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Orogenic to Non-Orogenic Magmatic Events: Overview of the Late Variscan Magmatic Evolution of the Alpine Belt

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Abstract: The Alpine belt comprises several pieces of Pre-Mesozoic basement, which have received various imprints of the successive Paleozoic orogenic episodes. If Pre-Mesozoic palinspatic reconstructions are taken into account, the Alpine basement can be considered as one single area before Mesozoic continental breakup. Contrasting magma associations were emplaced according to space and time.

There exists a controversy about the existence of the Caledonian orogenic episode. The Lower Paleozoic orogenesis was advocated through different lines of evidences in the southern Alpine basement, such as emplacement of Ordovician and Silurian protoliths of calc-alkaline and alkaline orthogneisses.

The Variscan orogenic episode ended with the Late-Devonian collisional stage. Then, the Alpine basement was subjected to large-scale shearing effects accompanying lithosphere distensional thinning, high geothermal regimes and low-pressure regional metamorphism. The middle crust ultimately underwent "wet" and/or H_2O-deficient partial melting processes, which may or may not have been induced by the intrusion of mantle-derived melts. Peraluminous crustal melts were associated and/or mixed with high-K basic magmas.

Lower to Middle Carboniferous high-K calc alkaline suites characterize the culmination of the post-collisional stage, that was related to uplift and erosion in short-lived transpressional and/or transtensional environments. At the Permian-Carboniferous boundary, near alkaline suites, yielding both alkaline and calc-alkaline features, were emplaced as volcanic-plutonic massifs in a major distensional regime and mark the end of the Variscan orogenesis *sensu stricto*.

Upper Carboniferous to Early Permian calc-alkaline granitoids were emplaced only at the southern flank of the Variscan belt. They yield features characteristic of subduction-related suites and resemble closely the circum-Pacific Cordilleran batholiths. They indicate a renewed ocean-continent plate margin convergence, which could be related to the alleghanian orogenesis. This episode, well developed in the southern Appalachians, can be evidenced in North Africa, the Alpine belt and further east to Asia.

Mid-Permian post-orogenic and Late Permian to Triassic early anorogenic alkaline complexes constitute a part of the Western Mediterranean alkaline province. Associated thermal imprints were recorded in the basement mineral isotopic clocks. The anorogenic magmatic activity can be related both to continental consolidation of the European plate and precursory stage in the formation of the Meso-Tethys oceanic basin.

Orojenik ve Orojenik Olmayan Magmatik Olaylar: Alpin Kuşağının Geç Variskan Magmatik Evrimine Genel Bakış

Özet: Alpin kuşağı Mesozoik öncesine ait birkaç parçadan oluşan temele sahiptir. Bu parçalar ard arda gelişmiş Paleozoyik orojenik olayların izini taşır. Mesozoyik öncesi palinspastik rekonstruksiyonlar dikkate alındığında Alpin temelin Mesozoyik kıtasının parçalanmasından önce tek bir parça halinde bulunduğu anlaşılır. Zaman ve mekan içerisinde birçok farklı magma toplulukları temel içerisine yerleşmiştir.

Bu alan içerisinde Kaledoniyen döneminin varlığı tartışılmalıdır. Alt Paleozoyik orojenik kuşakların varlığı ile ilgili Alpin kuşağının güney bölümünde bazı ipuçları vardır. Örneğin kalkalkalen ve alkalen ortognaysların protolitleri Ordovisiyen ve Siluriyen yaşlıdır.

Varistik orojenez olayları Geç-devoniyen çarpışması ile sona ermiştir. Daha sonra, Alpin kuşağı büyük ölçekteki makaslama etkileri ile litosferin gerilmesiyle incelmesi, yüksek jeotermal rejim yaratmış ve düşük basınçlı bölgesel metamorfizma gelişmiştir. Sonuçta orta kabuk sulu ve/veya H_2O'ca fakir kısmi ergimeye uğramıştır. Bu olay manto kaynaklı eriyiklerin herhangi bir etkisi olmaksızın gelişmiştir. Peraluminyumlu kabuksal ergiyikler K açısından zengin bazik magmalar ile beraber veya onlarla karışarak yeralmıştır.

Alt-Orta Karboniferden yaşlı yüksek-K kalk-alkali toplulukları, çarpışma sonrası dönemin zirve noktasını işaret eder. Bu dönemde kısa süreli sıkışma ve/veya gerilme etkisinde yükselme ve erozyon olayları gelişmiştir. Permiyen-Karbonifer sınırında Alkalen toplulukların yakınında hem alkalen hem kalkalkalen özellikli oluşumların volkanik-plutonik masiflerin ana gerilme rejimi altında geliştiğini ve Varistik orojenezin sona erdiğine işaret eder.

Üst Karbonifer'den Erken Permiyen'e kadar kalkalkali karakterli granitoidler sadece Variskan kuşağının güney kanadında yerleşmiştir. Bunlar dalma batma ürünlerin özelliklerini göstermekte ve Pasifik çevresi Cordilleran batholitlerine benzerlik gösterirler. Bunlar yenilenmiş okyanus-kıta levha sınırlarını göstermekte ve alleghanian orojenez ile ilişkili olabilir. Bu dönem Appalachian'nın güneyinde, Kuzey Afrika'da, Alpin kuşağında ve Asya'nın doğusunda iyi gelişmiştir.

Orta-Permiyen geç-orojenik ve Geç-Permiyen'den Triyas'a kadar orojenik olmayan alkalin kompleksler Batı Akdeniz alkalen provenslerini oluşturur. Termal etkiler minerallerin izotop saatinde kayıtlıdır. Orojenik olmayan magmatik aktiviteler hem Avrupa levhasının konsolide olmasına hem de Meso-tetis okyanus basenin ilk oluşum aşamasına bağlı olabilir.

Introduction

Mobile belts are crustal segments that have experienced strong rigid and/or plastic deformations. Together with the occurrence of regionally metamorphosed rocks, the most outstanding feature of mobile belts is the abundance of numerous magmatic rocks with differing compositional, textural and geological characteristics (for reviews, see Pitcher, 1983, 1987; Barbarin, 1990). The Variscan belt of Europe evolved in connection with the Paleozoic convergence of Gondwana in the south and Laurasia in the north and was then consolidated in the Late Paleozoic. The major unsolved questions centre around the plate framework of the Variscan realm and, specifically, where oceans and subduction zones have been located in the Late Paleozoic (for reviews and contrasting hypotheses, see Matte, 1986; Neugebauer, 1988; Ziegler, 1986, 1993).

In the Alpine belt, primary features were obscured by the superimposition of episodes of differing ages. The oldest ages determined by radiometric methods are Precambrian, from Proterozoic (Jager, 1983) to Archaean (Frisch et. al., 1990), the oldest detrital zircon dated so far within the Alps yielding a U-Pb age of 3.43 Ga (Gebauer, 1993). In addition to the Paleozoic (Caledonian-Variscan) orogenies, Upper Proterozoic (Pan-African/Codomian) and Cretaceous-Tertiary (Alpine) events have left their imprints (Schaltegger, 1993; Waibel, 1993). The major difficulty raised in this study is that present Alpine structural units have nothing or little to do with previous Variscan structural units. In the Helvetic realm for example, the 100 km-long and 10 km-wide Belledonne massif (external crystalline massifs, France) was built up by the "collage" of three discrete domains differing by their lithological, magmatic and tectono-metamorphic evolution (Ménot, 1987, 1988; Vivier et. al., 1987). Thus, Late Variscan magmatic bodies belonging to the same geodynamic suite can be encountered in several distinct Alpine units, while, in the same Alpine unit, magmatic formations can be related to distinct geodynamic environments.

The aim of this paper, updated from the compilation by Bonin et. al. (1993), is to provide an overview of the pattern and evolution of Late Variscan granitic massifs and associated volcanics in the pre- Mesozoic basement of the Alps. 'Late Variscan' is given hereafter a wide sense to encompass all events occurring after the major collisional stage, i.e. the end of the Devonian, and before the beginning of the Alpine orogeny, i.e. the Permo-Triassic. In part 1, the *rationale* of the geodynamic interpretation of the magmatic provinces is presented. In part 2, a comparative summary and speculations on the possible geodynamic framework is provided for the interpretation of the Late Variscan magmatic activity.

Basic Concepts and A General Scheme for Space and Time Evolution

In their review of basic concepts of granite geology, which can be enlarged to magma associations as well, Bonin and Markopoulos (1991) stress that:

(i) current classifications based on modal and major-element compositions are at a first step convenient for unravelling the nature of magma associations;

(ii) the significance of radiometric data in terms of meaningful geological ages should be carefully examined;

(iii) the spatial distribution of the suites should be considered in connection with the chronological framework.

Geological Constraints

Present-day geodynamic settings are relatively easy to define, but it is not the same story in older orogenic belts. During the last few decades, considerable attention has been paid to past geodynamic environments in which magmatic rocks were emplaced. Actually, a granitoid is almost always associated with other rock types, such as basic-intermediate rocks and volcanic formations. The association can constitute a suite of magmas, cogenetic or not. Rock-forming minerals and whole-rock chemistries have been shown to provide useful indications of the thermodynamic conditions prevailing during melt generation, evolution, crystallization, and rock consolidation and cooling. The most sensitive parameters are:

– modal data, reduced to QAP plot

– zircon morphology, according to the method of Pupin (1976, 1980)

– mineral compositions

– whole-rock major elements: TAS, A/CNK, R1-R2, FMA plots

– trace-element normalized spiderdiagrams, REE patterns, Rb-(Y+Nb), Rb-Ba-Sr plots...

Thus, a granitic massif can be used as a geodynamic indicator if all pieces constituting the geological puzzle are assembled, i.e. the rock types making up the massif as well as their wall rocks. Geological, structural, petrological, mineralogical and geochemical data should be collected together in order to provide such a coherent framework.

All magmatic massifs that have been studied yield a data base which has been compiled from published as well as from unpublished results. The whole seet of data exceeds the length of this paper, pertinent references are provided by von Raumer and Neubauer eds. (1993) and, as far as Late Variscan magmatism is concerned, by Bonin et. al. (1993).

An example of comprasion of data is given on Table 1, which concerns two nearby and yet contrasting granites: Vallorcine (Aiguilles-Rouges massif) and Mont-Blanc. The different criteria used to define geodynamic settings concur to substantiate that source rocks of the melts, modes of differentiation and crystallization of the magmas, levels of emplacement, etc. are different, even though these granites seem at a first glance to be rather similar (e.g. parallelogram shape of the intrusive complex, abundant K-feldspar megacrysts, emplacement in relation to large-scale shear zones, etc.).

Geochronological Intricacies

A reasonable number of high-quality age determinations is unfortunately lacking for most of the massifs. Many formations are currently considered as Late Variscan only on the basis of ill-defined criteria, such as the so-called “monocyclic” metamorphic evolution of a massif unconformably overlain by a Mesozoic sedimentary cover, or on the unproven assumption that red K-rich rhyolites should be Permian in age. A good example is afforded by the Acceglio Zone, the innermost part of the Briançonnais area. The siliceous volcaniclastic series, allegedly of Westphalian-Stephanian age, is actually considerably older, as muscovite from late *intrusive* meta-aplite and metagranite has retained $^{40}Ar/^{39}Ar$ closure ages of 365 ± 4Ma and 335 ± 7 Ma, respectively (Monié, 1990). Secure interpretation of isotopic data can be difficult to obtain, owing to the following reasons:

(i) many magmatic bodies have suffered at different degrees of the effects of Alpine folding and associated metamorphic events. Some massifs are presently converted into orthogneissic lenses and primary magmatic features are preserved only locally. Due to widespread retromorphic effects, isotopic clocks can be reset more or less compeletely to zero. In this respect, many data concerning minerals are suspect and should be used carefully. For a review and discussion, see Hunziker et. al. (1992).

(ii) large-scale homogenity of radiometric data can indicate culmination of a low-pressure thermal metamorphic event obliterating older emplacement ages. Pre-tectonic and synkinematic magmatic bodies are highly sensitive to overprinting effects.

(iii) radiometric determinations can not always be controlled on geological grounds, because relative chronological and paleontological criteria are lacking or difficult to interpret unequivocally in metamorphosed areas. Isotopic data conflict sometimes with geological evidence: they are younger or, more rarely, too much older.

(iv) it is not yet possible to get distinct dates for discrete pulses of magma within a Late Paleozoic massif, as dating methods are marked by analytical errors and systematic uncertainties in data processing.

Magmatism within the Alpine belt appears to have been continuous from the Devonian up to the Permian and, in some places, even to the Triassic. The chronological gaps now existing in some areas are merely due to the smaller number of dated and/or datable magmatic occurrences. However, examination of the present set of reliable ages of emplacement suggests that, as far as magmatic episodes are concerned, the Alpine belt is composed of two discrete domains.

In Helvetic and Penninic realms, Variscan magmatism was characterized by calc-alkaline and anatectic suites predating near-alkaline suites, with an age distribution ranging from Late Devonian to Late Carboniferous (Stephanian), i.e. from 350 to 300 Ma. Permian magmatism, when present, was scarce and poorly developed within graben and troughs infilled with molassic sediments.

In contrast, in the Austro-Alpine realm and the Southern Alps, no age older than 320 Ma is presently recorded and the maximum of data is centred around 290 and 270 Ma. Additional and abundant Permian (i.e. from 300 to 250 Ma) magmatism was particularly well developed and displays a clear sequence of (high-K) calc-alkaline and alkaline suites. Some of these peculiar features are shared also by southern France, Corsica-Sardinia, and Morocco.

Towards A Geodynamic Interpretation

Areas subjected to Variscan folding, metamorphism and magmatism occur within the entire Alpine belt, as well as outside the Alpine front. Most of the intra-Alpine Variscan outcrops constitute the basement to the Alpine thrust sheets, where they underwent Cretaceous-Tertiary deformation and metamorphism at various scales and levels. Fragments of Permian-Carboniferous magmatic massifs are exposed in both external and internal domains, together with relics of pre-existing continental crust of poorly known age. Although the present location of the Paleozoic massifs are largerly disturbed by Alpine tectonics, they have formed parts of the southern flank of the Variscan fold belt (Frisch et. al., 1990). The different domains are presented and discussed in the review books edited by Dallmeyer (1989) and von Raumer and Neubauer (1993).

The distribution of the Late Variscan magmatic formations in the pre-Mesozoic Alpine basement is described in detail by Bonin et al. (1993). Abundance and compositional characteristics of the magmatic suites in the different Alpine realms are strongly differing in both space and time and can be compared with the other domains of Western Europe.

Unravelling the geodynamic involvement of Late Variscan magmatic episodes would require:

(i) a good knowledge of the framework of Pangaea super-continent at the end of Paleozoic times (how many continental fragments?),

(ii) unequivocal discrimination of the magmatic suites in terms of magma associations and times of emplacement.

Up to now, these tasks are far from being completed for the entire Alpine belt.

The Basement of the Alpine Belt and Its European Foreland

The geodynamic evidence is obscured by the fact that the precise location of the different Alpine structural units, before Permian-Triassic dismembering of Pangea and subsequent readjustment during Cretaceous-Tertiary tectonic episodes, remains a matter for speculations. The last attempts of palinspatic pre-Mesozoic reconstructions (Figure 1) are discussed by Von Raumer and Neubauer (1993).

Within the basement of the Alpine belt, small fragments of oceanic and/or back-arc basinal crust are

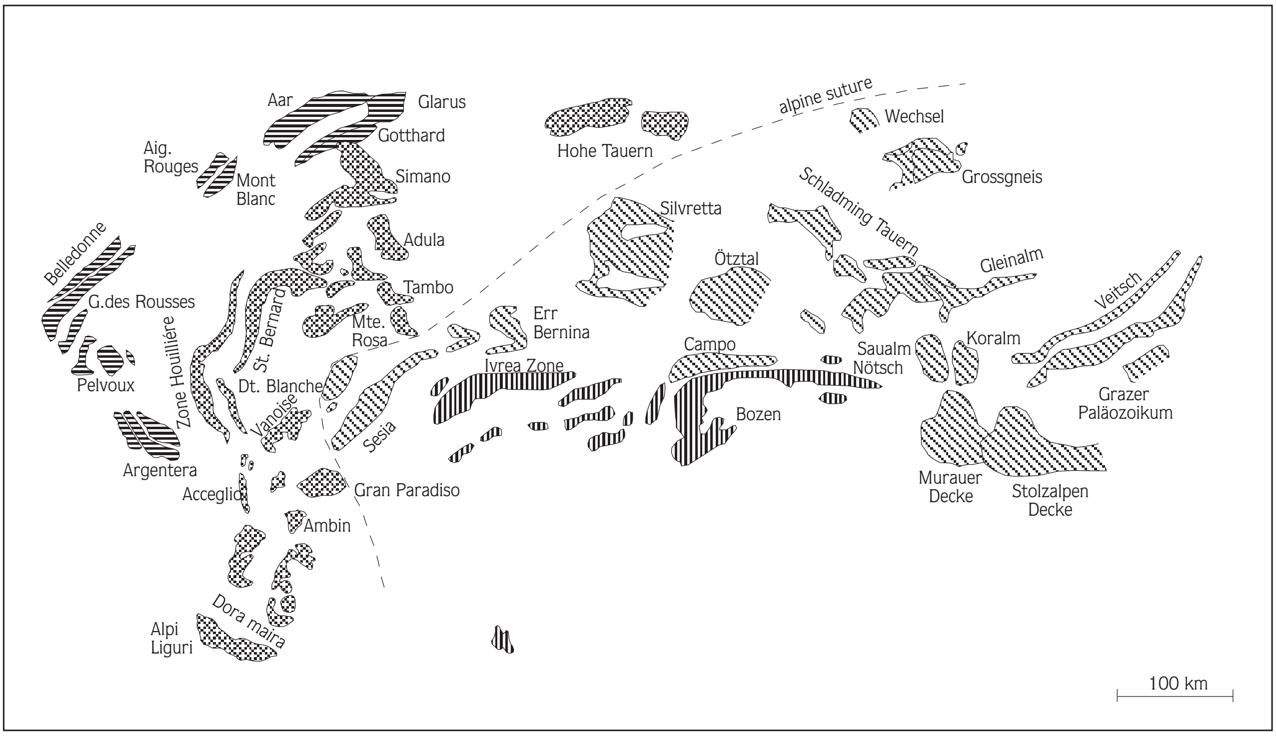


Figure 1. Sketch map of the pre-Alpine basement units, according to pre-Mesozoic reconstruction (von Raumer and Neubauer, 1993). Horizontal rules: Helvetic realm; cross hatches: Penninic realm; diagonal rules: Austro-Alpine realm; vertical rules: Southern Alps.

preserved as sparse ophiolitic masses and/or eclogitic lenses, suggesting: (i) evolution of one or several oceanic basins, (ii) subsequent subduction processes during Lower Paleozoic times. The Late Variscan period is characterized by the end of oceanic crust subduction, the closure of the oceanic basin(s), the collision of Gondwana with Laurasia and smaller terrains, and the amalgamation onto the Pangaea super-continent.

Discrete Terrains? The “Caledonian Controversy”

The presence of discrete terrains can be suspected from different points of view. The European foreland of the Alpine belt is considered as an amalgamation of (micro)continental blocks that collided with the Laurasian mega-continent during the Paleozoic. The scattered occurrence of Pan-African ages in south Europe (Armorica and Iberia) have been interpreted as evidence of Gondwana-derived microcontinents (Ziegler, 1986; Guerrot et al., 1989). This type of terrains coming from the south can extend to the north as far as the Ardennes. On the basis of U-Pb zircon data, Schaltegger (1993) concludes that the Helvetic realm and the European foreland (Schwarzwald) were consolidated within the present configuration prior to the Caledonian episode.

By contrast, orthogneisses and meta-volcanics in the Austro-Alpine realm (Loeschke and Heinisch, 1993), the Southern Alps (Boriani et al., 1982-1983, 1988; Sassi and Spiess, 1993; Siletto et al., 1993), southern France and parts of the Meditarrenean area (Delaperrieré and Soliva, 1992), yield Ordovician-Silurian ages of emplacement and define a sequence from an older (465 to 440 Ma) orogenic calc-alkaline suite to a younger (ca. 425 Ma) post-orogenic alkaline suite. The term “Caledonian” has not always been accepted because of its geographic connotation (Sassi and Schmidt, 1982; Sassi et al., 1987), but the occurrence of a sequence of Lower Paleozoic magmatic suites suggests strongly an orogenic episode resembling the Caledonian event in the British Isles.

Lower Paleozoic orogenic calc-alkaline massifs have been described in other parts of the Alpine belt as well as in the European foreland (e.g. French Massif Central, Armorica, Schwarzwald). They record a long-lived subduction regime and do not substantiate a complete orogenic cycle because post-orogenic alkaline suites are lacking. Thus, a discrete “Caledonian” event is not evidenced so far in the rest of the Alps and their European foreland, substantiating the view that the Southern Alps could represent a discrete terrain, with its own specific geodynamic evolution before the assembly of continental fragments onto Pangaea.

Space and Time Relationships of Orogenic Magma Associations

The following Late to Post-Variscan orogenic magma associations have been observed (Figure 2): (i) calc-alkaline suites with low-K and high-K variants, referred to as I-type plutons (e.g. Finger and Steyrer, 1990), (ii) crustal peraluminous granites, referred to as S-type plutons. Ultimately, alkaline and subalkaline A-type suites were emplaced.

Low-K calc-alkaline diorite-tonalite-trondhjemite suites are rare and yield ages of emplacement ranging between 360 and 350 Ma (Devonian-Dinantian boundary), very close to the major collisional event and just after culmination of the Barrowian metamorphic episode. They cannot be considered as Late Variscan s.s.

Normal-K and high-K calc-alkaline suites are widespread and yield compositionally expanded suites from (monzo)diorite through granodiorite to monzogranite. Their ages of emplacement cover the whole Carboniferous and yield a maximum centred at 330-320 Ma (Middle Carboniferous) characterised by large batholiths and associated volcanics. They fit closely enough to the original definition of I-type granitoids by Chappel and White (1974) and belong to the H_{LO} group of “calc-alkaline rocks with mixed (crust+mantle) origin” of Barbarin (1990). The significance of calc-alkaline I-type suites is not yet fully clear. Normal-K calc-alkaline associations can represent the “Cordilleran-type” of Pitcher (1983, 1987), while the high-K massifs define the “Caledonian-type” and indicate instead post-collisional regimes. Finger and Steyrer (1990) point out that almost all rocks are metaluminous in character and fall in the “Volcanic Arc Granites” (VAG) field defined by Pearce et. al. (1984). Then: subduction or post-collisional stages?

Examination of space and time distribution of medium-K versus high-K calc-alkaline suites makes the problem even more complex. In Helvetic and Penninic realms, dominantly high-K and clearly post-tectonic Carboniferous batholiths were followed by Lower Permian high-K volcanic activity. On the contrary, in the southern edge of the Alps (Austro-Alpine realm and Southern Alps), a continuous record of medium-K calc-alkaline activity is preserved from the Carboniferous up to the Lower Permian and subsequent Middle Permian high-K suites were emplaced. This distribution implies that, during the Carboniferous, the southern Alpine edge was located along an active margin plate boundary, while northern areas were already intra-continental.

Tectono-metamorphic and magmatic episods that define the alleghanian orogeny are described westward in

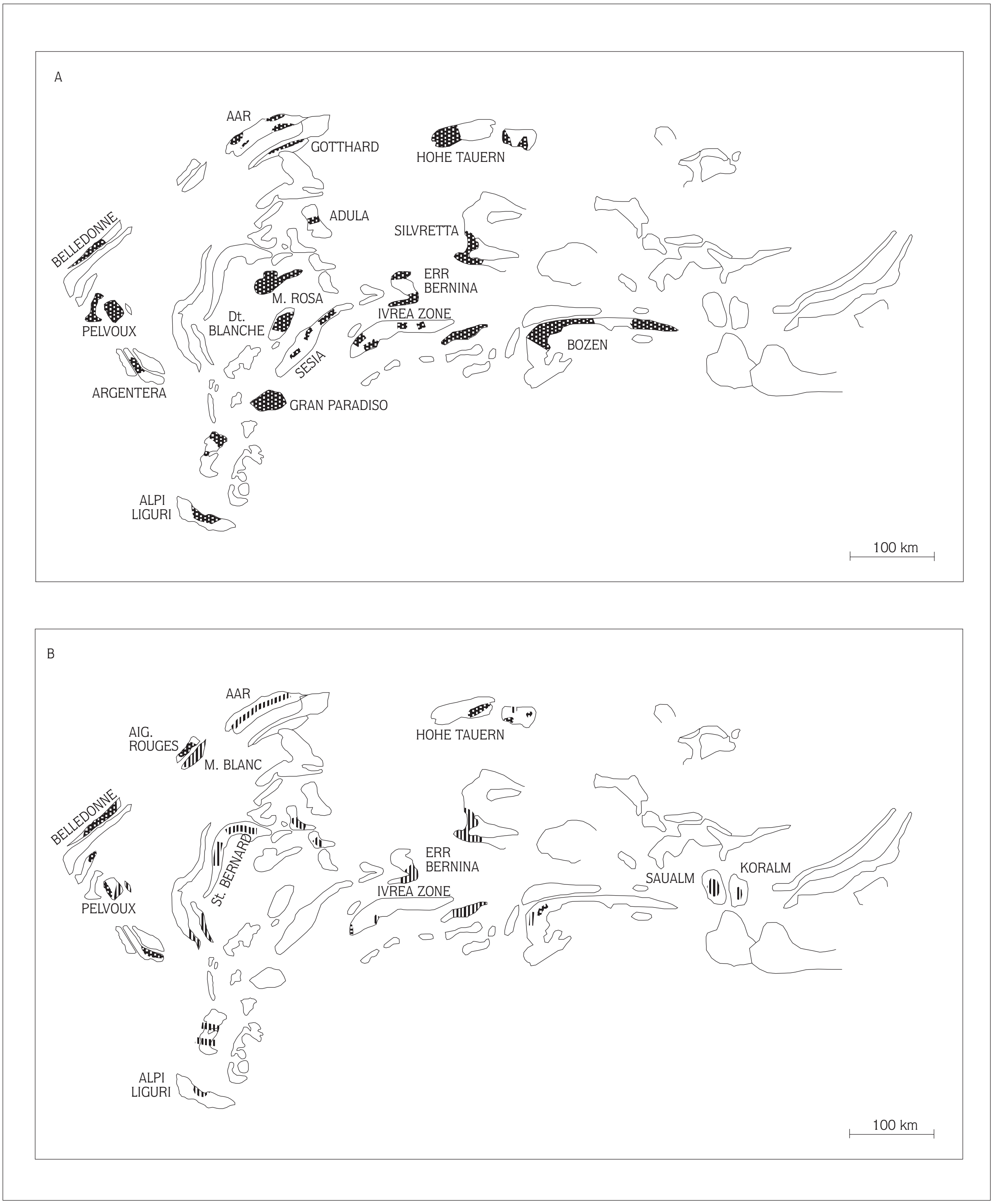


Figure 2. Sketch map of the pre-Alpine basement units, with emphasizes on magma suites (from Bonin et al., 1993). A. dots: High-K calc-alkaline post-collisional suites and medium-K calc-alkaline suites. B. dots: crustal anatectic syn-collisional (?) peraluminous associations; vertical rules: alkali-calcic and alkaline post-orogenic suites.

the South Appalachians of USA as well as in the Mauritanides of West Africa (Dallmeyer, 1989). Subduction-related events are also recorded eastward along the Laurasian active margin. As the South Alpine realms are located between the Appalachians and the eastern boundary of Laurasia, it is suggested that they underwent the same discrete and younger orogenic event, which is not recorded in the more external parts of the Alps and the European foreland. Similar sequences of Permian-Carboniferous magmatic suites were emplaced in other parts of the Mediterranean region (Corsica-Sardinia, Pyrénées, Catalonia, North Africa) and provide further evidence for a wider alleghanian event.

Carboniferous anatectic suites comprise parautochthonous and allochthonous granitoid massifs. As a general rule, the peraluminous granodiorite-monzogranite suite, which corresponds to S-type granitoids (Chappel & White, 1974), predates the two-mica leucogranites, which are quite different (Barbarin, 1990). They belong to the C_{ST}, C_{CA} and C_{CI} groups of "peraluminous rocks with crustal origin" of Barbarin (1990) and fall in the "Syn-Collisional Granites" (Syn-COLG) field of Pearce et al. (1984). They are often associated with K-rich lamprophyric basic rocks, which suggests that the heat input provided by basic magmas was sufficient to induce local crustal anatexis. The peraluminuous granitoid association characterizes the "Hercynotype" of Pitcher (1983, 1987).

Upper Carboniferous-Permian A-Type Granitoid Suites

Upper Carboniferous to Permian A-type granitoid suites are relatively widespread within the Alpine basement. They occur as mafic enclave-bearing porphyritic granitoid massifs, such as Mont-Blanc and Aar, and bimodal mafic-felsic alkaline centred complexes, such as Combeynot and Lugano massifs which resemble so closely the Corsican ring-complexes (Bonin et al., 1987). Their A-type nature was defined from mafic and felsic rock compositions.

On the basis of ages of emplacement and compositional ranges, the late to post-orogenic A-type suites have been subdivided into two contrasting groups:

(i) the 300 Ma subalkaline association of Aar, Mont-Blanc and Saint-Gothard massifs is made up of a compositionally expanded suite (granodiorite-monzogranite-syenogranite, scarce alkali feldspar granite, abundance of mafic enclaves) which yields alkali-calcic compositions and markedly alkaline affinities (zircon morphology, Fe enriched mineral chemistry, HFSE-enrichment typical of "Within-Plate Granites"). The post-collisional late-orogenic suite closely resembles the Ploumanac'h association, for which the name of "Fe-rich subalkaline series" was proposed (Barriére, 1977).

(ii) the 270-230 Ma alkaline association is well developed in Southern Alps and related massifs have also been described in Austro-Alpine, Penninic and Helvetic realms (Bonin et. al., 1987). This magmatic A-type suite, with scarce basic rocks and a wealth of acidic (rhyolite-granite) rocks, belongs to the "anorogenic Nigeria-type" of Pitcher (1987) and the A group of "alkaline granitoids with a mantle origin" of Barbarin (1990). Like the 300-290 Ma-old association, they fall in the "Within-Plate Granites" (WPG) field of Pearce et al. (1984) near the boundary with the VAG field. According to Bonin (1990), the 270 Ma granitoids constitute the discrete group of "post-orogenic alkaline granites", while the 250-230 Ma granitoids define the "early anorogenic alkaline granites".

Basic rocks from Mont-Blanc (Figure 3a) and Corsica (Figure 3b) do not represent pure mantle partial melts, as indicated by low Cr and Ni abundances. In MORB-normalized spiderdiagrams, mineral fractionation-cumulation effects are responsible for Ce-P positive anomalies and, in the case of Mont-Blanc enclaves, Ti negative anomaly. Mont-Blanc enclaves exhibit a pattern of high abundances, that were interpreted by mixing with the granitic host-melt (Bussy, 1990). Provided that these secondary effects are taken into acount, both A-type suites share: (i) a relatively flat pattern from Nb to Yb, indicating common mantle sources and partial melting conditions, (ii) a marked LILE-enrichment, a relatively common feature in within-plate basalt provinces, which can be induced by flushing of fluids released by dehydration of mantle metasomatised by fluides issued from older subduction events, but can be equally ascribed to crustal contamination at the magma chamber level.

Granitoid rocks display features of highly evolved liquids. Though ORG-normalized spiderdiagrams are relatively similar, enrichment levels are lower in Mont-Blanc granites (Figure 3c) than in Corsican alkali granites (Figure 3d), especially for HFSE, which are depleted in metaluminous and peraluminous melts and enriched in peralkaline melts. Alkali-feldspar fractionation, that is measured by the extent of Ba negative anomaly (Bonin, 1990), was more efficient in Corsica than in Mont-Blanc, which suggests lower water pressures and/or shallower depths of emplacement for Late Permian magma chambers.

According to their Y/Nb ratios, both suites belong to the post-collisional to post-orogenic A2 group of Eby (1992), which shows certain similarities to average crust.

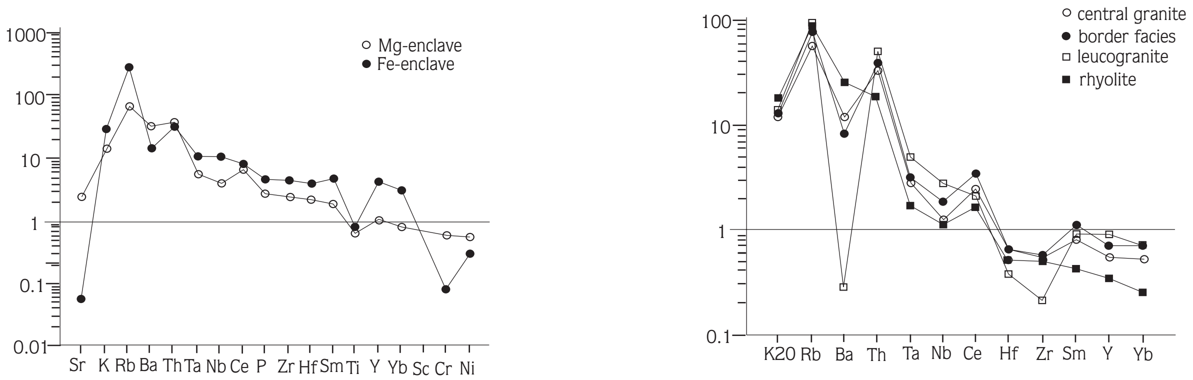
Y/Nb ratios are higher in the Mont-Blanc granites (≥3.0) than in the Corsican syenite-granite association (1.5 up to 2.5). These data substantiate a progressive modification of continental crust characteristics, from relatively thick, warm and hydrated conditions during the post-collisional stage, promoting crustal contamination of mantle-derived melts, to thinning, cooling and dehydrating conditions during the early anorogenic stage, without significant contamination. Subsequent Triassic continental breakup prevented more mature anorogenic environments.

Summary and Conclusion

Geological, petrological and geochemical data are consistent with the current models of magma generation within a major orogeny. The most likely geodynamic scheme can be summarized as follows:

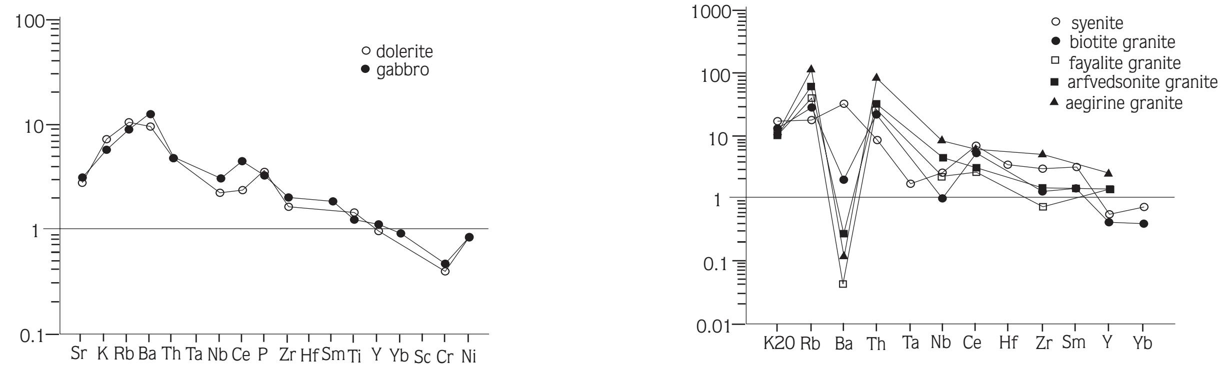
(i) The Late Devonian major collisional stage, recorded throughout the entire Variscan belt of Europe, was followed by emplacemnt of peraluminous crustal magmas associated and/or mixed with high-K basic magmas. “Wet” and/or H_2O-deficient crustal anatexis was induced by intrusion of mantle-derived melts. The magmatic association characterizes the “Hercynotype” of Pitcher, which corresponds to uplift, development of “Basin-and-Range” tectonics and low-P/high-T regional metamorphism, within a crust experiencing high geothermal gradients.

(ii) Lower to Middle Carboniferous high-K calc-alkaline suites, emplaced as crystal mushes (K-feldspar megacryst-bearing porphyritic texture) at shallow levels, represent the "Caledonian type" of Pitcher and indicate a post-collisional stage characterized by rapid uplift and



a. MORB-normalized spidergrams of Mont-Blanc basic rocks

c. ORG-normalized spidergrams of Mont-Blanc granites



b. MORB-normalized spidergrams of Corsican basic rocks

d. ORG-normalized spidergrams of Corsican alkali granites

Figure 3. Compared chemical compositions of A-type granitoid suites (data from Bonin , 1988; Bussy, 1990; Platevoet, 1990).

Table 1. Comparision of geological and petrological data on Vallorcine and Mont-Blanc granites (adapted from Bonin et. al., 1993).

Criteria	Vallorcine Massi	Mont-Blanc Massif
Rock types	Porphyritic coarse-grained	Porphyritic coarse-grained
	Syenogranite	Syenogranite
	Zonation from core to rim	Zonation from core to rim
	Magmatic mafic enclaves	Magmatic mafic enclaves
	Restitic supermicaceous lenses	(Mg-and Fe-types)
	Gneissic xenoliths	
Age of emplacement	Permian-Carboniferous boundary	
	ca. 300 Ma (U-Pb on zircon)	
Geological features	Sheet-like body	Elongated body
	15 km-long, 1 km thick	55 km-long, 14 km-wide
	Intrusive contacts (NW)	Intrusive contacts (SW)
	Tectonic contacts (SE)	Tectonic contacts (NW, SE)
	Magmatic flow texture	Magmatic flow texture
	Dextral strike-slip shear zone	Strike-slip shear zone
Mineral compositions		
K-feldspar	Zoned megacrysts	Zoned megacrysts
Biotite compositions	Alumino-potassic field	Fe-rich (sub) alkaline field
Zircon morphology	Crustal anatectic trend	Alkaline to subalkaline ternd
Accessory minerals	Al-silicates, topaz, tourmaline	Allanite
Whole-rock chemistry	S-type	A-type, with minor I-type
	A/CNK > 1.1	0.95 < A/CNK < 1.5
	K_2O/Na_2O = 1.25-1.65	K_2O/Na_2O = 1.1-1.5
R_1-R_2	Anatectic field	Late-orogenic field
Mafic enclaves	Calc-alkaline field	Calc-alkaline field
Rb-(Y+ Nb)	Syn-collisional field	Within-plate field
REE patterns	Moderate Eu anomalies	Large Eu anomalies
Petrogenesis		
Acid/basic melt ratio	Extremely high	Moderate to low
Crustal source	Metapelites	Dry granulites (?)
Mantle source	Contaminated mantle	Contaminated mantle
	Weak contribution	Major contribution
Tectonic setting	Post-collisional	Post-collisional
	Transtensional uplift	Transtensional uplift

erosion, followed by molassic deposition in intracontinental basins created in a short-lived (trans)pressional and/or tensional regime. These were followed rapidly by the Late Carboniferous alkali-calcic (near-alkaline) associations, emplaced as volcanic-plutonic massifs in a protracted major "Basin and Range" distensional regime.

The Carboniferous overall magmatic evolution from "Hercynotype" to "Caledonian-type" associations clearly substantiates that the Alpine basement became incaslingly intra-continental after complete suturing of Gondwana and Laurasia continental blocks.

(iii) Subduction-related calc-alkaline associations, defining the "Cordilleran I-type", are acordingly very scarce during the Carboniferous. However, in some areas, specifially Eastern and Southern Alps, Late Carboniferous to Early Permian granitoids, displaying normal-K to high-K chemistries, are strongly reminiscent of the circum-Pacific Cordilleran batholiths. They can indicate a renewed ocean-continent plate margin convergence at the southern flank of the Varsican belt. The subduction-collision episode is tentatively correlated with the Alleghanian event of the southern Appalachians.

Contrasting distribution of the subduction-related and post-collisional calc-alkaline suites substantiate that the Alpine basement is made up by at least two discrete terrains. The external Helvetic and Penninic realms underwent only the major Variscan orogenic event. The southern realms recorded: (1) the "Caledonian" event, (2) the major Variscan collisional stage and (3) ultimately, the "Alleghanian" event. That these specific zones were so easily remobilized by three distinct events could be due to the large number of oceanic basins that were closed successively by subduction process during the Paleozoic and/or the small size of the micro-continental blocks involved in the processes of shortening and collision. The fact that the Mesozoic continental breakup took place preferably at the boundary between the two terrains is certainly not fortuitous.

(iv) Mid-Permian post-orogenic and Late Permian to Triassic early anorogenic A-type plutonic-volcanic complexes constitute the Western Mediterranean alkaline province. Associated thermal imprints are recorded in mineral ages (Ferrara and Innocenti, 1974). The large alkaline magmatic activity of the Western Mediterranean province (Bonin et. al., 1987) was related both to post-orogenic continental consolidation of the European plate, containing fragments of Gondwana aggregated to Laurasia, and to precursory stages of the formation of Meso-Tethys oceanic basin created from the Paleo-Tethys ocean and propogating westwards within the Gondwanaland.

References

Barbarin B., 1990, Granitoids: main petrogenetic classifications in relation to origin and tectonic setting. Geol. J., 25, 227-238.

Barriére M., 1977, Le complexe de Ploumanac'h, Massif Armoricain. Essai sur la mise en place et l'évolution pétrologique d'une association plutonique sub-alcaline tardi-orogénique. Thése de Doctorat d'Etat és-Sciences, Université de Bretagne Occidentale, Brest, 290 pp.

Bonin B., 1988, Peralkaline granites in Corsica: some petrological and geochemical constraints. Rend. Soc. Ital. Mineral. Petrol., Ettore Artini volume, 43, 281-306.

Bonin, B., 1990, From orogenic to anorogenic settings: evolution of granitoid suites after a major orogenesis. Geol. J., 25, 261-270.

Bonin B., Platevoet B. and Vialette Y., 1987, The geodynamic significance of alkaline magmatism in the western Mediterranean compared with West Africa. In: Bowden, P. and Kinnaird, J.A., (Eds.), African Geology Reviews. Geol. J., 22, 361-387.

Bonin B. and Markopoulos Th., 1991, The Paleozoic granitic plutonism in the present Alpine fold belt: basic concepts and a general scheme for space and time evolution. In: Baud, A. and Thélin, Ph. And Stampfli, G., (Eds.), Paleozoic Geodynamic Domains and Their Alpidic Evolution in the Tethys, IGCP Project No.276, Newsletter No.2, Mémories de Géologie (Lausanne) No. 10, 43-53.

Bonin B., Brandlein P., Bussy F., Desmonds J., Eggenberger U., Finger F., Graf K., Marro Ch., Mercolli I., Oberhansli R., Ploquin A., von Quadt A., von Raumer J.F., Schaltegger U., Steyrer H.P., Visona D. and Vivier G., 1993, Late Variscan magmatic evolution of the Alpine basement. In: von Raumer, J.F and Neubauer, F., (Eds.), Pre-Mesozoic Geology in the Alps. Springer-Verlag, Berlin-Heidelberg, 171-201.

Boriani A., Giobbi Origoni E. and Del Moro A., 1982-1983, Composition, level of intrusion and age of the "Serie dei Laghi" orthogneisses (northern Italy-Ticino, Switzerland). Rend. Soc. Ital. mineral. Petrol., 38, 191-205.

Boriani A., Burlini L., Caironi V., Giobbi Origoni E., Sassi A. and Sesana E., 1988, Geological and petrological studies of the Hercynian plutonism of Serie dei Laghi-geological map of its occurrence between Valsesia and Lago Maggiore (N-Italy). Rend. Soc. Ital. Mineral. Petrol., Ettore Artini volume, 43, 367-384.

Bussy F., 1990, Pétrogenése des enclaves microgrenues associées aux graitoides caloalcalins: example des massifs varisque du Mont-Blanc (Alpes occidentales) et Miocéne du Monte Capanne (Ile d'Elbe, Italie). Mémories de Géologie (Lausanna) No. 7, 309 pp.

Chappel B.W. and White A.J.R., 1974, Two contrasting granite types. Pacific Geology, 8, 173-174.

Dallmeyer R.D. (ed), 1989, Terranes in the Circum-Atlantic Paleozoic orogens. Geol. Soc. Amer. Spec. Paper 230.

Delaperriére E. and Soliva J., 1992, Détermination d'un age Ordovicien supériuer-Silurien des gneiss de Casemi (Massif du Canigou, Pyrénées Orientales) par la méthode d'évaporation de plomb sur monozircon. C.R. Acad. Sci.Paris, 314, 345-350.

Eby G.N., 1992, Chemical subdivision of the A-type granitoids: petrogenetic and tectonic implications. Geology, 20, 641-644.

Ferrara, G. and Innocenti F., 1974, Radiometric age evidences of a Triassic thermal event in the Southern Alps. Geol. Rundschau., 63, 572-581.

Finger, F. and Steyrer H.P., 1990, I-type granitoids as indicators of a late Paleozoic convergent ocean-continent margin along the Southern flank of the central European Variscan orogen. Geology, 18, 1207-1210.

Frisch, W., Ménot, R.P., Neubauer, F. and von Raumer, J.F., 1990, Correlation and evolution of the Alpine basement. Schweiz. Mineral. Petrogr. Mitt., 70, 265-285.

Gebauer, D., 1993, The pre-Alpine evolution of the continental crust of the Central Alps-an overview. In: von Raumer, J.F. and Neubauer, F., (Eds.), Pre-Mesozoic Geology in the Alps, Springer-Verlag, Berlin-Heidelberg, 93-117.

Hunziker, J.C., Desmons, J. and Hurford, A.J.,1992, Thirty- two years of geochronological work in the Central and Western Alps: a review and seven maps. Mémories de Géologie (Lausanne) No. 13, 59 pp.

J‰ger, E., 1983, The age of the continental crust of Central, Southern and Western Europe-arguments from geochemistry and isotope geology. Schweiz. Mineral. Petrogr. Mitt., 63, 339-346.

Loeschke, J. and Heinisch, H., 1993, Paleozoic volcanism of the Eastern Alps and its paleotectonic significance. In: von Raumer, J.F. and Neubauer, F., (Eds.), Pre-Mesozoic Geology in the Alps, Springer-Verlag, Berlin-Heidelberg, 441-455.

Matte, Ph., 1986, Tectonics and plate tectonic model for the Variscan belt of Europe. Tectonophysics, 126, 329-374.

Ménot, R.P., 1987, Magmatismes et structuration orogénique Paléozoiques de la chaine de Belledonne (Massifs cristallins externes alpins). Le domaine sud-occidental. Géologie Alpine, 63, 55-93.

Ménot, R.P., 1988, The geology of the Belledonne massif: an overview (External crystalline massifs of the Western Alps). Schweiz. Mineral. Petrogr. Mitt., 68, 531-542.

Monié, P., 1990, Preservation of ^{40}Ar / ^{39}Ar ages through high-pressure low-temperature Alpine metamorphism in the Western Alps. Eur. J. Mineral., 2, 343-361.

Neugebauer, J., 1988, The Variscan plate tectonic evolution: an improved "lapetus model". Schweiz. Mineral. Petrogr. Mitt., 68, 313-334.

Pearce, J.A., Harris, N.B.W. and Tindle, A.G., 1984, Trace element discrimination diagrams for the tectonic interpretation of granitic rocks. J. Petrol., 25, 956-983.

Platevoet, B., 1990, Le plutonisme basique et intermédiaire dans le magmatisme anorogénique de Corse. Thése de Doctorat d'Etat és-Sciences, Université de Paris-Sud, Orsay, 526 pp.

Pupin, J.P., 1976, Signification des caractéres morphologiques du zircon commun des roches en pétrologie. Base de la méthode typologique. Thése de Doctorat d'Etat és-Sciences, Université de Nice, 394 pp.

Pupin, J.P., 1980, Zircon and granite petrology. Contrib. Mineral. Petrol., 73, 207-220.

Pitcher, W.S., 1983, Granite type and tectonic environment. In: Hsü, K., (Ed.), Mountain Building Processes. Academic Press, London, 19-40.

Pitcher, W.S., 1987, Granites and yet more granites forty years on. Geol. Rundschau., 76, 51-79.

Sassi, F.P. and Schmidt, K., 1982, The "Caledonian" event in the Eastern Alps: guide-lines for its geodynamic interpretation. In: Sassi, F.P. and Varga, I., (Eds.), IGCP Project No 5, Newsletter 4, 78-81.

Sassi, F.P., Zanferrari G. and Zirpoli G., 1987, The Caledonian event in the Eastern Alps: a review. In: Flügel, F.W., Sassi, F.P. and Grecula, P., (Eds.), Pre-Variscan and Variscan Events in the Alpine-Mediterranean Mountain Belts. Mineralia Slovaca-Monography, Alfa Publishers, Bratislava, 431-434.

Sassi, F.P. and Spiess, R., 1993, The South-Alpine metamorphic basement in the Eastern Alps. In: von Raumer, J.F. and Neubauer, F., (Eds.), Pre-Mesozoic Geology in the Alps. Springer-Verlag, Berlin-Heidelberg, 599-607.

Schaltegger, U., 1993, The evolution of the polymetamorphic basement in the Central Alps unravelled by precise U-Pb zircon dating. Contrib. Mineral. Petrol., 113, 446-478.

Siletto, G.B., Spalla, M.I., Tunesi, A., Lardeaux, J.M. and Colombo, A., 1993, Pre-Alpine structural and metamorphic histories in the Orobic Southern Alps, Italy. In: von Raumer, J.F. and Neubauer, F., (Eds.), Pre-Mesozoic Geology in the Alps, Springer-Berlag, Berlin-Heidelberg, 585-598.

Vivier, G., Ménot, R.P. & Giraud, P., 1987, Magmatismes et structuration orogénique Paléozoiques de la chaine de Belledonne (Massifs cristallins externes alpins). Le domaine nord-oriental. Géologie Alpine, 63, 25-51.

Von Raumer, J.F. and Neubauer, F. (eds.), 1993, Pre-Mesozoic Geology in the Alps. Springer-Verlag, Berlin-Heidelberg, 677 pp.

Waibel, A.F., 1993, Nature and plate-tectonic significance of orogenic magmatism in the European Alps: a review. Schweiz. Mineral. Petrogr. Mitt., 73, 391-405.

Ziegler, P.A., 1986, Geodynamic model for the Paleozoic crustal consolidation of Western and Central Europe. Tectonophysics, 126, 303-328.

Ziegler, P.A., 1993, Late Paleozoic-Early Mesozoic plate reorganization: evolution and demise of the Variscan fold belt. In: von Raumer, J.F. and Neubauer, F., (Eds.), Pre-Mesozoic Geology in the Alps. Springer-Verlag, Berlin-Heidelberg, 203-216.