

# The birth of the Rheic Ocean – Early Palaeozoic subsidence patterns and subsequent tectonic plate scenarios

Jürgen F. von Raumer<sup>a,\*</sup>, Gérard M. Stampfli<sup>b</sup>

<sup>a</sup> Department de Géosciences, Université de Fribourg, Suisse, Switzerland

<sup>b</sup> Géologie-Paléontologie, Université de Lausanne, Suisse, Switzerland

## A B S T R A C T

New plate-tectonic reconstructions of the Gondwana margin suggest that the location of Gondwana-derived terranes should not only be guided by the models, but should also consider the possible detrital input from some Asian blocks (Hunia), supposed to have been located along the Cambrian Gondwana margin, and accreted in the Silurian to the North-Chinese block. Consequently, the Gondwana margin has to be subdivided into a more western domain, where the future Avalonian blocks will be separated from Gondwana by the opening Rheic Ocean, whereas in its eastern continuation, hosting the future basement areas of Central Europe, different periods of crustal extension should be distinguished. Instead of applying a rather cylindrical model, it is supposed that crustal extension follows a much more complex pattern, where local back-arcs or intra-continental rifts are involved.

Guided by the age data of magmatic rocks and the pattern of subsidence curves, the following extensional events can be distinguished:

- During the early to middle Cambrian, a back-arc setting guided the evolution at the Gondwana margin. Contemporaneous intra-continental rift basins developed at other places related to a general post-Pan-African extensional phase affecting Africa
- Upper Cambrian formation of oceanic crust is manifested in the Chamrousse area, and may have lateral cryptic relics preserved in other places. This is regarded as the oceanisation of some marginal basins in a context of back-arc rifting. These basins were closed in a mid-Ordovician tectonic phase, related to the subduction of buoyant material (mid-ocean ridge?)
- Since the Early Ordovician, a new phase of extension is observed, accompanied by a large-scale volcanic activity, erosion of the rift shoulders generated detritus (Armorican Quartzite) and the rift basins collected detrital zircons from a wide hinterland. This phase heralded the opening of Palaeotethys, but it failed due to the Silurian collision (Eo-Variscan phase) of an intra-oceanic arc with the Gondwana margin.

During this time period, at the eastern wing of the Gondwana margin begins the drift of the future Hunia microcontinents, through the opening of an eastern prolongation of the already existing Rheic Ocean. The passive margin of the remaining Gondwana was composed of the Galatian superterrane, constituents of the future Variscan basement areas. Remaining under the influence of crustal extension, they will start their drift to Laurussia since the earliest Devonian during the opening of the Palaeotethys Ocean.

Keywords:  
Early Palaeozoic  
Subsidence  
Extensional crust  
Rheic Ocean  
Gondwana margin  
Palaeotethys

## 1. Introduction

Great advances in reconstructing the birth and life of the Rheic Ocean have been made during the last years, leading to scenarios showing the evolution of the Gondwana margin from the Neoproterozoic to the Ordovician. A model of Neoproterozoic–Cambrian

cordillera was applied to the Avalonian part of the Gondwana margin (Nance et al., 2002), completed by new insight (Murphy et al., 2006; Arenas et al., 2007b; Linnemann et al., 2007). Equally in our scenario, after the Cadomian orogenic events, many of the Gondwana-derived microcontinents resided in a convergent margin setting (Fig. 1), with an oceanic domain (called Prototethys in the more eastern parts, Iapetus or Tornquist Ocean for the more western parts) subducting under Gondwana. Relics of a Neoproterozoic–Cambrian arc can be identified from the Ossa Morena (Bandres et al., 2002; Sánchez García et al., 2003; Pereira et al., 2007) and the Central Iberian Zone (Fernández-Suárez et al., 2000; Rodríguez Alonso, 2004) in the west,

\* Corresponding author.  
E-mail addresses: juergen.vonRaumer@unifr.ch (J.F. von Raumer),  
Gerard.Stampfli@unil.ch (G.M. Stampfli).

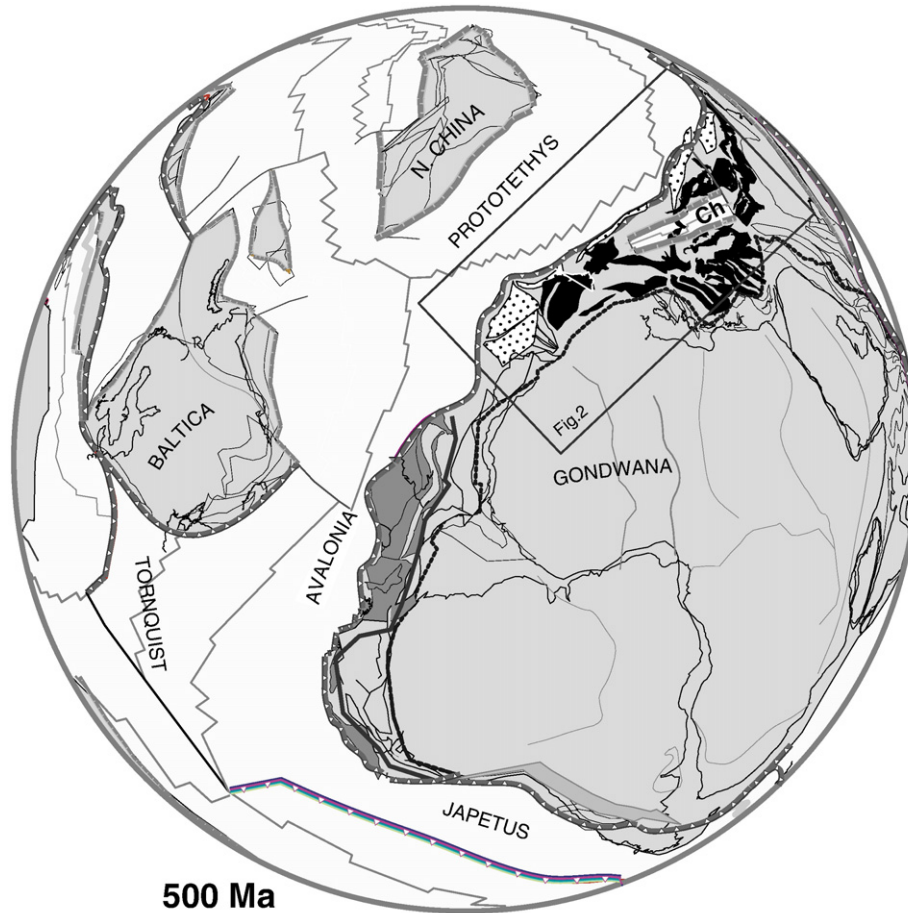


Fig. 1. Plate-tectonic situation for the Late Cambrian period (500 Ma), with the reconstruction of the peri-Gondwanan terranes at the Gondwana margin. Grey – terranes, composing the future basement areas of Avalonia; black – terranes, composing the future basement areas of Pangea; black with a white margin – allochthonous Iberian exotic terrane (Galicia – Trás-os-Montes); stippled – future “Chinese” blocks located at the Gondwana margin. Hatched dark line: future opening of Rheic Ocean; narrowly dotted line: future opening of Palaeotethys. Ch: opening Chamrousse oceanic domain. In the plate-tectonic reconstructions presented in this paper, the Gondwana-derived continental blocks only are represented, assuming that they carry in most cases their contemporaneous sedimentary cover.

across the Black Forest (Chen et al., 2000), the Saxothuringian units (Kemnitz et al., 2002), and the Bohemian Massif (Zulauf et al., 1999; Stipska et al., 2001; Dörr et al., 2002) to the Central Alps (Lower Penninic nappes, Ticino, Schaltegger et al., 2002; Austro-Alpine units, Silvretta, Schaltegger et al., 1997), the Eastern Alps (Schulz et al., 2004) and Western Carpathes (Putis et al., 2008), and the Western Pontides (Ustaömer et al., 2005) in the East.

Many sedimentological environments would have existed in the convergent margin, including fore-arc basins with deep-sea trenches, intra-arc, back-arc and rift basin settings. The present-day Neoproterozoic to Cambrian cover-sequences, well preserved in the Moroccan Anti-Atlas region, may represent the low-grade counterparts of the mostly highly metamorphosed lithologies widely distributed in the Gondwana-derived continental blocks, which were transformed during the Variscan and/or Alpine orogenies (von Raumer et al., 2003). All of these areas would have provided a wide variety of potential ecological niches, which would have encouraged the progressive evolutions of their biotas. Published lithostratigraphic data from different regions allow us to assess the subsidence history and tectonic evolution of distinct areas along the Gondwana margin. The Early Cambrian represents a time period when major plate interactions initiated a new plate-tectonic configuration. Consequently, a short review of this Cambrian plate-tectonic evolution may define the problems to be resolved. It is the aim of this paper to introduce reconstructed subsidence patterns to learn more about the

geodynamic evolution at the Gondwana margin, and to introduce the problems emerging around the existence and opening of Palaeotethys.

## 2. Reconstructions – their philosophy

Plate-tectonic concept have been systematically applied to our palinspastic models, moving away from pure continental drift models, not constrained by plate limits, to produce a model which finally is more and more self-constrained. In this approach (first explained in Stampfli and Borel, 2004) inter-dependent reconstructions are created from the past to the present. Except during collisions, plates are moved step by step, as single rigid entities. The only evolving elements are the plate boundaries, which are preserved and follow a consistent geodynamic evolution through time and an interconnected network through space. Hence, lithospheric plates are constructed by adding/removing oceanic material (symbolized by synthetic isochrones) to major continents and terranes. In the last years we changed our tools and moved into GIS softwares and built a geodynamic database to support the reconstructions, and the model was, and still is, extended to the whole globe. An example of this new approach can be found in Ferrari et al. (2008). The plate-tectonic reconstructions presented here (500 Ma, 460 Ma, 394 Ma) are part of a series starting at 600 Ma and ending at 20 Ma done at a global scale with a reconstruction every 15 Ma in average. The corresponding palinspastic cross-sections (Fig. 7) are not fixed to a terrane or continent, they present the

characteristic situation for a given time in a 2D model. This is a totally non-fixist approach, in which terranes are always moving in and out of such cross-sections. The basic principle here is that the present-day juxtaposition of terranes does not represent, in most cases, the original relationships of the terranes. The relative motion of many Variscan terranes is measured in thousands of kilometers.

### 3. The Cambrian period

Palaeogeographic analyses for the Cambrian (Courjault-Radé et al., 1992; Alvaro et al., 2003) show an extensive distribution of epicontinental sediments, which have been previously interpreted as having been deposited on the rifting Gondwana margin (Franke, 1992). Related extensional faults were discussed by Zulauf et al. (1997), and the deposition of Cambrian epicontinental sediments was accompanied by contemporaneous rifting (Liñan and Quesada, 1990) and volcanic activity (Extebarria et al., 2006). Robardet et al. (1994), Patočka and Storch (2004), and Silva and Pereira (2004) discussed the presence of marine to intra-cratonic basins, long rivers recycling the products of erosion of the cratonic areas (Zeh et al., 2001). The resulting sediments and their chemical composition recorded the increasing erosion of pre-existing crust with a considerable geochemical homogeneity of the shaly components (Ugidos et al., 2003). A maximum depositional age of c. 600 Ma for the detrital sediments is constrained by the youngest detrital zircons (Schaltegger and Gebauer, 1999; Thöni, 1999) in the Alpine pre-Mesozoic basement. Such zircon assemblages may also be represented in the “pre-orogenic age populations” (Martínez Catalán et al., 2004) from the Central Iberian domain. Although interpreted to represent uninterrupted erosion, such populations may in fact have resulted from several erosional events. This includes complete reworking during the uplift of rift shoulders and formation of younger syn-rift sediments during and after the Ordovician, during which locally thousands of meters of detrital sediments were deposited, representing the reworking of the large hinterland exposed near the rift systems.

In the general situation for the Late Cambrian (Fig. 1), most of the basement areas known from Central Europe were located at the Gondwana margin (Stampfli et al., 2006). In this model, the future Variscan blocks now found from Central America to the Caucasus, have been spread along the Gondwana margin, representing a future ribbon-like terrane of more than 10,000 km long. We formerly called this terrane the Hun superterrane (Stampfli et al., 2002), however, we now reserved the term Hunia for terranes that were accreted to the North China block, and we now refer to this ribbon continent as Greater Galatian superterrane (its European part being called Galatian terrane s.str.).

### 4. The subsidence patterns

We cannot repeat all the data published about the Cambrian–Ordovician sedimentary evolution at the Gondwana margin. The published lithostratigraphic data (references, see Figs. 3,4, and 6) allow us to illustrate the subsidence history and, hence, to constrain the tectonic evolution of Early Palaeozoic basins along the Gondwana margin. In an earlier paper (von Raumer et al., 2006) the four main subsidence patterns of the Iberian Massif were discussed specifically, showing a contemporaneous evolution of sedimentary troughs occupying, at present-day, distinct tectonostratigraphic units (Ossa Morena, Central Iberian, West Asturian Leonese and Cantabrian Zones).

#### 4.1. Lower Cambrian

In the larger European frame, since the earliest Cambrian (540–510 Ma), strong subsidence is seen as the expression of an extensional setting at the Gondwana margin, either related to subduction and roll-

back of Prototethys or to contemporaneous intra-continental rifting related to a post-Pan-African extension. Such subsidence patterns are documented (Fig. 3) from the Anti-Atlas, Ossa Morena, Central Iberian; West Asturian Leonese, and Cantabrian Zones, and for the Montagne Noire, and the Barrandian as well. Early Cambrian is identified in the Pyrenean and Saxothuringian Zones, and it is supposed that Cambrian sediments were present (at least partially) in all the domains (comp. Fig. 4). Striking similarities in the subsidence patterns exist for the Ossa Morena and Anti-Atlas areas, and again, subsidence is comparable in the Central Iberian and the Barrandian domains.

#### 4.2. Upper Cambrian

After the earliest rifting period, a new large-scale tectonic event is marked by the Upper Cambrian formation of oceanic crust manifested in the Chamrousse area (comp. Fig. 2), which may have lateral cryptic relics preserved in other places (see below). This event can be regarded as the oceanisation of some marginal basins in a context of back-arc rifting (see discussion below) due to increased roll-back of Prototethys. A corresponding stronger subsidence is observed for the West Asturian Leonese, and the Barrandian areas. Is the opening of the Chamrousse a time equivalent event to the already initial opening of the Rheic Ocean to the west?

#### 4.3. Ordovician

Starting in the Lower Ordovician (Fig. 4), a new phase of subsidence was recorded by the sediments of the Central Iberian Zone (Fig. 4), accompanied by a large-scale volcanic activity. Although the subsidence pattern of the Cantabrian zone remains rather regular, Ordovician volcanics (comp. Fig. 4) indicate the Ordovician rifting event in this zone (Gutiérrez-Marco and Bernárdez, 2003; Gutiérrez-Alonso et al., 2007). Contemporaneously, in the subsidence patterns of the Saxothuringian and the Barrandian areas (Fig. 3), a striking thermal uplift is documented. Although illustrating only burial, the patterns for the Southern Brittany area (Robardet et al., 1994) correspond narrowly to the evolution of the western Central Iberian subsidence curve.

Interestingly, tectonic subsidence curves for the Lower Palaeozoic from Eastern Avalonia (Prigmore et al., 1997) and a cumulative thickness curve from the Brabant massif (Verniers et al., 2002) underline an early rifting period during the Lower Cambrian with subsequent periods of more rapid subsidence during the Late Cambrian/Tremadoc and Arenig–Llanvirn periods. Even in the easternmost portions of the margin prolongation (East Alborz, High Lahul, Central Taurus) the initial subsidence patterns for the Cambro-Ordovician (Stampfli et al., 2001) show the fingerprints of the mid-Cambrian rifting and continued Ordovician subsidence. The subsequent rapid subsidence records the opening Palaeotethys rift system in these regions, and in the Pyrenees and Carnic Alps (Fig. 4).

### 5. The Early Palaeozoic plate-tectonic evolution – a discussion

Strike-slip models (Murphy and Nance, 1989) may explain the different scenarios at the Gondwana margin. During oblique convergence, plume-like structures may have existed beneath pull apart (e.g. in the Bohemian Massif, Floyd et al., 2000) or isolated rift basins. Detrital sediments record the maximum subsidence and were coeval with rift volcanism in longitudinal continuity, for example, in the Sudetes (Kryza et al., 2007), in the Bohemian Massif (Kachlik and Patočka, 1996; Zulauf et al., 1997), in the Saxothuringian domain (Linnemann et al., 1998; Kemnitz et al., 2002), in the Ossa Morena Zone (Sánchez García et al., 2003) or at the limits between Ossa Morena and Central Iberian Zones (Rodríguez Alonso et al., 2004).

New plate-tectonic reconstructions (Fig. 1) of the Gondwana margin suggest that the location of Gondwana-derived terranes should not

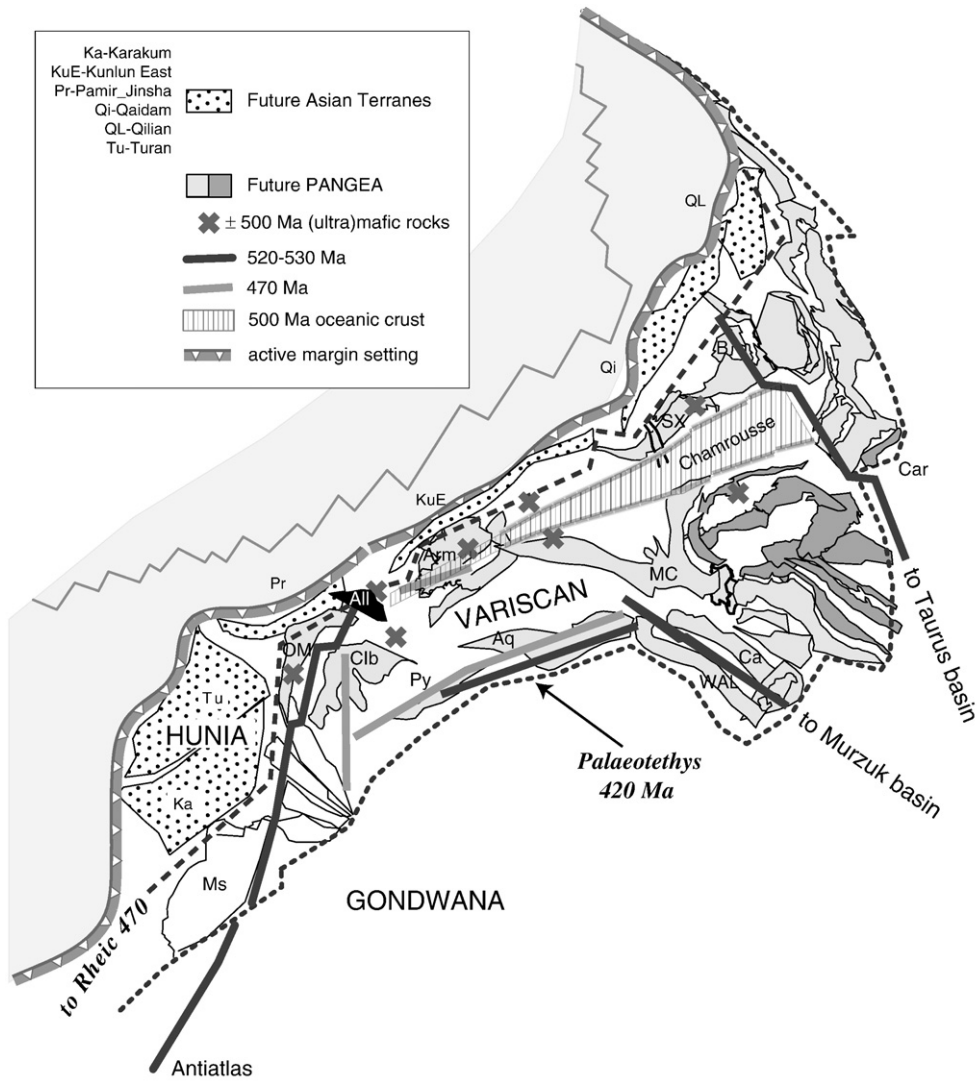


Fig. 2. Detail sketch of the plate-tectonic reconstruction of the Gondwana margin (500 Ma, comp. Fig. 1) indicating the future "Chinese" terranes (dotted) and terranes composing the future Pangea (light grey) the Alps included (dark grey), and the Iberian allochthonous areas (black, All). Ossa Morena (OM) and Iberian Allochthonous areas (All) separated from the Gondwana margin through the 500 Ma back-arc initial rifting. The main sutures: future opening Rheic Ocean (dark interrupted line) and Palaeotethys (narrowly hatched line); and tectonic lineaments: subsidence since the Early Cambrian (dark grey lines) and the Ordovician (light grey lines). Vertically hatched area: areas influenced by the Late Cambrian formation of oceanic crust (Chamrousse, Western Alps, Ménot et al., 1988). All – Iberian Allochthonous; Aq – Aquitaine; Arm – Armorica; B – Barrandian; Ca – Cantabrian; Car – Carnic Alps; Clb – Central Iberia; MC – Massif Central; Ms – Meseta; OM – Ossa Morena; Py – Pyrenees; SX – Saxothuringian; WAL – West Asturian Leonese.

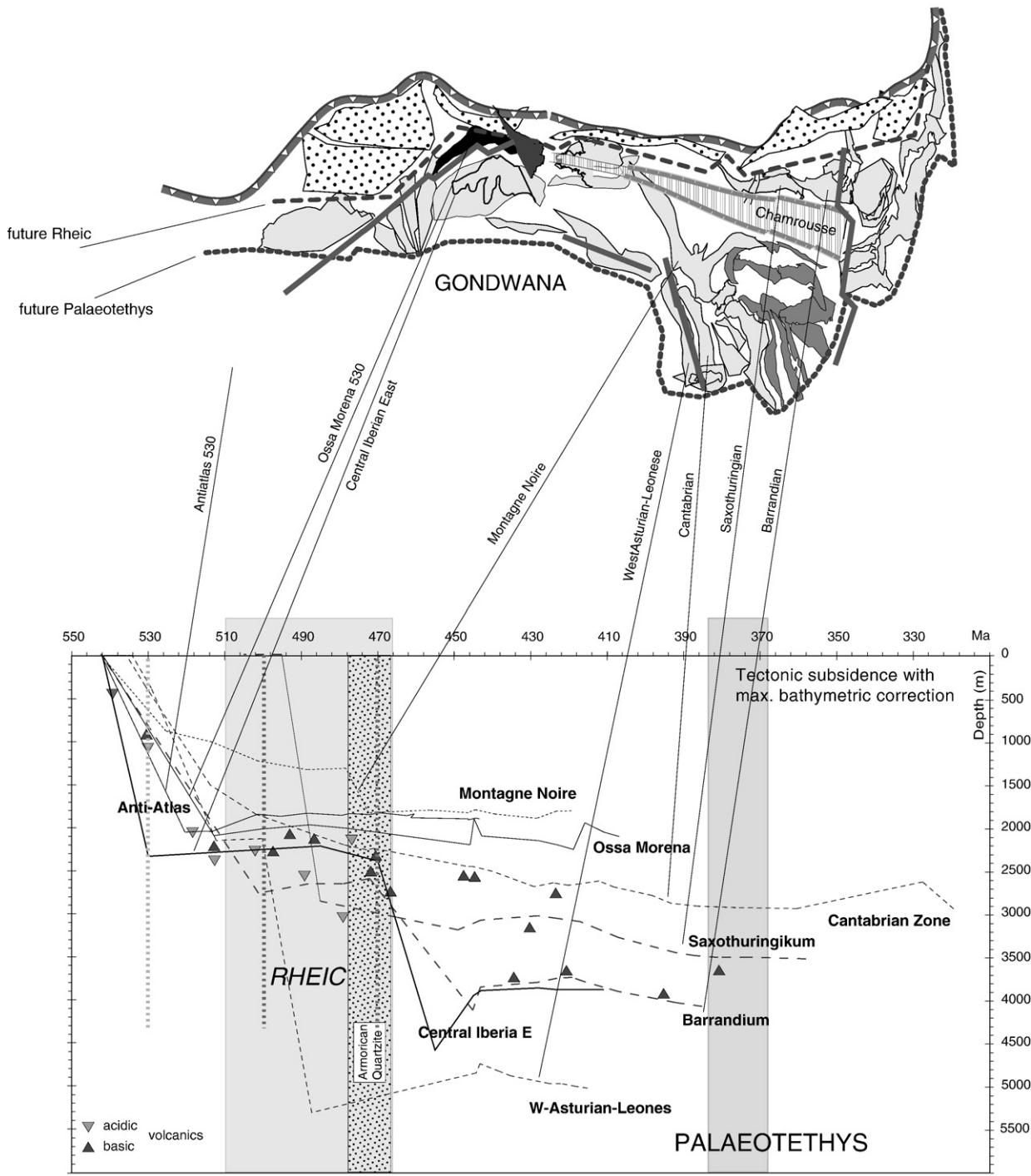
only be guided by the hitherto applied models (e.g. Winchester et al., 2002; Stampfli and Borel 2004), but should also include possible detrital input from some Asian blocks (Hunia), supposed to have been also located along the Cambrian Gondwana margin (Fig. 1). Comparing the localities along the Gondwana margin (Figs. 1 and 2), different palaeogeographic models can be distinguished through the quantity and nature of sediments accumulated in the sedimentary troughs. Consequently, the Gondwana margin can be subdivided into a more western domain, where the future Avalonian blocks will be separated from Gondwana by the opening Rheic Ocean; the Iberian allochthonous units may have been part of the Avalonian domain (compare Arenas et al., 2007a), as well as the Sehouf in Morocco (Hoepffner et al., 2005). In contrast, the more eastern continuation of the converging margin hosts the future basement areas of Central Europe, in which different periods of crustal extension should be distinguished.

5.1. Cambrian

The above presented subsidence patterns and the contemporaneous evolution of major structures constrain a plate-tectonic model

for the evolution of the Gondwana margin (Figs. 2 and 7). The Neoproterozoic–earliest Cambrian active margin setting of many peri-Gondwana-derived terranes was subsequently replaced by widespread Early Cambrian extension over wide areas of the Gondwana margin. Instead of a simple cylindrical evolution with little or no along-strike variation, it is supposed that crustal extension during the Lower Cambrian followed a more complex pattern with local back-arcs and isolated intra-continental rifts (comp. Fig. 2), attaining, still during the Early Cambrian, the stage of carbonate platform evolution.

A subsequent major event is recognized at 500 Ma (comp. Figs. 1, 2 and 7), which, for the eastern regions, corresponds to the formation of oceanic crust of the Chamrousse area (Belledonne massif, Western Alps; Ménot et al., 1988), an event which may correspond, along-strike to the east to mafic-ultramafic bodies in the Saxothuringian and related klippen (Vesser area, Kemnitz et al., 2002; Erbenndorf-Hohenstrauss and Münchberg Klippe, Franke, 1995) and the Bohemian Massif (Marianske Lasné Complex, Timmermann et al., 2006). In the Bohemian Massif, Floyd et al. (2000) and Crowley et al. (2002) interpreted the Cambrian continental break-up as a consequence of interaction with a mantle-plume. Upper Cambrian rifting is also reported from the more western continuation in



**Fig. 3.** Subsidence patterns (tectonic subsidence with maximum bathymetric correction) of Palaeozoic sediments from the Gondwana margin. Map: compare Fig. 2. Data: anti-Atlas (Destombes et al., 1985); Barrandian (Chlupač et al., 1998); MN – Montagne Noire (Feist et al., 1994), Saxothuringian (Linnemann, 2004); Central Iberian Zone (Butenweg, 1968; Kettel, 1968); Cantabrian – Westasturian Leonese- and Ossa Morena Zones (Radig, 1961; Robardet et al., 1994; Gutiérrez Marco et al., 2003; Liñan et al., 2003; Robardet and Gutierrez-Marco, 2004).

the Massif Central domain, (Limousin area, Pin and Marini, 1993; Briand et al., 1995; Berger et al., 2005). The Upper Cambrian oceanisation of some marginal basins in a context of back-arc rifting, scattered through the Iberian Allochthonous (Arenas et al., 2007a,b) and the formerly nearby areas of rifting like the Ossa Morena Zone (Sánchez García et al., 2003; Quesada, 2006) could equally represent the westward continuation of the Gondwana margin. The location of the Central Iberian Allochthonous and the Ossa Morena Zone were equally near to Cambrian subduction

and Cambrian rifting (Figs. 1 and 2). The parallels of sedimentological and volcanic evolution during the Cambrian do not necessarily exclude some freedom in placing Ossa Morena and the Iberian Allochthonous domains along the Gondwana margin. The rather comparable subsidence between the eastern Central Iberian Zone and the Barrandian (Fig. 3) suggests at least the possibility, that both areas had also a comparable location along the Gondwana margin.

How to reconcile this Late Cambrian extension in a general frame? The formation of a large volcanic arc with intrusion of subvolcanic

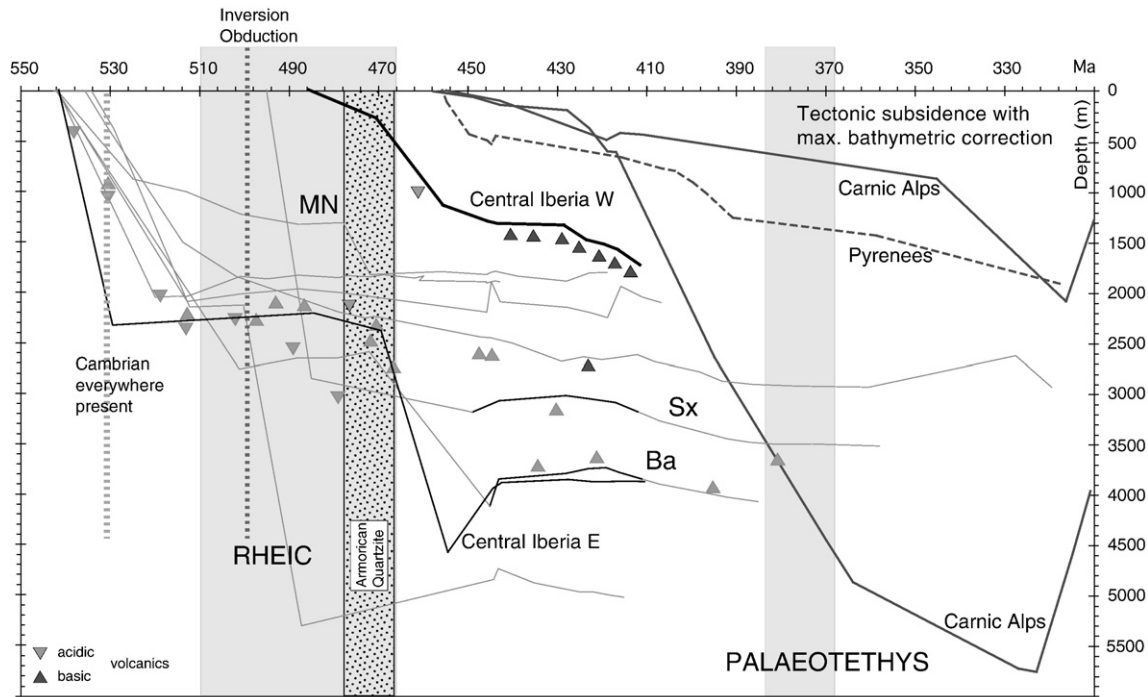


Fig. 4. Subsidence patterns (tectonic subsidence with maximum bathymetric correction) of Palaeozoic sediments from the Central Iberian Zone, the Pyrenees and the Carnic Alps, with references. The curves from Fig. 3 (in grey) are repeated to allow for comparison. Two different curves illustrate the evolution for the Central Iberian Zone, for the western part from Almadén (Saupé, 1973), and for the eastern part (Eastern Sierra Morena with the information about the Ordovician from the easternmost Sierra Morena (Kettel, 1968) and for the Lower Cambrian from the Victoria area (Butenweg, 1968). Notify the subsidence of the Central Iberian Zone and the contemporaneous evolution of a thermal uplift in the Barrandian and the Saxothuringian Zones (highlighted by a thicker line). Data: Pyrenees (Harteveld, 1970); Central Iberia East (Eastern Sierra Morena; Butenweg, 1968; Kettel, 1968; Central Iberia West (Almadén, Saupé, 1973); Carnic Alps (Schönlau, 1993), other references in Fig. 3.

bodies (Ollo do Sapo, Díez Montes, 2007) and the contemporaneous back-arc opening of the future Rheic Ocean is discussed for the NW-Iberian Gondwana margin (Arenas et al., 2007b). In applying a model of extending crust, evolving from initial transtension to simple shear extension (Stampfli et al., 1991), we related (Stampfli et al., 2002) the Upper Cambrian granite and gabbro intrusions of the Allochthonous units in NW Spain, accompanied by granulite facies metamorphism and anatexis (Abati et al., 1999), to extensional processes leading to the initial opening and rifting of the Rheic Ocean. Considerable crustal events must have accompanied this evolution and, in Fig. 4, we interpret this short time period as a time of crustal inversion, perhaps accompanied by obduction. Interestingly, Linnemann et al. (2004) discuss the Upper Cambrian inversion of a former rift basin with intrusion of Cambro-Ordovician granitoids. Since our discussion of Cambrian granitoids at the eastern Gondwana margin (von Raumer et al., 2002, 2003), new data confirm the general picture of Late Cambrian crustal extension (Creta, Romano et al., 2004; Turkey (Ustaömer et al., 2005).

The same geodynamic scenario cannot be applied to the entire margin. The ocean opening between Avalonia and Gondwana is usually named Rheic (Fig. 5), and Prigmore et al. (1997) attributed the Late Cambrian-Tremadoc or the Arenig-Llanvirn periods of rifting to the separation of Avalonia from Gondwana. However, Avalonia did not extend along the length of the margin. The eastern continuation of the Rheic Ocean, opening north of the Galatian terranes and separating a ribbon continent (Hunia) represents the eastern branch of the Rheic Ocean (Fig. 5). The Hunia ribbon continent later accreted to the Tarim-North China block, whereas Avalonia accreted to North-America-Baltica. Eastward, on the Galatian transect (Fig. 7), the Cambrian basins closed during a mid-Ordovician tectonic event (Biino, 1994; Oberli et al., 1994; Schaltegger et al., 2003; Franz and Romer, 2007) that we attribute to the diachronous subduction of the Prototethys mid-oceanic ridge. The Hunia terrane can only be detached

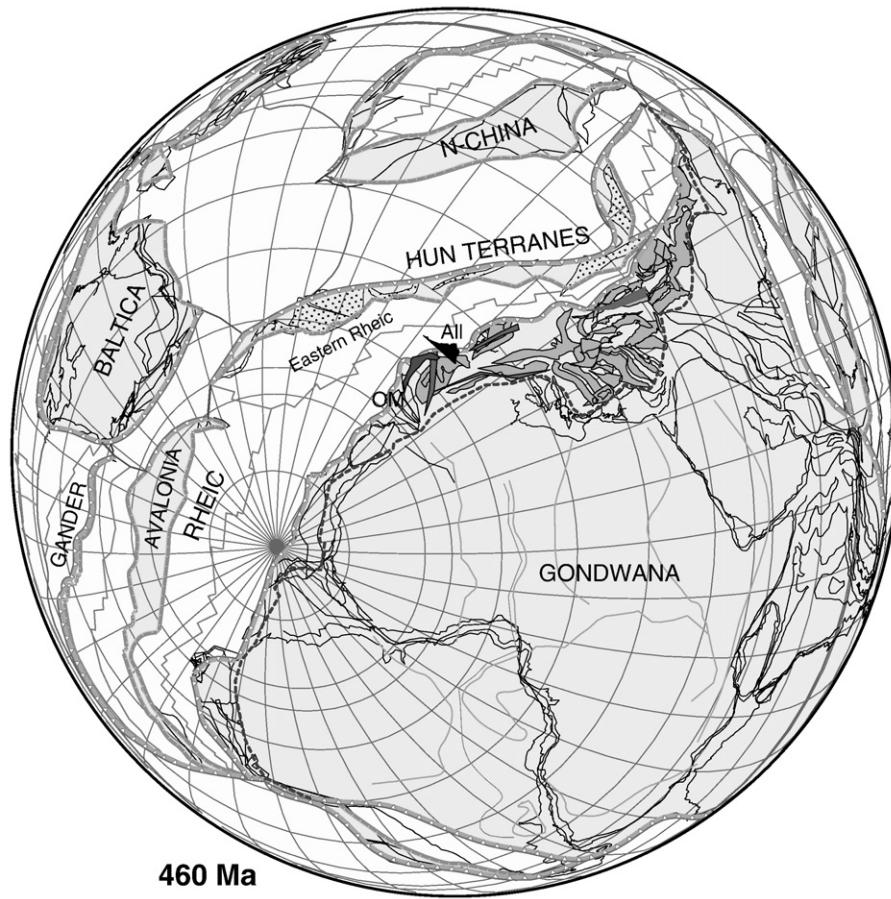
from Gondwana after this event, through renewed roll-back of the Prototethys sea-floor and total subduction of its mid-oceanic ridge.

The question arises, if the Rheic Ocean opened 470–460 Ma years ago (comp. Prigmore et al., 1997), leading to the separation of the Avalonian terrane, or if the Rheic opened already during the preceding Upper Cambrian opening of a back-arc basin and drifting of the Gander terranes in Upper Cambrian times (comp. discussion in Arenas et al., 2007a, p.29)? We follow the idea that the Gander terrane was most likely detached when Avalonia was already drifting from Gondwana (Valverde-Vaquero et al., 2003), not before, due to accelerating roll-back of the Iapetus Ocean.

## 6. From Gondwana to Palaeotethys

### 6.1. The Ordovician period

It was only after the onset of sea-floor spreading and the consequent drift of Avalonia and Hunia, that the Armorica/Cadomian terranes and the more easterly Intra-Alpine blocks followed an independent plate-tectonic evolution. Faunal distributions from the time of formation of the Rheic Ocean to the Devonian marine areas characterize the continuous evolution of faunal provinces from the Ordovician to the Devonian (Robardet, 2002, 2003; Fortey and Cocks, 2003). The many Early Palaeozoic, mostly detrital, sediments from Armorica/Cadomia carry benthic faunas and shallow-shelf lithofacies indicating that the underlying continental structures were not separated from the main Gondwana continent by a wide ocean (Robardet, 2002). The model using just one intervening ocean, the Rheic Ocean, rather than postulating several oceanic regions, thus seemed the most economical way to explain the interaction of continental plates. However, whilst accepting these observations and criteria, the solely palaeontological criteria and the construction of biogeographic maps do not prove that there was a stable tectonic shelf, since an epicontinental sea opening



460 Ma

Fig. 5. Plate-tectonic reconstruction of the Gondwana margin (460 Ma): the Avalonian terranes separating from Gondwana through the opening Rheic Ocean, and its eastern prolongation separates the future "Chinese" blocks (dotted) from the terranes representing the future basement areas (light grey) of Pangea. Medium grey: possible location of Early Ordovician rim-basin deposits (e.g. Armorican Quartzite); black: location of Ossa Morena and Iberian Allochthonous areas (Galicia – Trás-os-Montes).

through crustal thinning would also carry a comparable evolution of sediments with identical faunas.

6.1.1. Sediments and tectonics

The stronger subsidence since the Ordovician, visible in the corresponding patterns (Figs. 3 and 4), can be explained by the continuation of rifting, and the reworking of the rift shoulders generating voluminous detritus (Armorican Quartzite). The detrital zircons indicate sediment derivation from a wide hinterland (e.g. Martínez Catalán et al., 2004; Drost et al., 2004) into a rim-basin, located at the southern rim of the Cambrian rift system (comp. Fig. 7D). The regional transgression of the Lower Ordovician is documented in Southern Brittany (Robardet et al., 1994; Robardet, 2002, area 1, Fig. 6), and in the Central Iberian domain (Gutierrez Marco et al., 1990; Martínez Catalán et al., 2004; Fig. 6), and subsidence (Figs. 3 and 4) was accompanied by strong volcanic activity. In the Saxothuringian (Fig. 6), the subsidence (compare Figs. 3 and 4) indicates a new rift phase (erosion, denudation), with transgression of the Ordovician on Cambrian sediments or Cadomian basement (comp. Linnemann and Buschmann, 1995). Extension was accompanied by large-scale volcanic activity and thermal uplift (Figs. 3 and 4) in the Saxothuringian and the Barrandian areas (area 5, Figs. 6, 3 and 4). This Ordovician phase of extension heralded the opening of Palaeotethys, but its location in an already thinned lithosphere resulted in a less evident subsidence pattern.

6.1.2. Magmatic evolution

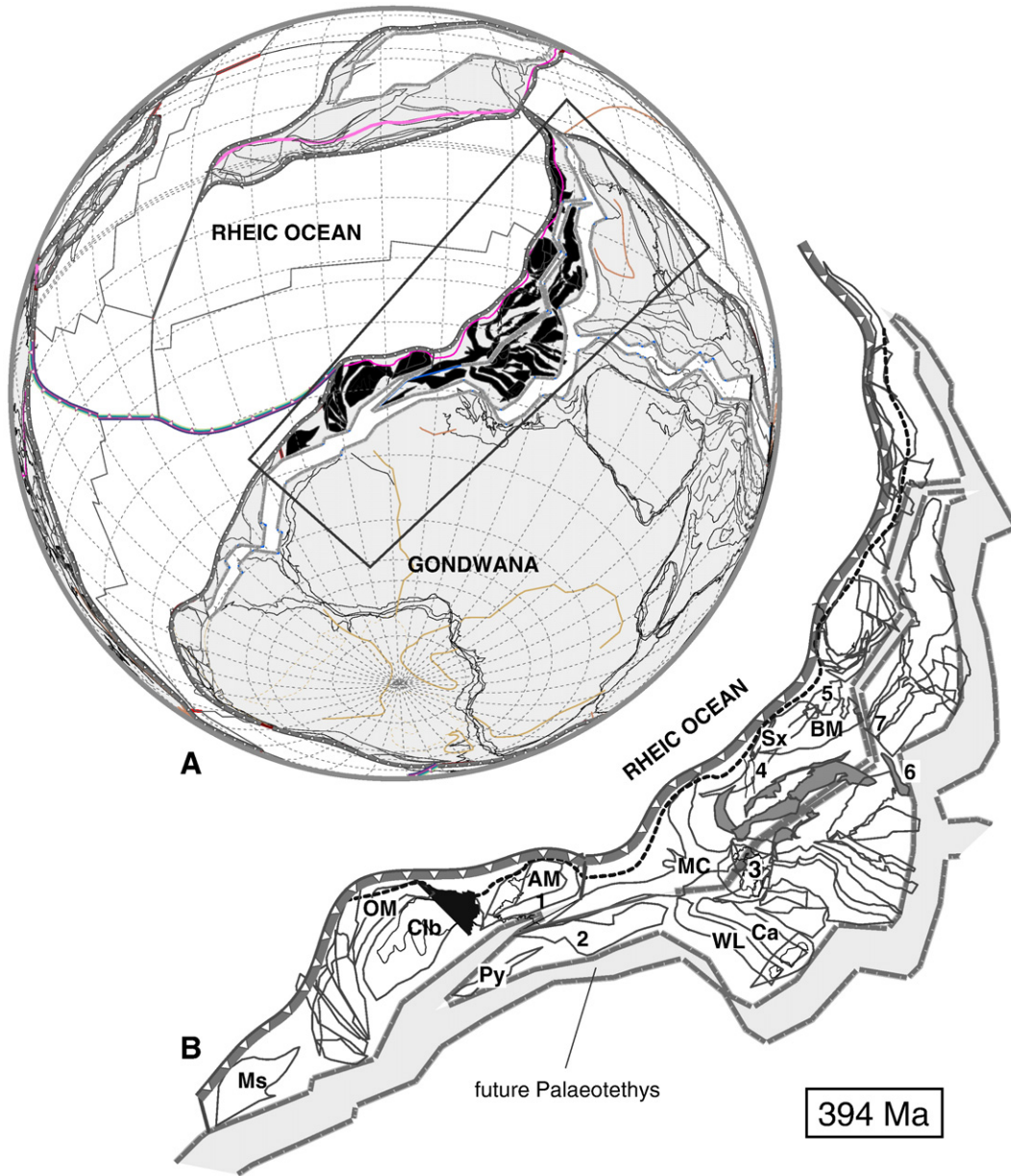
The Ordovician rifting period is underlined by a strong magmatic activity at the level of the lower crust. Since our comprehensive discussion

on Ordovician granitoids (von Raumer et al., 2002; von Raumer et al., 2003) and their narrow relation to Ordovician subduction and subsequent crustal extension, new data are at disposal from different Alpine realms (Bertrand et al., 2000; Guillot et al., 2002; Schulz and Bombach, 2003), from the Carpathian mountains (Gaab et al., 2005), from Sardinia (Helbing 2003; Helbing and Tiepolo 2005; Giacomini et al., 2006), from Sicily (Trombetta et al., 2004), from the Pyrenees (Deloule et al., 2002) and from the Bohemian Massif (Bavarian Forest, Teipel et al., 2004).

Equally, the contemporaneous (460 Ma) gabbroic intrusions in the External Alpine massifs (Paquette et al., 1989; Oberli et al., 1994; Abrecht et al., 1995; Rubatto et al., 2001) and the Austroalpine Silvretta Massif (Poller, 1997) plead for a major crustal event along the eastern part of the Gondwana margin.

7. Hirnantian glaciation and Silurian crustal extension

In the Late Ordovician, many areas were covered by the detrital sediments of the Hirnantian glaciation (e.g. Hamoumi 1999; Monod et al., 2003) and, consequently, the future terranes building up Pangea were still located at rather high southern longitudes. The contemporaneous thermal expansion could explain local unconformities or sedimentary gaps, and the rift shoulders may have been the site of ice sheets (e.g. in the Taurus Mountains of Turkey, Monod et al., 2003), whereas in the grabens, graptolite-bearing black-shales were preserved which would otherwise have been eroded. The still epicontinental marine areas allowed the free migration of faunas and, depending on latitude, the passive margins, from the Upper Silurian onwards, were colonised by platform carbonates as the whole area drifted generally northwards (Cocks and Torsvik, 2002).

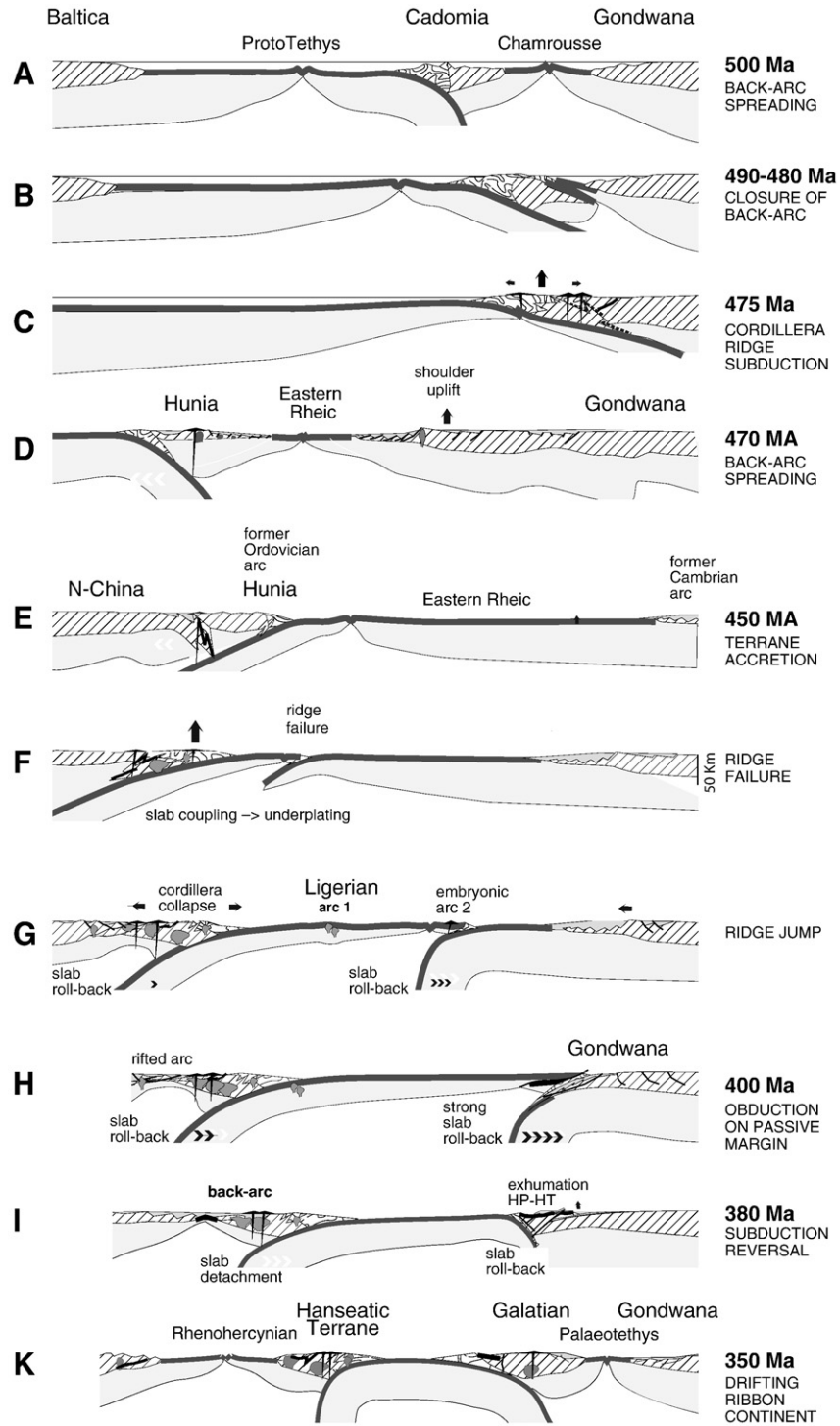


**Fig. 6.** Plate-tectonic situation at the beginning of the Devonian (394 Ma), the period of initial opening of Palaeotethys. A – global reconstruction with the Galatian ribbon continent (in black), initial separation from Gondwana and earliest stages preparing the opening of Palaeotethys; B – detail presentation of the Galatian terrane assemblage, a ribbon continent containing the future crustal blocks composing future Pangea. Dark grey: future Alps; black: Iberian Allochthonous. Localities – detail information and references about the initial crustal extension preceding the opening of Palaeotethys (see text): 1: Southern Brittany (Robardet et al., 1994); 2: Julivert and Duran, 1990; Gil Iburguchi et al., 1990); 3: Sardinia (Stampfli et al., 2002); 4: S. Black Forest (Vaida et al., 2004); 5: Barrandian (Chlupač et al., 1998; Patočka and Storch, 2004); 6: Carnic Alps (Schönlaub, 1993); 7: Graz Palaeozoic (Fritz and Neubauer, 1988). AM – Armorican Massif; BM – Moldanubian part of the Bohemian Massif; Ca – Cantabrian Zone; Clb – Central Iberia (Saupé, 1973; Diez Balda, 1986, Gutiérrez Marco et al., 1990; Martínez Catalán et al., 1992; Silva and Pereira 2004); MC – French Massif Central; Ms – Meseta (Piqué, 1989); OM – Ossa Morena Zone; Py – Pyrenees; Sx – Saxothuringian (Linnemann et al., 2003); WL – Westasturian Leonese Zone.

Transtensive extension with syn-rift volcanism during the Ashgill is observed in the Armorican domain (Chateaulin, Normandie, Robardet et al., 1994), in the Central Iberian domain (Almadén, Gutiérrez Marco et al., 1990; Saupé, 1973), in the Catalanian coastal ranges (locality 2, Fig. 6; Julivert and Duran, 1990; alkaline volcanics, Gil Iburguchi et al., 1990), in the Prague-basin (Barrandian) of the Bohemian Massif (Patočka and Storch, 2004), in Sardinia (flood basalts, Stampfli et al., 2002), and in Iran (flood basalts of up to 500 m thick extending over 1000 km of the margin; Bagheri and Stampfli, 2008). In the Eastern Alps (7, Fig. 6; Palaeozoic of Graz, Fritz and Neubauer, 1988), intra-continental alkaline volcanics of Silurian age with subsequent accumulation of siliciclastics in an extensional regime are observed. Silurian “vertical tectonics in a distensive

environment (Pieren, 1986 in: Gutiérrez Marco et al., 1990), observed at the southern margin of the central Iberian domain, yielded  $Ar^{40}/Ar^{39}$  cooling ages of 420–423 Ma (Dallmeyer and Pieren, 1987, recalculated 1989) indicating a contemporaneous metamorphic event in the Precambrian basement. Deposition of volcanosedimentary interbeds and peralkaline volcanics accompany these tectonic events (Diez Balda, 1986; Saupé, 1973). Saupé (1973) argues for an epicontinental environment with shallow basins and ridges, and Diez Balda (1986) describes the extrusion of alkaline basanites, containing breccia and vesicles. In addition, at the northern limit of the Central Iberian domain, Silurian extensional faults strongly influenced the distribution of Silurian sediments (Martínez Catalán et al., 1992, 2004).





**Fig. 7.** Cross-sections palinspastic model for the possible plate-tectonic evolution between Baltica and Gondwana during the Early Palaeozoic. A – subduction of Cambrian Proto-Tethys Ocean under Gondwana and opening of a Cambrian back-arc trough with oceanic crust (Chamrousse); B – closure of the Cambrian back-arc; C – ridge subduction and formation of cordillera; D – back-arc spreading and opening of the eastern branch of the Rheic Ocean, separation of the Hun ribbon continent; shoulder uplift on the Gondwana side with formation of rim-basins (Armorican Quartzite); E – terrane accretion of the Chinese blocks (N-China and Hunia); F – ridge failure, subduction and underplating between the Chinese blocks; G – ridge jump and formation of embryonic arc; H – rifted arc in the Chinese blocks, obduction of oceanic crust on the Gondwana passive margin; I – subduction reversal, exhumation of HP-HT units on the Gondwana side; K – opening of Palaeotethys with separation of the Galatian terranes; opening of the Rhenohercynian Ocean.

Among the various sedimentary basins formed since the Ordovician, the Barrandian and Saxothuringian domains were probably part of the northern margin of Palaeotethys before the lateral displacement of the Moldanubian zone to the south of the Saxothuringian Zone. Following the re-interpretation by Stampfli et al. (2002), its autochthonous sequence (Falk et al., 1995) is marked

by basin deepening in Silurian times, accompanied by lavas and tuffs in the Ludlow representing the syn-rift event, whereas pelagic Gedinnian to Givetian sediments represent the drift sequence (compare Linnemann, 2004).

Equally, the Central Iberian Zone with its well-known Cambrian to Silurian stratigraphy (Figs. 3 and 4) was the place of tectonic events

which indicate the initial opening of Palaeotethys. Admittedly, the primary location of the Central Iberian domain together with its adjacent areas may have been very different before the Variscan orogenic events. The sedimentary basins constituting the Lower Palaeozoic cover series in the Eastern Alps represented the northern margin of Palaeotethys. They contain acidic volcanics among Lower Palaeozoic sediments (Loeschke and Heinisch, 1993) with a well-documented sedimentary evolution (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). In contrast, the southern passive margin of Palaeotethys is located in the Iranian occurrences, and a similar evolution is found in the Cimmerian part of Turkey (references in Stampfli and Kozur, 2006), and North Africa. In this context, the Moroccan Central Meseta represents the northern margin of Palaeotethys, and was detached from Gondwana together with the Galatian terrane. A syn-rift sequence of Silurian–Lower Devonian age precedes the establishment of a large Devonian carbonate platform related to the drift sequence (Hoepffner et al., 2005). The eastern zone with its totally different stratigraphic record did not belong to the Galatian terrane, but was most likely located to the north of it. The Anti-Atlas formed the southern margin of Palaeotethys.

Concluding, the Gondwana margin had been a passive margin since rifting away of the Hunia terrane, but this evolution failed in some areas due to the Silurian collision (Eo-Variscan phase, see Stampfli et al., 2002 for references) of an intra-oceanic arc with the eastern portion of the Gondwana margin, which took place between 400 and 380 Ma (Fig. 7H). The colliding arc and related obduction developed in the oceanic space that opened between Hunia and Gondwana, The traces of the obducted ophiolite can be found in Spain (e.g. Ordenes complex), France (Champtoceaux complex) and Germany (Münchberg Klippe) and surrounding areas. As the ophiolite obduction is regarded as a hallmark of the outer margin of the Galatian terrane (Fig. 6), this ophiolite belt was used to reconstruct the Galatian terrane geometry (Stampfli et al., 2006). The ophiolite obduction event is not known at the southern margin of the Rheic ocean s.str., preserved in the north and central American terranes, that were later accreted to Laurentia.

Subduction inversion following obduction, inducing opening of Palaeotethys in Upper Devonian times, gave rise to the 10,000 km long Greater Galatian superterrane (Fig. 6). Apparently the opening of Palaeotethys was nearly synchronous all along the margin but the onset of spreading may have been diachronous, from Middle to late Devonian times.

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