Sardinia–Corsica batholith (data from Cocherie et al., 1994). Isotopic data are re-calculated back to the time of emplacement. The vertical [ε_{Nd}=0] and horizontal [$^{87}Sr/^{86}Sr$=0.7045] lines correspond to the present Bulk Silicate Earth composition. At the end of the Paleozoic era (300 Ma), the Bulk Silicate Earth had a composition of $\varepsilon_{Nd}(300)=0$ and $^{87}Sr/^{86}Sr(300)=0.7041$. The "orogenic mantle array" is delineated by two dashed lines defined by the isotopic compositions of the most primitive Ni–Cr-rich mafic rocks. Felsic rocks of U1 and U2 associations occupy the two shaded areas.

represented by the high-K calc-alkaline U2 suite of the Sardinia–Corsica batholith.

Though the concept of contrasting sources cannot be ruled out by the available data set, it is not substantiated by the significant overlap in Sr and Nd isotope compositions which is observed between U1 and U2 felsic rocks, as well as between mafic and felsic rocks of both associations (Fig. 3). Furthermore, no field and isotopic evidence for crustal anatexis younger than 345 Ma was observed so far in Sardinia and Corsica. The migmatitic formations are everywhere in the Sardinia–Corsica batholith intruded by the different rock types, sometimes with a narrow contact aureole suggesting temperature gradients between cold wall-rocks and calc-alkaline magmas.

4.2. The postorogenic alkaline ring complexes and associated formations

The onset of the postorogenic magmatic episode was marked by emplacement of ultramafic to mafic layered complexes during the Mid-Permian (285–279 Ma, Paquette et al., 2003), during or shortly after outpouring of the latest high-K calc-alkaline volcanics. Then, plutonic–volcanic complexes sharing alkaline affinities were emplaced in Corsica and Esterel (France), Sardinia (Italy), Costa Brava (Catalonia, Spain), the Briançonnais zone (Switzerland and France), etc., in at least two episodes from the Mid-Permian to the Mid-Triassic (for a review, see Bonin et al., 1998). In the Tana–Peloso composite massif (Platevoet, 1990), the layered mafic complex is coeval (278±28 Ma, Pb–Pb evaporation age on zircon, Rossi et al., 1992) and spatially related to the monzonite–subsolvus granite alkaline suite (273±4 Ma, Rb–Sr whole-rock isochrone, Poitrasson et al., 1994b). Mafic–felsic associations occur also as basalt blobs within rhyolitic ignimbrite sheets (Platevoet et al., 1988) and as gabbro–granite net-veined complexes yielding a mean fractal dimension around 1.17 (Bébien et al., 1987; Platevoet and Bonin, 1991).

In the "sliding normalization" plot (Liégeois et al., 1998), the alkaline suite defines a distinct field characterised by high SNX–SNY values (Fig. 4). The peralkaline trend tends to yield higher and higher SNX–SNY values and occupies the alkaline field entirely. The biotite-bearing aluminous trend displays markedly lower SNX values and the more evolved subsolvus granites can enter the high-K calc-alkaline and shoshonitic field, mimicking high-K calc-alkaline leuco-monzogranites. Liégeois et al. (1998) argue that the differences observed in the post-collisional Mg–K and high-K calc-alkaline suites and in the postorogenic alkaline suite are linked to the sources themselves and, to a minor extent only, to differentiation processes.

Accordingly, Sr–Nd isotope systematics (Table 1) reveal a completely different picture emerging from the previous post-collisional episode. The more

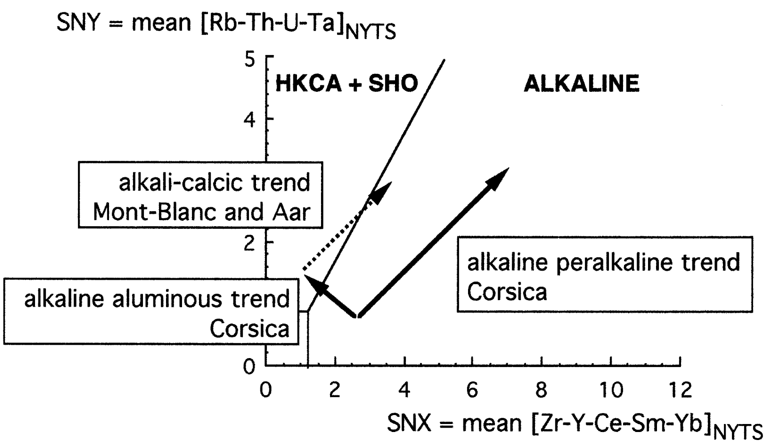

Fig. 4. SNX–SNY plot for postorogenic A-type alkali-calcic (Aar–Mont-Blanc) and alkaline (Corsica) magmatic suites (modified after Bonin et al., 1998).

Table 1

Name of the complex	Rock types	Age	($^{87}Sr/^{86}Sr$)i range of values	$\varepsilon_{Nd}(t)$ range of values (mean)	References
Pila Canale	Peridotite–gabbro	279±1 Ma	0.70393–0.70484	+4.3 to +0.5	Cocherie et al. (1994), Paquette et al. (2003)
Tana–Peloso	Gabbro–anorthosite	263±22 Ma	0.70413–0.70525	+0.5 to −1.0	Poitrasson et al. (1994a)
	Monzonite	273±4 Ma	0.70427–0.70520	−0.1 to −2.0	Poitrasson et al. (1994b)
	Subsolvus granite	276±3 Ma	0.7095	−2.2 to −4.7	Poitrasson et al. (1994b)
Mizane	Hypersolvus granite	270 Ma (assumed)	n.d.	−1.5 to −1.7 (−1.6)	Poitrasson et al. (1995)
	Subsolvus granite	270 Ma (assumed)	n.d.	−3.8	Poitrasson et al. (1995)
Pastricciola	Subsolvus granite	268±6 Ma	0.7222	−4.7 to −5.8 (−5.0)	Bonin et al. (1987), Poitrasson et al. (1995)
Cauro–Bastelica	Fayalite hypersolvus granite	283±1 Ma	n.d.	−1.4 to −2.2 (−1.7)	Poitrasson et al. 1995, 1998)
	Biotite hypersolvus granite	246±7 Ma	0.7073	−1.5 to −1.9 (−1.7)	Bonin et al. (1987), Poitrasson et al. (1995)
	Amphibole hypersolvus granite	246 Ma (assumed)	n.d.	−0.8 to −1.4 (−1.0)	Bonin et al. (1987), Poitrasson et al. (1995)
	Subsolvus biotite granite	238±4 Ma	0.7111	−3.5 to −4.6 (−4.3)	Bonin et al. (1987), Poitrasson et al. (1995)
Porto–Ota	Gabbro	274 Ma (assumed)	n.d.	+1.9 to −0.7	Poitrasson et al. (1995)
	White subsolvus granite	274±4 Ma	0.70428	−0.1 to −0.5 (0.0)	Poitrasson et al. (1995), Van Tellingen et al. (1988)
	Red subsolvus granite	251±14 Ma	poorly defined	−0.1 to −0.2 (−0.1)	Poitrasson et al. (1995), Van Tellingen et al. (1988)
Evisa	Hypersolvus granite	249±3 Ma	0.7081	−0.8 to −1.2 (−1.0)	Poitrasson et al. (1995, 1998)
	Albitic granite	246±7 Ma	0.7034	+0.4 to +0.3 (+0.3)	Bonin et al. (1987), Poitrasson et al. (1995)
Bonifatto	Hypersolvus granite	243±15 Ma	n.d.	+0.1 to 0.0 (0.0)	Bonin et al. (1987), Poitrasson et al. (1995)
Esterel	Basalt–trachybasalt	270 Ma (assumed)	n.d.	+0.7 to −0.5	Poitrasson and Pin (1998)
	Mugearite	270 Ma (assumed)	n.d.	+0.8 to +0.1	Poitrasson and Pin (1998)
	Trachyte	270 Ma (assumed)	n.d.	+0.4 to −1.2	Poitrasson and Pin (1998)
	Rhyolite	270 Ma (assumed)	n.d.	0.0 to −1.0	Poitrasson and Pin (1998)
	Basalt	250 Ma (assumed)	0.70728–0.70754	+1.7 to +0.2	Lapierre et al. (1999)
	Trachyte	250 Ma (assumed)	0.74257	+5.2 to +0.8	Lapierre et al. (1999)

n.d.=not determined.

obvious feature is the very large range of values displayed by the isotopic ratios. ($^{87}Sr/^{86}Sr$)i varies from 0.704 up to the extreme value of 0.7222, while $\varepsilon_{Nd}(t)$ exhibit values from +5.2 down to −5.8. Poitrasson et al. (1995) define a heterogeneity index IH using the χ^2 statistical test to check whether the isotopic scatter within an intrusion is significant (IH>0), or not (IH<0). Such indices vary from −1.0 (peralkaline granite) to +0.75 (subsolvus granite), with an extreme value of +15.5 computed for the Tana subsolvus granite (Poitrasson et al., 1995).

During the first postorogenic magmatic episode of the Mid-Permian, the basaltic lava flows, the mafic layered complexes and the gabbroic masses included within granite yield $\varepsilon_{Nd}(t)$ constantly higher than -0.7 up to +4.3 and $(^{87}Sr/^{86}Sr)i$ lower than 0.70525, evidencing a more depleted mantle source than during the previous post-collisional magmatic episode. Felsic rocks yield more variable compositions, which are attributed to crustal contamination either through wall-rock assimilation or to hydrothermal alteration disturbing the original isotopic record. Both Sr and Nd isotopic systems were affected, resulting into the extremely high $(^{87}Sr/^{86}Sr)i$ found in a Sn-mineralized granite (Bonin et al., 1987) and Sm–Nd mineral errorchrons. Poitrasson et al. (1998) report in a fayalite hypersolvus granite two Sm–Nd mineral alignments of 291±13 and 330±10 Ma, the former being related to the U–Pb age of emplacement of 283±1 Ma; the latter could correspond to the effects of hydrothermal convection interacting with Carboniferous country rocks at the end of crystallisation of the granite. Widespread hydrothermal effects within the most alkaline granites imply that it is likely that their original isotopic signatures were modified by crustal contamination. As a result, the more primitive mafic rocks yield depleted mantle signatures, while the associated felsic suite display more radiogenic crustal-like signatures.

The second postorogenic magmatic episode of the Permian–Triassic boundary displays similar features. Basaltic and trachytic rocks yield positive $\varepsilon_{Nd}(t)$ values, substantiating again a depleted mantle source. The associated felsic rocks are subdivided into two groups: the hypersolvus granite group, peralkaline or not, and the related rhyolitic ignimbrites yield in general higher $\varepsilon_{Nd}(t)$ and lower $(^{87}Sr/^{86}Sr)i$ than the subsolvus granite group, though exceptions do exist. The Nd isotopic system was also affected at the hand specimen scale: a peralkaline hypersolvus granite yields two Sm–Nd mineral alignments of 259±6 and 209±14 Ma (Poitrasson et al., 1998), the former is close to the Rb–Sr age of 249±3 Ma, while the latter could be due to re-equilibration during the important thermal event of the Triassic–Liassic boundary recorded in the Alpine area (Ferrara and Innocenti, 1974; D'Amico and Del Moro, 1988).

There is no consensus so far as to whether magmas of the alkaline felsic association were mantle-derived, or originated in the mafic lower crust (for contrasting views, see Poitrasson et al., 1995; Bonin et al., 1998). Field and petrological evidence show that the primary magmas were monzonitic in composition and produced at 900–1000 °C (Platevoet, 1990) in volumes large enough to be able to differentiate into highly evolved alkaline–peralkaline residual liquids.

Numerical simulations show that periodic influx of basaltic magma at 1300 °C can induce partial melting of a mafic (amphibolitic) lower crust (Petford and Gallagher, 2001), but the available experimental data demonstrate that dehydration melting reactions of amphibolites can produce granodioritic to trondhjemitic, not monzonitic, anatectic liquids (Rushmer, 1993, and references therein).

As during the previous Carboniferous–Lower Permian post-collisional episode, there is no evidence for coeval crustal anatexis during the Permian–Triassic. The foliation of migmatitic paragneisses is crosscut at wide angles by the chilled margins of alkaline complexes (Bonin, 1986), implying that anatexis and subsequent cooling were completed well before the Permian–Triassic magmatic episode. In the lower crust exposed in Corsica (Libourel, 1985), a layered igneous complex comprising hornblendite, gabbro, norite and diorite encloses rafts of kinzigitic paragneiss yielding Paleoproterozoic (2.5–2.1 Ga) inherited components and metamorphosed under granulite-facies conditions slightly before the emplacement of the complex (about 286 Ma versus 281–279 Ma) (U–Pb zircon ages, Paquette et al., 2003).

Even in the Ivrea Zone (Southern Alps, Italy) is the classical relationship (Sinigoi et al., 1994) between emplacement of mafic magma under or near the base of the lower crust and crustal anatexis questioned. The Upper Carboniferous regional granulite facies metamorphism resulted into the extraction of 20–40% granite melts issued from muscovite dehydration melting reactions (for a review of chronological data, see Handy et al., 1999). By contrast, the country rocks of the 285–275 Ma mafic complex show that periodic and repeated injection of about 5000 km^3 of hot magma and associated cumulates (Quick et al., 1994) generated only a modest volume of anatectic melts represented by tonalite to granodiorite diatexites and trondhjemitic leucosomes in a restricted ~2-km-wide aureole overlying the intrusion (Barboza et al., 1999).

For those reasons, the widely accepted paradigm that alkaline felsic magmas can develop by crustal anatexis is rejected. Unequivocal evidence, such as, e.g., (per)alkaline granitic leucosomes, are yet to be found (for review and discussion, see Bonin, 1996). The preferred model involves multiple injections of either primitive, or evolved, mantle-derived magmas, contaminated by crustal materials (Bonin, 1986, 1990). Isotopic crustal assimilation is documented at various scales. For example, the mafic layered complex of Peloso displays a shift to decreasing $(^{87}Sr/^{86}Sr)i$ and increasing $\varepsilon_{Nd}(t)$ from the less evolved (bottom) to the more evolved (top) rocks, illustrating replenishment–tapping–fractional crystallisation processes (RTF) (Poitrasson et al., 1994a). On a whole province scale, the aluminous subsolvus granites yield higher $(^{87}Sr/^{86}Sr)i$ and lower $\varepsilon_{Nd}(t)$ than the aluminous hypersolvus and peralkaline granites, though this is not always the case (Table 1). Temperatures in the range of 900–1000°C or more are easy to envisage in the case of mantle-derived mafic to intermediate magmas cooling and crystallising in steady chambers emplaced at the mantle–crust boundary or within the lower crust (Bonin, 1996). There, magma differentiation by fractional crystallisation is likely to be accompanied by wall-rock assimilation.

5. The External Crystalline Massifs of Western Alps

The Tertiary Alpine orogeny reworked a significant part of the Variscan belt of central Europe. The best exposed outcrops of Variscan rocks are located in the weakly overprinted outer zone of the Alpine arc (Fig. 1), i.e., the "External Crystalline Massifs" of the French and Swiss Alps, such as Mont-Blanc, Aiguilles-Rouges, Aar and Gotthard massifs (Bonin et al., 1993, 1998). All four massifs consist of a complex assemblage of tectonic units composed of partly migmatised ortho- and paragneisses, interlayered volcanics, mafic–ultramafic lenses and granitic plutons. This assemblage, reminiscent of a metamorphosed accretionary prism, probably resulted from a large-scale thrust and transcurrent fault tectonics linked to oblique accretion of terranes or continental blocks by docking or hypercollision. Continent–continent or continent–[island arc+accretionary prism] collision started during the Devonian and led to major crustal thickening. Barrowian-type metamorphism subsequently developed in mid-crustal levels 330–327 Ma ago (Schaltegger, 1994; Bussy and Hernandez, 1997).

5.1. The post-collisional episodes

The post-collision dominantly granitic magmatic activity consists of very short-lived syn-tectonic episodes of a few million years, strongly controlled by the transcurrent crustal-scale faults. Early K-rich magmatism is widely recorded between 345 and 330 Ma from the Alps (Debon and Lemmet, 1999) to the Bohemian massif (Janousek et al., 2000). Shoshonitic to ultrapotassic plutons were emplaced 334–333 Ma ago in the Aar massif (Schaltegger, 1994) and 332 Ma ago in the Aiguilles-Rouges massif (Bussy et al., 1998). Numerous melanocratic stocks and enclaves of vaugnerite to durbachite compositions are set within a monzodiorite–monzosyenite–syenite–monzogranite suite resembling the Mg–K U1 association of northwest Corsica (Cocherie et al., 1994). Hf isotope systematics evidence that the magmas originated from a subduction-enriched lithospheric mantle source and were hardly affected by crustal contamination processes (Schaltegger and Corfu, 1992).

Subsequent magmatic pulses took place during the Stephanian in the Aar massif. The 310–308 Ma high-K calc-alkaline suite comprises meladiorite, diorite, granodiorite and monzogranite. Though the high-K calc-alkaline suite was inferred to have experienced extensive contamination by crustal melts (Schaltegger et al., 1991), its Hf isotope characteristics suggest that it derived from the same source as the previous shoshonitic to ultrapotassic suite (Schaltegger, 1994). Later on, a 303 Ma porphyritic granite coeval with the migmatites was derived from mixing of an intermediate magma with older metamorphic rocks (Olsen et al., 2000).

In the Mont-Blanc–Aiguilles-Rouges area, the high-K calc-alkaline episode is lacking and synkinematic 307 Ma peraluminous magmas were emplaced along dextral strike-slip faults (Bussy and Hernandez, 1997). Though a dominantly crustal source is inferred by Al-rich minerals, restitic xenoliths and relationship with migmatites (Brändlein et al., 1994), coeval gabbro and mafic microgranular enclaves document some mantle contribution.

In the French External Crystalline Massifs, the 308 Ma shoshonitic Croix de Fer volcanic suite yields negative $\varepsilon_{Nd}(t)$, implying origin from an enriched lithospheric mantle source with possible involvement of the Variscan crust (Cannic et al., 2002).

5.2. The postorogenic episode

The last magmatic episode, postorogenic and alkali-calcic, is documented by the 303 Ma Mont-Blanc granite (Bussy and von Raumer, 1993), the 300–296 Ma Central Aar granite pluton and by abundant 303–299 Ma intermediate to acid volcanic–clastic deposits (Schaltegger, 1994). The Central Aar granite comprises granodiorite, monzogranite, syenogranite and aplite. The Mont-Blanc granite differs from the Central Aar granite by numerous MME, monzodioritic stocks and synplutonic dykes, illustrating repetitive magma mingling processes.

In the "sliding normalization" plot (Liégeois et al., 1998), the alkali-calcic suite straddles the boundary between the [high-K calc-alkaline+shoshonitic] field and the alkaline field and follows a trend parallel to the alkaline–peralkaline trend, with but lower SNX values (Fig. 4). Albeit differing in age (303 Ma versus 280–274 Ma), the mafic rocks of Mont-Blanc and Corsica yield similar MORB patterns and the felsic rocks yield similar ORG patterns (Fig. 5), suggesting similar sources. In the Central Aar granite, low initial Sr isotope ratios, positive $\varepsilon_{Hf}(t)$ and lack of inherited zircon cores all point to an ultimate mantle source. Sharp contrast between the negative $\varepsilon_{Hf}(t)$ values of -8 in the ultrapotassic 334 Ma monzonite and the positive values of +3.5 in the Central Aar granite and +5 in

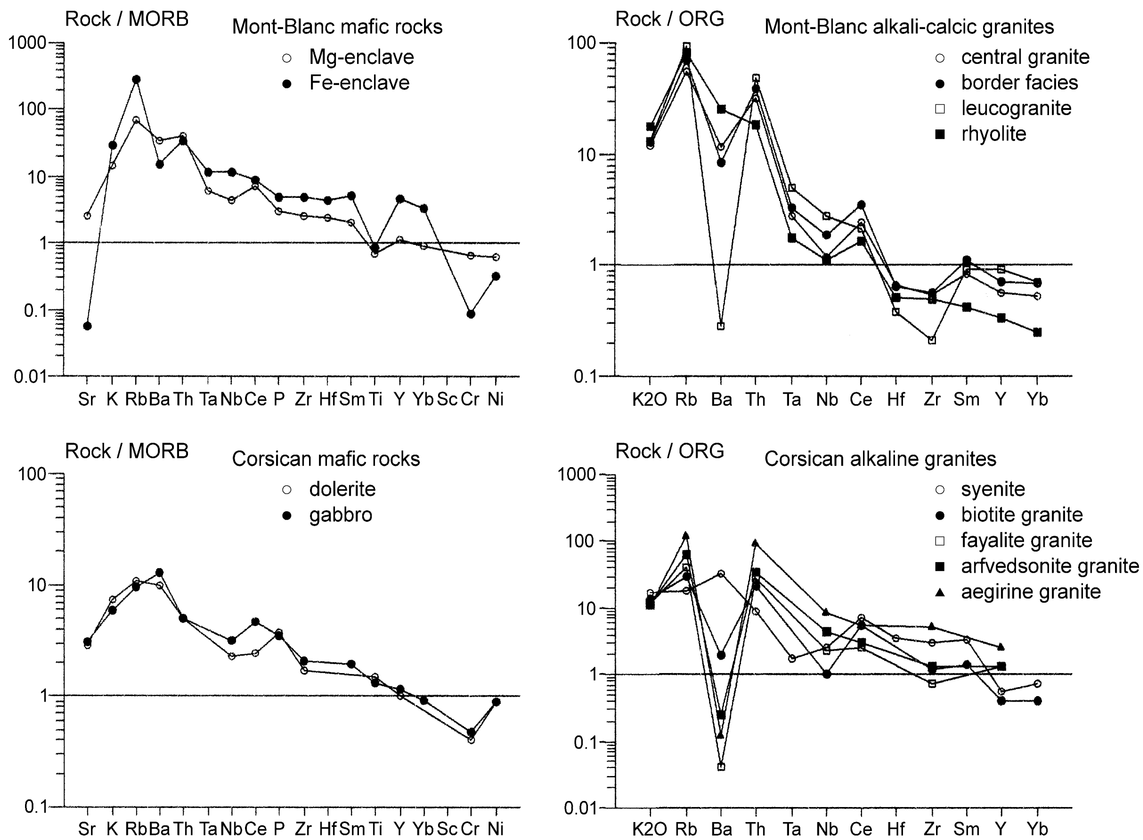

Fig. 5. Compared MORB-normalised and ORG-normalised multi-element spidergrams for alkali-calcic Mont-Blanc and alkaline Corsican A-type magmatic suites (data from Bonin, 1988; Bussy, 1990; Platevoet, 1990).

late lamprophyre indicate that the Stephanian isotopically depleted, LILE-enriched mantle source was markedly different from the subcontinental lithospheric mantle source that produced the 334 Ma rocks (Schaltegger, 1994). In the Mont-Blanc granite, inherited 630 Ma zircon cores reflect crustal contamination of unknown magnitude.

5.3. Comparison of Sardinia–Corsica with the External Crystalline Massifs of Western Alps

In both areas, post collisional suites were derived from enriched lithospheric mantle sources, with crustal involvement. Later on, in a few million years, postorogenic suites originated in isotopically depleted, LILE-enriched mantle sources, with variable crustal contribution. The differences are related to the mineralogical composition of mantle sources and/or the thermodynamical conditions prevailing in upper mantle and overlying continental crust.

With the exception of the Carboniferous Mg–K U1 suite restricted to northwestern Corsica, which is coeval to and share the same characteristics as the shoshonitic to ultrapotassic post-collisional suites of Central Europe, the post-collisional and postorogenic episodes differ markedly in the two areas investigated:

- During the post-collisional episodes, shoshonitic to ultrapotassic suites predominated in the External Crystalline Massifs of Western Alps, while a huge medium-K to high-K calc-alkaline batholith was emplaced in Sardinia–Corsica,
- Crustal anatexis during the Stephanian in the External Crystalline Massifs of Western Alps is lacking in the Sardinia–Corsica batholith,
- The postorogenic episodes are diachronous and marked by 300 Ma alkali-calcic A-type suite in the External Crystalline Massifs of Western Alps, and by 280–235 Ma alkaline–peralkaline A-type suite in the Western Mediterranean area.

The main characteristics of the Cenozoic post-collisional to postorogenic contrasting suites in the Alpine–Apenninic orogenic belt will now be briefly examined and the possible processes that could induce large variations in magmatic suites in a restricted area discussed.

6. The Alpine–Apenninic belt-related post-collisional to postorogenic magmatism

The Alpine s.l. orogen is a worldwide feature. In Europe, it comprises the Alps–Carpathian double arc, and the Apennines mountain range. In Asia, other orogenic belts, such as the Himalayan mountain range, formed during the same periods of time. The Alps and the Apennines provide ample evidence for widespread post-collisional and incipient postorogenic magmatic episodes. Two discrete areas with markedly different Tertiary magmatic suites will be examined: the Periadriatic Lineament (Von Blanckenburg et al., 1998) and the Tuscan Magmatic Province (Poli et al., 2002).

6.1. The periadriatic lineament

Several granitoid intrusions and numerous basaltic dykes are located along the Periadriatic Lineament (Fig. 1), a first-order tectonic boundary in the Alps (Coward and Dietrich, 1989). Most massifs were emplaced into thrusted, and in some places also steepened nappes, such as, e.g., the Bergell massif, which crosscuts both Penninic and Austroalpine nappe systems (Gieré, 1996). Emplacement ages of plutonic bodies range from 43 to 28 Ma, with a peak at 33–31 Ma, while intrusion ages of mafic dykes span a slightly wider range from 42 to 24 Ma, suggesting a protracted episode of melting in mantle sources (Von Blanckenburg et al., 1998).

The magmatic suites yield contrasting features as a function of their location within the orogen. In the Central Alps, the monzodiorite–monzonite–syenite–monzogranite suite is high-K calc-alkaline to shoshonitic. In the Eastern Alps, the gabbro–tonalite–granodiorite$\pm$monzogranite suite defines a typical medium-K calc-alkaline series, with tonalite followed by granodiorite. Though following the medium-K trend, the Pohorje biotite-rich tonalite is described as high-K, compared to the K-poor TTG suites (Altherr et al., 1995). Cumulitic hornblendites occur in Bergell and South Adamello batholiths. The mafic dykes are lamprophyres, many of them akin to lamproites (Venturelli et al., 1984).

Coeval volcanic products are scarce and are found as pebbles and clasts in intra-montane molassic basins of Western and Central Alps (Waibel, 1993).

Their late emergence in relation to the onset of continental convergence and limited duration around 33–31 Ma (Ruffini et al., 1997) are commonly regarded as conflicting with the plate tectonics paradigm. They are coeval to esterellite laccoliths and yield high-K calc-alkaline to shoshonitic features (Boyet et al., 2001).

The Nd–Sr isotopic data (Fig. 6) require that source materials of the Periadriatic plutons are mixtures between magmas from subcontinental lithospheric mantle (ε_{Nd}=+4 to −4, ($^{87}Sr/^{86}Sr$)i=0.704 to 0.708) and melted/assimilated continental crust (ε_{Nd}=−8 to −10, ($^{87}Sr/^{86}Sr$)i=0.710 to 0.720) (for a review, see Von Blanckenburg et al., 1998). Calculations using the thermal model of Thompson (1992) show that large volumes of tonalite could also result from melting–assimilation of 30–45% of mafic lower crust induced by a major thermal perturbation of about 1250 °C (Von Blanckenburg et al., 1998).

The younger 25 Ma Novate two-mica leucogranite is exceptional because of peraluminous mineralogy and chemistry, suggesting a purely crustal origin. Its isotopic compositions (ε_{Nd}=−8.5 and ($^{87}Sr/^{86}Sr$)i=0.710, Fig. 6) correspond grossly to one of the crustal contaminants inferred for the 33–31 Ma mafic–felsic association (Von Blanckenburg et al., 1998).

The post-collisional episode (Von Blanckenburg and Davies, 1995) is characterised by: (i) exhumation of high pressure (blueschist facies) to ultrahigh pressure (eclogite and coesite facies) continental slices, (ii) the 38 Ma Lepontine kyanite–sillimanite thermal metamorphism, (iii) crustal extension related to gravitational collapse of the thickened continental crust, (iv) intra-montane molassic basins filled with erosion (e.g., volcanic) products, (v) magmatic episodes with a climax at 33–31 Ma and hybrid [mantle+crust]-derived mafic and felsic rocks, and the 25 Ma crustal Novate leucogranite.

The model proposing that oceanic lithosphere detaches from continental lithosphere during continent–continent collision by slab breakoff (Liégeois and Black, 1984, 1987) allows to explain syn- to post-collisional magmatic and metamorphic episodes around the Periadriatic Lineament. For a subduction velocity of 1 cm year^{-1}, breakoff could occur at depths of 50–120 km (Davies and von Blanckenburg, 1995). As a result, the upwelling asthenosphere impinges on the mechanical boundary layer of overlying lithosphere. Medium-K calc-alkaline magmas

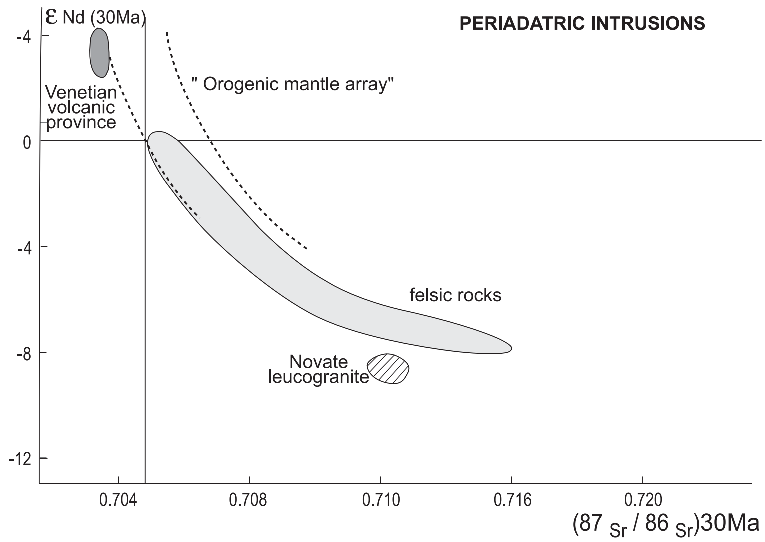

Fig. 6. Isotopic Sr–Nd plot for the post-collisional Periadriatic Lineament intrusions (adapted from Von Blanckenburg et al., 1998). Isotopic data are re-calculated back to the time of emplacement. Shaded area=within-plate alkaline magmatic Venetian volcanic province (data from Milani, 1996). Dashed area=Novate leucogranite (data from Von Blanckenburg et al., 1998). The "orogenic mantle array" is delineated by two dashed lines defined by the isotopic compositions of the most primitive Ni–Cr-rich mafic rocks. Felsic rocks occupy the white area.

originate in amphibole-bearing mantle with subsequent crustal contamination, whereas high-K calc-alkaline to shoshonitic magmas are issued from phlogopite-bearing mantle. Breakoff and enhanced heating effects both facilitate the ascent and ultimate exhumation of the buoyant crustal sheets (e.g., Burov et al., 2001).

The slab breakoff model is substantiated by the mantle structure below the western-central Mediterranean basins (Carminati et al., 1998). Seismological studies demonstrate the presence of High velocity material in the upper mantle, that is interpreted as a subducted lithospheric slab. Complete detachment is inferred in some areas by the first 150–200 km depths exhibiting lower velocities, and the slab anomaly being imaged only below that depth.

Postorogenic magmatic episodes are currently unknown within the Alpine–Carpathian belt. In the Po Plain (Northern Italy), the Venetian volcanic province comprises subordinate alkaline to tholeiitic mafic lavas and predominant trachytes and rhyolites. Positive Nb anomalies, high LILE and P concentrations as well as Sr–Nd isotope systematics indicate an OIB-type source, with little or no crustal contamination (Milani, 1996). Pliocene to Quaternary volcanics occur also in the Pannonian basin and neighbour areas (Waibel, 1993).

In the European foreland, widespread Neogene to Quaternary volcanic activity is recorded from the French Massif Central to the Bohemian massif. The heterogeneous lithospheric mantle contains amphibole and mica, whereas the asthenosphere yields affinities with a HIMU OIB source. Wilson and Downes (1991) suggest that their European Asthenospheric Reservoir (EAR) could correspond to a zone of heated enriched mantle at the base of the subcontinental lithosphere and conclude that there is no need to invoke deep mantle plumes to explain the HIMU characteristics.

6.2. The Tuscan Magmatic Province and the neighbour areas

The Tyrrhenian sea (Fig. 1) is occupied and bordered by large Neogene igneous provinces (e.g., Savelli, 2002). The northern provinces, including the Tuscan one, have alkaline, potassic (K_2O/Na_2O ranging from 0.8 to 2.5) to ultrapotassic (K_2O/Na_2O from 2.5 up to extreme values around 30), mildly to strongly silica-undersaturated compositions. The Tuscan ultrapotassic peralkaline lamproites constitute a noticeable exception by straddling the silica-saturation boundary (Peccerillo, 1992). The Tuscan Magmatic Province (Fig. 1) covers a large area including a continental zone, north of Rome (Italy), and a marine zone dotted with islands and seamounts, corresponding to the northern basin, where the continental crust is preserved. Extensive reviews on the province are available (see Poli et al., 2002, and references therein). The various sources involved in the build-up of the province and the mantle structure will be examined.

The mafic rocks have Sr–Nd isotope systematics reflecting a highly enriched "orogenic mantle array", with Capraia high-K andesites yielding isotopic compositions less radiogenic in Sr and more radiogenic in Nd than Tuscan lamproites. $(^{87}Sr/^{86}Sr)i$ range from 0.7075 to 0.716 and $\varepsilon_{Nd}(t)$ from -3 to -11 (Fig. 7), which are higher figures than those observed in the Sardinia–Corsica batholith (0.7046 to 0.708 and +0.7 to -5.0, respectively). Major and trace element bulk-rock compositions, coupled with the isotopic evidence, suggest that the less radiogenic magmas originated in an amphibole-bearing lherzolite and the more radiogenic magmas, represented by the lamproites, were issued from partial melting at shallow depths of a phlogopite–carbonate harzburgite fertilised by supracrustal materials resembling Dora-Maira metagranitoids, which were carried at mantle depths by Alpine subduction (Peccerillo, 1999).

The felsic rocks occur as ignimbrite or lava flows and laccoliths or dykes, accompanied by fossil or active geothermal fields. From their peraluminous compositions and the occurrence of Al–Fe–Mg minerals, such as cordierite, muscovite and/or tourmaline, they are inferred to derive from anatexis of the continental crust. Isotopic evidence show that crustal components involved in their generation were highly heterogeneous. Some felsic rocks are completely devoid of MME, like, e.g., the Capo Bianco aplite (Elba Island). The other felsic plutonic bodies are crowded with MME and mafic schlieren (Bussy, 1990; Perugini and Poli, 2000), suggesting a significant mantle input and a hybrid nature (Poli, 1992; Dini et al., 2002). Accordingly, their isotopic compositions do not plot along the "orogenic mantle array".

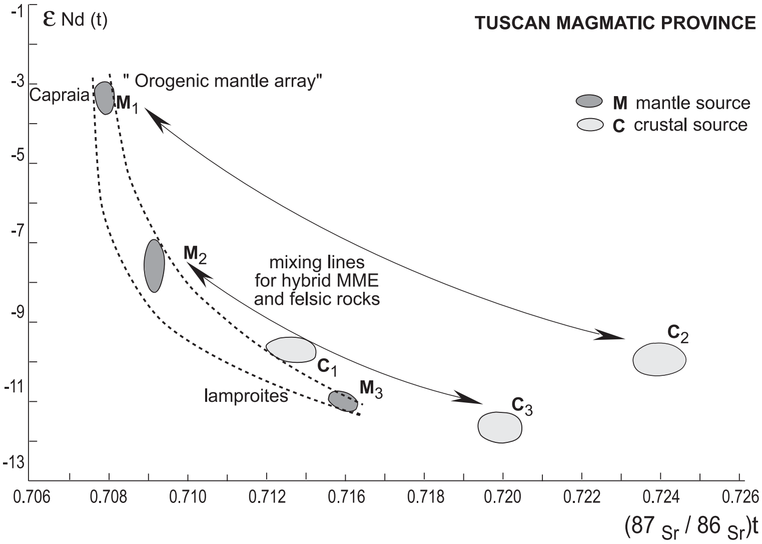

Fig. 7. Isotopic Sr–Nd plot for the Tuscan Magmatic Province (adapted from Dini et al., 2002). Isotopic data are re-calculated back to the time of emplacement. The "orogenic mantle array" is delineated by two dashed lines defined by the isotopic compositions of the most primitive Ni–Cr-rich mafic rocks. For the definition of different mantle and crustal sources, see Dini et al. (2002). Mixing lines connecting liquids issued from discrete crustal and mantle sources are indicated.

The felsic rocks and related MME define mixing lines between different crustal and mantle sources (Fig. 7).

Tomographic studies, deduced from the seismological data available along the Corsica–Tyrrhenian–Apennines transect, evidence the presence of high velocity material in the upper mantle, which is interpreted as subducted lithospheric slab. The Apenninic belt is composed of the stacking of Austro-Alpine nappes overthrusted onto the 100-km-thick lithosphere of Adria plate. Below Tuscany, the 50- to 60-km-thick overriding lithosphere is composed of a 20-km-thick Austro-Alpine continental crust overlying a thin lithospheric upper mantle. In the marine area between Corsica and Elba Islands, this piece of lithosphere is underlain by another piece of lithosphere comprising a slice of lower crust of the former European passive margin. Lithospheric duplication resulted into subsidence of the Tyrrhenian Sea, accompanied by stretching, extension and incipient oceanic crust within the southern basin.

As continental slices are set within the lithospheric upper mantle(s), the sources of mafic magmas are obviously contaminated by crustal materials as far as incompatible element abundances and radiogenic isotope ratios are concerned, especially in the case of previously severely depleted sources. Lithosphere stretching favoured rising of the geotherms and thinning of the mechanical boundary layer, which in turn induced crustal anatexis through dehydration melting reactions. Thus, mafic magmas derived from contaminated mantle sources were coeval and mixed with crustal anatectic magmas, explaining the complexity of magmatic suites of the Tuscan Magmatic Province.

There is no evidence for postorogenic magmatism in the Tuscan Magmatic Province. In the vicinity, alkaline magmatic episodes are known: basalts (Lustrino et al., 2000) and comendite (Morra et al., 1994) in Sardinia, Ponza syenite-bearing trachyte (Belkin et al., 1996) and Palmarola rhyolite (Cadoux et al., 2002) in the Pontine Archipelago. This incipient postorogenic magmatism within the European plate share common features with the within-African plate volcanic provinces, such as Etna and Iblei in Sicily, Linosa and Pantelleria Islands (Esperança and Crisci, 1995).

6.3. Comparison of periadriatic lineament intrusions with the Tuscan Magmatic Province

The post-collisional episodes in the Alpine–Apenninic orogen were accompanied by the Periadriatic Lineament and Tyrrhenian–Tuscan magmatic provinces (Fig. 1). Both are composed of plutonic bodies crosscutting older thrust planes and of volcanic formations. Isotopic evidence show a significant crustal input associated with mantle sources (Fig. 8).

The Periadriatic Lineament intrusions were not coeval with crustal anatexis, nor did they induce migmatisation of their country rocks. They postdate the Lepontine thermal event and predate the Novate crustal-derived leucogranite. Mafic rocks are issued from amphibole peridotite, yielding depleted to enriched isotopic compositions, corresponding to a subcontinental lithospheric upper mantle metasomatised from below by subducted material. Felsic rocks can also incorporate a mafic lower crust component. On the contrary, the Tuscan magmatic rocks are obviously coeval with anatexis of supracrustal formations. They yield complex source systems, with an expanded mantle array, composed of various pieces of metasomatised lherzolite–harzburgite upper mantle, and mixtures with anatectic magmas issued from the overlying continental crust, as illustrated by the common felsic rocks–MME associations.

7. Discussion: lithosphere stacking and delamination versus slab break-off

Orogens are formed by lithospheric shortening on time scales much shorter than that of thermal diffusion (Schott and Schmeling, 1998). For time scales of a few million years, the major part of orogenic uplift occurs during transition from crustal shortening to extension, due to delamination of mantle lithosphere rather than to convective thinning by thermal erosion of the thermal boundary layer. Four stages of mantle unrooting process are identified (Marotta et al., 1998): (i) orogenic growth, (ii) initiation of gravitational instability until lithospheric failure, (iii) sinking of the detached lithosphere,and (iv) relaxation of the system. These stages correspond to the successive collision, post-collisional, postorogenic and, ultimately, within-plate settings.

The outstanding questions regarding the crustal input in post-collisional magmas are: Where and what is the crustal component? Where does it come from? All collisional orogenies begin by a pre-collisional episode, characterised by subduction leading to oceanic basin closure and terrane docking. Geological and geophysical observations show that the conver-

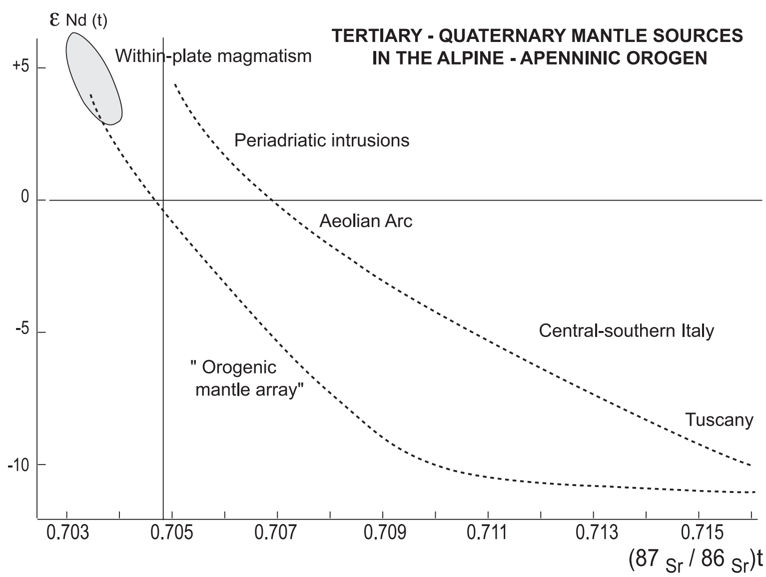

Fig. 8. Isotopic Sr–Nd plot for the post-collisional suites of the Alpine–Apenninic orogenic belt. Isotopic data are re-calculated back to the time of emplacement. The "orogenic mantle array" is delineated by two dashed lines defined by the isotopic compositions of the most primitive Ni–Cr-rich mafic rocks. Shaded area=within-plate alkaline magmatic suites (data from Milani, 1996). The fields of the Periadriatic intrusions, the Aeolian Arc, central-southern Italy and Tuscany are largely overlapping (data from Von Blanckenburg et al., 1998; Poli et al., 2002).

gent plate margins feature sediment subduction within a subduction channel shear zone, subduction erosion of the overriding plate and formation of chaotic melanges (Cloos and Shreve, 1988). As subducted detrital sediments have a dominantly continental crust component, they can be largely responsible for isotopic crustal signatures of post-collisional magmas. Other materials are capable to subduct, as a function of lithospheric buoyancy. Less than 15-km-thick continental and oceanic island arc crusts are inherently subductable, whereas the threshold for basaltic plateaus ranges at ~30 km (Cloos, 1993).

Exhumation of high to ultrahigh pressure metamorphic rocks, initiation and development of topographic positive anomalies, evolution of post-collisional thermal metamorphism and generation of post-collisional to postorogenic magmatic suites are controlled by subduction zones. Doglioni et al. (1999) suggest that, probably due to the drift of lithosphere relative to asthenosphere, the decollement plane of a subduction zone can be either warped and subducted, or ramping at the surface. According to this scheme, contrasting characteristics of the subduction events during the pre-collisional stage can be imaged by various features of the magmatic suites and sources during the post-collisional and postorogenic stages.

7.1. Lithosphere stacking: the potassic to ultrapotassic story

In the case of lithosphere stacking, the topography of the orogen is rapidly growing upward and the overriding lithosphere expands laterally. The underlying lithosphere includes eclogite facies oceanic crust as well as coesite facies continental crust, favouring its buoyancy. Partial melting of the lithospheric depleted upper mantle, whether it is made up of amphibole spinel lherzolite, or phlogopite garnet harzburgite, both fertilised by subducted crustal material, would result into potassic primary magmas generating high-K calc-alkaline to shoshonitic to ultrapotassic suites.

As this regime is long-lived, repetitive magma generation, ascent and emplacement within the continental crust of the upper plate would induce and promote dehydration melting reactions by muscovite and biotite breakdown, producing peraluminous magmas. Commingling of mantle-derived potassic and crustal peraluminous magmas favours physical and chemical mixing processes leading to the felsic rocks–MME association.

7.2. Slab break-off: the medium-K to high-K calc-alkaline story

When the subducted slab breaks off, the upwelling asthenosphere induces partial melting at shallow depths within the mechanical boundary layer of overlying lithosphere. Medium-K calc-alkaline magmas originate in amphibole peridotite with some subsequent crustal contamination by the mafic lower crust, whereas high-K calc-alkaline to shoshonitic magmas are issued from deeper phlogopite–garnet peridotite. The crustal components evidenced in mantle-derived magmas could come from either dehydration-derived fluids, plus adakitic partial melts issued from the subducted slab, or assimilation–contamination processes within the overlying lithosphere.

7.3. Lithosphere delamination: the shift to alkali-calcic to alkaline–peralkaline suites

At the very end of the post-collisional stage, the continental lithosphere becomes more and more depleted and dehydrated by repetitive generation of water-bearing magmas. Its thickness decreases, due to extensional episodes accompanied by and/or promoting heating from below. Lithospheric thinning through delamination (Black and Liégeois, 1993, and references therein) is induced by thermal and mechanical instability of the continental lithosphere (Marotta et al., 1998) and the weak link with the crust (Meissner and Mooney, 1998). Rapid unroofing by isostasy is accompanied by hot asthenosphere upwelling and magmatic underplating. Dehydration of the thinning lithosphere results ultimately into the shift in a few million years from high-K calc-alkaline to alkaline magmatic suites (Liégeois and Black, 1984; Bonin, 1986, 1988, 1990).

Within-plate settings correspond to formation of an incipient craton by consolidation of the new continent created by amalgamation of continental terranes. The subcontinental lithosphere grows with time by cooling and by underplating of deeper material. Partial melting occurs at deeper and deeper levels from less and less hydrous regions in the upper mantle, as illustrated by the ~500-million-year-long evolution from silica-oversaturated to silica-undersaturated alkaline suites (Black et al., 1985). Crustal anatexis is definitively hindered by dry characteristics of lower crust materials and too low temperatures at the crust–mantle boundary, down to 400 °C in the case of very ancient stabilised cratons (Black and Liégeois, 1993).

8. Summary and conclusions

Mafic–felsic associations, so common in post-collisional to postorogenic magmatic suites, reflect the contrasting rates of magma generation and differentiation. Basically, any granitic rock with MME was produced by magma differentiation within a reservoir somewhere in the crust and, while still evolving, was invaded by influx and disruption of a new magma coming from below. It is safe to assume that mafic rocks originate in mantle-derived magmas. The more primitive mafic rocks define an "orogenic mantle array", rooted in the depleted quadrant of a Sr–Nd isotopic plot and spreading within the enriched quadrant, evidencing the role played by crustal components in mantle sources. Regarding the felsic rocks, crust and upper mantle constitute two likely candidates for their sources.

The orogenic climax is represented by the collision stage. The subsequent stages are marked by widespread and voluminous magmatic activity. The nature, origin and evolution of post-collisional to postorogenic magmatic suites depend largely upon the pre-collision subduction styles.

Lithosphere stacking due to buoyancy of subducted continental material favours generation of potassic to ultrapotassic compositions from a metasomatised phlogopite–garnet peridotite. Large influx of mantle-derived magmas can induce coeval crustal anatexis aided by large-scale heating and dehydration melting reactions of the more fertile micaceous formations.

On the contrary, steeply dipping subduction due to positive density anomaly of the eclogite oceanic crust results into slab breakoff and generation of medium-K to high-K calc-alkaline suites, dominated by tonalite and granodiorite, from a metasomatised amphibole–spinel peridotite. Only rarely can the weakly heated lower continental crust undergo incipient anatexis, which can occur only in the aureole of intrusive bodies.

Bimodal postorogenic magmatic suites are derived from OIB-type mantle sources, and undergo contamination–assimilation processes through wall-rock reactions. Fast cooling conditions prevailing within the interiors of the orogen imply that crustal anatexis can no longer occur.

During the evolution from post-collision to within-plate regimes, crustal anatexis induced by dehydration melting reactions plays a waning role and disappears completely, substantiating a decrease in heat input and lithosphere cooling. Upper mantle sources are less and less dominated by hydrous crustal components, and acquire OIB-type compositions.

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