Int J Earth Sci (Geol Rundsch) (2015) 104:1107–1121
DOI 10.1007/s00531-015-1142-x

SHORT NOTE

# Ediacaran to Cambrian oceanic rocks of the Gondwana margin and their tectonic interpretation

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Received: 22 October 2014 / Accepted: 4 January 2015 / Published online: 24 January 2015

**Abstract** In tectonic maps of Variscan Europe, allochthonous pieces of Cadomian basement clearly stand out with their predominant metabasic to ultrabasic elements, the so-called exotic terranes with ophiolites. Most of these domains are observed in basements of the Central Iberian Allochthone, the South Armorican domain, the nappe structures of the French Massif Central, the Saxothuringian Zone and the Bohemian Massif. Similar relics can be recognized in many Alpine basement areas, and correlations with supposedly more autochthonous basements, such as the Ossa Morena Zone and the Central Iberian basement, can be envisaged. All of these relics are thought to represent the interrupted trace of a former continuous or discontinuous structure, characterized by the presence of ocean-derived proto-Rheic rock suites. These can be interpreted as pieces of former magmatic arcs of Ediacaran to Cambrian age accreted to the Gondwana margin, which later were scattered as allochthonous units during the Variscan plate-tectonic processes. The presence of similar rock suites of Ordovician age in the Alpine realm is explained by the accretion of exotic China-derived basements and their collision with the Gondwana margin during the opening of the Rheic Ocean.

**Keywords** Neoproterozoic–Cambrian · Geodynamic reconstruction · Gondwana margin · Correlation with western Gondwana

## Introduction

The Palaeozoic Gondwana margin and its interaction with Laurentia–Baltica are strongly related to the history of the Rheic Ocean (Nance et al. 2010; Stampfli et al. 2013). Distinct interpretations have been envisaged for the European Variscan context (Ballèvre et al. 2009; Martínez Catalán et al. 2009; Linnemann et al. 2007; Stampfli et al. 2011), involving models of early interaction with Laurentia–Baltica, the accretion of proto-Rheic intra-oceanic pieces, or only Gondwana-derived terranes, and the formation of the Rheic Ocean was seen either as an intracontinental rift zone or as a widely stretching oceanic space.

Although great progress has been made in the interpretation of the Variscan plate-tectonic evolution (Kroner and Romer 2013; Ballèvre et al. 2014; Lardeaux et al. 2014; Schulmann et al. 2009), the plate-tectonic interpretation of the Variscan basement domains hosting the so-called exotic terranes with ophiolites drawn in Fig. 1a did not change.

The pre-existing omnipresent Cadomian basement (e.g. Linnemann et al. 2007) appears as relics in the highly transformed Variscan basement, and in this framework, we hypothesize the “exotic terranes with ophiolites” (Fig. 1a), and some adjacent autochthonous basements, to represent remnants of a former continuous or

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discontinuous suture zone. The latter can be characterized through the presence of ocean-derived rock suites, which are probably representing pieces of a former continuous magmatic arc of Ediacaran to Cambrian (proto-Rheic) age accreted to the Gondwana margin before being dissipated as allochthonous units during the Variscan plate-tectonic processes.

Our arguments are based on the singular distribution of these units when placed in an already published Early Palaeozoic reconstruction (Stampfli et al. 2011): In tracing terranes back to their possible position around Gondwana, obviously, not all could be positioned north of Africa. The new concept proposes a ribbon-like Galatian superterrane, comprising most of the "European" Variscan elements and extending in Ordovician times from the north of South America to South China (located formerly in continuity to Africa). Evidently, along such a length, the geodynamic evolution presents variations. Instead of terminating the considerations at the Tornquist Line, the hitherto used model and knowledge from the Altaids (Wilhem et al. 2012) let us adopt geodynamic scenarios for the extended Gondwana margin including the Chinese basement areas thus reviving the discussion by von Raumer et al. (2002) and Kalvoda and Bábek (2010). In this enlarged frame, we want to demonstrate, that the allochthonous "exotic terranes with ophiolites" (presented in Fig. 1a) could represent the relics of a former Ediacaran–Cambrian active margin setting along the Gondwana margin, also comprising pieces of Chinese blocks, usually ignored in general considerations.

## Ediacaran–Cambrian elements

In the European geodynamic context, the so-called allochthonous domains with ophiolites (Arenas et al. 2007a, their Fig. 1) basements hosting Ediacaran–Cambrian mafic to ultramafic rock suites (Fig. 1a) appear above the Central Iberian basement, possibly in the South Armorican zone and in the Limousin domain of the French Massif Central, in the Saxothuringian, the Teplá–Barrandian of the Bohemian Massif, and in comparable Cambrian–Neoproterozoic elements from the Alpine domains (e.g. Austroalpine and Briançonnais), all supposed to host mafic and/or ultramafic rock units predating the opening of the Rheic Ocean. Additionally, the Neoproterozoic–Cambrian metabasites from the Ossa Morena Zone and the Central Iberian basement are included in our considerations.

We present in the following lines only the above mentioned basements, proceeding from the most western located Ossa Morena Zone to the most eastern located Alpine domains, independent of their Variscan evolution (comp Table 1):

**Fig. 1** Geodynamic units hosting allochthonous "exotic" terranes ▶ with ophiolites as relics of former Ediacaran–Cambrian Geodynamic units from the Gondwana margin. **a** Late Variscan geological map modified after Arenas et al. (2007a). **b**, **c** Late Variscan (**b**) and Hirnantian (**c**) plate-tectonic reconstructions, modified after Stampfli et al. (2011). *Stars* (*black* and *violet*) meta-eclogites; *Crosses* autochthonous, low-grade rift-related magmatic rocks. *Light blue* Avalonian basements; *Light brown* Rhenohercynian domain. A–A′: Section 450 Ma in Fig. 4. *Ad* Adria and Sardinia, *All* Allochthonous above the Iberian basement, *al-Sx* allochthonous Saxothuringian, *An* Anatolic, *AP* Aquitaine Pyrenees and Corsica, *Ar* Armorica, *ArS* South Armorica, *Au* Austroalpine, *Bri* Briançonnais, *BRK* Betics-Rif-Kabbilies, *Bw* Brunswick, *Ca* Cantabrian and West Asturian-Leonese zones, *CC* Caucasus, *Ch* Channel, *ChR* Chamrousse, *cI* Central Iberia, *Cr* Carpathian, *Ct* Catalunia, *Db* Dobrogea, *D–B* Dacides–Bucovinian, *eM* Eastern Moroccan Meseta (interpreted after Herbig and Aretz (2013, with references), *Gt* Getic nappes, *He* External Alpine massifs, *Hl* Hellenidic, *Is* Istanbul, *Li* Ligerian block, *Md* Moldanubian (Black Forest and Vosges included) and Teplá–Barrandian, *MC* French Massif Central, *Me* Moroccan Meseta, *Mg* Meguma, *MM* Montagne Noire-Maures and Tanneron, *Mo* Moesia, *MR* Mid-German Rise, *OM* Ossa Morena, *Po* south Portuguese, *Pt* Pontides (Karakaya), *Rd* Rhodope, *Sh* Sehoul block, *Sx* Saxothuringian domain, *TB* Teplá–Barrandian unit of the Bohemian Massif, *TW* Tauern Window, *Tz* Tizia

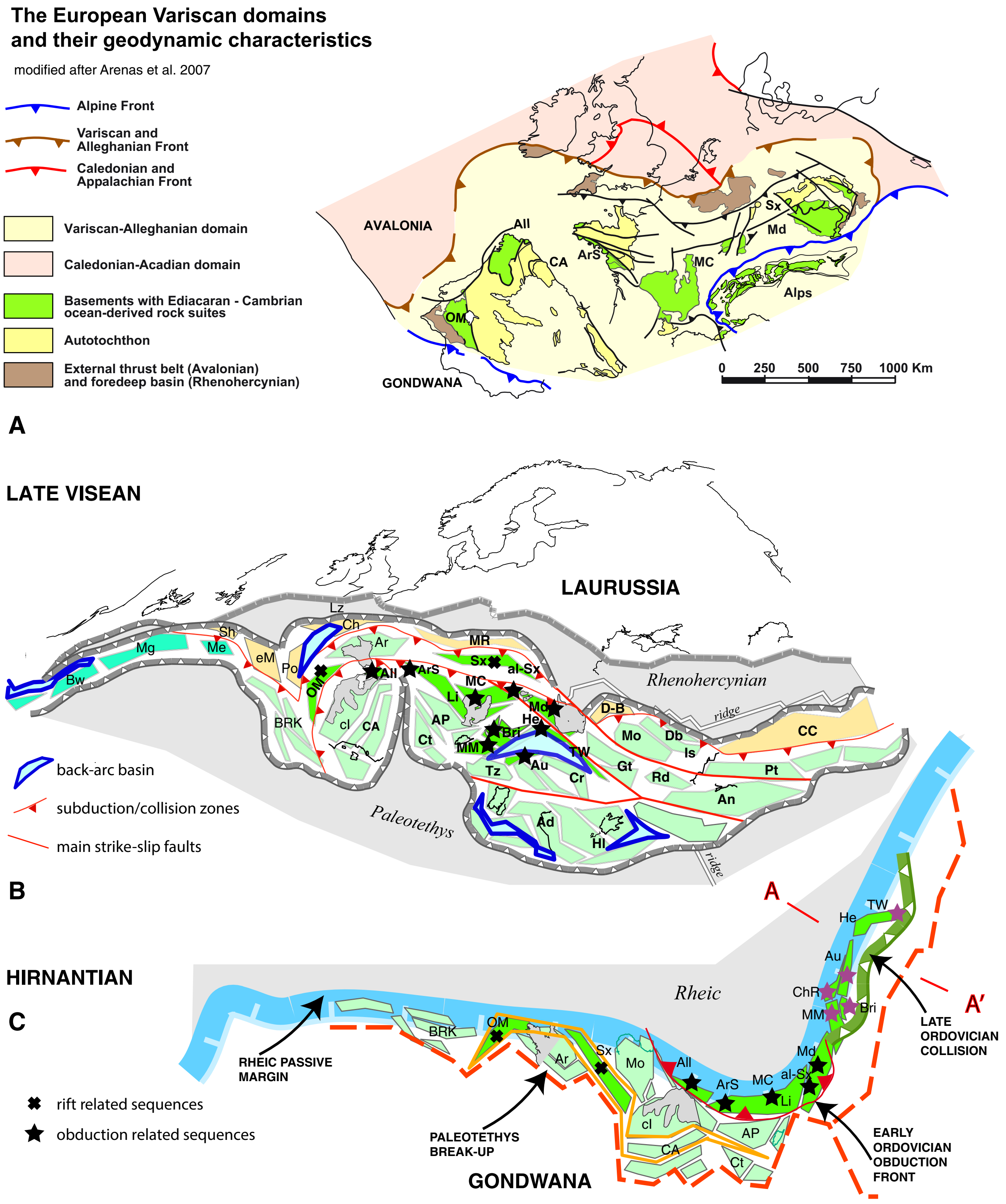
### Ossa Morena Zone

Two rift-related magmatic events (Sánchez-García et al. 2008; Chichorro et al. 2008; Pereira et al. 2012), comprising an Early Cambrian magmatic cycle dominated by calc-alkaline felsic rocks followed by a Middle Cambrian to Early Ordovician magmatic suite with bimodal alkaline and tholeiitic magmatic rocks, were interpreted as the opening and subduction of a Late Cambrian to Ordovician oceanic ridge (Sánchez-García et al. 2010), after Cambeses et al. (2014) a Cambro-Ordovician rifted volcanic margin. Sánchez Lorda et al. (2014a, b) identify the metabasic series hosted by the Serie Negra metasediments as a Late Ediacaran magmatic arc.

### The allochthonous units above the Central Iberian Zone

Derived from peri-Gondwanan regions, they include the Variscan suture s.l. outlined by a suite of Devonian ophiolitic units.

*In the northern allochthonous domain*, the uppermost terrane is formed by a thick sequence of Cambrian siliciclastic rocks intruded by large massifs of gabbros (Monte Castelo gabbro) and granitoids (Corredoiras orthogneiss) dated at ~500 Ma (Abati et al. 1999; Andonaegui et al. 2012). The contemporaneous intermediate pressure tectonothermal evolution was followed by a high-pressure and high-temperature event dated at c. 400 Ma (Abati et al. 2007; Fernández-Suárez et al. 2007). In the underlying Variscan "suture", two main types of ophiolites have been described: a younger group with Devonian ages and an older group dated at ca. 500 Ma. From the latter, Sánchez



Martínez et al. (2012) interpreted the Late Cambrian Bazar ophiolite as derived from the Iapetus–Tornquist Ocean, which, subsequently, was accreted to a dissected Ordovician arc before or during the opening of the Rheic Ocean.

The Vila de Cruces ophiolite (Table 1, N-MORB, Arenas et al. 2007b), by contrast, is considered as a remnant of a Cambrian back-arc basin generated during the beginning of the opening of the Rheic Ocean. The basal units of the

**Table 1** Ediacaran–Cambrian ages of metabasic and ultramafic rocks along the Gondwana margin (for older references, see Neubauer 2002, von Raumer et al. 2002)

| Terrane | Rock-type | Age (Ma) | References |
|---|---|---|---|
| 1. Ossa Morena | Felsic volcanics early rift | (~530) | Sánchez-García et al. (2010) |
| | Main rift basalts | 502 | |
| | Amphibolites N-MORB, E-MORB, VA | ~580 εNd +0.8 to +8.4 | Sánchez Lorda et al. (2014) |
| 2. Central Iberia | | | |
| Allochthon | Monte Castelo gabbro | 499 ± 2 | Abati et al. (1999) |
| | Vila de Cruzes ophiolite, N-MORB | 497 ± 4 | Arenas et al. (2007a, b) |
| | Bazar ophiolite | 495 ± 2 | Sánchez Martínez et al. (2012) |
| | Malpica Tuy eclogites | 494, 498 | Abati et al. (2010) |
| | Eclogite protolith | ~491 | Roper et al. (2013) |
| Autochthon Tamames | Neoproterozoic–lowermost Cambrian metaandesites | Lithostratigraphy | Rodríguez Alonso et al. (2004) |
| 3. South Armorica | Granitoids, gabbros | 480, 470 | Ballèvre et al. (2014) |
| 4. French Massif Central | | | |
| Marvejols | Bimodal volcanics | ~480 | Pin and Lancelot. (1982) |
| Limousin | Eclogite, N-MORB tholeiite | 489–475 | Berger et al. (2010, 2012) |
| Massif de Maures | Supra-subduction lithosphere | Early Palaeozoic | Bellot et al. (2010) |
| 5. Alps | | | |
| External domain | Chamrousse oceanic granite | 498 | Ménot et al. (1988) |
| | Chamrousse oceanic granite | 500 | Pin and Carme (1987) |
| | Aarmassif, gabbro | 475–467 | Oberli et al. (1994) |
| | Aarmassif, gabbro | 478 ± 5 | Schaltegger et al. (2003) |
| | HT stage | 456–450 | |
| | Cordierite-pegmatite | 445 ± 2 | |
| Penninic domain | | | |
| Briançonnais | Thyon granite | 500 +3/−4 | Bussy et al. (1996) |
| | Metagabbro, | 504 ± 2 | Sartori et al. (2006) |
| | Cambro-Ordovician | Lithostratigraphy | |
| | Oceanic metabasites | | |
| Métailler formation | Gabbros, tholeiites E-MORB | 457, 462 detrital zircon 520 | Gauthiez et al. (2011) |
| Berisal unit | Tholeiitic amphibolites | 546 ± 21 Sm/Nd wh.r | Stille and Tatsumoto (1985) |
| | Gabbro | 475 εNd + 5.4 | |
| Biasca–Loderio | Mafics–ultramafics IA/T-MORB | ~518 7.3 to 4.2 | Schaltegger et al. (2002) |
| | Sasso Nero metadiorites | 533, 544 | Bussien et al. (2011) |
| Adula Salahorn | Back-arc tholeiites | 514–518 | Cavargna-Sani et al. (2014) |
| Adula Treskolmen | MORB tholeiite affinity | 521.1 | Cavargna-Sani et al. (2014) |
| Austroalpine domain | | | |
| Silvretta nappe | Gabbro | 475, 510 | Poller (1997) |
| | Arc metadiorites | ~610 | Schaltegger et al. (1997) |
| | Metagabbros, metatonalites | 523 | Schaltegger et al. (1997) |
| | Oceanic granite | 500 | Müller et al. (1996) |
| Tauern Window | Supra-subduction | Cambrian | Frisch and Neubauer (1989) |
| | Basalts | 547 ± 27 | Eichhorn et al. (1999) |
| Habach terrane | Mafic–ultramafic cumulates | 496–482 | Eichhorn et al. (2001) |
| Tauern Window South | Eclogite protolith | 488 | Von Quadt et al. (1997) |
| | N-Morb intra-oceanic arc | 590 εNd 6.9 | Schulz et al. (2004) |
| | Arc basalt | 550–530 εNd −.3 + 2.5 | |
| | Metagabbro | 477 | Loth et al. (2001) |
| Oetztal | Metagabbro, ultramafics | 530–521 | Miller and Thöni (1995) |
| Southern Alps | Eclogites HP event | 457 ± 5, 443 ± 19 | Franz and Romer (2007) |

**Table 1** continued

| Terrane | Rock-type | Age (Ma) | References |
|---|---|---|---|
| 6. Saxothuringian | | | |
| Vesser area | MOR gabbro | 501.7 | Kemnitz et al. (2002) |
| Münchberg Klippe | Eclogiteic metagabbro | ~500 | Gebauer and Grünenfelder (1979) |
| Erbendorf-Hohenstrauss | Metagabbro | 494 ± 3 | Von Quadt (1990) |
| 7. Bohemian Massif | | | |
| Letovice Complex | Tholeiitic metabasalt | 530 ± 6 | Soejono et al. (2010) |
| Marianske Lasné | Coronitic metagabbro | 516–496 | Stedra et al. (2002) |
| | Oceanic crust protolith | ~540 | Timmermann et al. (2004) |
| | Coronitic metagabbro | 503, 496 | Timmermann et al. (2006) |
| Tepla–Barrandian unit | Smrzovice meta-quartzdiorite | ~550 K–Ar Hbl | Bues et al. (2002) |
| | Leucotonalite pebble | 610 ± 17 | Smala et al.Sláma et al. (2008) |
| | Volcanic rocks | 568 ± 3 | Dörr et al. (2002) |
| | Metarhyolite | 524 ± 8.8 | Žák et al. (2013a, b) |
| Bavarian Forest | Epidote–amphibolite | 548 | Teipel et al. (2004) |
| | Eclogitic amphibolite | 481–482 | Teipel et al. (2004) |

Presented εNd ages already may reflect alteration (Schaltegger et al. 2002). The authors recognize that many of the observed metabasic units in the Variscan mountain chain still wait for identification, needing future investigations. Consult references for analytical data

allochthonous complexes would represent the most external margin of Gondwana, constituted by Ediacaran to Cambrian terrigenous sequences, intruded by calc-alkaline to peralkaline granitoids and minor mafic rocks dated at around 510–470 Ma (Abati et al. 2010; Díez Fernández et al. 2010).

*In the southern allochthonous* Morais domain, Dias da Silva et al. (2012) brought the first evidence for a Late Cambrian bimodal Mora volcanic suite, observed at its base.

In *the subjacent Central Iberian basement*, andesitic volcanics testify to a Neoproterozoic–earliest Cambrian synsedimentary magmatism (Rodríguez Alonso et al. 2004), supposed to be closely related to the subduction of the Ossa Morena Zone.

### South Armorican domain

Following Ballèvre et al. (2014), the metabasic units in the Bay d'Audierne domain have an Ordovician age and, together with the Champtoceaux and Essarts areas, could possibly host Ediacaran–Cambrian basic to ultrabasic rock suites (Fig. 1a).

### French Massif Central

Strongly metamorphosed relics of Late Neoproterozoic to Early Palaeozoic oceanic rock suites were supposed to be part of the Upper Gneiss Unit (Ledru et al. 1989; Faure et al. 2009), being interpreted to represent an Early Ordovician continental break-up (Pin 1990; Pin and Marini 1993; Santallier 1994). Specifically, the Limousin area presents features of an early magmatic evolution (Lardeaux et al. 2001; Berger et al. 2005, 2010, 2012), hosting relics of a former pre-Cambrian to Cambrian oceanic crust, equally discussed for the Maures Massif (Bellot et al. 2010). Ultra-high-pressure relics dated about 412 Ma in the Limousin area (Berger et al. 2010) may represent a lower Devonian intra-oceanic subduction event before the general Early Variscan HP evolution around 380 Ma (comp. Stampfli et al. 2013, their Figs. 7, 4–5).

### Saxothuringian Zone and Bohemian Massif

These basements were object of a general re-interpretation (Franke 2000; Friedl et al. 2004; Schulmann et al. 2009, 2014; Žák et al. 2014). After the Cadomian accretionary evolution (Linnemann et al. 2007, 2008), Lower to Middle Cambrian rift basins in the Saxothuringian Zone resulted in an oblique incision of an oceanic ridge into the continent (Linnemann et al. 1998), and the Vesser ultramafic body (501 Ma, Kemnitz et al. 2002) preceded the opening of the Rheic Ocean (Tremadoc). The Münchberg eclogitic metagabbro (~500 Ma, Table 1) was tectonically related to the Bohemian Teplá–Barrandian Zone (Franke 2000).

The Teplá–Barandian unit in the Bohemian Massif (Hajná et al. 2013; Sláma et al. 2008; Žák et al. 2013b; Zulauf et al. 1999) testifies to Cadomian island-arc volcanism (620–560 Ma) and subsequent (560–530 Ma) arc erosion, before crustal extension since 510 Ma and back-arc-type opening of the Prague basin contemporaneous to the opening of the Rheic Ocean with basic submarine volcanism (Table 1). The Mariánské Lázně complex is characterized by large mafic-dominated Cambro–Ordovician bimodal series (e.g. Crowley et al. 2002; Floyd et al. 2000; Stedra et al. 2002) with N-MORB to within-plate alkali basalts. Bues et al. (2002) and Teipel et al. (2004) dated Ediacarian magmatism in the western Teplá–Barrandian Zone (Table 1).

The Brunovistulian unit in the south-east of the Bohemian Massif hosts a distinctly older assemblage of rock units with different types of metabasic rocks representing the Avalonian margin of the rock series under discussion in this paper (Finger et al. 2000).

### Alpine terrane assemblages

Following Neubauer's (2002) comparative paper, Schulz (2008) reported from distinct Austroalpine domains (comp. Table 1) a rather long-lasting magmatic evolution, comprising intra-oceanic arcs (metadiorites around 610 Ma; N-MORB-type eclogitic metabasalts around 590 Ma), subsequent 550–530 Ma volcanic arc basalts and 520–530 Ma eclogitized gabbroic and tonalitic melts intruding a continental (Gondwana) margin magmatic arc. These were followed by 500 Ma oceanic plagiogranites in a supposed fore- or back-arc environment and the subsequent intrusion of gabbroic melts (475 Ma) in a collisional to post-collisional context. Sartori et al. (2006) and Scheiber et al. (2014) suggest an extensional Neoproterozoic–Cambrian evolution for the Briançonnais Siviez-Mischabel type basement. Equally, in the lower Penninic nappes (Schaltegger et al. 1997; Bussien et al. 2011), Early Cambrian metadiorites (533, 544 Ma) from a banded mafic complex and Cambrian (~518 Ma) oceanic magmatism as dismembered relics of mafic and ultramafic rocks testify to a Cambrian magmatic evolution dominated by metabasic magmatic rocks. For the South Alpine Strona-Ceneri Zone, an upper Ordovician HP evolution is discussed (Zurbriggen et al. 1997; Franz and Romer 2007), with an upper Ordovician orogenic evolution for this area (Zurbriggen 2014). An Ordovician orogenic evolution has also been proposed for the external parts of the Alps (Schaltegger et al. 2003). Supposed Ediacaran–Cambrian meta-volcanic series from the Aiguilles Rouges basement (von Raumer et al. 2013; external alpine basement) can be compared to nearly identical lithostratigraphies from the Central Iberian basement (Rodríguez Alonso et al. 2004). The "root-less" Alpine ultramafic Chamrousse ophiolite complex from the external domain (Belledonne, Ménot et al. 1988) represents an allochthonous Late Cambrian magmatic body involved in the Variscan tectonic evolution (Guillot et al. 2009).

## Discussion

Summarizing the data (Table 1), an Ediacaran to Cambrian age group (~650–510 Ma) is documented through intra-oceanic dismembered sequences, representing an early magmatic arc (Ossa Morena, Saxothuringian–Teplá Barandian Units, Austroalpine domains), which accreted over a period of time to form a Cambrian peri-Gondwana cordillera (Fig. 2). The Ossa Morena and the Teplá–Barrandian domains areas (see preceding chapter) show some interesting parallels when considering their more or less synchronous rifting-type subsidence patterns (Von Raumer and Stampfli 2008). The observations of widely distributed sedimentary horizons hosting amphibolites in the Ossa Morena Zone (Sánchez Lorda et al. 2014), probably former Ediacaran arc basalts, and possibly also in the Bohemian Massif (Hajná et al. 2013) reinforce these parallels. Comparable arc volcanics are known from the Austroalpine domain (Schulz et al. 2004) and compose also the Penninic Briançonnais basement nappes (Sartori et al. 2006). The Siviez-Mischabel and Mont Fort nappes (Escher 1988) represent parts of different types of basement, the former could represent the Ediacaran arc, intruded by Late Cambrian gabbros and granitoids (Bussy et al. 1996, and in Sartori et al. 2006), whereas the latter may comprise a suture zone (serpentinites, mélange type) of Ordovician age (comp. Gauthiez et al. 2011). The pre-Rheic igneous evolution ended apparently with a period of crustal extension along the Gondwana margin, accompanied by the emplacement of c. 500 Ma mafic to granitoid rocks: "where in a scenario of oblique convergence, pull-apart may have facilitated the appearance of ophiolites, accompanied laterally by incomplete intra-oceanic rock suites, or simply by volcanic rocks and/or detrital sediments" (Von Raumer et al. 2002, p. 45), strike-slip models having been evoked since Murphy and Nance (1989). Reconstruction of cross sections (Fernández-Suárez et al. 2014; Zulauf et al. 1999; Schulz et al. 2004; Linnemann et al. 2007; Sánchez Martínez et al. 2012; Žák et al. 2013a; Ballèvre et al. 2014) present intra-cordillera rifting at lower crustal level triggering the upwelling of asthenosphere, leading to back-arc rifting during the Early Ordovician. Similarly, in the Saxothuringian basin (Linnemann et al. 2014), a synrift sequence from the Tremadoc onwards is supposed to accompany the opening of the Rheic Ocean, and in the Prague basin, it is accompanied by basic submarine volcanism (Patočka et al. 1994; Žák et al. 2013b). The South Armorican units could have formed in a comparable context, as Ordovician igneous rocks (Table 1) seem to represent the main Early Palaeozoic manifestation.

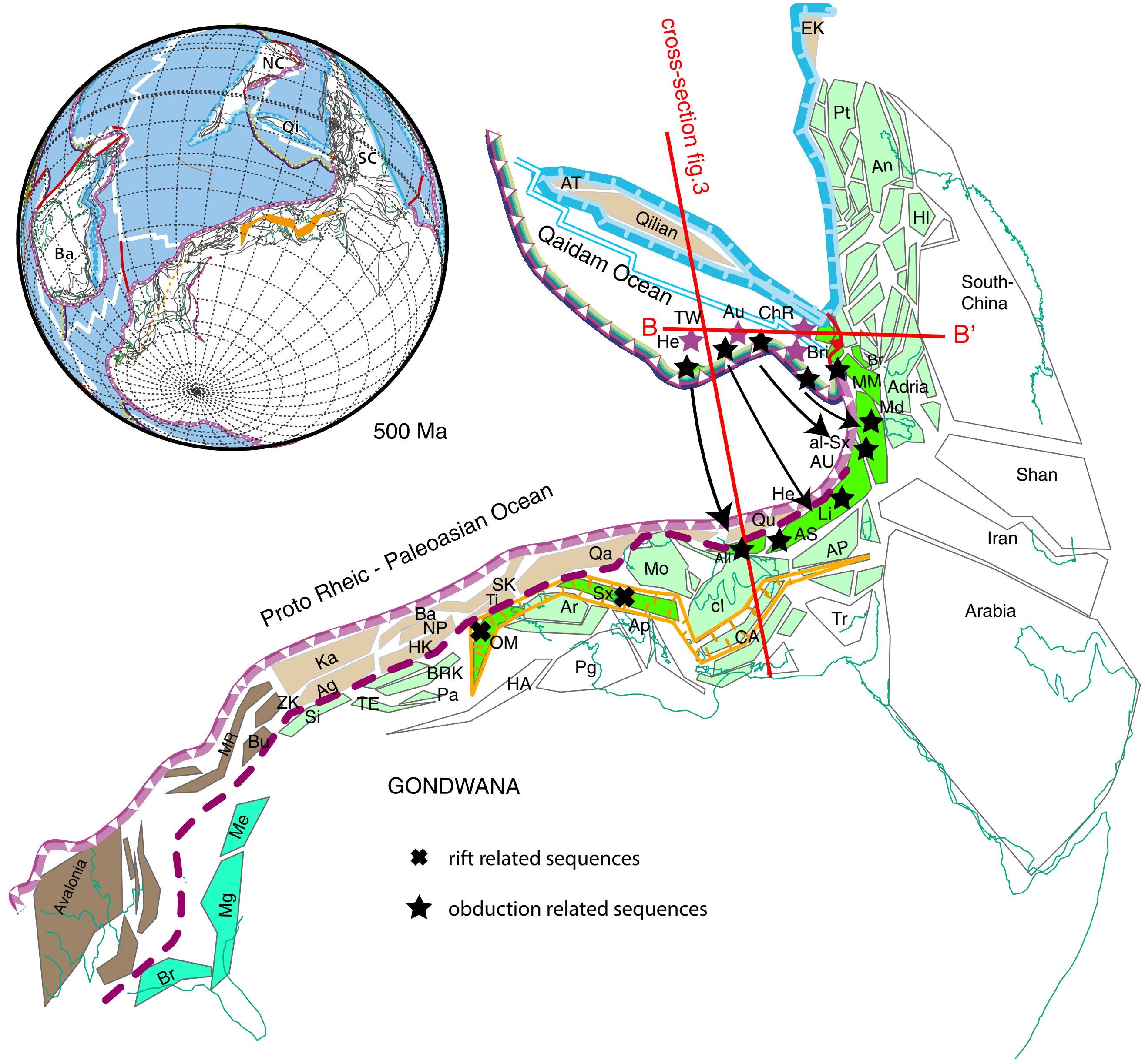


**Fig. 2** Cambrian (500 Ma) plate-tectonic reconstruction (modified after Stampfli et al. 2011). *Stars* (*black* and *violet*) Magmatic rocks as meta-eclogites, *Crosses* Cambrian rift-related magmatic rocks. The future break-up of the Rheic Ocean is marked as a *dashed purple line*. **a** *Inset* Geodynamic units along the Gondwana margin, presented in detail in **b** Geodynamic units along the Gondwana margin. *Light brown* Hunic terranes, future Chinese basement domains; *Light green* Central European. Variscan basements with domains (*dark green*) hosting allochthonous former proto-Rheic oceanic basements. *Orange* Rift zone with strong subsidence and accumulation of detrital sediments (comp. von Raumer and Stampfli 2008). *Stars* Magmatic rocks as meta-eclogites, *crosses* Cambrian rift-related magmatic rocks. B–B′: Section 500 Ma in Fig. 4. QILIAN ARC: *All* Iberian Allocthomous, *al-Sx* allochtonous Saxothuringian, *ChR* Chamrousse. GALATIAN: *Ar* Armorica, *Au* Austroalpine, *Md* Moldanubian Teplá–Barrandian unit, *He* External massifs, *Li* Limousin, *OM* Ossa Morena, *Sx* Saxothuringian, *BRK* Betic Rif Kabbylies, *TE* Tell East, *Si* Sidi, *Pa* Panormides. AVALONIA-HANSEATIC: *MR* Mid-German Rise, *ZK* Zonguldag-Kure, *Bu* Bukovina. GONDWANA: *Ap* Apulia, *HA* High Atlas, *Pg* Pelagian, *Tr* Taurus. HUNIA: *Ag* Aghdarband, *An* Anarak, *AT* Altyn Tagh, *Ba* Badakshan, *EK* East Kunlun, *HK* Hindukush, *Ka* Karakum, *NP* North Pamir, *Qa* Qaidam, *Qi* Qilian, *Qu* Qinling, *SK* South Kunlun, *Ti* Tianshuihal

## Plate-tectonic considerations

The existence of pre-Palaeozoic active margin sequences along the Gondwana margin has been discussed since Frisch and Neubauer (1989; Austroalpine gneiss-amphibolite association; Schulz et al. 2004). In view of their location at the margin border, Stampfli et al. (2011) proposed to correlate part of them with a pre-Rheic arc located in the

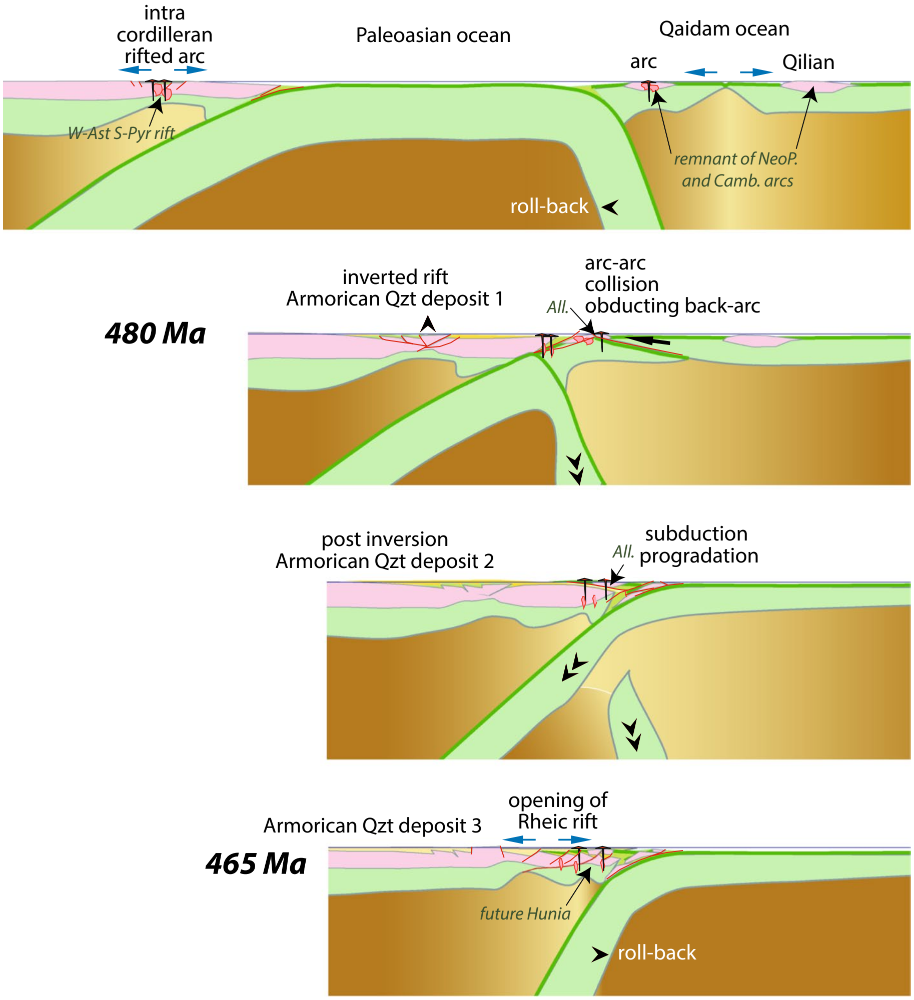


**Fig. 3** Geodynamic scenarios from the Late Cambrian to the Silurian across the future Alpine and adjacent domains at the Gondwana margin: from Late Cambrian arc–arc collision and subsequent back-arc obduction (480 Ma) along the Gondwana border. After subduction reversal, slab rollback is triggering the opening of the Rheic rift and Rheic Ocean (465 Ma) in eastern Gondwana. The arc–arc collision was diachronous, as well as the opening of the Rheic Ocean, both events taking place sooner westwards (c.10 Ma). The different stages of "Armorican Quartzite I, II, III" are commented in the *text*

Palaeo-Asian Ocean. The exotic Qilian–Qaidam arc basement of Fig. 2 could possibly be derived from these eastern regions (Wilhem 2010; Wilhem et al. 2012; Stampfli et al. 2013) and would consist of a Cadomian type basement. Ridge jump detached a fragment of Qilian to form the Qaidam arc (Fig. 3) accreted to the Gondwana margin around 475 Ma. Potential remnants of this arc could be represented by arc sequences at the top of the Iberian nappe pile dated around 500 Ma. The presence of 500 Ma plagiogranites (Chamrousse) could also be interpreted as derived from an intra proto-Rheic/Palaeo-Asian oceanic crust. Similarly, the Métailler formation of the Penninic domain (Sartori et al. 2006; Gauthiez et al. 2011) represents a potential post-Cambrian mélange of oceanic nature, comprising ultramafite, OIB, E-MORB and some carbonates. In this context, some mafic to ultramafic rock suites interpreted as related to intra-cordillera rifting (South Armorica, allochthonous Saxothuringian, parts of the Moldanubian) may have been derived from this exotic arc domain.

The topmost (Floian) Armorican Quartzite s.str. (Gutiérrez-Alonso et al. 2007; Shaw et al. 2012, 2014) in Iberia represents erosion of the rift shoulder of the opening Rheic Ocean; however, its base generally lies unconformably on a thick, folded, Late Precambrian to Cambrian turbidite sequence (McDougall et al. 1987) that we relate with the collision of the Gondwana active margin with the Qaidam arc, soon followed by the accretion of the Qilian block. Comparably, the Sardic tectonic phase (e.g. Martini et al. 1991) is of similar age and is found from Catalonia to the Montagne Noire and the nappe zone of Sardinia (Oggiano et al. 2010) where it marks the eastern limit of this Early Ordovician obduction event and related tectonic inversion of pre-existing rifts (Fig. 1).

The proposed cross-sectional model (Figs. 2, 3) is located at the junction between two types of setting. North of Africa the incoming Qaidam arc was most likely underplated and would have been removed by subsequent rifting of a relatively large (up to 500 km) Hunia during the opening of the Rheic Ocean (Fig. 3), whereas, eastward, the arc–arc collision was followed by the obduction of the young and buoyant Qaidam supra-subduction ocean. Part of these obducted arc/back-arc sequences have been preserved along this

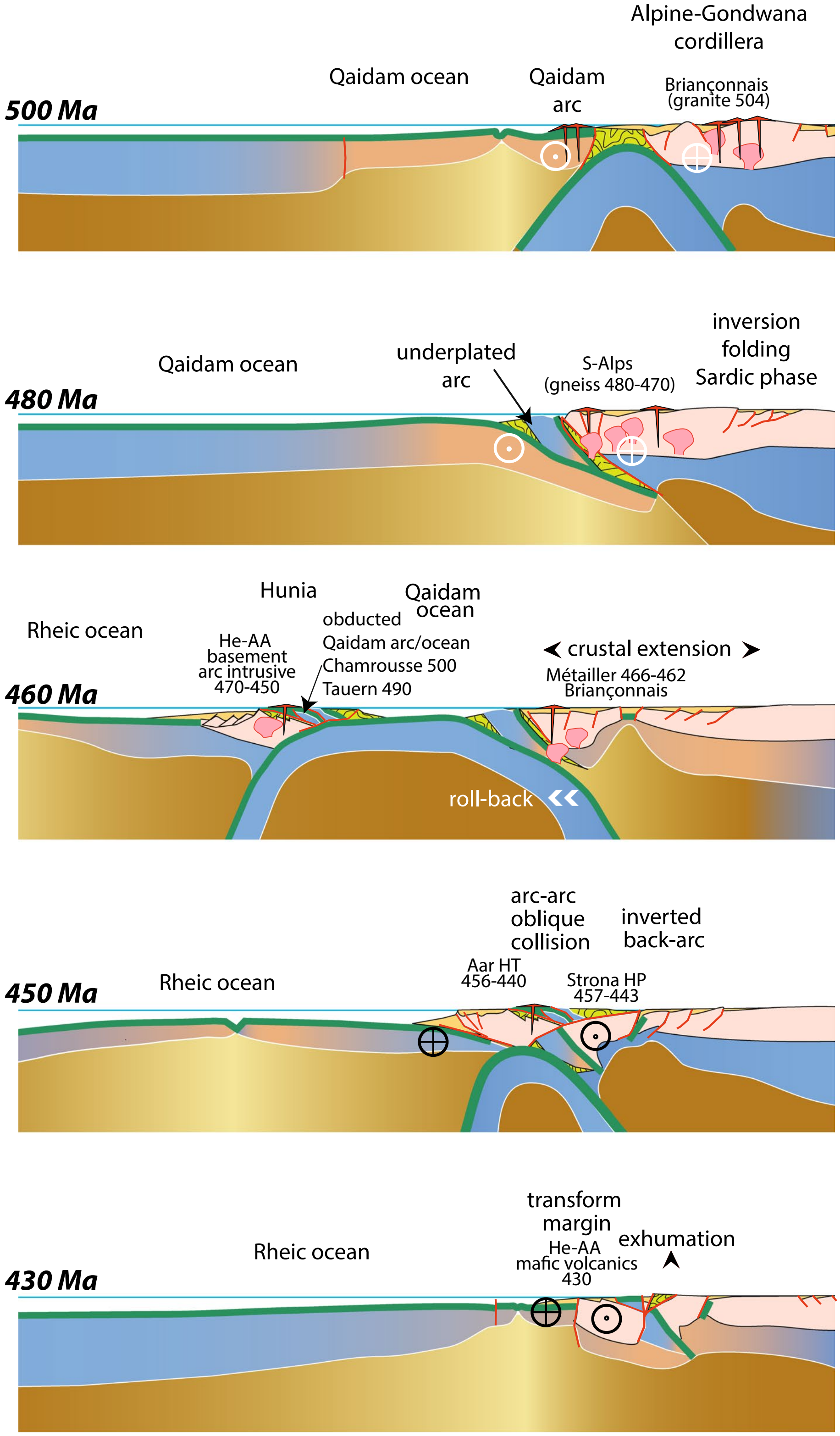


**Fig. 4** Early Palaeozoic geodynamic scenarios for the Alpine Briançonnais–Austroalpine basements and adjacent areas: from a Cambrian Gondwanan cordillera (500 Ma) to underplated arc and Sardic inverse folding (Sardic Phase 480 Ma), subsequent crustal extension (460 Ma), arc–arc oblique collision (450 Ma) and exhumation at a transform margin (430 Ma). Age data from Table 1 and from von Raumer et al. (2013)

portion of the margin (from the allochtonous sequences of Spain to the Alpine domains) due to the removal of a relatively thin (100 km) Hunia ribbon terrane along that portion of the margin. The obducted sequences would then form the toe of the Gondwanan Rheic passive margin north of Spain, Ligeria and Moldanubian domains (palaeomagnetic data correspond to our Ordovician placing of the Prague basin, Patocka et al. 1994) after the opening of the Rheic Ocean.

The internal part of the obducted arc (and its Cadomian substratum) was removed during the drifting of Hunia (violet stars of Figs. 1, 2) and re-accreted north-eastwards along the future transform margin west of S-China (Fig. 4). This scenario is confirmed by the presence of a Late Ordovician orogenic evolution (Zurbriggen et al. 1997; Zurbriggen 2014) involving fore-arc sequences in the Strona-Ceneri Zone (Southern Alps) with possible parallels in the Austroalpine (Schulz et al. 2004) and external domains. The dated eclogites and HP evolution in a subduction zone (~457 Ma: Franz and Romer 2007: Strona-Ceneri Zone; Schaltegger et al. 2003: Helvetic domain) comprise mafic magmatism and resulted in crustal thickening from Early to Late Ordovician. The Métailler back-arc-type mafic rocks (Gauthiez et al. 2011) are interpreted here as a witness of a short-lived back-arc basin within the margin west of S-China, in view of its age too young to pertain to the Qaidam back-arc complex. After the Strona-Ceneri tectonic event, this "Alpine" domain margin became a passive transform margin, in which basic rocks were intruded at the passage of the Rheic mid-ocean ridge during the Silurian. This margin was also affected by a first phase of Paleo-Tethys rifting during that period that aborted in the Early Devonian (Stampfli et al. 2013). Most of the Alpine basement blocks are therefore regarded as pertaining to Hunia (cf. Schulz et al. 2004), before to be detached from Gondwana in the Devonian to form the large Galatian ribbon terrane.

When comparing structures along the Gondwana margin (Von Raumer et al. 2014), it becomes evident that structures observed at the eastern end of the Gondwana margin cannot directly be compared to the westernmost ones, where the main suture is supposed to represent mainly the amalgamation of Gondwana through Cadomian events (Murphy et al. 2006; Linnemann et al. 2008). The provenance of the involved basements may have had their origin in northern China or in north-eastern Baltica, and the suture is likely of Ediacaran (540–530 Ma) age. Eastern equivalents may be found in more eastern Variscan basement blocks, but the proximity of Panafrican and Cadomian sutures prevented any distinction so far.

The eastern Gondwana margin, the subject of this paper, contains Sardic and Strona type sutures in addition to older Cadomian, Panafrican ones which are related to the colliding Qaidam arc with Gondwana (African and Alpine type basements), and the drifting of Hunia, which occurred when Avalonia was already separated from Gondwana.

## Location in the Variscan nappe pile

The allochthonous units (Fig. 2) found in the Variscan nappe pile underwent an HP event well established around 390 Ma in the whole Variscan chain (Abati et al. 2010; Ballèvre et al. 2009; Faryad and Kachlík 2013; Godard 2009; Lardeaux et al. 2001; Lucks et al. 2002; Stampfli et al. 2002). Diverging points of view regard that event either as an early collision between Gondwana and Laurussia (Matte 2002, and references therein; Arenas et al. 2014), or as peri-Gondwanan (Stampfli et al. 2013, and reference therein). The Cambro–Ordovician oceanic relics that remained on the Gondwana passive margin of the Rheic have certainly been re-displaced and locally metamorphosed during this c. 410–390 Ma obduction/collision event (e.g. Timmermann et al. 2004; Berger et al. 2010) and also during younger Variscan HP–HT events (Abati et al. 2007; Fernández-Suárez et al. 2007) when Galatian blocks started to collide with each other (Stampfli et al. 2013). The main Variscan collision started around 360 Ma, locally accompanied by HP metamorphism (Maluski and Patočka 1997), and complex nappe structures were formed until the final closure of the Rhenohercynian Ocean in the Late Carboniferous. Therefore, the final juxtaposition of allochtonous units hosting Early Palaeozoic oceanic relics with other Variscan units is certainly not representative of their original position and still needs to be properly re-assessed.

The collision of these Variscan terranes with Laurasia-derived terranes (Hanseatic) started the Variscan cycle of collision s.str. In this context, the 390 Ma event is regarded as Early Variscan and peri-Gondwanan. The Variscan collision started around 360 Ma, and complex nappe structures were formed until the final closure of the Rhenohercynian Ocean in the Late Carboniferous.

## Summary and conclusion

The preceding chapters demonstrate the presence of an Ediacaran–Cambrian active margin setting along the Gondwana margin (Figs. 2, 3). Despite local differences, the basement areas under consideration must have evolved continuously and in a more or less cylindrical way during this earlier time period, resulting in the building of a cordillera along the Gondwana margin. But different to the sutures observed in the more western domains (Murphy et al. 2006; Linnemann et al. 2008), those of the eastern Gondwana margin, including the sectors from Iberia and Ossa Morena to the Bohemian Massif and the Eastern Alps, host younger Ordovician sutures in which older structures were preserved (Fig. 4). This diversified evolution is related to a possible juxtaposition of China-derived blocks and intra-oceanic arcs of the Palaeo-Asian/proto-Rheic Ocean with parts of this eastern Gondwana margin (see earlier discussion, von Raumer et al. 2002).

These eastern sectors of the Gondwana margin document the emplacement of Late Cambrian metabasic, ultrabasic or granitoid rocks possibly related to extensional environment of different origins. The thickened crust of the ageing Gondwanan cordillera may have collapsed more easily, also due to accelerating rollback as exotic terranes approached the margin in Early Cambrian times. Gabbros in intra-cordillera rifts had their contemporaneous counter parts in the exotic Qaidam domain due to rollback of the same Palaeo-Asian Ocean, resulting in the opening of Late Cambrian supra-subduction back-arc basins.

Arc–arc collision and opening of the Rheic Ocean were diachronous along the Gondwana margin. The cross sections of Fig. 3 characterize a more eastern location (see Fig. 2), where a Late Cambrian arc–arc collision was followed by back-arc obduction (480 Ma). Subsequent subduction reversal triggered the rifting and opening of the Rheic Ocean (465 Ma) as the Hun terrane left the eastern Gondwana margin.

For the Alpine Briançonnais–Austroalpine basements and adjacent areas, the sections (Fig. 4) depict after the Sardic tectonic inversion and folding stage (Sardic phase 480 Ma), a younger arc–arc oblique collision (450 Ma) of the eastern tail of the Hun terrane with the internal Alpine margin, followed by exhumation in a transform margin setting (430 Ma).

We conclude that parallels of a pre-Rheic magmatic evolution in the different Variscan allochthonous ophiolitic basement areas is evident. Presenting relics of former Ediacaran to Cambrian arcs, part of them could include remnants of intra-oceanic proto-Rheic/Palaeo-Asian arcs/back-arcs, before they were accreted to the Gondwana margin and before the opening of the Rheic Ocean. Time parallels with more western Neoproterozoic sutures (comp. Murphy et al. 2006) are evident, but differences appear in the more eastern Gondwana margin, where the evolution terminated with Late Ordovician suturing. The postulated obduction/collision event (c. 390 Ma) and the subsequent Variscan orogenic evolution explain the final tectonic situation of these ophiolitic sequences. We are conscious that much more detail research has to be performed for reconstituting the original pre-Cambrian to Ordovician plate-tectonic configurations, and it was only our intention to stimulate discussion for coming research.

**Acknowledgments** We acknowledge the constructive comments by Jiří Žák (Prague) on an earlier version of this paper, Fritz Finger (Salzburg) is thanked for careful comments and suggestions, and we are grateful to the Editor in Chief Wolf Christian Dullo for his understanding help. RA and SSM have been funded by the Spanish project CGL2012-34618. Walter Joyce (Fribourg) is thanked for English proof reading.

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