Gondwana-derived microcontinents — the constituents of the Variscan and Alpine collisional orogens

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Abstract

The European Variscan and Alpine mountain chains are collisional orogens, and are built up of pre-Variscan "building blocks" which, in most cases, originated at the Gondwana margin. Such pre-Variscan elements were part of a pre-Ordovician archipelago-like continental ribbon in the former eastern prolongation of Avalonia, and their present-day distribution resulted from juxtaposition through Variscan and/or Alpine tectonic evolution. The well-known nomenclatures applied to these mountain chains are the mirror of Variscan resp. Alpine organization. It is the aim of this paper to present a terminology taking into account their pre-Variscan evolution at the Gondwana margin. They may contain relics of volcanic islands with pieces of Cadomian crust, relics of volcanic arc settings, and accretionary wedges, which were separated from Gondwana by initial stages of Rheic ocean opening. After a short-lived Ordovician orogenic event and amalgamation of these elements at the Gondwanan margin, the still continuing Gondwana-directed subduction triggered the formation of Ordovician Al-rich granitoids and the latest Ordovician opening of Palaeo-Tethys. An example from the Alps (External Massifs) illustrates the gradual reworking of Gondwana-derived, pre-Variscan elements during the Variscan and Alpine/Tertiary orogenic cycles.

1. Introduction

Careful reconstructions of the Alpine collisional belt are a sound base for comparison of pre-Mesozoic basement areas in the Alps (Frey et al., 1999; Pfiffner et al., 1996; Stampfli et al., 2001a). Alpine cross-sections (e.g. Escher et al., 1996; Steck et al., 2001) reveal the complex imbrication of pre-Mesozoic basement blocks juxtaposed by large-scale nappe and strike-slip tectonics. The gradual incorporation of basement units into the nappe structures depends largely on the rheology of the involved rocks resp. minerals, a historical observation made for the Alpine cross-section by Voll (1976). Again, reconstructions of the Variscan orogenic belt (Franke et al., 2000; Matte, 1986; Oncken, 1997) illustrate its complex tectonic evolution and juxtaposition of

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pre-Variscan elements. Deformation similar to the Alpine imbrication of pre-Mesozoic basement had already affected the Pre-Variscan domains before and during the Late Variscan orogenic phase resulting in superposed structures (e.g. Hatcher, 1983). It is the aim of this paper to introduce a terminology characterizing the former peri-Gondwanan plate-tectonic evolution of pre-Variscan basement units constituting part of the Variscan collisional orogen, and to give examples of the stepwise involvement of such basement elements during the Variscan and/or Alpine orogenesis. For this purpose, we are obliged to review certain data, which were largely discussed by von Raumer et al. (2002) and Stampfli et al. (2002).

2. Peri-Gondwanan evolution

Pre-Variscan basement relics are essential components in the Variscan basement areas of Europe (Fig. 1), and most of the basement areas under concern are thought to be located, before the Ordovician, in the former eastern prolongation of future Avalonia (see Ordovician reconstruction modified from Stampfli and Borel, 2002, schematic representation in Fig. 2) and had a comparable evolution until the break-off of Avalonia. This holds also for the Alpine realms (External domain, Penninic domain, and parts of the AustroAlpine domain), sharing this geological evolution since the Proterozoic in the prolongation of Avalonia, whereas the Southern
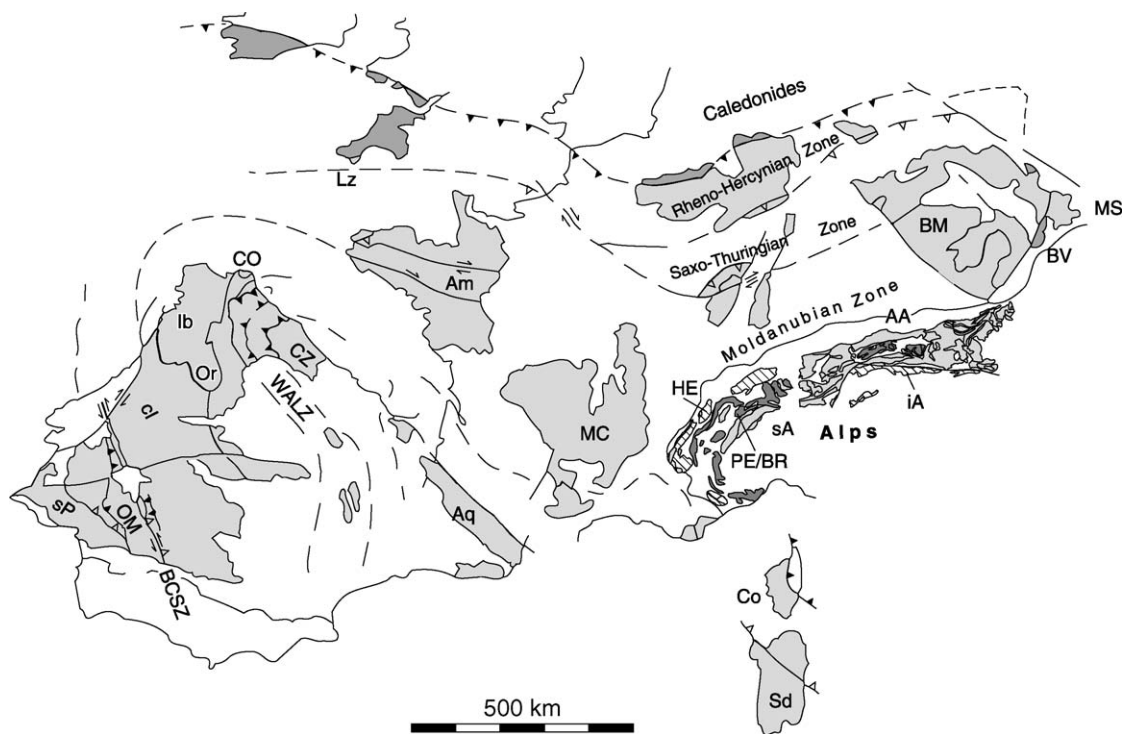

Fig. 1. Geological map of Variscan basement areas in Central Europe based on Franke (1989), Martínez-Catalán (1990), and Ribeiro and Sanderson (1996); nomenclature of the main Variscan units after Kossmat (1927). AA, AustroAlpine (light grey; subdivisions, see Neubauer and Frisch, 1993); Am, Armorican Massif; Aq, Aquitaine; BCSZ, Badajoz–Cordoba Shear Zone; BM, Bohemian Massif; BV, Brunovistulicum; cI, Central Iberian Zone; CO, Cabo Ortegal Complex; CZ, Cantabrian Zone; Co, Corsica; HE, Helvetic Zone (diagonal pattern); iA, Intra-Alpine (diagonal pattern); Ib, Iberia, allochtonous; Lz, Lizard; MC, French Central Massif; MS, Moravo-Silesian; Or, Ordenes ophiolites; OM, Ossa Morena Zone; PE/BR, Penninic/Briançonnais (dark grey); sA, Southalpine; Sd, Sardinia; sP, South Portuguese Zone; WALZ, West Asturias Leon Zone.

490 Ma

Fig. 2. Early Ordovician plate-tectonic reconstruction (based on Gmap, Torsvik and Smethurst, 1999), centered 60°N/80°E, containing informations from Pharaoh (1999), Sengör (1985), Torsvik (1998), Van der Voo (1993), Van Staal et al. (1998); modified from Stampfli and Borel (2002). Dashed line—Future opening of Palaeo-Tethys. Abbreviations: Avalonian Terranes: GS, Gory Sowie; Mg, Meguma; sP, South Portuguese; Avalonian satellites: Is, Istanbul; Mo, Moesia; drift previous to Avalonia (Belka et al., 2002): LM, Lysogory–Malapolska; BV, BrunoVistulikum; Baltica: Zo, Zonguldak; South America: Cs, Chortis; Yu, Yucatan; Cr, Carolina; European Hunic Terranes: AA, AustroAlpine; Ab, Alboran plate; Ad, Adria s.str.; Am, Armorica; cI, central Iberia; Cm, Cadomia; Ct, Cantabria–Asturia; iA, Intra-Alpine terrane; Ib, Iberia, allochthonous; Lg, Ligerian; MD, Moldanubian; Ms, Meseta; OM, Ossa Morena; Pe, Penninic; SM, Serbo-Macedonian; Sx, Saxothuringian; Asiatic Hunic Terranes: Kb, Karaburun; KT, Karakum–Turan; nC, north Caspian; Pr, Pamir; Qi, Qilian; Qs, Qinling south; Tn, Tarim north; Ts, Tarim south; Gondwana (future Cimmerian terrane): Al, Alborz; Ap, Apulia; cA, central Afganistan; DH, Dinarides–Hellenides; Ki, Kirshehir; LT, Lut–Tabas–Yazd; Mn, Menderes; Si, Sicilia; SS, Sanandaj–Sirjan; sT, Sitia; Ta, Taurus s.l.

Alps were related to the opening of Palaeo-Tethys (von Raumer, 1998).

Referring to von Raumer et al. (2002, with references therein), the occurrences of widespread Neoproterozoic sediments and volcanic arc sequences are the expression of a Neoproterozoic/Early Cambrian active margin setting (e.g. Chen et al., 2000; Crowley et al., 2000; Fernández-Suárez et al., 2000; Finger et al., 2000; Haydoutov, 1989; Schaltegger and Gebauer, 1999; Schaltegger et al., 1997; von Quadt, 1992; Zulauf et al., 1999). Initial rift zones became apparent along the Gondwana margin. Wide areas of detrital sediments and carbonates occupied the Gondwana platform, their maximum depositional age around

600 Ma is constrained by the youngest detrital zircons (Schaltegger and Gebauer, 1999). Formation of Cambro-Ordovician oceanic crust is documented from all basement areas (von Raumer et al., 2002), but in contrast to Avalonia, only early stages of the Rheic ocean may have existed in the former eastern continuation of Avalonia (Fig. 2). Differences of evolution through time along the former Gondwana margin may indicate that oceanic crust subducted obliquely and slab roll-back was diachronous. This oblique convergence created different scenarios along the Gondwana margin, where true oceanic crust emplacement appeared in separated pull-apart basins. Laterally, they would have been replaced by isolated continental basins, by activity of plume-like structures (e.g. Bohemian Massif, Floyd et al., 2000), or by volcanites and/or detrital sediment fill. Such strike-slip models had already been proposed by Murphy and Nance (1989); and Murphy et al. (1999) for the Gondwana margin, and have been discussed for the Variscan domain (e.g. Saxothuringian area, Linnemann et al., 1998).

2.1. Provenance of detrital sediments

Comparing Nd-isotopic compositions, Liew and Hofmann (1988) gave a medium value of crustal residence ages of 1.4–1.7 Ga for the European Variscan fold belt, and Nance and Murphy (1994, 1996) identified the terrane assemblage "Cadomia" through mainly negative ε_{Nd} values and crustal residence ages of 1.9–1.0 Ga from granitoid rocks. Recent data from metasediments of the Mid-German Crystalline Rise yielded concordant U–Pb SHRIMP zircon ages, which cluster around 550 Ma, 1.0 and 2.0 Ga, and Nd model ages between 0.9 and 1.3 Ga. The combined isotopic data are interpreted to reflect derivation of these sediments from at least three distinct crustal source regions, the Avalonian Cadomian belt, the West African and/or Amazonian cratons and the Grenvillian belt (Zeh et al., 2001). Inherited zircons from protoliths of Ordovician granitoids from Gory Sowie, in the eastern Bohemian Massif, yielded ages of 1.1–1.3, 1.6–1.8, and 2.2–2.6 Ga with a scatter of 0.86–1.56-Ga Nd model ages (Kröner and Hegner, 1998). Hegner and Kröner (2000) report mainly 1.7–1.4-Ga Nd model ages for the areas of the northeastern Bohemian Massif, and U–Pb ages of

detrital zircons or zircon xenocrysts clustering from 600 to 850 Ma, 1.0 to 1.3 Ga, and 1.7 to 2.3 Ga. Following the model of Fernández-Suárez et al. (2000), they place most of the source areas in an active margin setting along the Amazonian craton, only few areas showing Grenvillian sources. In the Cambrian of the Lysogory Massif, U–Pb single-grain dating of detrital zircons reflects sources of 600, 1.8–2.0 and >2.5 Ma attributed to Gondwana (Valverde-Vaquero et al., 2000). In the southeastern Bohemian massif, the Moravo-Silesian unit, Friedl et al. (2000) obtained from inherited zircons in a Late Neoproterozoic (580 Ma) orthogneiss concordant U–Pb zircon SHRIMP ages around 1.2, 1.5 and 1.65–1.8, and 2.3 Ga (Friedl et al., 2002) supporting an affiliation to Avalonia and a relationship with the Grenvillian domain from South America. In the Southern Alps (Lucomagno area), U/Pb zircon ages from augengneisses indicate 1.0, 2.0–2.1 and 2.7–2.9-Ga-inherited source materials, and U–Pb zircon ages from paragneisses indicate 1015-Ma source materials (Böhm, 1996), and T_{DM} Nd model ages in the ortho- and paragneisses range from 1.0 to 1.4 Ga resp. 1.3–1.7 Ga. In the AustroAlpine Silvretta basement unit, Cambro-Ordovician orthogneisses have upper U/Pb zircon intercepts at 2.9 Ga, lower intercepts at 470 Ma, and 1.7–1.2 Nd model ages (Liebetrau and Nägler, 1994; Poller, 1997). The 1.7 Nd model age was interpreted as a homogeneous mixture of continental sediments (max. 2.3 Ga) and younger basic components (Poller et al., 1997). Cambrian (520 Ma) metagabbros (with IAB signature) and metatonalites yielded 0.9–1.1-Ga Sm–Nd-depleted mantle model ages (Schaltegger et al., 1997). U–Pb zircon ages on xenocrysts or detrital zircons from the pre-Alpine basement of the Internal Western Alps yielded Archean and Grenvillian ages (Bertrand et al., 2000). All these data show that the different continental blocks inherited detritus from source areas having undergone older orogenies around 1.0, 1.7 and 2.0 Ga.

Considering the age groups discussed above, the different authors agree in the existing relationship between age of zircon xenocrysts, detrital zircons and their source areas in the older gneiss cores of South America and/or the West African craton, and in the Grenville Belt. The question arises on what kind of relationship existed between the continental blocks

located in the eastern prolongation of Avalonia and Cadomia during the Cambro-Ordovician and the Amazonas resp. the West African regions. Keppie and Dostal (1998) place the Avalon Composite Terrane in a 630-Ma reconstruction adjacent to the Amazon Craton and the Grenville Belt. The different microcontinental blocks composing Avalonia, Cadomia and the Hunic terranes (Fig. 2) underwent the Cadomian/Pan-African orogenic events at the Gondwana margin. Before and during this long lasting orogenic evolution, there has been time enough for recycling material, thus allowing to find xenocrysts and detrital zircons of Archean and Grenville age in the Late Proterozoic to Cambrian detrital sediments recycled in many of the pre-Variscan and Variscan granitoids in Europe. Long distance river transport of sediments has been discussed by Zeh et al. (2001). Many of the interpretations mentioned above and the situation of source areas were based on Hoffman's (1991) Rodinia model. Although we cannot give a different interpretation, we would like to point out that besides the South American or West African areas, other source areas may have existed, when considering the plate-tectonic evolution of blocks occupying the former eastern Gondwanan areas, at present being part of India and of the Himalayas. Additionally, Wingate et al. (2002) propose a Rodinia model, where Grenvillian elements have a very different distribution and, consequently, there may be an additional degree of freedom to place Archean and Grenville age sources along the Gondwana margin. Such major revisions of reconstructions could have considerable consequences for placing Gondwana-derived microcontinents at the Gondwana margin.

2.2. Evolution of magmatic rocks

During the Cambro-Ordovician plate-tectonic evolution of the Gondwana-derived microcontinents, magmatic rocks have played an important role. Different emplacement processes, taking place at rift, at active margin or at collisional setting, have been invoked to explain their emplacement. The nearly identical chemical composition of Cambro-Ordovician granitoids in mantle-normalized multi-element variation diagrams supposes recycling of widely distributed, homogeneous detrital sedimentary sources (e.g. Ugidos et al., 1997). Despite this homogeneity,

the chemical evolution of the many Cambro-Ordovician granitoids cannot be simply explained in applying a single rifting, active margin or collisional tectonic model. Depending on age and emplacement of granitoids, evolution through time has to take into account all three settings. Although presentation in a plate-tectonic discrimination diagram (Maniar and Piccoli, 1989) cannot be a satisfying solution, a trend of chemical evolution through time becomes apparent (Fig. 3, with localities and references), as granitoids plot more or less into fields, defining a distinct plate-tectonic setting (Maniar and Piccoli, 1989). Dated Cambrian plagiogranites from different localities (Fig. 3) plot into the field of oceanic granites defined by Maniar and Piccoli (1989), and are related to formation of oceanic crust during the opening of the Rheic ocean. Cambrian to Early Ordovician alkaline granitoids from several localities plot into the field of alkaline granites (Fig. 3) and should represent rifting stages of thickened crust contemporaneous to the opening of the Rheic ocean. Relatively early (Early Ordovician) calc-alkaline metaluminous granites plot into the field of arc-related granites (Maniar and Piccoli, 1989), and were probably related to a nearby Cambro-Ordovician active margin setting. The many, relatively younger ($\pm$ 450 Ma), more or less calc-alkaline peraluminous granitoids, plot into the well-defined field of collisional granites and carry the characteristics of a late- to post-orogenic evolution (von Raumer et al., 1999b, 2002).

Intrusion of Cambro-Ordovician granitoid rocks is accompanied, at several places, by Early Palaeozoic metabasic rock series. The Cambrian granite and gabbro intrusions of NW Spain, accompanied by metamorphism, and anatexis (Abati et al., 1999), are in our opinion closely related to the rifting of the Rheic ocean. Equally, time parallels of intrusions of mafic rocks and opening of early stages of the Rheic ocean exist in the French Central Massif (Briand et al., 1995; Pin and Marini, 1993), in the Alpine External Massifs (Ménot, 1987), in the Saxothuringian domain (Kemnitz et al., 2002), and in the Bohemian Massif (Furnes et al., 1994; Stipska et al., 2001). Based on many chemical data from the Bohemian Massif (Floyd et al., 2000), Crowley et al. (2000) apply Storey's (1995) model, interpreting the general Cambrian continental break-up as a consequence of mantle-plume evolution through time. Mantle plumes may
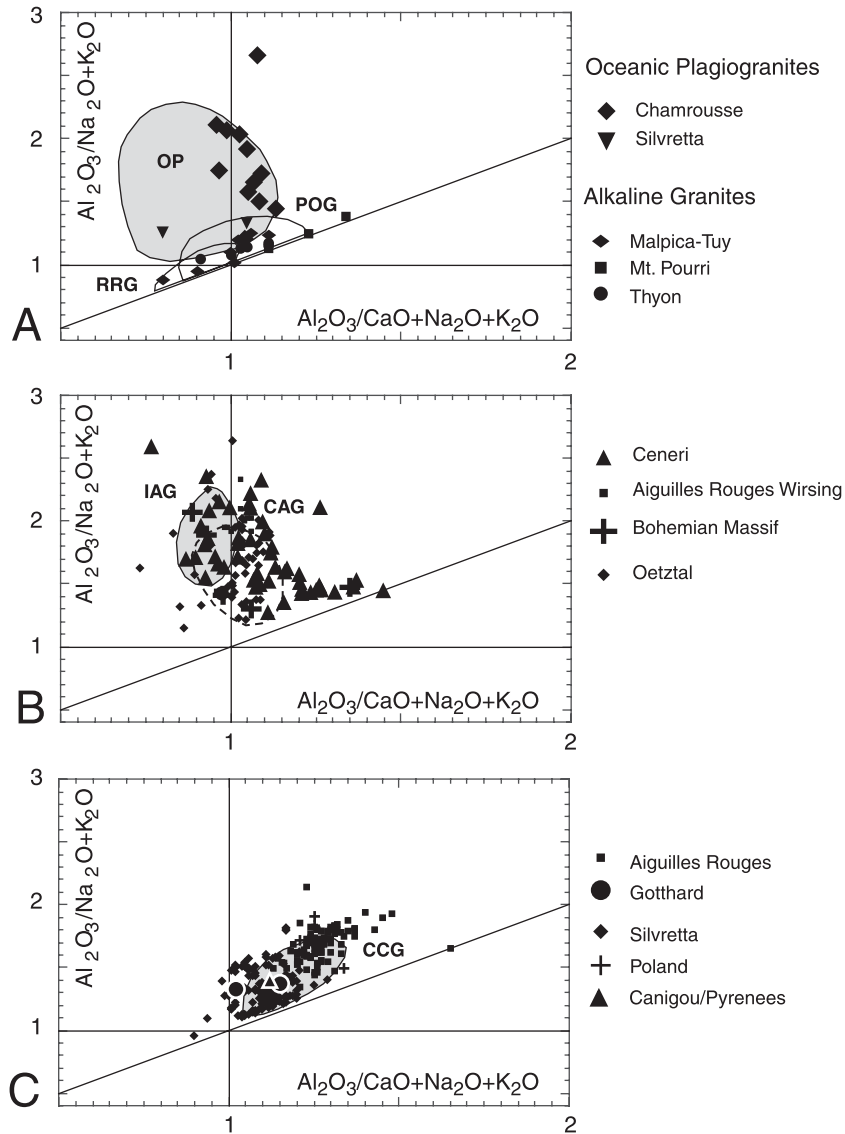
Fig. 3. Plate-tectonic discrimination of granites after Maniar and Piccoli (1989)—application to pre-Variscan granitoids in the peri-Gondwanan domain. Definitions and fields after Maniar and Piccoli (1989): OP, oceanic plagiogranites; IAG, island-arc (Calcic to calc-alkaline); CAG, continental arc granites (calc-alkaline); RRG, rift-related granitoids (alcalic); POG, post-orogenic granitoids (alcali-calcic); CCG, continental collision granitoids (calc-alkaline to alkali-calcic). (A) Mainly Cambrian granitoid rocks (Plagiogranites: Chamrousse (Ménot, 1987); Silvretta (Müller et al., 1996); Alcaline granitoids: Malpica–Tuy, Ordovician (Pin et al., 1992); Mt. Pourri (Guillot et al., 1991); Thyon (Bussy et al., 1996). (B) Cambro-Ordovician I-type granitoids: Aiguilles Rouges (Wirsing, 1997); Bohemian Massif (Kröner et al., 2000); Oetztal (Schindlmayr, 1999); Ceneri (Boriani et al., 1981; Pezotta and Pinarelli, 1994); part of the Ceneri-gneisses plot into the field of collisional granites. (C) Ordovician collisional-type granitoids: Gotthard (Sergeev, unpublished data); Aiguilles Rouges (Wirsing, 1997; von Raumer, unpublished data; Pyrenees, Canigou (Barbey et al., 2001); Poland (Kröner and Hegner, 1998).

have played an important role in preparing rifting of the Rheic ocean but, in the strike-slip model presented above, rifting as a consequence of stress applied at the plate boundaries during initial back-arc opening is probably as important for the location of oceanic basins as presence of mantle plumes.

2.2.1. Separation from Gondwana

After the initial stages of Cambrian rifting at the Gondwana margin, the pre-Variscan basement blocks which are to become involved into the future Variscan mountain chain, still underwent several steps of plate-tectonic evolution before their drift towards Laurussia (Stampfli et al., 2002; von Raumer et al., 2002).

When Avalonia and its supposed satellites (e.g. BV, GS, Is, LM, Mo; see Fig. 2) separated from Gondwana, during the Early Ordovician, drifting was hampered in the former easterly situated continental blocks (Cadomia, IntraAlpine Terranes) by the still existing oceanic ridge of Proto-Tethys. The Ordovician collision of the detaching terranes with Gondwana triggered the consumption of the embryonic eastern Rheic ocean and the amalgamation of volcanic arcs and continental ribbons with Gondwana in a rather short-lived orogenic pulse (von Raumer, 1998, with references therein). The cordillera, resulting from mid-ocean ridge subduction during the Ordovician, started to collapse already during the Late Ordovician leading to the opening of the Paleo-Tethys rift, followed by the Late Silurian drift of the composite Hun-superterrane (Stampfli, 2000).

Well known from the Alpine basement areas, few relics of this episode, either sedimentation in a back-arc situation, or a Late Ordovician/Early Silurian
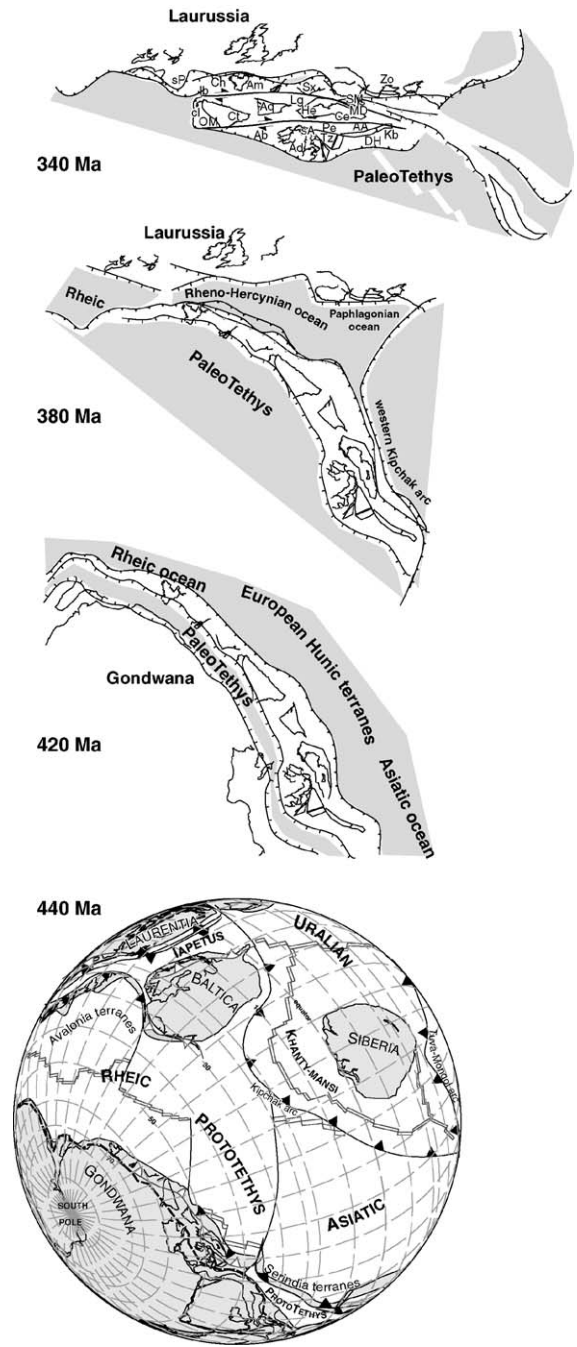

Fig. 4. Schematic representation of drift history of Gondwanan-derived basement areas from the Silurian to the Carboniferous, with representation of the oceanic domains, modified from Stampfli et al. (2002, with more details therein). 440 Ma—Indication of intervening main oceanic plates. Avalonia and its satellites (Malapolska, Lysogory, Brunovistulikum, see Belka et al., 2002) are already amalgamated with Laurussia. Subduction at the Gondwana margin continued in the former more eastern located domains. The dashed line indicates location of the future opening of Palaeo-Tethys. 420 Ma—An archipelago-like ribbon-continent separated from Gondwana (European Hunic Terranes) during opening of Palaeo-Tethys along the Gondwana margin. Its opening is interpreted as back-arc spreading related to Gondwana-directed subduction of Rheic/Proto-Tethys. 380 Ma—Early collision of Gondwana-derived European Hunic Terranes with Laurussia-derived terranes. 340 Ma—Major collision and closure of Rhenohercynian domain. Abbreviations: AA, AustroAlpine; Ab, Alboran plate; Ad, Adria s.str. Am, Armorica; Aq, Aquitaine/French Pyrenees; Bk, Bolkardag; Ce, Cetic; Ch, Channel Islands; cI, central Iberia; Ct, Cantabria–Asturia; Spanish Pyrenees; DH, Dinarides–Hellenides; He, Helvetic; Ib, Iberia, NW-allochthon; Kb, Karaburun; Lg, Ligerian; MD, Moldanubian; OM, Ossa Morena; Pe, Penninic; sA, South Alpine; SM, Serbo-Mazedonian; sP, South Portugese; Sx, Saxothuringian; Tz, Tizia; Zo, Zonguldak.

active margin setting are known. If they were not completely consumed during large-scale Variscan subduction, they have still to be identified in many basement areas.

Lack of knowledge about relics of Palaeo-Tethys induced differences when appreciating Variscan tectonic events at the Laurussia border. In contrast to existing reconstructions of the Variscan plate-tectonic evolution (Franke et al., 2000; Matte, 1986), Stampfli et al. (2002) include a Devonian collision between continental ribbons derived from Laurussia/Avalonia and Gondwana which subsequently was followed by the Late Carboniferous collision between Gondwana and Laurussia, leading to the complex Late Variscan terrane duplication known from the European part of the orogen (Fig. 4). However, Palaeo-Tethys was not closed in the Mediterranean area before the Late Triassic (Stampfli and Borel, 2002), and the future Alpine area was subject to large-scale Permian extension and volcanism related to final stages of Palaeo-Tethys subduction (Ziegler et al., 2001).

3. The External Massifs—an example of polymetamorphic basement in the Alps

Nearly half of the Alpine domain is underlain by pre-Mesozoic basement (von Raumer and Neubauer, 1993, 1994). The External Crystalline Massifs of the western/central Alps, especially in the Aiguilles Rouges/Mont-Blanc area, record the Ordovician–Variscan–Alpine polyorogenic evolution outlined above. Understanding of superposed geological events was made possible from precise U–Pb zircon and monazite dating (Bussy et al., 2000; Bussy and von Raumer, 1994; Bussy et al., 2001). Magmatic ages on zircon of ∼ 450 Ma (Paquette et al., 1989) have been obtained both for eclogitized MORB-like basic rocks and for S- and I-type orthogneisses. They have been interpreted as evidence for a Late Ordovician subduction zone, either in an island-arc, or an active continental margin environment (e.g. Gotthard area, Oberli et al., 1994).

3.1. The Variscan evolution

Paragneisses, possibly part of an accretionary prism (Ordovician or Silurian), display a succession of deformation events ascribed to terrane (or microcontinent) accretion, with thrust movements and nappe stacking, leading to continental crust thickening and the development of a Barrovian-type metamorphism (von Raumer et al., 1999a). During Carboniferous times, the continental lithosphere progressively recovered its original thickness in a transcurrent to extensional tectonic regime ascribed to the roll-back effect of the subducting Palaeo-Tethys slab (back-arc extension). Fast uplift (ca. 1 mm/year) and vigorous erosion are recorded in a Late Carboniferous intra-continental detrital basin (Capuzzo and Bussy, 2000). The whole area experienced a metamorphic evolution, where paragneisses of favourable composition underwent in situ decompression melting at 320 ± 1 Ma (U–Pb monazite dating), and metapelites yielded a monazite age of 327 ± 2 Ma.

Contrasting types of early magmatic rocks (331–332 Ma, peraluminous monzogranites, Mg–K-rich monzonites) intruded syntectonically along major dextral strike-slip faults (Bussy et al., 2001). The Mg–K-rich monzonites host meter-sized comagmatic durbachitic enclaves of mantle origin (Bussy et al., 2001), and belong to a well-known group of Mg–K granites of the Variscan belt emplaced between ∼ 340 and 330 Ma (Debon et al., 1998). Mg–K magmas are thought to result from the partial fusion of a high-K lithospheric mantle (metasomatized during an earlier subduction event) with subsequent contamination by crustal material (Bussy et al., 2001). Local production of S-type anatectic melts would be favoured by heat transfer from the mantle-derived magmas. Several peraluminous magmatic bodies intruded simultaneously at 307 Ma, either syntectonically as vertical sheet-like intrusions within major dextral transtensive zones (Vallorcine and Montenvers granites), or as a large mass of mobile migmatites (Fully anatectic granodiorite). Comagmatic gabbros and mafic microgranular enclaves evidence a mantle magmatic input. The large 304 Ma, alkalicalcic, Fe–K-rich Mont-Blanc granite is the youngest intrusion in the area. Comagmatic mafic rocks occurring as monzodioritic microgranular enclave swarms, stocks and synplutonic dykes, again document a mantle activity.

The Carboniferous granite magmatism in the Mont-Blanc/Aiguilles Rouges area is thus characterized by the systematic association of Al-rich, crustal-derived melts, on the one hand, and mantle-derived

mafic melts with variable amounts of crustal contamination on the other hand. Their emplacement is influenced by lithospheric-scale transcurrent faults (Burg et al., 1994). The minor volumes of anatectic melts produced by in situ decompression melting must be considered separately.

Following the interpretations by Bussy et al. (2001), this bimodal magmatism is interpreted according to the following scenario: (1) deep-seated crustal rocks are heated up through thermal relaxation after crustal thickening due to the Variscan accretion; (2) the thickened lithosphere is re-equilibrating through extension, mantle upwelling and exhumation/erosion; (3) the metasomatized lithospheric mantle is melting, Mg–K liquids are produced and emplaced in upper crustal levels through lithospheric-scale faults; (4) hot mid-crustal rock units experience in situ decompression melting while uplifted; (5) as crust is thinning, mantle is upwelling and evolves towards more primitive asthenospheric composition; mantle magmas of increasingly anorogenic affinity are produced and underplate the crust; (6) mafic magmas bring more heat to the already hot lower crustal levels, triggering large-scale dehydration melting of various lithologies; (7) large volumes of magmas are extracted and collected along active crustal-scale faults and move syntectonically to higher levels.

The proposed evolution is explained in a geodynamic context of oblique, anti-clockwise collision of Gondwana with Laurassia in the western, Appalachian side of the latter during Early Carboniferous times (Stampfli and Borel, 2002), inducing large-scale dextral transcurrent movements in the orogenic zone (e.g. Giorgis et al., 1999). At the same time, but on the eastern side, the Palaeo-Tethys oceanic crust was still subducting underneath the accreted margin of Laurassia (i.e. the Variscan belt, e.g. Vavassis et al., 2000). Slab roll-back induced the above-described Late Carboniferous/Permian extension and magmatic activity.

3.2. The Alpine overprint

The Alpine evolution on the other hand is quite different. After reaching a thermal equilibrium in the Helvetic–Penninic units in Permo-Triassic times, the European lithosphere suffered again a major rifting phase starting in Late Triassic and ending in Middle Jurassic with the opening of the Alpine Tethys (Stampfli et al., 1998). The Variscan basement units were then redistributed as elements of the northern and southern passive margins of this narrow ocean. During the closure of the ocean in Cretaceous and Paleogene times, the southern margin became an active margin, however, with hardly any volcanicity (Stampfli, 2001). The northern margin was flexured and buried sometimes to great depth in Oligocene–Miocene time and part of it was obducted and thrusted onto the flexural molassic basin to form the external massifs. This scheme is somewhat perturbed by duplication of both margins in Cretaceous times, with lateral displacement of some units in the order of several hundreds of kilometres, bringing one more perturbation to the former distribution of Variscan elements. A striking example of margin duplication is given by the Alpine "Briançonnais" domain, the present-day Penninic basement areas, which is regarded as an exotic terrane belonging to the European northern margin until Late Jurassic (Stampfli, 1993), which then was transported eastward during the drift of Iberia, and appearing on a present-day Alpine cross-section as a duplication of the European continental margin (Stampfli, 2001). In any case, it is difficult to distinguish a Variscan unit belonging to the northern margin from one of the southern margins.

The Variscan basement areas of the External Massifs have undergone, together with their Mesozoic cover, the tectonic and metamorphic evolution of Alpine/Tertiary age (Frey et al., 1999). In the first distribution map of Alpine metamorphic minerals (Niggli, 1960), it became evident that Alpine metamorphism evolves from lowermost greenschist facies in the North to amphibolite facies grade in the South. Consequently, in the southern sections, even Late Variscan granites are transformed to amphibolite facies grade gneisses (e.g. Fibbia granite, Gotthard Pass, garnet-bearing orthogneiss). Comparable granites in the more external part of the Alps exhibit greenschist facies overprint (e.g. Mont-Blanc granite, von Raumer, 1967), where original brown biotite is mostly replaced by a mosaic of new, green coloured biotite with exsolved sphene following the direction of former cleavage. Original K-feldspar is replaced by chessboard-albite and enlarged perthitic albite veins, the latter still following the original crystallographic orientation of the host. Plagioclase is replaced by

albite, phengitic white mica and epidote, and quartz shows typical low-temperature polygonal recrystallization.

In such an Alpine greenschist facies environment, some pre-Variscan elements can still be recognized. They mostly attained Variscan amphibolite facies grade and incipient anatectic melting, and were intruded by Late Variscan granites. The Late Variscan high-temperature overprint and the contemporaneous large-scale strike-slip triggered juxtaposition of various pre-Variscan elements, and former plate-tectonic relationships were strongly destroyed. Relics of Ordovician granitoids may serve as a typical example of pre-Variscan elements preserved in the pre-Mesozoic/Variscan basement areas of the Alps. In contrast to the Variscan granitoids, they mostly appear as pre-Variscan orthogneisses. In high-grade Alpine metamorphic regions such as the Penninic domain, their distinction from Variscan-deformed granitoids remains a challenge (Thélin et al., 1993), which can be resolved only through isotopic dating. In contrast, in lower-grade Alpine greenschist facies regions (e.g. the External Massifs), such orthogneisses can be easily distinguished from Late Variscan granites, as they carry the imprint of Variscan anatectic remelting (e.g. Aiguilles Rouges and Mont-Blanc external massifs, von Raumer, 1998). In such cases, all transitions from shear-bands containing newly formed sillimanite to stringers of melt following the foliation produced during strike-slip to a microgranular new granitoid are observed, where former K-feldspars appear as black coloured, preserved relics, and the former foliation as ghost structure. Variscan strike-slip produced large-scale isoclinal folds of orthogneisses (von Raumer, 1984), whose limbs are strongly sheared and develop characteristic microstructures. The Alpine overprint, following the high-grade Variscan events, depends on the temperature attained. In the Mont-Blanc area (von Raumer, 1984), where Alpi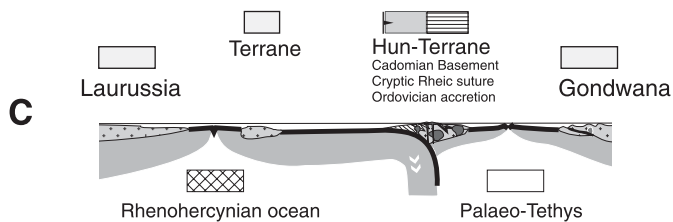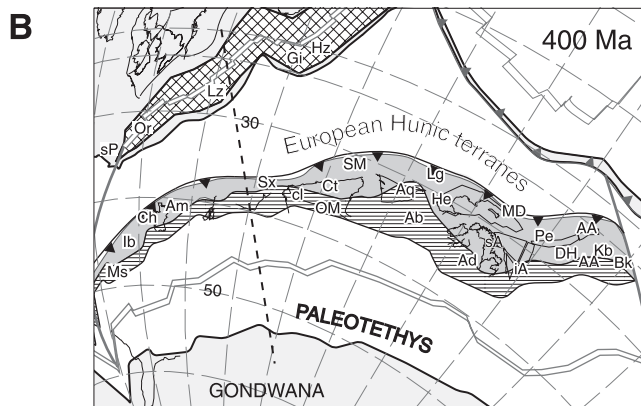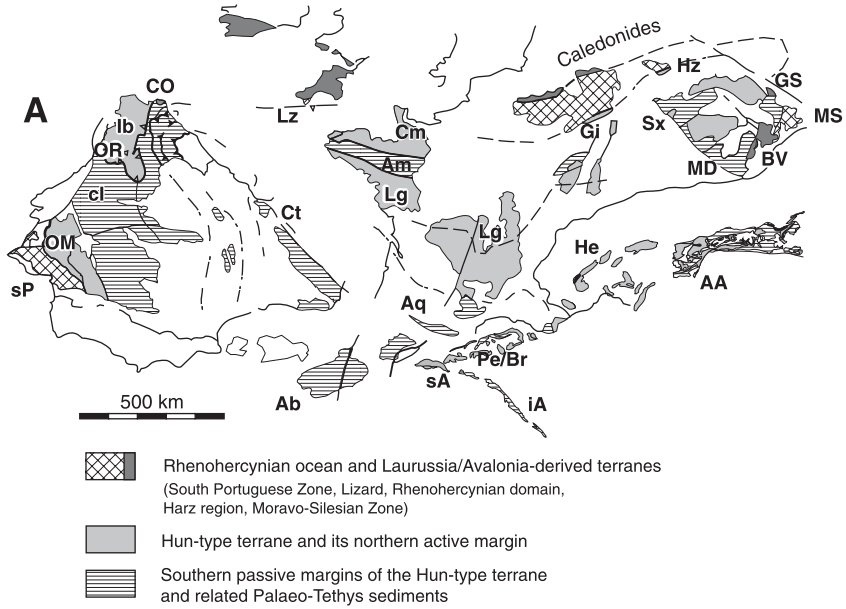ne metamorphism reached the biotite-grade, the former granitic matrix of the Ordovician orthogneisses has been transformed into strongly flattened white mica–albite–epidote–chlorite–quartz–biotite–schists, and the large K-feldspar phenocrysts have been stretched about 300%, resulting in a structure of angular relics of blackened microcline, separated by fluid inclusion-filled stretching fibres of albite and quartz. In the domain of lowest grade of Alpine metamorphism (e.g. Aiguilles Rouges), such orthogneisses display formation of chlorite–albite, and very early stages of polygonization of quartz (von Raumer, 1984). Alpine brittle deformation appears as a multitude of tiny chlorite–albite filled cracks, arranged in en-echelon sets, indicating conjugate Alpine shear planes.

The difficulty to distinguish between lithologies is even higher when dealing with metasediments with their former gradual transitions, and basic magmatic rocks, older than Ordovician granitoids. Metabasites very quickly loose important characteristics, when transformed to greenschists, and metasediments with their variable composition are not easy to identify, when transformed into migmatites. Despite such difficulties, comparative studies reveal parallels of evolution across the many Variscan basement areas (von Raumer et al., 2002) and, consequently, we propose in the following chapter a terminology taking into account their pre-Variscan origin.

4. Plate-tectonic terminology and conclusion

Modern reconstructions for the Early Ordovician (Stampfli and Borel, 2002 , and Fig. 2) see a lateral continuation of Avalonian-type crustal pieces at the Gondwana margin. Avalonia and some of its supposed lateral satellites separated from Gondwana around 480 Ma, accompanied by the opening of the Rheic ocean. Most of the Pre-Variscan relics of the present-day Variscan basement (the constituents of the Hun terrane, Fig. 5) are separated from Gondwana during the

Fig. 5. Plate-tectonic interpretation of basement areas in Central Europe in terms of former plate-tectonic location of pre-Variscan relics at the Gondwana margin. (A) Permian reconstruction modified from Stampfli et al. (2001b); (B) Silurian reconstruction and abbreviations modified from Stampfli and Borel (2002); (C) Silurian cross-section, interrupted line in B. Abbreviations: AA, AustroAlpine; Ab, Alboran plate; Ad, Adria s.str.; Am, Armorica; Aq, Aquitaine/French Pyrenees; Bk, Bolkardag; BV, Brunovistulian; Ch, Channel Islands; cI, central Iberia; Cm, Cadomia s.str.; CO, Cabo Ortegal; Ct, Cantabria–Asturia; Spanish Pyrenees; DH, Dinarides–Hellenides; GS, Gory Sowie; Gi, Giessen-nappe; He, Helvetic; Hz, Harz mountain; iA, Intra-Alpine terrane; Ib, Iberia, NW-allochthon; Kb, Karaburun; Lg, Ligerian; Lz, Lizard; MD, Moldanubian; Ms, Meseta, Morocco; MS, Moravo-Silesian; OM, Ossa Morena; Or, Ordenes ophiolites; Pe, Penninic; Pe/Br Penninic/Briançonnais; sA, South Alpine; SM, Serbo-Mazedonian; sP, South Portugese; Sx, Saxothuringian.

A

Caledonides

CO, Ib, OR, cl, OM, sP, Lz, Cm, Am, Lg, Ct, Aq, Lg, He, sA, Ab, Pe/Br, iA, Gi, Hz, Sx, MD, BV, GS, MS, AA

500 km

Rhenohercynian ocean and Laurussia/Avalonia-derived terranes
(South Portuguese Zone, Lizard, Rhenohercynian domain,
Harz region, Moravo-Silesian Zone)

Hun-type terrane and its northern active margin

Southern passive margins of the Hun-type terrane
and related Palaeo-Tethys sediments

B

400 Ma

Gi, Hz, Lz, Or, 30, European Hunic terranes, sP, Sx, SM, Lg, Ct, Aq, Am, cl, OM, He, Ab, MD, AA, Ch, Ib, sA, Pe, Ms, 50, Ad, iA, DH, AA, Kb, Bk

PALEOTETHYS

GONDWANA

Terrane

Hun-Terrane
Cadomian Basement
Cryptic Rheic suture
Ordovician accretion

Laurussia

Gondwana

C

Rhenohercynian ocean

Palaeo-Tethys

Silurian, accompanied by the opening of the Palaeo-Tethys (Fig. 4). Most of these future constituents of the Variscan orogen in Central Europe were strongly overprinted during Variscan and/or Alpine events, and their nomenclature is largely dominated by their belonging to Variscan (e.g. Kossmat, 1927), resp. Alpine (Alpine Realms) tectonostratigraphic units. Considering their pre-Variscan origin and evolution, we tentatively propose a terminology being the mirror of their Early Palaeozoic evolution (von Raumer et al., 2001; von Raumer et al., 2002).

We distinguished tectonostratigraphic units containing Cadomian basement, Neoproterozoic to Cambrian active margin settings, and Ordovician accretionary stages, which belong to the Hun superterrane, formerly situated at the eastern continuation of Avalonia along the Gondwanan border. These units represent the leading edge of the Hun superterrane and include a Middle Ordovician suture of an aborted Rheic ocean (Fig. 5). Units to the south of those are characterized by the opening of the Palaeo-Tethys, which separated the Hun superterrane from Gondwana in Late Silurian times.

This distribution was transformed during the Variscan orogeny with the addition of elements derived from Laurussia resp. Avalonia. This is the case for the classical Rhenohercynian zone, together with the Lizard, the South Portuguese and the Moravo-Silesian Zones (Figs. 3 and 5). They represent a Devonian oceanic domain opened within the Laurussian southern margin, due to a Gondwana-directed slab pull. The leading edge of the Hun superterrane is represented at that time by a Silurian–Devonian active margin (the mid-German Crystalline Rise).

We thus obtain the following main plate-tectonic units (Fig. 5):

– Terranes detached from either Laurentia–Baltica or Avalonia (e.g. BV, GS, Is, LM, Mo) and opening of the Rhenohercynian ocean (South Portuguese Zone, Lizard complex, Rhenohercynian domain, Moravo-Silesian region).
– Hun-type terranes and its northern active margin (Phyllite zone—Rheic accretionary prism, and the Harz–Giessen zone—Rhenohercynian accretionary prism).
– Southern passive margin of the Hun-type terranes and related Palaeo-Tethys sediments (e.g. Saxo-thuringian zone, Central-Armorican zone).

A similar distribution is repeated with the Ligerian–Moldanubian, Helvetic–Cetic and Penninic–AustroAlpine (partly) units representing the leading active margin of the superterrane, then the Noric–Bosnian, Aquitaine–Cantabrian units represent the southern passive margin of the terrane (northern Palaeo-Tethys margin). Thus, it is obvious that major lateral translations and duplication of terranes took place during the Variscan orogeny, possibly in a model similar to the one proposed by Johnston (2001) for the Great Alaskan Terrane. Finally to the south of these duplicated terranes, we find (Fig. 5):

– Gondwana—the southern Palaeo-Tethys passive margin.

After a geological history made of contrasting geodynamic stages since the Neoproterozoic/Cambrian, and going from an active margin setting to accretion of terranes and their duplication to ensialic rifting and continent–continent collision, the pre-Variscan building blocks, separated at different times from Gondwana, were reassembled during the Variscan orogeny. Part of them was strongly involved in the Alpine orogen. Consequently, collisional orogens do not just represent newly formed crust, but are mainly built up by large inherited continental blocks, including their lithospheric roots (e.g. Rampone and Piccardo, 2000). The Variscan cordillera stage contributed for a certain amount to crustal growth through large-scale granitic emplacement. This crustal material was preserved through Permo-Carboniferous widespread rifting. In contrast, the Alpine orogeny and the duplication of the lithosphere induced a loss of continental material through subduction/underplating and important erosion. We are aware that such comparative studies can only serve as a contribution for necessary further discussion.

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