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Organization of pre-Variscan basement areas at the north-Gondwanan margin

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Abstract Pre-Variscan basement elements of Central Europe appear in polymetamorphic domains juxtaposed through Variscan and/or Alpine tectonic events. Consequently, nomenclatures and zonations applied to Variscan and Alpine structures, respectively, cannot be valid for pre-Variscan structures. Comparing pre-Variscan relics hidden in the Variscan basement areas of Central Europe, the Alps included, large parallels between the evolution of basement areas of future Avalonia and its former peri-Gondwanan eastern prolongations (e.g. Cadomia, Intra-Alpine Terrane) become evident. Their plate-tectonic evolution from the Late Proterozoic to the Late Ordovician is interpreted as a continuous Gondwana-directed evolution. Cadomian basement, late Cadomian granitoids, late Proterozoic detrital sediments and active margin settings characterize the pre-Cambrian evolution of most of the Gondwana-derived microcontinental pieces. Also the Rheic ocean, separating Avalonia from Gondwana, should have had, at its early stages, a lateral continuation in the former eastern prolongation of peri-Gondwanan microcontinents (e.g. Cadomia, Intra-Alpine Terrane). Subduction of oceanic ridge (Proto-Tethys) triggered the break-off of Avalonia, whereas in the eastern prolongation, the presence of the ridge may have triggered the amalgamation of volcanic arcs and continental ribbons with Gondwana (Ordovician orogenic event). Renewed Gondwana-directed subduction led to the opening of Palaeo-Tethys.

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Introduction

Pre-Variscan elements of Central Europe are mostly exposed as pre-Mesozoic basement areas that underwent the Variscan thermotectonic events, and occur as polymetamorphic domains which, after their respective drift and amalgamation, have been stacked and "shovelled" during Variscan (e.g. Bard 1997; Oncken 1997) and Alpine events one in front of the other to produce the present-day juxtaposition. During their large-scale accretion and strike-slip transport, many of these basement areas left behind their lithospheric roots. Consequently, in the European Variscan basement areas (Fig. 1; e.g. Iberia, Armorica, Moesia, French Massif Central, Saxothuringian and Moldanubian domains, External massifs, Penninic domain, parts of the southern Alps and the Austroalpine basement), nappe and strike-slip structures of different ages repeat elements which, initially, had a distinct pre-Variscan location, and a common evolution, comprising different steps since the Precambrian. The current nomenclatures and zonations applied to Variscan or Alpine regional structures cannot characterize the original location of pre-Variscan crustal elements and, necessarily, a new nomenclature has to be based on plate tectonic criteria considering the geotectonic evolution of these elements during the Neoproterozoic and Early Palaeozoic. As we are dealing mostly with lithostratigraphies of metamorphic areas, we try to maintain a standpoint independent of models of Variscan evolution of these areas.

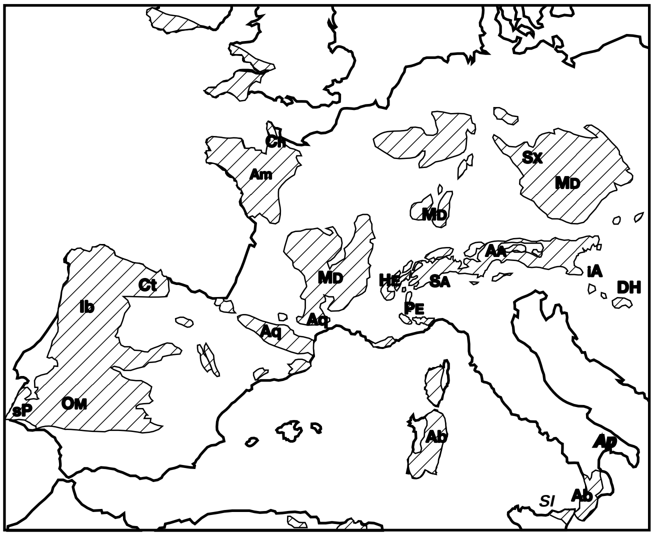


Fig. 1 Distribution of Pre-Mesozoic (Variscan and/or older) units in Europe (Zwart and Dornsiepen 1978) with indication of distinct microcontinents (see Fig. 7). *AA* Austro-Alpine; *Ab* Alboran; *Am* Armorica; *Ap* Apulia; *AQ* Aquitaine; *AR* Armorica; *Ch* Channel terrane; *Ct* Cantabria; *DH* Dinarides-Hellenides; *He* Helvetic; *iA* intra-Alpine; *Ib* Iberia; *MD* Moldanubian; *OM* Ossa-Morena; *Or* Ortegal; *Pe* Penninic; *sP* south Portuguese; *Sx* Saxothuringian

Examples of the Early Palaeozoic evolution preserved in the Variscan mountain chain of Europe are numerous (see Dallmeyer et al. 1995; Keppie 1994; von Raumer and Neubauer 1993a, 1993b; Franke et al. 2000). Sedimentary and fossil records, as well as age determinations, show the overall presence of Neoproterozoic to Early Palaeozoic basements supposed to have evolved along the margin of Gondwana, and sharing specific structural elements and events. For the time period after the Ordovician, different plate-tectonic evolutions are proposed, favouring either one (Robardet et al. 1990) or two major mid-European oceanic separations (Matte 1986), or the separation of a basement assemblage ("Hun-superterrane"; Stampfli 1996, 2000). Such divergent reconstructions need to be tested, and it is the aim of this paper to discuss, from a "Gondwanan" standpoint, and independently of the Variscan structures, parallels of pre-Variscan evolution among the polymetamorphic basement areas mentioned previously.

Pre-Ordovician peri-Gondwana evolution

Among the different pre-Variscan relics preserved in the Variscan basement areas – the pre-Mesozoic Alpine basement areas included – we can distinguish distinct geodynamic settings from the Precambrian to the Ordovician, comprising Precambrian basement blocks (Cadomian/PanAfrican basement) and their sedimentary cover, formation of Late Precambrian to Cambro-Ordovician oceanic crust, volcanic arcs, and active margin remnants, and zones of amalgamation (accretion, collision) of Early Palaeozoic age.

Fig. 2 Plate tectonic re-interpretation of pre-Variscan units in the Alps. Compared with Frisch and Neubauer (1989, terminology in italic with quotation marks), all Early Palaeozoic terranes of the Alps are re-interpreted in terms of their peri-Gondwanian origin. Pieces comparable to those of the "*Noric composite Terrane*" are interpreted to be related to the opening of Palaeotethys. The arc volcanic *"Celtic Terrane"* and its counterparts in the Western Alps represent units with Early Palaeozoic metamorphism. Terranes related to the opening of Early Palaeozoic oceanic domains (*"Speik Terrane"*) represent either contemporaneous or successor stages of Rheic ocean and/or its equivalents. Arc volcanics (*"Habach Terrane"*) represent Early Palaeozoic active margin settings. Other signatures in the domain of the Eastern Alps, not mentioned in the explanations, refer to Variscan elements and structures (see Frisch and Neubauer, 1989). *Inset* General situation of the Alpine pre-Mesozoic basement terranes (*black*) within their present-day Variscan framework. *MC* French Central Massif; *BM* Bohemian Massif

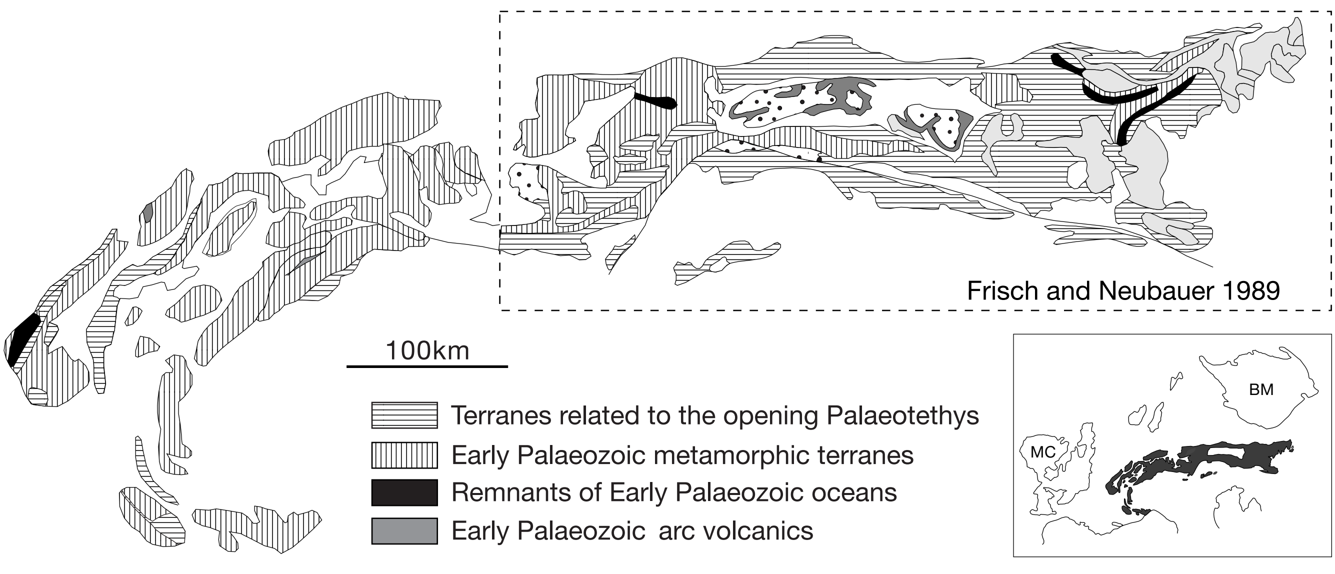
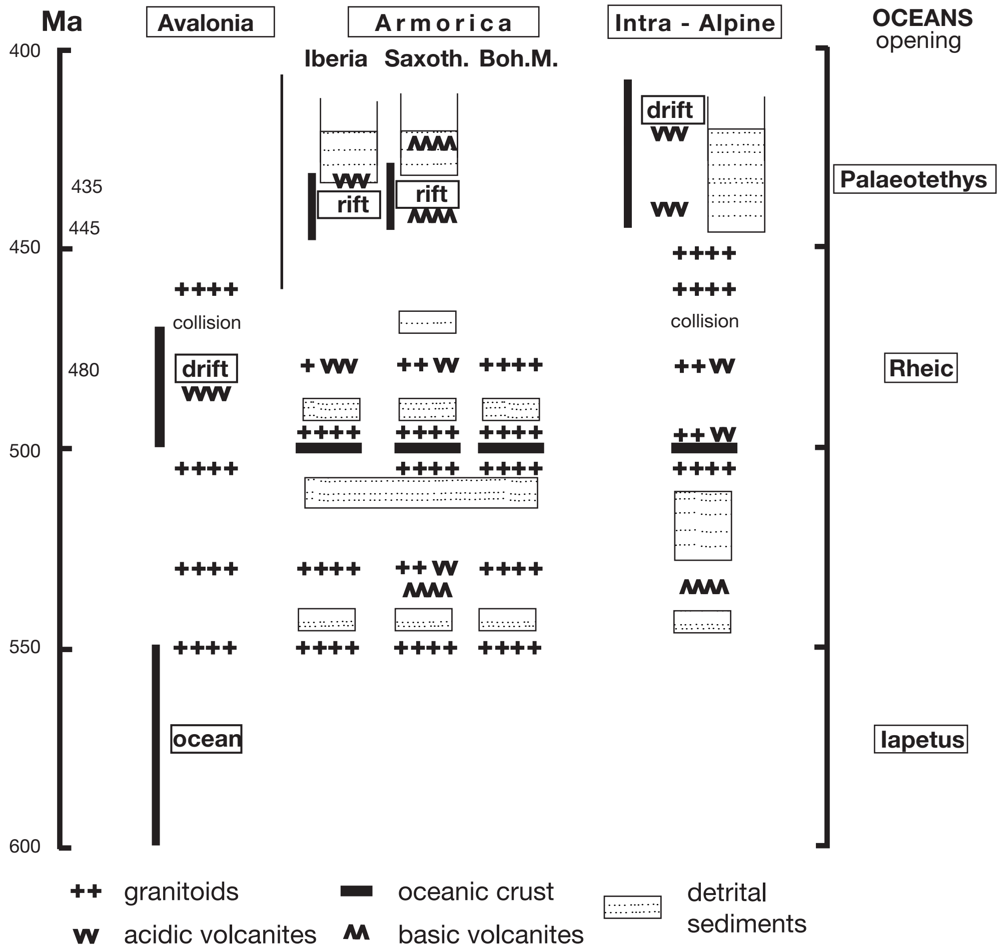


Fig. 3 Comparative time-table of tectonic and magmatic events in the different peri-Gondwanan microcontinents



Although less evident, a comparable evolution is hidden among the basement areas in the Alps. Re-interpreting the terrane model of Frisch and Neubauer (1989) from the Eastern Alps and the corresponding lithological units (Neubauer et al. 1999) in the frame of polymetamorphic basement areas in the entire Alps (Fig. 2), we can distinguish (a) a lower Palaeozoic sedimentary cover sequence, interlayered by volcanic rocks, in this paper interpreted as units related to the opening Palaeo-Tethys (see below); and (b) units, hidden in the polymetamorphic domains, containing older, mostly Cadomian/pan-African metamorphic basement units with relics of Cambrian-Neoproterozoic magmatic arcs and/or Cambrian ophiolites, with an (not in all places) Early Palaeozoic cover sequence, either intruded by Ordovician granitoids or containing Ordovician volcanites.

Consequently, the Intra-Alpine basement areas (Helvetic, Penninic, Austroalpine, Southalpine) fit well with the pre-Variscan evolution observed in their present-day Variscan framework (Fig. 3) and, when thinking in terms of a peri-Gondwanan location, they are thought to have occupied a former eastern lateral continuation of the present-day Variscan framework (see Fig. 7; von Raumer 1998). The different pre-Silurian stages of evolution mentioned previously are compared using observations from the Alps as well as from Variscan basement areas in Europe.

Cadomian basement

The peri-Gondwanan microcontinents and their Cadomian elements represent successor stages of a disintegrating Neoproterozoic supercontinent. Independent of configuration (Rodinia: Hoffmann 1991, Dalziel 1992, Unrug 1997; Palaeopangaea: Piper 2000), continental dispersal led to the Cambrian formation of Gondwana (e.g. Powell et al. 1993). Rapid drift of large continents is assumed for the Neoproterozoic (Gurnis and Torsvik 1994), and an active continental margin setting is accepted for the Cadomian belt (Brown 1995; Torsvik et al. 1994), where subduction may have been related to the opening of Iapetus (Grunow et al. 1996).

Zwart and Dornsiepen (1978), Cogné and Wright (1980), and Ziegler (1984) derived pre-Variscan units from the former Proterozoic Europe-African Block, and such basement relics are assumed to be part of Avalonia (e.g. Rast and Skehan 1983; Skehan and

Rast 1983). It is not the scope of this paper to recall the complex evolution of these oldest elements which either appear as low-grade or as polymetamorphic domains (pan-African/Cadomian orogeny), and for which the relationship between Cadomian basement areas and Neoproterozoic to Early Palaeozoic sedimentary cover have been the subject of extensive research. The general picture of small continental blocks bordering the Gondwana margin (Nance and Murphy 1994) explains best the many relationships which existed between all these pieces. Large-scale magmatic activity is documented by syn- and postorogenic granitoids or acidic volcanites in the wider framework of Gondwanan evolution (see below). Also in the Alpine domain, a distinction can be made between a Proterozoic and Archean inheritance, Late Precambrian mafic and ultramafic rocks, and relics of Precambrian–Cambrian sediments (Schaltegger and Gebauer 1999). Widely distributed across the different Alpine realms, these sediments contain detrital zircons suggesting derivation from Cadomian–pan-African and older basement units. Comparable results were obtained from detrital micas (Dallmeyer and Neubauer 1994; Dallmeyer et al. 1996a, 1996b; Handler et al. 1997; Panwitz et al. 2000). Pre-Cambrian basement is discussed for a few regions in the Western and Central Alps (Gebauer 1993), including the Gotthard area of the External domain (Gebauer et al. 1988), the Berisal Complex (Stille and Tatsumoto 1985; Zingg 1989) and Siviez-Mischabel unit (Thélin et al. 1993) of the Penninic domain, probably the "ancient basement" in the internal zones of the Western Alps (Desmons et al. 1999), the Silvretta area of the Austroalpine basement (Schaltegger et al. 1997), and in the Eastern Alps (Neubauer 1991; von Quadt 1992; Thöni 1999). Sm–Nd data (e.g. Liebetrau and Nägler 1994; Böhm 1996; Poller et al. 1997) from Cambro-Ordovician or Variscan granitoids closely match values observed in the Bohemian Massif (Hegner and Kröner 2000), in NW Iberia (Fernández Suárez et al. 1998) and from West Avalonia (Nance and Murphy 1996). Findings of Cadomian ages in the Pontides (Üstaömer 1999) would allow extension of this domain eastward maybe up to the Caucasus.

Early Palaeozoic sedimentary troughs–oceanic settings

Subsidence analysis shows the large-scale opening of early Palaeozoic sedimentary basins for Laurentia and western Gondwana (Williams 1997), and contemporaneous events are registered in the Armorican Massif (Paris and Robardet 1990; Robardet et al. 1994), and in the Ossa Morena domain (Liñan and Quesada 1990). In an Early Cambrian reconstruction (McKerrow et al. 1992), Archaeocyathan assemblages indicate a climate-sensitive palaeogeographic location within 30° of the equator. Regular fracture patterns determine the direction of intra-continental sedimentary troughs (Courjault-Radé et al. 1992), and delimit large areas with deposits of continental-margin environment in the Gondwana platform during the Cambrian. In fact, the most important lithology, locally highly metamorphosed association of metagreywackes, metapelites, a few quartzites, carbonates, and metavolcanic interlayers, is well known in the Central Iberian domain, and in the Montagne Noire area, but also from several Alpine domains (e.g. External Massifs, Southern Alps, von Raumer 1998; ancient basement areas of the Penninic domain, Desmons et al. 1999), or the Pyrenees (Laumonier 1998), and has astonishing parallels with fossil-bearing, Neoproterozoic to Cambrian lithostratigraphies from the Saxothuringian domain (e.g. Buschmann et al. 1995), with several localities around the Mediterranean Sea (Sdzuy et al. 1999), or well-preserved examples observed in the Anti-Atlas mountain chain of Morocco; however, in addition to the aforementioned parallels also discrepancies exist. Comparable lithologies may remain undiscovered in the polymetamorphic areas of the Variscan mountain chain, as the high plasticity of marbles during metamorphic overprint may reduce considerably original limestone occurrences, which may dissappear completely during metamorphic evolution. On the other hand, a specific palaeogeographic configuration may influence carbonate distribution. They may have been deposited on the Gondwana platform, they may have been resedimented as reduced detrital carbonate layers near a rift shoulder (e.g. Freyer and Suhr 1987), and may have been replaced by contemporaneous clastic sequences in the domain of Cambrian rift zones. Extensive Ordovician areas of similar sedimentary facies at the Gondwana shelf (Noblet and Lefort 1990; Robardet 1996) may explain comparable facies evolution in the Saxothuringian areas (Linnemann and Buschmann 1995), in the Armorican massif (Paris et al. 1999), and regions included in the polymetamorphic domains (e.g. Mingram 1996, 1998). Fossil findings confirm the presence of lower Palaeozoic metasediments even in Variscan high grade metamorphic rocks (e.g. Schwarzwald, Hanel et al. 1999) and in low-grade Alpine metamorphic series from the Southern Alps (Ordovician, Gansser and Pantic 1988) and Eastern Alps (Arenig, Grauwackenzone; Reitz and Höll 1991).

It is tempting to correlate the Cambrian period of rifting (see above) and the distribution of relics of oceanic domains. From the Late Precambrian to the Ordovician different generations of oceanic domains were involved in the plate-tectonic evolution. Late Precambrian oceanic crust and Cambrian volcanic arcs (Haydoutov 1989; von Quadt 1992; Schaltegger et al. 1997; Schaltegger and Gebauer 1999; Chen et al. 2000; Crowley et al. 2000; Fernández Suárez et al. 2000) confirm the relationship of several domains with the Neoproterozoic orogenic belt and the existence of different tectonic regimes along the Gondwana margin. Traces of what is assumed to represent the former time equivalents of the Rheic ocean are found in the Cambrian mafic–ultramafic complexes such as the Chamrousse ophiolite of the Alps (Ménot 1987) and the Vesser zone of the Saxothuringian domain (H. Kemnitz et al., submitted), and can be followed through different metamorphic complexes in the Bohemian massif (Finger et al. 1998; Mingram et al. 1998; Stipska et al. 1998; Winchester et al. 1998; Kröner et al. 2000). Relics may occur in the French Central Massif (Pin 1991), and exist in the Iberian basement areas (Fernández-Suárez et al. 1998; Ordoñez Casado 1998; Abati et al. 1999; Andonaegui et al. 1999), and in the northern part of Sardinia (Carmignani et al. 1994). However, it cannot be excluded that relics of Cambro-Ordovician oceanic crust may represent one or more parallel "Rheic" rifts separated by ribbons of "Cadomian" or "Avalonian-type" basement areas (microcontinents) and, additionally, metabasites partly may represent either the Ordovician–Silurian successors of the Rheic ocean or time equivalents of the Proto-Tethys.

Comparing the peri-Gondwanan evolution

From the Neoproterozoic to the Ordovician detachment of Avalonia from Gondwana, striking parallels of plate-tectonic evolution become visible (Fig. 3) between Avalonia, Armorica and the peri-Gondwanan microcontinents located farther to the east, confirming in some way the lateral alignment of the microcontinents at the Gondwana margin. The rifting period accompanying the opening of Iapetus certainly left structures on either side of the future Iapetus ocean. Such intraplate rift systems may have guided the emplacement of Precambrian/Cambrian volcanites and intrusions, and also initial formation of oceanic crust in basement areas located at the eastern prolongation of future Avalonia. A general situation of Neoproterozoic active margin at the Gondwana border (see above) is documented (e.g. Iberia: Fernández-Suárez et al. 1999; Bohemian Massif: Zulauf et al. 1999, Kröner et al. 2000; Saxothuringian domain: Linnemann et al. 2000; in the Alps: Neubauer 1991; von Quadt 1992; Schaltegger et al. 1997), and the picture of widespread late Proterozoic sediments and volcanic rocks, and the formation of Cambrian sedimentary troughs and initial rift zones, become apparent for the Gondwana margin. The continuation of rifting, initially in a back-arc situation, triggered upwelling of asthenosphere, with contemporaneous Cambrian gabbros, granitoids and metamorphic conditions of lower crust (Abati et al. 1999) which announce the future opening of Rheic ocean. Comparable observations come from the Gotthard (Biino 1994) and Silvretta areas (Schaltegger et al. 1997). Pieces of oceanic crust, such as the Chamrousse area (Western Alps) or the Vesser zone (Saxothuringian zone), could represent the eastern continuation of the Rheic ocean (or pieces of oceanic crust contemporaneous to the Rheic ocean), and corresponding highly transformed relics of the same could be hidden among the many pieces of "amphibolites" found in the polymetamorphic areas of the Variscan mountain chain, indicating the former suture of an eastern continuation of an early Rheic ocean. Also the eclogitized remnants of Early Palaeozoic oceanic crust (Pulo do Lobo, Cabo Ortegal; Ordoñez Casado 1998) have to be incorporated in the general pattern of the Rheic ocean. Interestingly, Kleinschrodt and Gayk (1999) underlined the striking parallels of structural evolution and exhumation ages of the eclogite complexes of the Münchberg Massif and from Cabo Ortegal, former protoliths of the Rheic ocean.

Also Ordovician events known from the Avalonian plate have their contemporaneous events in the adjacent microcontinental plates. During the Ordovician break-up of Avalonia (485 Ma, Van Staal et al. 1998; East Avalonia, 480–465 Ma, Prigmore et al. 1997), the birth of the Rheic ocean, contemporaneous rift-related magmatism is observed in NW Spain (Fig. 4; Santos Zalduegui et al. 1995; Ordoñez Casado 1998; Fernandez-Suarez et al. 1999; Montero et al. 2000; Valverde-Vaquero and Dunning 2000), in the French Central Massif (Pin and Marini 1993) and in the subterranes of the Saxothuringian domain (Linnemann et al. 1998a). Additional criteria for appreciating the general plate-tectonic situation are furnished by the widespread granitoid rocks of Early Palaeozoic age, by the evidence of an Ordovician orogenic event, and by the discussion of the possible continuation of Avalonian pieces preserved as relics in the former eastern continuation of Avalonia.

Parallels of granitoid evolution

During the plate-tectonic evolution of Avalonia (e.g. rifting related to the opening of Iapetus), accompanied by several magmatic cycles (e.g. early Cadomian, 580–570 Ma; Neoproterozoic, 550–540 Ma; Cambro-Ordovician, 500–480 Ma), and its break-off from Gondwana (formation of Rheic ocean, Cambro-Ordovician, 500–480 Ma), contemporaneous tectonic events and corresponding pulses of granitoids or their surface equivalents can be observed (Fig. 3) in most of the adjacent peri-Gondwanan continental blocks. Most Ordovician granitoids and acidic volcanic rocks from the Alps and areas outside the Alps (Fig. 4, 5), Avalonian outcrop areas (Tremblay et al. 1994; Keppie et al. 1997), the Himalayan domain (Girard and Bussy 1999), the Argentine Precordillera (Huff et al. 1998), and even from many Late Cadomian granitoids, independent of locality and age, show strong anomalies of Ba, Nb, Sr and Ti in mantle-normalized multi-element variation diagrams (von Raumer et al. 1999), and Late Proterozoic to Early Palaeozoic detrital sediments (e.g. Bollin 1994; Mingram 1996; Ugidos et al. 1997)

Fig. 4 Ages of Cambro-Ordovician granitoids and metamorphism

Alps	Helvetic Realm	
438±5 Ma U/Pb SHRIMP	meta-dacite, Arg.	Lombardo et al. 1997
489±22 Ma U/Pb Zrn	granite, Bell.	Barféty et al. 1997
496±6 Ma U/Pb Zrn	plagiogranite, Bell.	Ménot et al. 1988:
453±3 Ma U/Pb Zrn	granitoids, Mt. Blanc	Bussy & von Raumer 1994
436±17 Ma Rb/Sr wr	granitoids, Gotthard	Arnold 1970
>440 Ma U/Pb Zrn	" "	Bossart et al. 1986
439±5 Ma U/Pb Zrn	" "	Sergeev & Steiger 1993
445±2 Ma U/Pb Zrn	migmatites, Aar massif	Schaltegger 1993
456±2 Ma U/Pb Zrn		
±450 U/Pb Zrn	granitic gneiss, Si.	Köppel et al. 1981
461 Ma Sm/Nd grt wr	eclogite, Gotthard	Gebauer et al. 1988:
468 Ma U/Pb Zrn	eclogite, Gotthard	
467-475 Ma U/Pb Zrn	island arc gabbro, Gotthard + eclogite facies	Oberli et al. 1994:
479±3 Ma U/Pb Zrn	island arc gabbro	Abrecht et al. 1995:
475-450 Ma U/Pb Zrn	metabasic protoliths	Paquette et al. 1989:
424 Ma U/Pb Zrn	eclogite, Argentera	Paquette et al. 1989:
	Penninic Realm	
507±9 U/Pb Zrn	granophyre	Guillot et al. 1991
507±9 U/Pb Zrn	Vanoise nord, granite	Guillot et al. 1998
482±5 SHRIMP	Peclet granite	Guillot et al. 1998
451±5 SHRIMP	Modane granite	Guillot et al. 1998
500±10 SHRIMP	metarhyolite, Ambin	Guillot et al. 1998
500±4 U/Pb Zrn	alkaline granite	Bussy et al. 1996
497±4 U/Pb Zrn	Vanoise,granite	Bertrand & Leterrier 1997
±450 U/Pb Zrn	granitic gneiss, Berisal	Köppel et al. 1981
458±11 U-Pb SHRIMP	anatexis, Tauern	Eichhorn et al. 1999
	Austroalpine Realm	
420-450 U/Pb Zrn	Flüela-granite, Silv	Liebetrau 1996
451±2 Rb/Sr WR	Flüela-granite, Silv	Flisch 1987
490±9 U/Pb EvZrn	Ötztal, migmatite	Klötzli-Chovanetz et al. 1997
445±24 Rb/Sr WR	gramitoid gneiss, TS.	Hammerschmidt 1981
494±73 Sm-Nd WR	Ötztal meta-granite	Hoinkes et al. 1997
487±5 Sm-NdTit WR	Ötztal meta-granite	Bernhard et al. 1996
485 Pb-Pb EvZrn	Ötztal meta-granite	Bernhard et al. 1996
468 Ma U/Pb Zrn	Porphyroid Greywacke zone	Söllner et al. 1991
476 ±14 Ma U/Pb SHRIMP	Metagabbro Greywacke zone	Loth et al. 1999
	Southalpine Realm	
466±5 Rb/Sr WR	Ceneri gneiss	Boriani et al. 1981
457±7 U/Pb Zrn		Zurbriggen et al. 1997
		Romer et al. 1996
457-450 U/Pb, Pb/Pb	Staur. formation	Romer & Franz 1998
Ordovcian, stratigraphy	Comelico-Porphyroid	Hubich & Loeschke 1993
Saxothuringikum		
479±2 Ma ev Zrn	Bärentiegel Porphyroid	Linnemann et al. 2000
487±6 Ma ev Zrn	Blambach Rhyolite	Linnemann et al. 2000
484±5 Ma ev Zrn	rhyolitic tuff Wurzelberg	Linnemann et al. 2000
485±6 Ma ev Zrn	Tourmaline granite	Linnemann et al. 2000
486±4 Ma ev Zrn	Metarhyolite	Linnemann et al. 2000
≈490 Ma ev Zrn	rhyolite pebbles	Linnemann et al. 2000
Bohemian Massif + Schwarzwald		
±480	ZEV, pegmatoids, metamorphism	O'Brien et al. 1997
487±.8 Ma U/Pb SHRIMP	Metaeklogite	O'Brien and Kröner 1999
482±6 SHRIMP Zrn	Gföhl gneiss	Friedl et al. 1998
≈480 Ma Rb/Sr recalc	thermic event	Chen et al. 2000
501-504 Ma U/Pb EvZrn	granitoids	Kröneret al. 2000
469.3 ±3.8 Ma SHRIMP Zrn	inherited magm. Grains	Kröner et al. 2000
481.7±1.1 Ma Pb/PbEv Zrn	Frankenstein gneiss	Kröner and Willner 1998
485±12 Ma Pb/Pb EvZrn	Metarhyolith Ehrenfriedersdorf	Mingram & Rötzler 1999
480±12Ma Pb/Pb EvZrn	Augengneiss Schwarzenberg	Mingram & Rötzler 1999
Polish Sudetes		
480-505 U/Pb Zrn	granitoids	Oliver et al. 1993
473-488 U/Pb EvZrn	Gory Sowie	Kröner & Hegner 1998
440 U/Pb EvZrn	anatectic granitoid	
NWIberia +Ossa Morena		
500±2 U/Pb Zrn	orthogneiss	Abati et al. 1999
484, 493 U/Pb Zrn	migmatization	Gonzalez Cuadra et al. 1999
465-480 U/Pb Zrn	Ollo de Sapo granitoid	Fernandez-Suarez et al. 1999
479.5 Ma U/Pb Zrn	meta-granodiorite	Santos Zalduegui et al. 1995
480±2 Ma U/Pb Zrn	Cardoso gneiss	Valverde-Vaquero & Dunning 2000
502±8MaPb/Pb Zrn	Castillo alkaline granite	Montero et al. 2000
480±7Ma Pb/Pb Zrn	Valuengo microgranite	Montero et al. 2000
French Massif Central		
478±6 Ma U/Pb Zrn	orthogneiss, "leptynite"	Pin and Lancelot 1982
Hungary		
462±6 Pb/Pb Ev Zrn	granitic gneiss , Sakarya	Özmen and Reischmann 1999
Turkey		
Ord. age, fossils	granite pebbles, Tisia	Kozur 1984 a,b

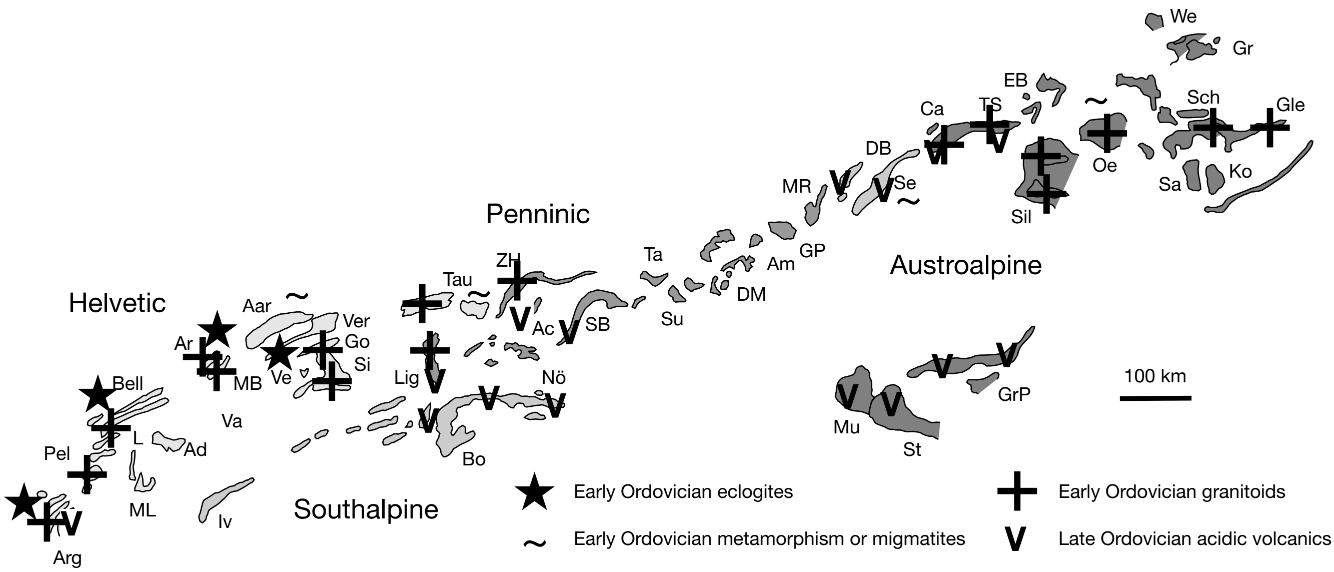


Fig. 5 Distribution of Ordovician granitoids in the Alpine domain – a tentative Silurian projection. Granitoids represent different stages of evolution of polymetamorphic domains at an active margin, and in relation with an Ordovician amalgamation, whereas late Ordovician volcanites represent the nearby situation of the opening Palaeotethys. Helvetic domain: *Aar* Aar massif; *Ad* Adula; *AR* Aiguilles Rouges massif; *Arg* different pieces of the Argentera massif, *Bell* Belledonne–Grandes Rousses; *Go* Gotthard massif; *L* Lebendun; *MB* Mont-Blanc; *ML* Monte Leone; *Si* Simano; *Tau* Tauern window units; *Ve* Verampio basement; *Ver* Carboniferous in the Verrucano unit. Penninic units: *Ac* Acceglio unit; *Lig* different pieces in the Ligurian Alps (new Ordovician age data, oral comm. M. Molina, Genova); *SB* St. Bernhard nappe; *Su* Suretta; *Ta* Tambo; *Va* Vanoise unit; *ZH* Zone Houillère. Austroalpine units: *Am* Ambin; *Ca* Campo; *Gl* Gleinalm; *DM* different pieces in the Dora Maira unit; *EB* Err-Bernina units; *Gle* Gleinalm; *GP* Gran Paradiso; *Gr* Grobgneis unit; *GrP* Graz Palaeozoic; *Iv* Ivrea-Zone; *Ko* Koriden; *MR* Monte Rosa; *Mu* Murau nappe; *Oe* Oetztal; *Sa* Saualm; *Sil* Silvretta nappe; *St* Stangalm; *Sch* Schladminger Tauern; *Ve* Veitsch units; *We* Wechsel unit. Southalpine units: *Bo* Bozen; *DB* Dt. Blanche; *Iv* Ivrea zone; *Nö* Nötsch; *KW* Karawanken; *Ka* Karnische Alpen; *Se* Sesia-zone

show similar normalized patterns indicating chemical homogeneity over wide areas. Such large-scale parallels, which may have resulted from comparable source areas of granitoids or sediments, show that normalized multi-element variation diagrams do not discriminate the plate-tectonic situation of the many granitoids.

Comparing trace elements, Linnemann et al. (2000) show that Cadomian detrital sediments of the Saxothuringian zone indicate the situation of a continental island arc, whereas Ordovician sediments carry the fingerprints of a passive margin. In geochemical plots (Maniar and Piccoli 1989), the Cambro-Ordovician granitoids follow, in some ways, distinct steps of a plate-tectonic evolution (Fig. 6). Local occurrences of Cambrian plagiogranites (Alps: Ménot et al. 1988, Müller et al. 1996; NW Iberia, Espasante) document evolution of oceanic crust, and Cambrian granitoids of more alkaline and metaluminous compositions (Alps: Guillot et al. 1991, Bussy et al. 1996; Ossa Morena: Montero et al. 2000; Pyrenees: Navidad and Carreras 1995) may have formed in a thickened crust (see also NW Iberia; Santos Zalduegui et al. 1995). Equally, in the Cambro-Ordovician granitoid associations (e.g. Oetztal, Schindlmayr 1999; Silvretta, Liebetrau 1996; External massifs, Wirsing 1997), the relatively early calc-alkaline metaluminous trends can be related to a Cambro-Ordovician active margin setting (Schaltegger et al. 1997; Schermaier et al. 1998), whereas the corresponding relatively younger granitoids (±450 Ma) have more or less calc-alkaline peraluminous compositions, carrying the characteristics of a late- to post-orogenic evolution. When plotted on a Rb/Y+Nb diagram (Pearce et al. 1984), older granitoids of Ordovician age in the Alps plot in the fields of VAG or intra-plate situation.

Post-Cambrian evolution of microcontinents

The presence of Cambro-Ordovician active margin setting, Ordovician rifting and the evolution of Cambro-Ordovician granitoids raises the question of the existence of an orogenic event characterizing part of the Gondwana margin. The presence of so many Ordovician granites and their pre-Variscan organization (Fig. 5) and geochemical evolution leads, necessarily, to the question of their plate-tectonic situation (Schmidt 1977; Ebner et al. 1987; Biino 1995; Oberli et al. 1994; Abrecht et al. 1995; Handy et al. 1999; O'Brien et al. 1997). Ordovician ages of granitoids (Fig. 4, with references), of eclogites (Nussbaum et al. 1998, not precise age; Gebauer et al. 1988; O'Brien and Kröner 1999) as well as anatexis and metamorphism (Schaltegger 1992, 1993; Klötzli-Chovanetz et al. 1997; Ordovician subduction, Biino 1994; O'Brien et al. 1997; Zurbriggen et al. 1997; Weger et al. 1999; staurolite formation, Romer and Franz 1998)

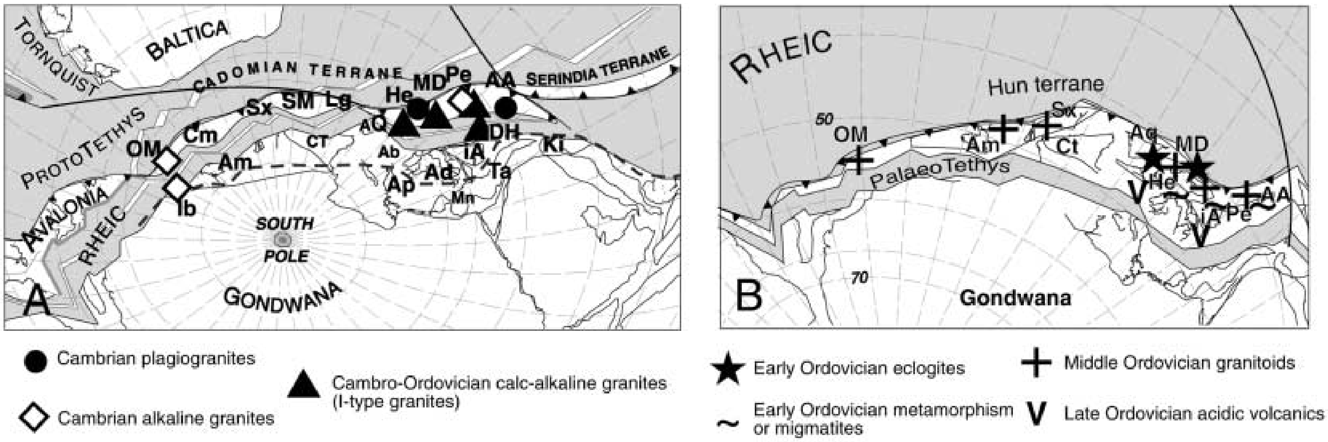


Fig. 6A, B Distribution of Early Palaeozoic granitoids at the peri-Gondwanan margin (nomenclature and reconstructions: see Fig. 7). A Early Ordovician reconstruction (Fig. 7A) with location of granitroids emplaced before the opening of the Rheic ocean. B A Silurian projection Fig. 7B) with granitoids and metamorphism related to the Ordovician orogenic event and to the opening of Palaeotethys

argue for the orogenic evolution from an active margin setting to a collision during a short time period (e.g. Gotthard massif, 5–20 Ma, Oberli et al. 1994: 467- to 475-Ma intrusion of metagabbros/440-Ma metamorphism of Streifengneis granitoids). Carmignani et al. (1994) discuss an evolution from Cambrian rift to an Ordovician Andean type margin for Sardinia. The coincidental evolution of certain types of granitoids through time mentioned previously confirms a plate-tectonic evolution including collisional and post-collisional events. We interpret the tectonic assemblage of Cadomian relics, Neoproterozoic arc setting, and/or Late Proterozoic to Early Palaeozoic sediments and oceanic crust, and Ordovician orogenic structures as indicating an Ordovician suture zone, where these elements were amalgamated to Gondwana during the Ordovician (Figs. 7, 8).

Ordovician palaeo-oceanographic reconstructions combine palaeocurrent data (Christiansen and Stouge 1999), palaeomagnetic criteria (MacNiocaill et al. 1997; Torsvik and Smethurst 1996) and faunal distributions (Harper et al. 1996; Paris 1993; Paris et al. 1999; Mélou et al. 1999) defining the Iapetus and Rheic oceans domains. The wide domain of Iapetus is characterized, since the Early Ordovician, by faunal provinces of brachiopods, where the peri-Gondwanan Avalonian border has cold-water Celtic faunas (Harper et al. 1996; Cocks 2000), and volcanic arc activity (MacNiocaill et al. 1997). Characteristics of Chitinozoan faunas give an idea about the early evolution of the Rheic ocean (Paris 1993; Paris et al. 1999) and, during the same time period, detrital sediments record maximum of subsidence and rift basin formation, accompanied by rift volcanism, in lateral continuity (e.g. Saxothuringian domain; Linnemann 1999).

Sedimentary basins, constituting the lower Palaeozoic cover series in the Eastern Alps, contain acidic volcanics among lower Palaeozoic sediments (Loeschke and Heinisch 1993) with a well-documented sedimentary evolution (Schönlaub 1997a, 1997b; Schönlaub and Heinisch 1993; Schönlaub and Histon 2000), representing a rifting environment since the Late Ordovician (Neubauer and von Raumer 1993; Neubauer and Sassi 1993; Sassi et al. 1994). Since the Late Ordovician, many areas are covered by the detrital sediments of Ordovician glaciation (e.g. Hamoumi 1999; Linnemann et al. 1999). It is only after the onset of the Avalonian drift that Armorica and the more easterly situated Intra-Alpine blocks followed a more independent plate-tectonic evolution.

Terrane detachment from Gondwana

Detachment from Gondwana started during the Mid-Ordovician (ATA; Tait et al. 1998), Caradoc/Ashgill (Saxothuringian domain, 445 Ma; Fig. 3; Linnemann et al. 1998b), and the latest Ordovician (Alpine domain, Ashgill/Llandovery, 435 Ma; Fig. 3; Stampfli 1996) when the Palaeo-Tethys rift opened. Sedimentological and faunistic criteria, and palaeomagnetic data, gave rise for models of detachment of Gondwana-derived continental blocks during the Ordovician and Silurian, favouring either the separation of a basement assemblage (Stampfli 1996) or a major mid-European oceanic separation (Robardet et al. 1990).

Stampfli (1996) introduced the Hun-Terrane model, a ribbon-like assemblage of continental blocks, not necessarily above sea level, or volcanic islands, including Armorica, the Intra-Alpine basement and microcontinents situated in the eastern prolongation. The observation of subsidence patterns in former peri-Gondwanan domains induced Stampfli (2000), and Stampfli and Mosar (1996), to reconstruct the contours of Palaeo-Tethys during the Early Silurian for the Intra-Alpine domains and the corresponding eastern prolongations. Prior to their Silurian separation from Gondwana, these Variscan terranes were located

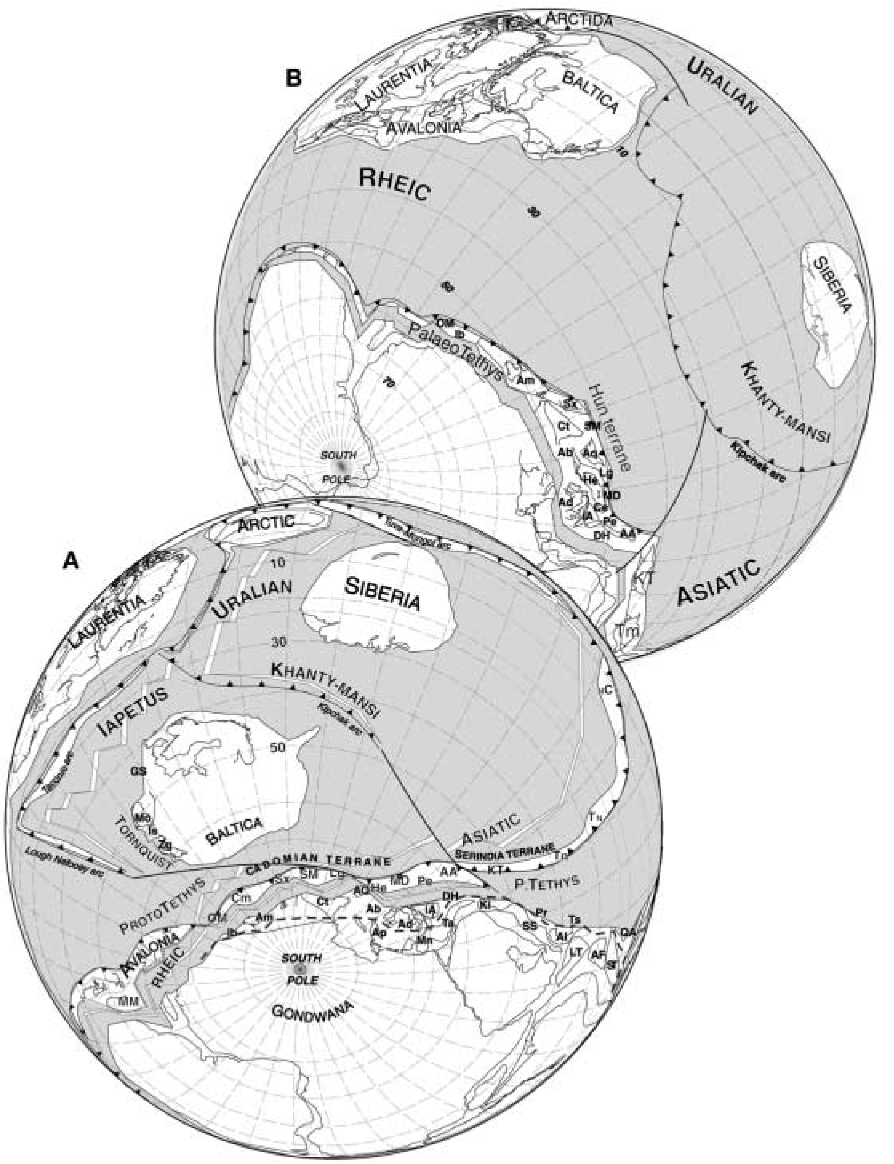


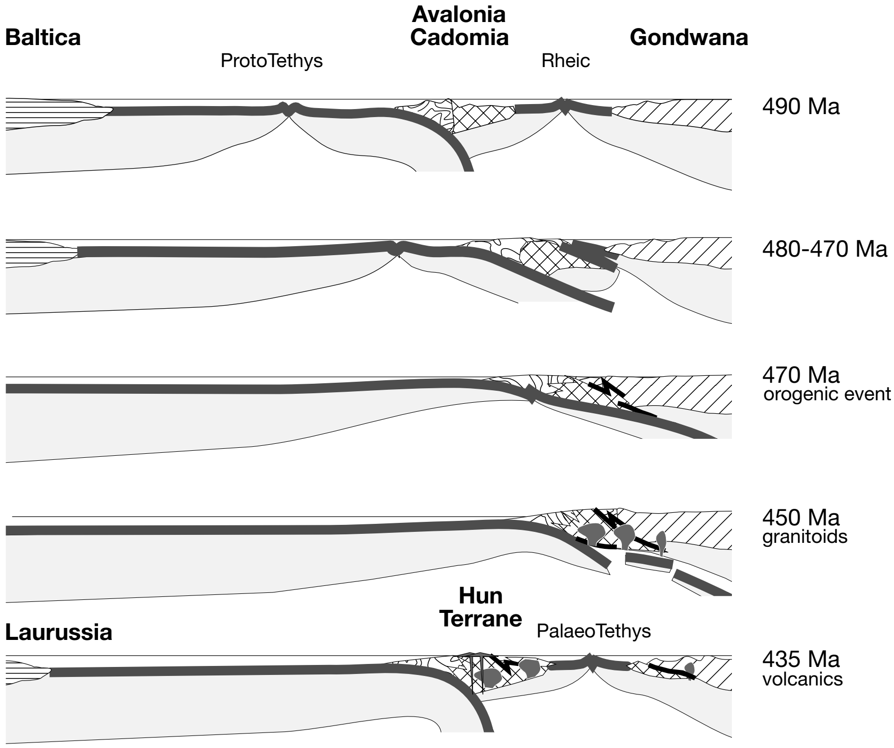
Fig. 7 **A** Location of pre-Variscan basement units at the Gondwanan margin during the Early Ordovician (490 Ma), modified from Stampfli (2000), showing the early stages of the Rheic ocean spreading. **B** A Silurian projection (420 Ma), modified from Stampfli (2000), showing the early stages of opening of PalaeoTethys. Baltica: *Is* Istanbul; *Mo* Moesia; *Zg* Zonguldak. Avalonia: *MM* Meseta-Meguma. Cadomia: *AA* Austro-Alpine; *Cm* Cadomia s.str.; *He* Helvetic; *Lg* Ligerian; *MD* Moldanubian; *OM* Ossa-Morena; *Pe* Penninic; *SM* Serbo-Macedonian; *Sx* Saxothuringian. Serindia: *KT* Karakum-Turan; *Tn* north Tarim. Gondwana: *Ab* Alboran; *Ad* Adria; *Al* Alborz; *Am* Armorica; *Ap* Apulia; *Aq* Aquitaine; *Ct* Cantabria; *DH* Dinarides-Hellenides; *iA* intra-Alpine; *Ib* Iberia; *Ki* Kirshehir; *LT* Lut-Tabas; *Mn* Menderes; *Pr* Pamir; *SS* Sanadaj-Sirjan; *Ta* Taurus; *Ts* south-Tarim

along the margin of Gondwana and represent the future northern margin of Palaeo-Tethys. Consequently, a tentative Silurian palaeo-tectonic configuration has been derived by back-modelling the present day distribution of Variscan elements in Europe (Fig. 7), including also the basement areas of Armorica assumed to contain relics of a former rifting period since the Ordovician.

The corresponding palaeo-reconstuctions are based on palaeomagnetic pole data and have been developed with the GMAP software package (Torsvik and Smethurst 1994; Torsvik and Smethurst 1999) using an orthographic (orthogonal) projection. The Early Ordovician (490 Ma) projection is centred on present-day latitude 60 °N, longitude 80 °E, the Late Silurian (420 Ma) projection is centered on present-day latitude 10 °N, longitude 25 °E. The palaeomagnetic pole data used for Baltica are from Torsvik et al. (1994) for the Hun terranes elements and Siberia from Van der Voo (1993), and references therein. The position of Gondwana is constrainded by the Australia data from Klootwijk (1996) and by Pangea tight-fit reconstruction. The Baltica poles are the absolute reference poles for all the reconstructions.

As a result of Ordovician to Early Devonian rifting events, the components of the Hun terrane were stepwise detached from Gondwana accompanying the opening of Palaeo-Tethys. Such reconstructions are not too different from palaeomagnetic reconstructions for the Armorican Terrane Assemblage (ATA; Tait et al. 1998), where distinct groups of microcontinents started to separate from Gondwana. The principle of a Hun-Terrane, which is grouping of certain microcontinental pieces, may thus be modified acknowledging a still more detailed individual separation from Gondwana. If we admit an opening of Palaeo-Tethys in a

Fig. 8 Cross sections model to illustrate the possible plate tectonic evolution between Baltica and Gondwana during the Early Palaeozoic. The Hun-superterrane resulted from the Ordovician collisional assemblage of elements possibly detached from Baltica-Siberia and areas comprising Cadomian basement (former eastern prolongation of Avalonia), Early Palaeozoic oceanic crust (Rheic), volcanic arcs and accretionary wedges, with the Gondwana margin.The opening of the Palaeotethys separated the composite Hun superterrane from Gondwana. This opening took place in a context of back-arc spreading of Palaeotethys and slab roll-back of the Mauretanian-Rheic ocean and was accompanied by the formation of volcanics



back-arc setting, the geometry of the detached upper plate is bound to be modified by differential slab roll-back behaviour of the lower plate as is observed presently along the Mariana trench, for example. It is clear that the opening of Palaeo-Tethys is diachronous (Stampfli 2000); however, subsidence curves alone cannot determine the onset of sea-floor spreading when very little Palaeotethyan sea-floor remnants are known. We propose a detachment of Gondwanan elements in three major steps: firstly, the Avalonia blocks; then, the mainly European Hun Terranes; and finally the Far-East Hun terranes. We assume that the latter could not be detached before the Silurian accretion to Gondwana of some exotic (Baltica–Siberia) elements grouped here as Serindia. There, the situation is quite different, amalgamation of terranes happened only in Silurian or Early Devonian times and larger continental fragments are involved such as the Pamir–south Tarim–Tsaidam block collision with the north Tarim–north China block (Yin and Nie 1996) or the north Qinling north China blocks collision (Meng and Zhang 1999). These drifting exotic blocks (Serindia terrane) followed the slab roll-back of the Proto-Tethys accompanied by the Asiatic ocean spreading in a back-arc position. An older western portion of the Asiatic ocean was involved in intra-oceanic subduction accompanied by the opening of the Khanti-Mansi back-arc ocean and development of the Kipchak arc (Sengör and Natal'in 1996). A southward connection between the Asiatic ocean mid-oceanic ridge and a remnant Proto-Tethys mid-oceanic ridge is suggested here. This Silurian collisional event affected also the South China block and part of the Indochina block (or the north Qinling north China blocks collision; Meng and Zhang 1999; Findlay 1997) and possibly has been recognized westward up to eastern Turkey (Göncüoglu and Kozur 1999).

Scenario of peri-Gondwanan evolution: a conclusion

When summing up the observations mentioned previously, we arrive, independently of Variscan tectonic complications, at the conclusion that most of pre-Variscan relics of the Variscan mountain chain had their origin at the Gondwana margin. Two evolution trends are noted:

1. Stampfli (2000) favoured the derivation of Cadomian basement blocks from Baltica triggered by a Baltica-directed subduction and island arc formation during the Early Ordovician which, during the Mid Ordovician, collided with the Gondwana margin (orogenic event). Inversion of subduction towards Gondwana produced the break-off of the Hun-superterrane and formation of Palaeo-Tethys as a back-arc ocean.
2. In our present model an opposite evolution is proposed for the Cadomian terrane. Assuming that already since the latest Precambrian subduction was generally directed towards Gondwana (Cadomian orogeny, Avalonian southern prong), we assume that most of the Cadomian basement blocks (exception Belka et al. 1998, 1999; Unrug et al. 1999) presently hidden in the Variscan mountain

chain should have derived from the Gondwana margin ("European margin"; Courjault-Radé et al. 1992). In this general picture, the Serindia terrane is still considered as derived from Baltica–Siberia.

Since the latest Cambrian (500 Ma) at several locations (see above) magmatic and metamorphic events are dated, presumably the consequence of general crustal extension and contemporaneous influence of rising asthenosphere. Such activity is accompanied, at several distant places, by formation of oceanic crust interpreted to represent the opening of the Rheic ocean. The alignment of the very different localities at the Gondwana margin suggests a contemporaneous opening over a large distance, from Ossa Morena, and Iberia to the Münchberg Massif. The question arises as to whether such oceanic trenches represent one uninterrupted long suture line, or if there existed parallel lines of opening (e.g. Rheic, Galicia-Massif Central; Matte 1986), compared with the parallel lines of Early Cambrian grabens intersecting the Gondwanan block. The large differences of oceanic crust at the different localities may indicate that oceanic crust did not result from cylindrical subduction and simultaneous slab roll-back, but from very oblique convergence, where either pull-aparts may have facilitated the appearance of true oceanic crust, accompanied laterally by only incomplete oceanic series, or simply volcanites and/or detrital sediments. Such strike-slip models have been proposed by Murphy and Nance (1989), Linnemann et al. (1998b) and Zulauf et al. (1999).

The striking parallels of evolution from the Late Neoproterozoic to the earliest Ordovician are best explained when using a ribbon-like lining-up model of pre-Variscan blocks along the Gondwana margin. Most of the continental pieces contain the relics of a Neoproterozoic active-margin setting and continental rift since the Late Cadomian, and early stages of Rheic ocean. Intrusion of granitoids and volcanites follow the regional tectonic pattern. We thus claim a common early evolution of Avalonia and its eastern continuation (e.g. Cadomia sensu lato, Intra-Alpine Terrane) at the Gondwana margin, and major differences of evolution between Avalonia and the remaining eastern microcontinents only after the successful break-off of Avalonia during the Early Ordovician (Figs. 3, 7, 8).

The independent drift story of the microcontinents situated in the eastern prolongation of Avalonia depended on the time of subduction of a remnant Proto-Tethys/Rheic mid-oceanic ridge; the latter was linked with the Asiatic ocean mid-oceanic and transform zone in between. The subsequent subduction/collision of the ridge/transform zone triggered the amalgamation of arc and continental ribbon with Gondwana leading to the Ordovician orogenic evolution. This collisional event produced a complex terrane configuration, the "Noric composite Terrane" (Eastern Alps; Frisch and Neubauer 1989) or "Hun superterrane" (Stampfli 1996). It comprises older (former Gondwanan) basement blocks, accretionary wedges, volcanic arcs, and pieces of an aborted eastern Rheic ocean, and may have, locally, the aspect of an archipelago, but it also can be composed by large continental blocks. It is evident that there has been tectonic interaction between the different elements, thus complicating the orogenic assemblage, and our proposed distribution of terranes (Fig. 7) is only tentative. As traces of the Ordovician orogenic event are seen mainly in the Intra-Alpine domain, with some parallels in the Bohemian massif (Cambrian and Ordovician zircon ages of eclogites; O'Brien and Kröner 1999), the question arises as to whether the Armorican Terrane Assemblage (Tait et al. 1998) and more western situated microcontinents were really independent from the more eastern ones, and that the assemblage of Bohemian massif and the Intra-Alpine terranes had a distinct drift history, interrupted by this short event, or if the Devonian lower crustal events observed in the more western parts have completely erased the memory of such events. The evidence of Early Ordovician volcanites and/or granites, sometimes of alkaline tendencies, in the more western blocks just indicates the rifting related to the break-off of Avalonia.

The constituents of the future Hun-composite terrane are interpreted to represent an eastern prolongation of Avalonia (Figs. 3, 7), and the suture zone hidden in the superterrane are interpreted to represent the eastern prolongation of an early stage of the Rheic ocean (see also Finger et al. 1998), before the Ordovician amalgamation (Figs. 7, 8). This amalgamation would have been the result of a diachronous consumption of the mid-ocean ridge of Proto-Tethys which triggered the intrusion of late Cadomian granitoids and consequently the early separation (480 Ma) of Avalonia from its neighbouring blocks following the onset of generalized slab roll-back of the remaining ocean. The opening of the eastern branch of the Rheic was stopped by the contemporaneous spreading of the Asiatic ocean (Zonenshain et al. 1985) and partial collision with a major transformation zone at the southern end of the exotic Karakum–Tarim–north China terrane. It is only since the break-off of Avalonia that the plate-tectonic evolution of the more eastern-situated microcontinents (e.g. Cadomia, Intra Alpine Terrane) became different, and the following events could have been the consequence of accretion and shifting of subduction zones to external domains, as discussed for the contemporaneous evolution at the Pacific Gondwana margin (Rapela et al. 1992; Tessensohn 1999).

The time period after the Ordovician amalgamation is characterized by the sucessive stages of subduction, and the contemporaneous formation of accretionary wedges and arc-volcanics at the Silurian active margin of Gondwana. This is supported by Silurian eclogite ages from the Tauern area (von Quadt et al. 1997) and comparable ages from the Argentera External

Massif (Paquette et al. 1989), and the Massif Central domain (e.g. Ducrot et al. 1983; high-pressure event: Pin and Lancelot 1982). Relics of Silurian volcanic arcs have been recognized in the domain of the North German Crystalline Rise, interpreted as an active margin setting in the South of the Rhenohercynian domain (Altenberger and Besch 1993; Reischmann and Anthes 1996a, 1996b; Zeh et al. 1997), and in our model the active margin is located on the northern border of the Hun-superterrane (Figs. 7, 8). The diachronous Palaeo-Tethys opening in Silurian-Early Devonian times is viewed as a back-arc opening along the Gondwana margin (Stampfli et al. 1991; Stampfli 2000). Faunistic assemblages (Schönlaub 1997a, 1997b; Schönlaub 1993; Schönlaub and Histon 2000) and palaeomagnetic data (Bachtadse et al. 1995; Schätz et al. 1997; Tait et al. 1998; Torsvik et al. 1994; Torsvik and Eide 1998) support the migration of the Hun superterrane towards Laurussia. It is interesting that Noblet and Lefort (1990) admit in their lower Ordovician stratigraphy a "future opening of the Tethys I ocean", and that in the Silurian palaeogeographic reconstruction (Paris and Robardet (1990) admit an opening oceanic domain as a branch of the Rheic ocean for the more eastern-situated domains of the large Gondwana shelf.

Difficulties arise when comparing drift models of continental pieces since the Silurian. Matte (1986) and Robardet (1996) propose the migration of Gondwana towards Laurussia, whereas Tait et al. (1998), based on palaeomagnetic data, discuss the migration of individual microcontinents or groups of continents, coinciding with predictions based on faunistic criteria (Schönlaub 1993), and such models could be correlated with a modified model of the Hun-superterrane and its migration (forthcoming discussion given by G.M. Stampfli et al., submitted).

Considering the parallels of pre-Variscan evolution of the different microcontinents preserved in the Variscan domain (Fig. 3), it is tempting to propose a nomenclature for the classical tectono-stratigraphic realms, taking into account the former geological evolution at the Gondwana margin. The assemblage of Cadomian basement, Neoproterozoic to Cambrian active margin setting, and Ordovician accretionary stages represent the leading edge of the Hun-superterrane and includes a Middle Ordovician suture of aborted Rheic ocean. Large areas of the Moldanubian, of the French Central Massif and from NW Iberia can be grouped under this assemblage. The units, characterized by the opening of the Paleo-Tethys which separated the Hun super-terrane from Gondwana in Late Silurian times, belong to the classical Saxothuringian domain and the southern part of Armorica s.l. As a consequence of the Variscan evolution since the Silurian (G.M. Stampfli et al., submitted), the classical Rhenohercynian zone together with the Lizard domain, and the South Portuguese and Moravo-Silesian zones, opened as a Devonian oceanic domain within the Laurussia margin, due to Gondwana-directed slab pull. The contemporaneous leading edge of the Hun-superterrane is represented by the Silurian-Devonian active margin (part of the mid-German Crystalline Rise).

Although the proposed models do not contradict palaeoreconstructions in terms of palaeomagnetic information and faunal distributions mentioned previously, an interdisciplinary discussion is still needed to better understand plate-tectonic evolution during Early Paleozoic times. Important information on key areas are still lacking, and we view this paper as stimulation for further discussion and research, which has started already through the stimulating contribution from the reviewers. Little is known about the larger distribution of the Ordovician orogenic event, and precise age determinations of magmatic rocks or refined provenance studies of sedimentary rocks, even of high-grade metamorphic rocks, are greatly needed.

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