Available online at www.sciencedirect.com

SCIENCE DIRECT®

Tectonophysics 398 (2005) 181–198

TECTONOPHYSICS

www.elsevier.com/locate/tecto

The tectonic frame of the Variscan–Alleghanian orogen in Southern Europe and Northern Africa

J. Fernando Simancas[a], Abdelfatah Tahiri[b], Antonio Azor[a,*], Francisco González Lodeiro[a], David J. Martínez Poyatos[a], Hassan El Hadi[c]

[a]*Departamento de Geodinámica, Facultad de Ciencias, Campus de Fuentenueva, Universidad de Granada, Granada 18071, Spain*
[b]*Institut Scientifique, BP 703, Rabat-Agdal, Morocco*
[c]*Faculté des Sciences Ben Msik-Sidi Othmane, Casablanca, Morocco*

Received 26 July 2004; received in revised form 16 February 2005; accepted 21 February 2005
Available online 19 March 2005

Abstract

By confronting different geological and geophysical data, we attempt to reconstruct the Variscan–Alleghanian orogenic belt, with especial emphasis on the links between Iberia, northwest Africa, and northeast America.

The northern Iberia transect corresponds to the rifted margin of Gondwana, inverted during the Variscan orogeny and overthrust in its westernmost sector by a pile of allochthonous units, some of them with oceanic affinity and witnessing an orogenic suture. The southern Iberia section reveals two sutures at both boundaries of a terrane closely tied to Gondwana, namely the Ossa–Morena Zone. The southern boundary of this zone (i.e., the contact with the South Portuguese Zone) is enhanced by amphibolites with oceanic affinity and probably represents the suture of the Rheic Ocean.

The Moroccan Variscides can be divided into: (i) a western external zone, namely the Coastal Block and the Central Massif; (ii) an internal zone, namely the Eastern Meseta; (iii) an eastern external zone represented in the Anti Atlas region; and (iv) the African cratonic foreland. Since neither ophiolites nor eclogites crop out along this transect of the orogen, we consider it to be an incomplete transect, lacking the main suture zone (Rheic Ocean).

Stratigraphic and faunal affinities between the Moroccan Meseta, on the one hand, and the Central Iberian, Western Asturian–Leonese, and Cantabrian zones of Iberia, on the other hand, suggest that they may well have been part of a common pre-orogenic domain at the margin of Gondwana. On the contrary, there are no counterparts in Morocco for the Ossa–Morena Zone. Thus, the northern Iberia palaeogeographic zones would prolong in the Moroccan Meseta through an eastward arcuate structure, while the suture of the Rheic Ocean would do so offshore Morocco. In our reconstruction, an Avalonian spur (Grand Banks indentor), which included the Caledonian Sehoul block in northern Morocco and the crust of the South Portuguese Zone in SW Iberia, played an important role on the kinematic evolution of the orogen as well as on the final configuration of the

* Corresponding author. Tel.: +34 958 242900; fax: +34 958 248527.
E-mail address: azor@ugr.es (A. Azor).

doi:10.1016/j.tecto.2005.02.006

suture of the Rheic Ocean. This suture would mould around the Avalonian spur, being laterally translated to southeastern Nova Scotia–Newfoundland.

Keywords: Rheic Ocean; Orogenic sutures; Gondwana; Avalonia; Moroccan Meseta; Iberian Massif; Variscan orogen

1. Introduction and fundamentals

The outcrops of the Variscan–Alleghanian Late Palaeozoic orogenic belt are dispersed in western Europe, northwest Africa and northeast America, due to both the opening of the Atlantic ocean and the Alpine tectonics around the Mediterranean. Moreover, despite the important advance on the knowledge of the different outcrops of this orogen in recent years, there still remains some uncertainty as to the position and number of oceanic domains as well as the linkage between the different palaeogeographic zones. For these reasons, the reconstruction of this orogen at pre-collisional and collisional stages is a rather complicated task, requiring a vast amount of geological and geophysical data.

The purpose of this paper is to briefly review the main features of the Variscan–Alleghanian orogen in its central segment, in order to propose a comprehensive view of its tectonic frame. The main problem hindering this reconstruction has traditionally been the tectonic Variscan linkage of Iberia with northwest Africa and northeast America. Our present-day geological knowledge enables us to propose a reasonably well-based tectonic picture.

The tectonic frame that we put forward in this paper is based on a model of Palaeozoic dispersal and aggregation of continents, which serves as a template for our more detailed account. This model arises out of a close scrutiny of geological (main tectonic boundaries), palaeontological (faunal affinities), and palaeomagnetic data (palaeolatitude of continental masses), trying to determine the point of convergence among these three different types of evidence. This attempt is subject to a number of shortcomings, especially the fact that palaeomagnetic models still conflict in some important points with geological and palaeontological data. Thus, different sets of data fit in well within a general model of Cambrian to Ordovician palaeogeography (Crowley et al., 2000a; Nysæther et al., 2002), but for Devonian time, palaeomagnetic reconstructions show a large ocean between Gondwana and Laurentia/Baltica (Torsvik et al., 1990; Tait et al., 1997), which is largely incompatible with palaeontological evidence (McKerrow et al., 2000; Robardet, 2003). The general model of continental dispersal and aggregation assumed here as a starting point is very close to the one proposed by Matte (2001), which includes: a) a Cambrian to Ordovician breaking of the Gondwana margin to form an independent, perhaps composite, continental mass (Avalonia) that drifted away until its Ordovician to Devonian complex collision with Laurentia/Baltica (Caledonian/Taconic and Acadian orogenic events); b) an additional Ordovician breaking of the Gondwana margin originating a number of terranes which, unlike Avalonia, remained closely tied to Gondwana (Kemnitz et al., 2002; Nysæther et al., 2002); c) a contemporaneous development of continental grabens/rifts along the margin of Gondwana; d) the formation of an Ordovician–Silurian ocean (the Rheic Ocean) between the wandering Avalonia and the Gondwana-related terranes; e) the closing of the Rheic Ocean in Devonian time and welding of the terranes around Gondwana (early Variscan orogenic events); and f) a Carboniferous collision of Avalonia, Gondwana, and the terranes in between (Variscan/Alleghanian orogenic events).

2. The Variscan tectonic organization in Iberia

The Alpine reworking is intense in the eastern areas of the Iberian Peninsula (Betic ranges, Pyrenees) but relatively weak in most of the so-called Iberian Massif, which is the largest continuous outcrop of the Variscan Belt (Fig. 1A and B). The Variscan tectonic organization of the Iberian Massif is better understood in terms of considering two different geological

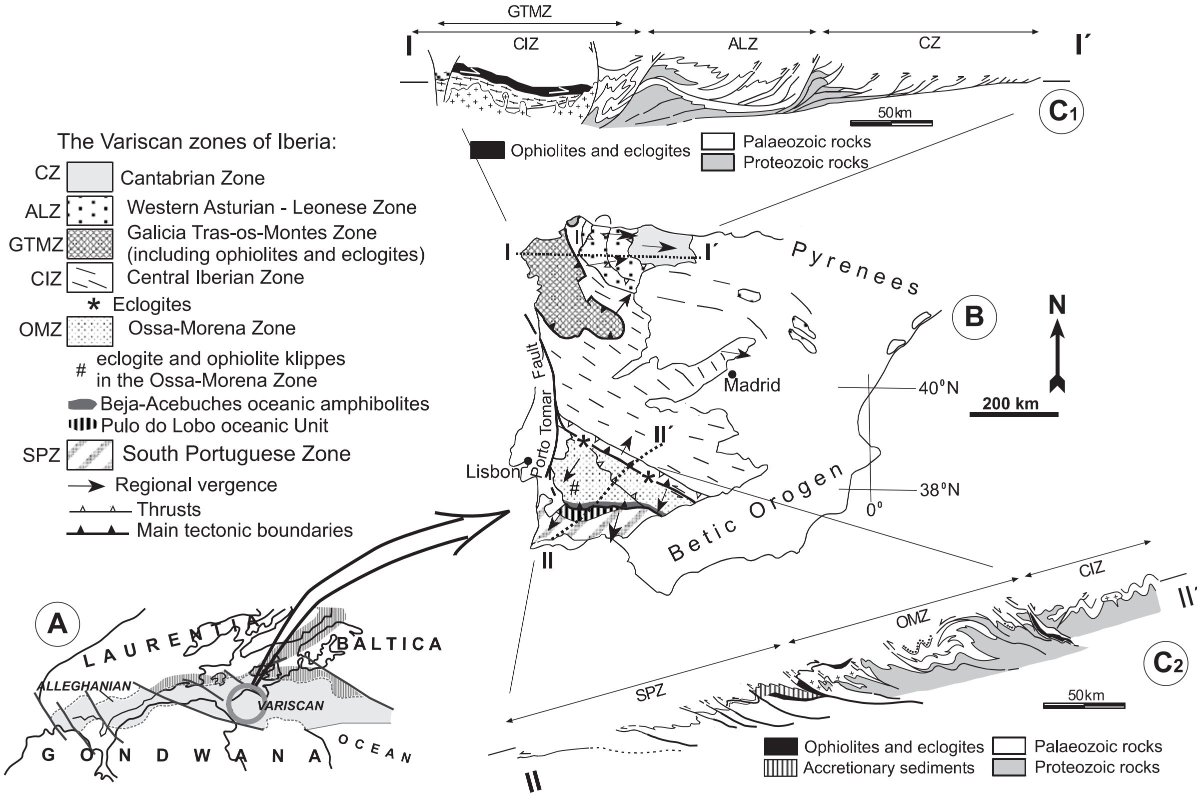

Fig. 1. (A) Location of Iberia in the Alleghanian–Variscan Orogenic belt. (B) Variscan tectonic zones in the Iberian Massif. C_1 and C_2: northern (Pérez Estaún et al., 1991) and southern (Simancas et al., 2001) cross-sections of the Iberian Massif. Note that the patterns are different in the Iberian map and the cross-sections.

transects: the northern Iberia transect and the southern Iberia transect (Fig. 1B).

In northern Iberia, the orogenic vergence is towards the east. From west to east, this transect is made up of the following tectonometamorphic domains (Fig. 1B and C_1): a) an internal zone with allochthonous units of continental and oceanic terranes, some of them having undergone granulitic and eclogitic metamorphism (Arenas et al., 1986; Martínez Catalán et al., 1996); b) an intermediate domain composed of schists intruded by some granites (western part) and slates (eastern part), deformed by east-vergent kilometer-scale recumbent folds and thrusts (Martínez Catalán et al., 1990); and c) an external zone consisting in a non-metamorphic thin-skinned thrust belt, with Lower Palaeozoic shelf sediments and a thick pile of Lower to Upper Carboniferous synorogenic deposits (Pérez Estaún and Bastida, 1990). Leaving aside some Caledonian ages recorded only in the uppermost allochthonous units (Abati et al., 1999; Fernández-Suárez et al., 2002), the age of the first tectonometamorphic events is Early Devonian in the allochthonous units. Deformation migrated eastward, reaching the easternmost units in Westphalian times. Thus, the northern Iberia section shows a complete orogenic wedge from allochtonous suture terranes in the west to a foreland fold-and-thrust belt in the east (Pérez Estaún et al., 1991; Dallmeyer et al., 1997). The Early Palaeozoic palaeogeography of the Gondwana border (before the orogenic events) was, from west to east: (i) a passive continental margin (represented by the lower units of the allochthonous Galicia Tras-os-Montes Zone; Martínez Catalán et al., 1996); (ii) an internal shelf (the Central Iberian Zone); (iii) a graben that trapped a great thickness of sediments (the Western Asturian–Leonese Zone; Pérez Estaún et al., 1990); and (iv) an external shelf (the Cantabrian Zone; Truyols et al., 1990).

The southern Iberia transect shows southward orogenic vergence and crosses two main tectonic boundaries coincident with the southern and northern contacts of the Ossa–Morena Zone (Fig. 1B and C_2). The southern boundary separates the Ossa–Morena and the South Portuguese zones, being marked by dismembered oceanic units: several small ophiolitic klippes, a strip of oceanic amphibolites, and a unit of schists with some oceanic metabasalts (Bard, 1977; Eden and Andrews, 1990; Fonseca and Ribeiro, 1993; Quesada et al., 1994; Castro et al., 1996; Fonseca et al., 1999). All those units attest the closure of some oceanic domain. The kinematics of the subsequent collision was markedly oblique (left-lateral transpression; Crespo Blanc and Orozco, 1988; Silva et al., 1990). The interpretation of the northern border of the Ossa–Morena Zone has been the object of some controversy. Structural work has shown that the boundary Ossa–Morena Zone/Central Iberian Zone (Fig. 1C_2) is the root of a pile of kilometer-scale southward-vergent recumbent folds and thrusts (Vauchez, 1975; Expósito et al., 2002; Simancas et al., 2003). Furthermore, the boundary unit is made up of metasediments, eclogites, gneisses, and amphibolites with oceanic affinity (Abalos et al., 1991; Azor et al., 1994; Ordóñez Casado, 1998; Gómez-Pugnaire et al., 2003; López Sánchez-Vizcaíno et al., 2003). Thus, despite some controversy based on the still poorly determined age of the high-pressure metamorphic event (Schäfer et al., 1991; Ordóñez Casado, 1998), this boundary can be considered as another orogenic suture (Burg et al., 1981; Matte, 1986; Azor et al., 1994; Simancas et al., 2001). In this respect, there are noticeable differences in the Ordovician to Devonian stratigraphy of the Ossa–Morena and Central Iberian zones (Robardet and Gutiérrez Marco, 1990), although faunal affinities suggest that the continental blocks of the Central Iberian and Ossa–Morena zones would not have got substantially separated (Robardet, 2002, 2003). Consequently, both boundaries of the

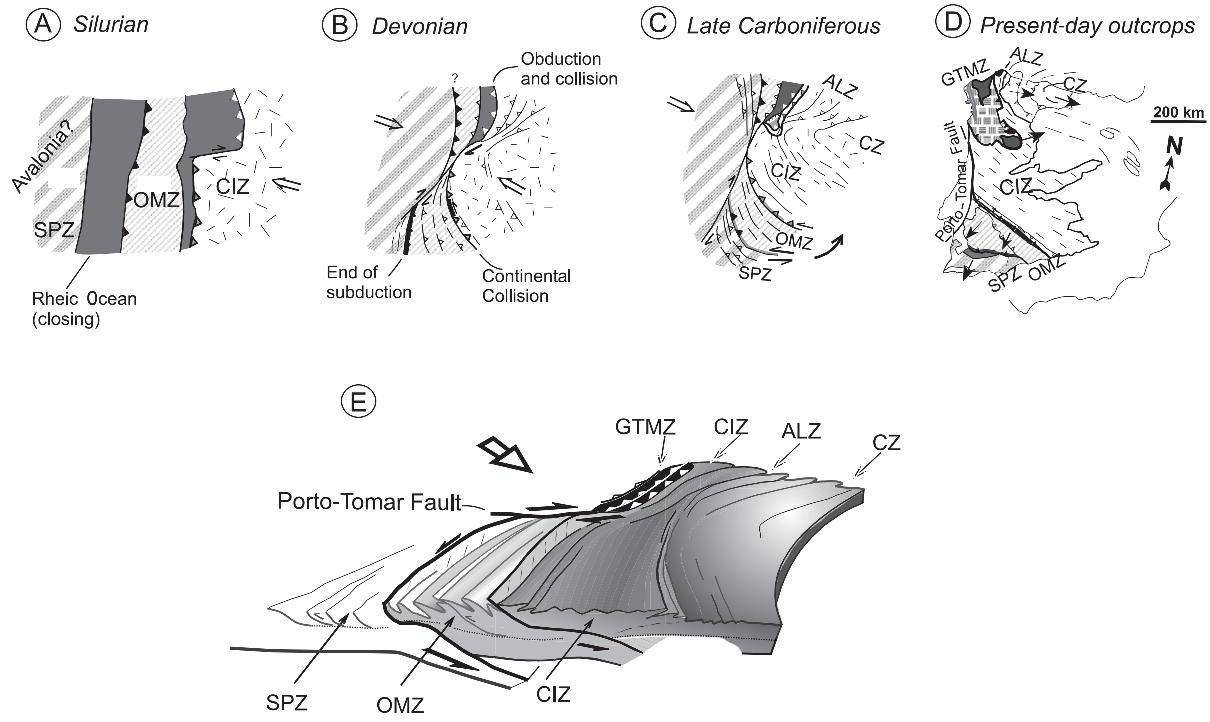

Fig. 2. (A–D) Sketches showing the evolution proposed for the Iberian Massif during the Variscan orogeny. The evolution of the GTMZ zone is perhaps particularly oversimplified. (E) 3D sketch of the Iberian Massif in Late Carboniferous time, which emphasizes the non-cylindrical structure of this orogenic region (after Simancas et al., 2002). SPZ: South Portuguese Zone; OMZ: Ossa–Morena Zone; CIZ: Central Iberian Zone; GTMZ: Galicia Tras-os-Montes Zone; ALZ: Western Asturian–Leonese Zone; CZ: Cantabrian Zone.

Ossa–Morena Zone seem to correspond to orogenic sutures, although the southern one (South Portuguese Zone/Ossa–Morena Zone) may be the suture of the Rheic Ocean, while the northern one may witness the welding of a terrane (the Ossa–Morena Zone) closely tied to the Gondwana margin (Central Iberian Zone). Closing of oceanic domains in southwest Iberia was completed in Devonian time because the early collisional deformation in the Ossa–Morena Zone is of Devonian age. Nevertheless, an extensional and magmatic event recognized in a large area of southwest Iberia took over during the latest Devonian–earliest Carboniferous, interrupting the normal development of the collision (Simancas et al., 2003). Before the Variscan orogenic events (i.e., in Early Palaeozoic times), the Ossa–Morena Zone underwent a rifting that started in Middle Cambrian, breaking a Lower Cambrian carbonate shelf (Liñán and Quesada, 1990). This rifting was highly magmatic, ending with the creation of the oceanic domains attested by the sutures referred to above at both boundaries of the Ossa–Morena Zone.

The correspondence between the sutures cropping out in southern Iberia and the one(s) indicated by the allochtonous terranes of northern Iberia is not straightforward (see different proposals in Bard et al., 1980; Burg et al., 1981; Matte, 1991, 2002; Ribeiro et al., 1995; Martínez Catalán et al., 1997, 2002, 2004; Simancas et al., 2002). Independently of the proposal to be chosen, the opposite orogenic vergence between the northern and southern Iberia sections (Fig. 1) suggests opposite subduction polarities. On this view, the Porto–Tomar fault (Ribeiro et al., 1980) could be a collisional fault derived from a former transform fault, which connected the opposite subduction zones as shown in Fig. 2 (Simancas et al., 2002).

3. The Variscides in Morocco

As in the case of Iberia, a large part of the Moroccan territory shows the effects of the Variscan orogeny (Piqué and Michard, 1989; Piqué, 1994). Most of that territory corresponds to the Moroccan Meseta, but Palaeozoic outcrops inside the Alpine ranges, both in Morocco (Rif, Middle, and High Atlas) and in northernmost Algeria (Kabilies), also provide some information about the Variscan events. However, the Palaeozoic rocks inside the Rif and Kabilies, as well as those in the Betics, are allochthonous (e.g., Sanz de Galdeano et al., 2001).

To the south, the northern African Precambrian craton constitutes the foreland of the Palaeozoic Moroccan Variscides (Fig. 3A and B). An intermediate region, the Anti Atlas, shows a basement reactivated at the end of the Proterozoic and weakly affected later by the Late Palaeozoic deformation. Leaving aside the Anti Atlas, the Variscan regions of Morocco are usually divided into Western and Eastern Meseta, separated by the Mesozoic rocks of the Middle Atlas (Piqué et al., 1993). In the Western Meseta, the following tectonic units can be distinguished, from west to east (Fig. 3B): the Coastal Block, the Central Massif/Rehamna/Jbilete, and the Nappe zone. The Nappe zone comprises the eastern borders of the Central Massif, Jbilete, and Ait Tamlil area, and constitutes the transition to the Eastern Meseta. The latter shows isolated Palaeozoic outcrops extending from Midelt to Oujda. Finally, the Sehoul Block (Piqué, 1979; El Hassani, 1991) is a Caledonian domain with a much reduced extent of outcrop, thrust onto the Western Meseta (Fig. 3A).

The Central Massif exhibits a complete Palaeozoic sequence. Lower Palaeozoic sediments formed part of an extensive platform connected with the Anti Atlas. Upper Devonian–Lower Carboniferous sediments and volcanics witness the breaking of that platform and the development of two NE–SW basins (Tahiri, 1991; Piqué, 1994). To the west, the Coastal Block shares with the Central Massif a similar stratigraphy except for the fact that it records the development of a graben in Middle Cambrian times, as indicated by the volcanism (Destombes and Jeannette, 1966; Ouali et al., 2003) and the greater thickness of sediments of this age (Bernardin et al., 1988; Piqué et al., 1995). The Coastal Block is weakly deformed, so that tectonic foliation appears only close to a dextral shear zone, which is the boundary with the Central Massif (Fig. 3B; Piqué et al., 1980). Tectonic foliation of Westphalian–Stephanian age has general development in the Central Massif (El Hassani, 1991; Tahiri, 1994), where a few granitic plutons intrude the Palaeozoic sequence. The eastern Central Massif (Nappe zone) presents a distinctive Devonian succession (calcareous flysch, olistoliths; Zahraoui, 1994), as well as a

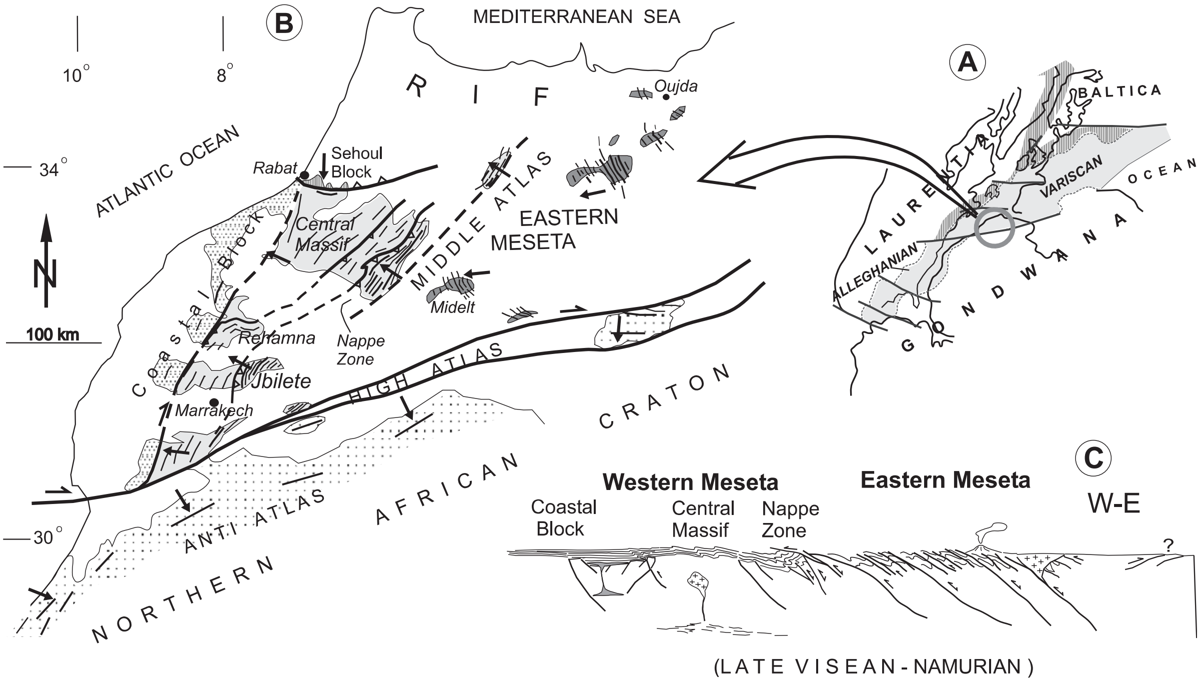

Fig. 3. (A) Location of the Moroccan Variscides in the Alleghanian–Variscan Orogenic belt. (B) Variscan zones of Morocco (compiled after different maps in Piqué, 1994). (C) Inferred cross-section of the Moroccan Variscides at Late Visean to Namurian time (modified after Piqué, 1994).

particular style and age of deformation (Bouabdelli, 1994), which makes it transitional to the Eastern Meseta.

The Eastern Meseta (Fig. 3B) can be distinguished from the Western Meseta in two main respects. First, it records different sedimentary environments, the Silurian being represented in the Eastern Meseta by pelagic deposits and the early–middle Devonian by turbidites (Hoepffener, 1987; Zahraoui, 1994). Second, both the intensity (greater in the Eastern Meseta) and the age of the first deformational event (Late Devonian in the Eastern Meseta and Carboniferous in the Western Meseta) are different (Hoepffener, 1987, 1994). As a whole, the Eastern Meseta can be interpreted as recording some crustal thinning, which gave way to an open sea to pelagic sedimentary realm during the upper part of the Early Palaeozoic. Later on, during the early–middle Devonian, it became a trough of turbiditic sediments, which announced a Late Devonian deformation (Piqué, 1994). Interestingly, although no Devonian rocks outcrop to the east of the Eastern Meseta, there are some indications (Devonian blocks in Carboniferous deposits) which can be taken to suggest that a carbonate platform would have existed east of the turbiditic trough (Hoepffener, 1987). In the allochthonous Palaeozoic rocks of the Malaguide Complex (Betic orogen, southeast Iberia; Fig. 1B), Herbig (1985) and Herbig and Stattegger (1989) have described just the same large blocks of Devonian limestones inside Visean deposits, so that the Malaguide and the Eastern Meseta might be palaeogeographically equivalent, perhaps representing the same trough bordered by the same carbonate platform.

The Late Devonian and Early Carboniferous evolution seems broadly common in the Moroccan Variscides. This time span is represented by clastic sedimentation and interbedded volcanic rocks, suggesting some kind of extensional tectonics. Firstly, sedimentation concentrated in two main grabens, the Sidi-Bettache and the Azrou–Kenifra basins, but from the middle Visean on, it expanded to a larger area (Piqué, 1994). In the Western Meseta, the Late

Devonian and Early Carboniferous volcanic rocks are tholeiitic to alkaline basalts, which characterize extensional tectonic settings. However, the volcanism of the same age in the Eastern Meseta is calc-alkaline and dominated by andesites (Karbouch, 1994).

In the Eastern Meseta (Fig. 3B), Lower Carboniferous sediments lie unconformable over Lower Palaeozoic deposits previously deformed and metamorphosed, thus indicating that the age of the first deformational event is Late Devonian. This first deformation was earlier here than in the Western Meseta, where Lower Carboniferous rocks conformably overlie Devonian ones and deformation did not start until the Visean or later. Apparently, the thinned crust extending at least from Marrakech to Oujda (the Eastern Meseta) had low strength by the time when the first compressive Variscan stresses were arising, so that deformation started earlier and thus concentrated here (Fig. 3C).

Based on the early age of the deformation, the synmetamorphic character, and the western vergence, the Eastern Meseta is thought to be the internal zone of the Moroccan Variscides (Boulin et al., 1988; Piqué and Michard, 1989; Piqué et al., 1993; Hoepffener, 1994). Accordingly, the tectonic arrangement of the outcropping Moroccan Variscides would be, from NW to SE: an external zone (the Coastal Block and Central Massif), an internal zone (the Eastern Meseta), another external zone (mostly hidden by a cover, but partially represented in the Anti Atlas region), and the African cratonic foreland. Since neither ophiolites nor eclogites crop out anywhere, most authors consider the Moroccan Variscides as an intracontinental orogen (Fig. 3C; Piqué and Michard, 1989; Piqué et al., 1993; Hoepffener, 1994). Nevertheless, the above statement is misleading in the sense that the Moroccan transect must fit into the Late Palaeozoic plate tectonic scenario, which includes the closing of at least one oceanic realm, the Rheic Ocean. On this view, it has been suggested that a main orogenic suture could be hidden under the cover, somewhere to the southeast of the Eastern Meseta (Boulin et al., 1988), but this interpretation is not, however, without problems (see discussion in Piqué et al., 1993; Piqué, 1994). Actually, the Moroccan Variscides must represent an incomplete transect of the orogen, which lacks the main suture zone.

4. Building up the Variscan tectonic frame

The Variscan tectonic frame depicted in Fig. 4 arises out of the following proposals of linkage between the different outcropping domains.

4.1. Links between Iberia and Central Europe

The main tectonic contacts between crustal domains in central and southern European Variscides are well known, the broad picture being dominated by an arcuated geometry, namely the Ibero–Armorican arc (see reviews in Bard et al., 1980; Matte and Burg, 1981; Behr et al., 1984; Matte, 1986, 1991; Franke, 1989, 2000; Ribeiro et al., 1995; Crowley et al., 2000b; Simancas et al., 2002; Winchester et al., 2002). Palaeontological and palaeomagnetic data help us to constrain how far away the continental masses were from each other at different times in the Palaeozoic (Torsvik et al., 1990; Robardet et al., 1993; Tait et al., 1997; Nysæther et al., 2002; McKerrow et al., 2000; Robardet, 2003). Therefore, a number of tectonic contacts considered as sutures due to their relationship with ophiolites and high-pressure metamorphic rocks seem to record the amalgamation of continental blocks that were drifted apart from the Gondwana margin, but never reached a sufficient degree of separation enough so as to provoke faunal dissimilarities (Matte, 2001; Nysæther et al., 2002; Kemnitz et al., 2002). The terranes bounded by such second-order sutures are collectively named Armorican Terrane Assemblage. The largest of those terranes was perhaps made up of the Saxothuringian Zone (central Europe) and the Ossa–Morena Zone (Iberia), which share many geological features and are bounded by similar suture contacts (Matte, 1991) that we correlate. The alternative model considering that the suture of the French Massif Central was continuous with both the Galicia-Tras-Os-Montes (NW Iberia) and the Ossa–Morena/Central Iberian sutures (Matte and Burg, 1981; Matte, 1986) has been criticized by Robardet (2002) because such suture would cut across two regions (Armorica and Central Iberian Zone) with strong faunal and stratigraphic similarities in the Ordovician. On this ground, we propose that a transfer fault would interrupt the continuity of the Massif Central oceanic domain, thus providing palaeogeographic continuity (Fig. 5; Simancas et al., 2002).

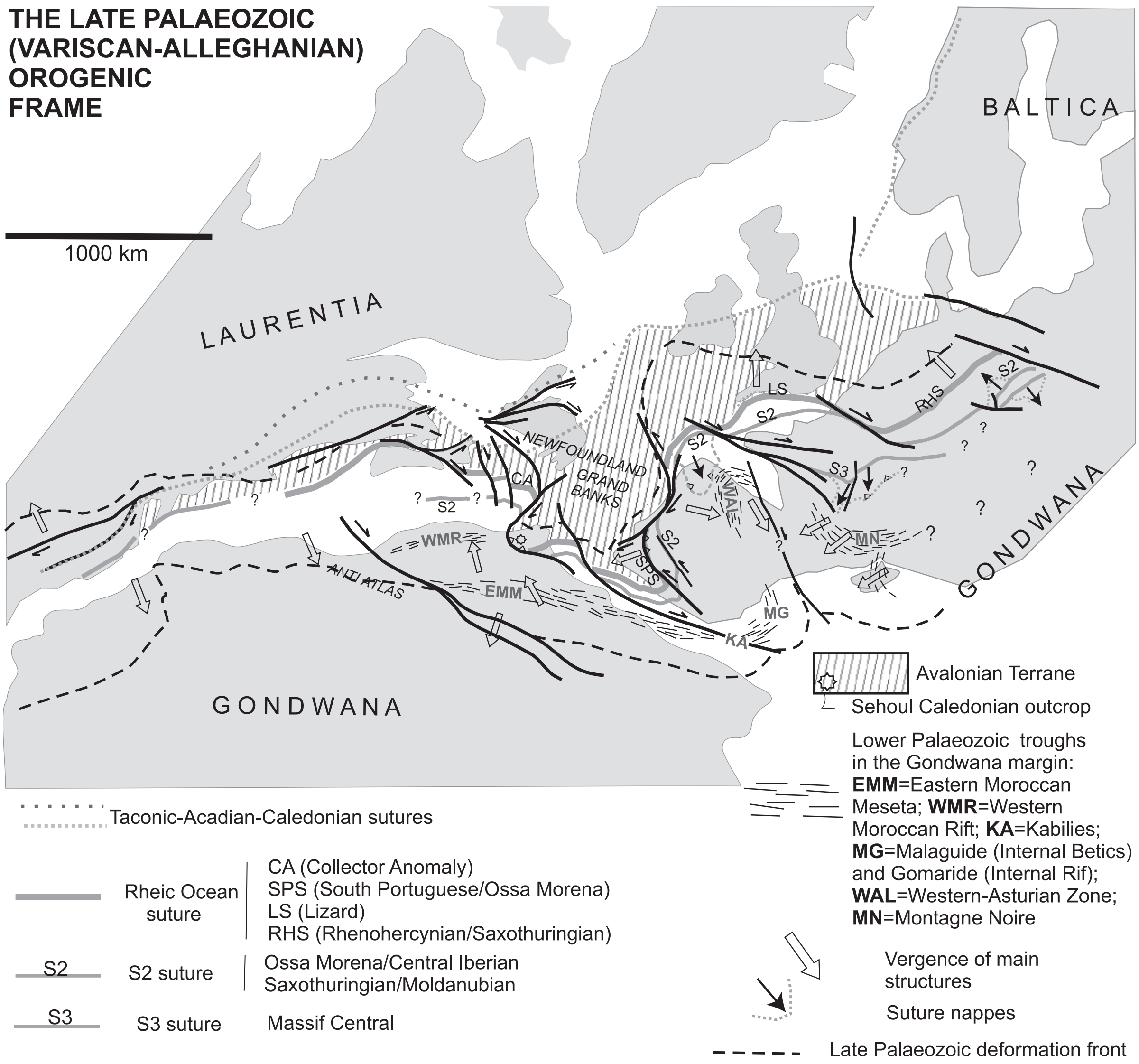

Fig. 4. Tectonic frame of the Variscan (Acadian–Alleghanian) Orogenic belt at the end of the Palaeozoic. The prominent features shown in this picture are: the extent of the Avalonian Composite Terrane (ruled area); the Variscan main suture (RHS, LS, SPS, and CA) and secondary sutures (S2, S3); the rifted areas in the margin of Gondwana (dashed bands); the regional vergences (arrows), the collisional faults (thick continuous lines), and the deformation fronts (thick dashed lines). The picture has been composed by drawing on our own data as well as on the following sources of information: Hatcher (1987) (southern Appalachians); Keppie (1982) (northern Appalachians and Newfoundland); Lefort and Ben Salmia (1992) (Nova Scotia–Newfoundland); Piqué et al. (1993) and Houari and Hoepffener (2003) (Morocco); Matte (1986,1991) (Europe). The fitting of continents at the end of the Palaeozoic is after Le Pichon et al. (1977).

The Rheic Ocean between Avalonia and the Armorican Terrane Assemblage seems to be represented by the suture between the Rhenohercynian and Saxothuringian zones of central Europe (Behr et al., 1984; Franke, 1989, 2000), which can be correlated with the suture represented by the Lizard ophiolite in SW England (Behr et al., 1984; Matte, 1986, 1991) and the boundary South Portuguese Zone/Ossa–Morena Zone in SW Iberia (Crespo Blanc and Orozco, 1988; Fonseca and Ribeiro, 1993). Moreover, there are

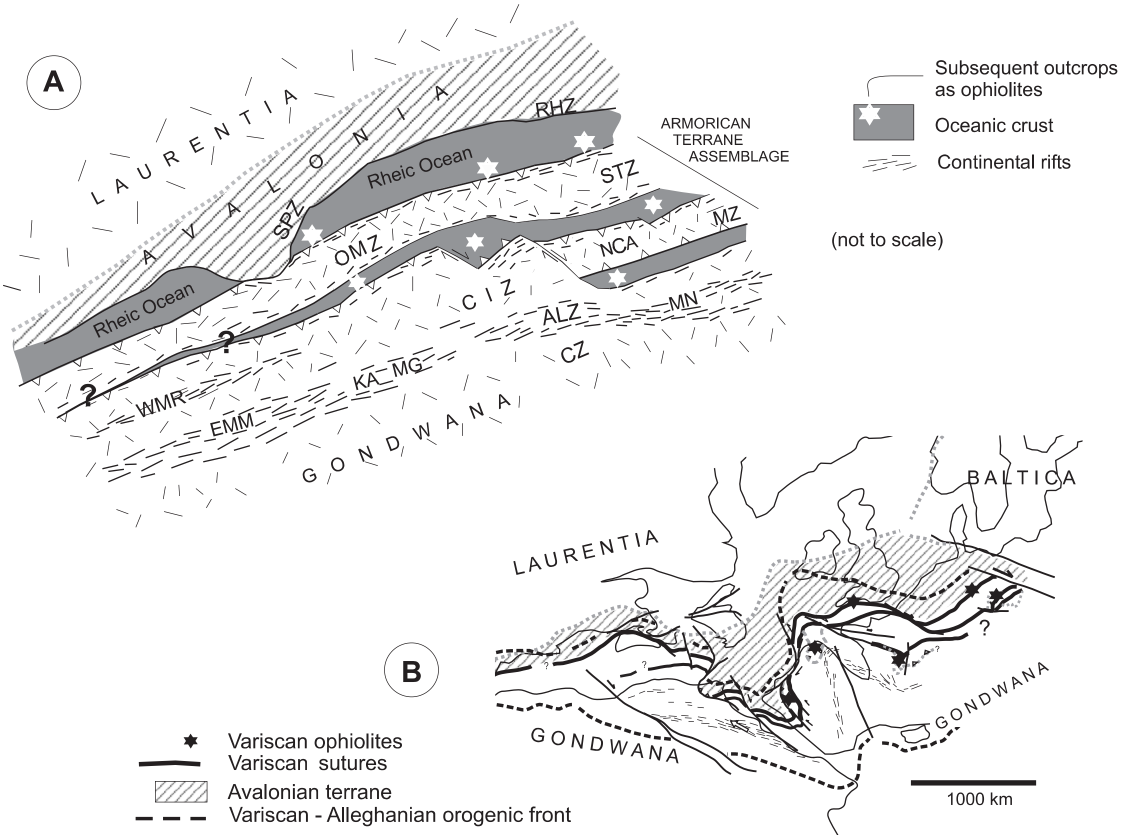

Fig. 5. (A) Sketch of the putative palaeogeography before consumption of the Rheic Ocean and amalgamation of the peri-Gondwana terranes to the Gondwana margin. The approximate sites from where future ophiolites will derive are indicated by stars. Note, however, that those ophiolites apparently related to the Rheic Ocean may have come from small marginal basins rather than being chips of the floor of the Rheic Ocean. The sketch may be particularly oversimplified for the Galicia Tras-os-Montes ophiolite. CIZ: Central Iberian Zone; CZ: Cantabrian Zone; EMM: Eastern Moroccan Meseta; KA: Kabilies; MG: Malaguide–Gomaride complex; MN: Montagne Noire; MZ: Moldanubian Zone; NCA: North-Central Armorica; OMZ: Ossa–Morena Zone; RHZ: Rhenohercynian Zone; SPZ: South Portuguese Zone; STZ: Saxothuringian Zone; ALZ: Western Asturian–Leonese Zone; WMR: Western Moroccan Rift. (B) Sketch of the orogenic belt resulting from collision of the continental pieces shown in (A); stars indicate ophiolite outcrops.

robust points of similarity between the sedimentary sequences in southwest England, the Rhenohercynian Zone in Germany, and the South Portuguese Zone in SW Iberia (Oliveira et al., 1979; Franke and Engel, 1982; Holder and Leveridge, 1986). North of the Rhenohercynian Zone, the Caledonian foreland (i.e., the Avalonian regions not reworked by the Late Palaeozoic continental collision) crops out. At southern central Europe, the Pyrenean–Alpine–Carpathian–Dinaride deformation belt has obliterated the southern part of the Variscan orogen, reworking some internal areas (Neubauer and Handler, 2000) and most of its southern external zone. Nevertheless, a number of points of convergence between the Palaeozoic outcrops of the Western Asturian–Leonese Zone in NW Iberia, the Pyrenees, and the Montagne Noire in SE France have been recognized for some time (Matte, 1991; Demange, 1994). Likewise, the present-day dispersed Palaeozoic outcrops in southern Sardinia, Minorca, and the Catalonian Coastal Ranges of NE Iberia were part of this external zone.

4.2. Links between Iberia and northern Africa

The Anti Atlas and the Meseta in Morocco as well as the Iberian Massif and a number of outcrops in Central Europe show calc-alkaline plutonic and volcanic igneous rocks of latest Neoproterozoic age overlain by Lower Cambrian carbonates (Piqué, 1981; Sánchez Carretero et al., 1990; Neubauer, 2002). These plutons and volcanosedimentary formations are manifestations of an extended postorogenic magmatism of the Pan-African orogeny, the Lower Cambrian being transgressive over the ruins of that Late Precambrian orogen. Since the Middle Cambrian, a number of rifted areas started to be defined, thus giving way to different Variscan domains. The main Variscan domains in Iberia and northern Africa are briefly described in the following paragraphs.

The Western Asturian–Leonese Zone in NW Iberia was a graben that accumulated about 10,000 m of Cambrian and Ordovician deposits, although synsedimentary volcanic rocks are scarce (Pérez Estaún et al., 1990). Less thick (about 5000 m), though nevertheless remarkable, Lower Palaeozoic successions have been described by Demange (1994) in the Montagne Noire and the Pyrenees.

The Ossa–Morena Zone of southern Iberia was a Cambro-Ordovician rifted area that shows copious magmatism and evolved to form two oceanic realms: one at the contact with the present-day South Portuguese Zone, the Rheic Ocean (Bard, 1977; Fonseca and Ribeiro, 1993), probably created in the Ordovician; the other at the contact with the Central Iberian Zone, perhaps a strait oceanic corridor which turned the Ossa–Morena into a Silurian terrane hardly independent from Gondwana (Matte, 1986; Simancas et al., 2001; Gómez-Pugnaire et al., 2003).

The Moroccan Western Meseta records a volcanic graben starting in Middle Cambrian, but it aborted soon, in Late Cambrian. The crustal thinning of the Eastern Moroccan Meseta apparently started later, in Ordovician times, but persisted until Middle Devonian times (Hoepffener, 1987; Piqué, 1994).

To conclude, the Moroccan Meseta and the Central Iberian, Western Asturian–Leonese, and Cantabrian zones of Iberia would have belonged to a common pre-orogenic domain at the border of Gondwana: a continental crust with some thinned strips recorded as sedimentary troughs. The affinity between these regions and the Brittany–Montagne Noire–Barrandian regions of central Europe is reinforced by strong similarities of Palaeozoic faunas (see reviews in Piqué, 1994; Robardet, 2003). Upon closer inspection, a number of strong similarities can be observed between the Eastern Moroccan Meseta, the Malaguide/Gomaride complex outcropping inside the Betic/Rif Alpine Ranges, the Western Asturian–Leonese Zone in NW Iberia, the Pyrenees, and the Montagne Noire in SE France. All these areas recorded Early Palaeozoic sedimentation in troughs probably related to thinned crustal areas, with scarce syn-extensional volcanism. Accordingly, all these regions were probably in approximate palaeogeographic continuity. On the contrary, there are no equivalents in Morocco of the highly magmatic Cambro-Ordovician rift (ending with creation of oceanic crust), represented by the Ossa–Morena Zone in Iberia and the Saxothuringian Zone in central Europe.

Upper Devonian and Lower Carboniferous deposits are mostly terrigenous and volcanosedimentary in Morocco and southwest Iberia. They are interpreted as revealing an extensional tectonic environment at this time, later on switched to a generalized compression. The reasons for the extension in question are debatable: in Morocco, it has been envisaged as a pull-apart basin formation in a broader context of transpression (Piqué, 1994); in southwest Iberia, the magmatic and extensional manifestations have been related to a mantle plume (Simancas et al., 2003). Independently of the interpretation preferred, the geographic distribution of the regions recording this extension has little to do with the Early Palaeozoic palaeogeographic domains.

A last issue to be emphasized is the comparison of the Variscan Late Carboniferous to Permian granitoids of Morocco and Iberia, which provide additional support to the broad correlation proposed above. In this respect, the granites of the Moroccan Central Massif (Fig. 3; Mahmood and Bennani, 1984; Amenzou and Mouraouah, 1995) show petrographic and geochemical features enabling us to consider them equivalent to others in the Central Iberian Zone (Fig. 1; Bea, 2004). In the same way, the calc-alkaline high-K granitoids outcropping in the Eastern Meseta (El Hadi et al., 2003) are similar to the granitoid stocks described in the Cantabrian Zone (Gallastegui et al., 2004). To the northeast, a similar plutonic zonation is found in the Moldanubian/Alps region (Finger and Steyrer, 1990).

4.3. Links between northwest Africa and eastern North America

As in the case of the Anti Atlas and the Moroccan Meseta, in the eastern Appalachians, there are some areas (the Avalon Peninsula, the Boston area, and the eastern Piedmont) which recorded igneous and metamorphic events of around 600 Ma. However, those areas are here exotic when compared to most of the North America margin and, accordingly, were African (Gondwanan) at that time (Rodgers, 1982; Suppe, 1985). They were later on accreted to America, after the closure of the Iapetus Ocean (Taconic plus Acadian orogenies). A witness of this Early Palaeozoic ocean is the discontinuous but distinct ophiolite line mapped along most of the Appalachians and northern Newfoundland. However, this ophiolitic line apparently marks oceanic domains developed between volcanic arcs or other terranes and the North America margin, to which they were accreted (Taconic orogeny) before the complete (Acadian) docking of Avalonia in Devonian time (Rodgers, 1982; Keppie, 1982; Suppe, 1985). For instance, the outcrops of mafic–ultramafic complexes in the southern Appalachians are interpreted as remains of a small oceanic domain between a Piedmont Terrane and the continental margin, while a more cryptic suture of the Iapetus Ocean (i.e., the northern edge of the Avalonian terrane) is envisaged to be found to the southeast, in central Piedmont (Hatcher, 1987).

Regardless of the location of sutures related to the Iapetus closure, we are here concerned with the southern edge of the Avalonian terrane (i.e., the suture marking the Devonian to Carboniferous closing of the Rheic Ocean separating Avalonia and Gondwana). In the southern Appalachians, the Rheic suture is probably hidden under the Coastal Plain. In the northern Appalachians, the location of this suture is not without controversy, with the main discussion being focused on the relationships between Avalonia and the Meguma terrane, which crops out just to the southeast, in southern Nova Scotia. Based on the finding of similar detrital zircon age populations, Murphy et al. (2004) have considered that Avalonia and Meguma were not two separate terranes, but a single one accreted to Laurentia–Baltica. This assumption would imply the location of the Rheic suture (between Avalonia and Gondwana) somewhere to the southeast of Nova Scotia, blurred by the Mesozoic opening of the Atlantic Ocean. However, the hypothesis considering that Avalonia and Meguma accreted as separate terranes (Schenk, 1997) seems to us more plausible based on: i) the Devonian deformation of Meguma, which is more easily explained as due to its collision with Avalonia; and ii) the prominent linear magnetic anomaly extending from Nova Scotia to southern Newfoundland (the Collector Anomaly), which strongly suggests the location of a suture here (Lefort and Ben Salmia, 1992; Lefort et al., 1996). Thus, in our view, the Collector Anomaly marks the boundary between the Avalon and Meguma terranes, representing the scar of the Rheic Ocean. Furthermore, according to Lefort and Ben Salmia (1992) and Lefort et al. (1996), the Moroccan Meseta and southern Nova Scotia would belong to the same crustal domain in Early Palaeozoic times, based on their similar geophysical features.

The Ordovician to Devonian deformation resulting from the complex docking of Avalonia to the North American continent is neither found in the Moroccan Meseta nor in Iberia. Only the allochthonous Sehoul block in northern Morocco exhibits an equivalent Caledonian imprint (El Hassani, 1991) and, accordingly, we suggest that this block is a portion of Avalonia. The two arguments mentioned above (i.e., the Collector Anomaly as the main suture of the Late Palaeozoic orogeny and the Sehoul block as a part of Avalonia) are essential to our tectonic picture envisaged below.

5. The tectonic frame of the Variscan–Alleghanian orogen

Arthaud and Matte (1977) were the first to present an integrated kinematic picture (a megadextral shear zone) for the Late Palaeozoic orogenic belt extending throughout Europe, northwest Africa, and eastern North America. As advanced above, a finer-grained analysis of the tectonic links between the outcropping portions of this orogen in Europe has already been furnished by a number of authors. However, there are few models on the connections between Iberia, Africa, and America. Most of the models in question suggest the linkage of the southwest Iberia zones (Ossa–

Morena and South Portuguese zones) with the Moroccan Meseta, either in a simple way (Piqué, 1981; Hoepffener, 1987) or placing in-between dextral transcurrent faults (Chalouan and Michard, 1990; Houari and Hoepffener, 2003). However, the Middle Cambrian to Early Carboniferous stratigraphy of southwest Iberia reveals a history without counterpart in Morocco.

Our interpretation of the overall tectonic frame is shown in Fig. 4. The northwest boundary of Avalonia has been delineated as passing through the central Piedmont suture (Hatcher, 1987), the central New England (Suppe, 1985), north of the Avalon Peninsula (Keppie, 1982), and the Solway line in the British Caledonides (Berthelsen, 1992). The outline of southern Avalonia, marked by the scar of the Rheic Ocean, looks more crooked: from west to east, it follows the Collector Anomaly, the Sehoul block, and the internal boundaries of the South Portuguese and Rhenohercynian zones. If we accept the validity of these northern and southern boundaries for the Avalonian terrane, it then becomes apparent that this terrane was markedly wider to the east than to the west (Fig. 4), with a maximum width in the Newfoundland Grand Banks.

The Sehoul block in northern Morocco (Figs. 3 and 4) is interpreted as a border of the Avalonian Grand Banks salient, thrust to the south onto Gondwana. Like the majority of the Appalachians, the Sehoul block records a Caledonian deformation, but this deformation did not affect other regions like the Moroccan Meseta and most of the European Variscides. Nevertheless, a Caledonian deformation has been found in some outcrops of the Rhenohercynian Zone (Franke, 2000), and it may also exist in the covered Lower Palaeozoic rocks of the South Portuguese Zone. In NW Iberia, a Caledonian tectonometamorphic event is recorded in some Upper Units of the Galicia Allochthonous Complex (Abati et al., 1999; Fernández-Suárez et al., 2002). Thus, the crust of the Sehoul block, the South Portuguese Zone, some Upper Units of the Galicia Allochthonous, and the Rhenohercynian Zone would be argued to belong to the southern border of Avalonia (Fig. 4).

The oblique dextral collision between Avalonia and Gondwana (with the outboard terrane of the Ossa–Morena–Saxothuringian zones sandwiched in between) developed a remarkable set of dextral transcurrent faults in Morocco and eastern North America. Most of the faults shown in Fig. 4 are mapped geological structures (Keppie, 1982; Houari and Hoepffener, 2003) or faults inferred from the displacement of the Collector Anomaly between Nova Scotia and Newfoundland (Lefort and Ben Salmia, 1992). South of Newfoundland, we envisage the suture represented by that magnetic anomaly to be displaced again towards the north of Morocco (Fig. 4). Here, the suture could be found perhaps under the Alpine allochthonous units of the Rif, but most probably has been disrupted, displaced, and subducted to a considerable extent during the Jurassic to present-day displacements between Africa and Iberia (e.g., Ricou, 1994). Nevertheless, a survivor witness of the suture in this area may be some rocks recently dredged about 100 km south of the southwest Iberian coast, which are similar to those cropping out in the northern South Portuguese Zone and its boundary with the Ossa–Morena Zone (Vegas et al., 2004). Furthermore, a dextral displacement of the suture in that missing area between Iberia and Africa can be inferred from the evidence of a deep-crustal Late Palaeozoic shear zone in the Kabilies (Fig. 4; Bossière, 1980; Bouillin et al., 1984; Piqué et al., 1993). This shear zone is described as approximately east–west, dextral, and cross-cutting low grade metamorphic rocks, with the shear zone itself exhibiting a medium-pressure, high-grade metamorphism. A granite dated as 271 (Rb–Sr)/273 (U–Pb) Ma (Bossière and Peucat, 1986; Peucat and Bossière, 1991) intruded after the blastomylonitization in this shear zone.

The prominent spur of Avalonia, which approximately coincides with the present-day Grand Banks, played a major role in the complex pattern of the central part of the Variscan orogenic belt. This is why the main Variscan suture presents an abrupt change of orientation, cropping out again in southern Iberia, as the boundary between the South Portuguese and Ossa–Morena zones (Fig. 4). The prolongation of this main suture in southern England (Lizard ophiolite) and along the boundary between the Rhenohercynian and Saxothuringian zones is generally accepted (e.g., Matte, 2002). From a kinematic point of view, our reconstruction suggests that the Grand Banks' indentor would have originated the Carboniferous prominent sinistral shearing in southern Iberia, in addition to some counterclockwise rotation of this region. Thus, the Grand Banks' indentor may have been more influential on the configuration of the Ibero–Armorican arc than the usually envisaged active indentor in the core of the arc (Matte and Ribeiro, 1975; Burg et al., 1981; Matte, 1986, 1991). In this respect, we note that recent palaeomagnetic studies by Weil et al. (2001) in the Asturian core of the Ibero–Armorican arc suggest that most of the tightening of this megastructure would have taken place in latest Carboniferous–Permian time, substantially later than the timing required by models based on strong indentation in the core of the arc. Our reconstruction furnishes us with a kinematic picture somewhat more compatible with those palaeomagnetic results because most of the rotations in the Asturian core of the arc can be delayed until a late collisional stage.

Despite the above statement, the Grand Banks' indentor did not behave as rigidly as, say, the Indian indentor in the Himalayan collision (Tapponier et al., 1982); on the contrary, it underwent an important deformation reshaping it. In this respect, some indentation of the Iberian core, on the one hand, and of northwest Africa, on the other hand, can be inferred from the fault pattern: escape tectonics in Iberia is illustrated in Figs. 2B and 4, while some northward penetration of Africa is suggested by the Nova Scotia–Newfoundland escape fault arrangement (Fig. 4). Actually, the Alleghanian deformation in the northern Appalachians is dominated by strike–slip faults (Keppie, 1982; Rodgers, 1982).

Second-order sutures between peri-Gondwana terranes and the border of Gondwana cannot be followed all along the orogen. The suture located at the boundary between the Saxothuringian and the Moldanubian zones in central Europe seems to be equivalent to the boundary Ossa–Morena Zone/Central Iberia Zone (S2 in Fig. 4; see also Fig. 5A). There are no data on the possible continuation to the southwest of this suture, but the gneissic rocks found in drill holes on the Atlantic platform of Morocco (Kreuzer et al., 1984) could be related to its continuation. On the other hand, the Massif Central suture in France (S3 in Fig. 4) apparently does not prolong towards Iberia (as discussed above), abutting perhaps on a transfer fault (Fig. 5).

The schematic palaeogeographic picture proposed here for the oceanic domains before continental collision took place is sketched in Fig. 5A. In this figure, the approximate sites from where future ophiolites will derive are suggested by stars, although the ophiolites apparently related to the closure of the Rheic Ocean may represent, rather than the ocean itself, pull-apart basins (the Lizard complex in Cornwall; Cook et al., 2002), young small "oceans" (the Rhenohercynian ocean; Franke, 2000), back-arc basins (the Beja–Acebuches ophiolite in southwest Iberia; Quesada et al., 1994), or other particular domains of a much more complex palaeogeographic scenario. As for the Galicia Tras-os-Montes ophiolitic units (Arenas et al., 2004), they may constitute a complex ophiolite, including units coming from different oceanic domains.

The continental grabens that developed in Early Palaeozoic times on the margin of Gondwana are also very schematically depicted in Fig. 5A: these are the Middle Cambrian Western Moroccan Rift, in the Coastal Block, and a long strip of more or less aligned grabens of Ordovician–Early Devonian age, now represented by the Eastern Meseta and the Palaeozoic of Kabilies/Malaguide/Gomarides (inliers in Alpine Ranges), plus the Cambro-Ordovician rifted area of the Western Asturian–Leonese Zone and the Montagne Noire–Pyrenees. This strip of grabens is the southernmost domain influenced by the Early Palaeozoic extension on the northern border of Gondwana.

6. Conclusion

We have proposed here a tectonic frame—obviously simplified, but coherent—for the Variscan–Alleghanian orogenic belt from central Europe to the southern Appalachians at both pre-collisional and late-collisional stages. Apart from other geological and geophysical data available from previous works, the two keystones in our reconstruction are as follows: (i) the suture-bounded Variscan zones of Iberia (Ossa–Morena and South Portuguese zones in the southern transect, and the allochthonous Galicia Tras-os-Montes Zone in the northern transect) have no equivalent in the Moroccan Variscides; and (ii) the Moroccan Meseta shows stratigraphic similarities with the central and northern zones of Iberia, considered to have been part of the Gondwana rifted margin at early Palaeozoic times. Thus, the northern Iberia palaeogeographic zones would prolong in the Moroccan Meseta through an eastward arcuate structure. Accordingly, the main suture of the Variscan orogen (Rheic Ocean), which is represented at the boundary between the South Portuguese and Ossa–Morena zones, moulds around an Avalonian spur (Grand Banks indentor), being laterally translated to south-eastern Nova Scotia–Newfoundland. The Caledonian Sehoul block in northern Morocco is considered to be part of that Avalonian spur, as well as the crust of the South Portuguese Zone in SW Iberia. We consider this Avalonian (Grand Banks) indentation and the counterparts late-collisional indentations of Iberia and northwest Africa to have played an important role on the tectonic pattern of the central segment of the Variscan orogenic belt.

Acknowledgements

Financial support has been given by the AECI (Agencia Española de Cooperación Internacional) grants number 65/03/P and 65/04/R/E, the Junta de Andalucía grant number A11/02 (M), and the Ministerio de Ciencia y Tecnología grant number BTE2003-05128. We thank Francisco Gonzálvez García for improving our English text. Comments and suggestions by two anonymous reviewers are greatly acknowledged.

References

Abalos, B., Gil Ibarguchi, J.I., Eguiluz, L., 1991. Cadomian subduction/collision and Variscan transpression in the Badajoz–Córdoba shear belt, southwest Spain. Tectonophysics 199, 51–72.

Abati, J., Dunning, G.R., Arenas, R., Díaz García, F., González Cuadra, P., Martínez Catalán, J.R., Andonaegui, P., 1999. Early Ordovician orogenic event in Galicia (NW Spain): evidence from U–Pb ages in the uppermost unit of the Ordenes Complex. Earth and Planetary Science Letters 165, 213–228.

Amenzou, M., Mouraouah, A. El Arab, 1995. Classification génétique des granitoïdes hercyniens du Massif Central marocain (Zaer, Oulmès, Ment; Méséta nord-occidentale, Maroc), d'après la typologie du zircon. Comptes Rendus de l'Académie des Sciences Paris 320 (IIa), 469–476.

Arenas, R., Gil Ibarguchi, J.I., González Lodeiro, F., Klein, E., Martínez Catalán, J.R., Ortega Gironés, E., de Pablo Maciá, J.G., Peinado, M., 1986. Tectonostratigraphic units in the complexes with mafic and related rocks of the NW of the Iberian Massif. Hercynica 2, 87–110.

Arenas, R., Díaz García, F., Martínez Catalán, J.R., Sánchez Martínez, S., 2004. Zona de Galicia-Trás-Os-Montes. Unidades ofiolíticas. In: Vera, J. (Ed.), Geología de España. SGE-IGME, Madrid, pp. 150–154.

Arthaud, F., Matte, Ph., 1977. Late Palaeozoic strike–slip faulting in southern Europe and northern Africa: result of a right-lateral shear zone between the Appalachians and the Urals. Geological Society of America Bulletin 88, 1305–1320.

Azor, A., González Lodeiro, F., Simancas, J.F., 1994. Tectonic evolution of the boundary between the Central Iberian and Ossa–Morena zones (Variscan Belt, southwest Spain). Tectonics 13, 45–61.

Bard, J.P., 1977. Signification tectonique des métatholeites d'affinité abyssale de la ceinture de basse pression d'Aracena (Huelva, Espagne). Bulletin de la Societé Géologique de France 19, 385–393.

Bard, J.P., Burg, J.P., Matte, Ph., Ribeiro, A., 1980. La chaine hercynienne d'Europe occidentale en termes de tectonique des plaques. 26ème Congrés Géologique International, Paris, Colloque C6. Mémoires BRGM 108, pp. 233–246.

Bea, F., 2004. La naturaleza del magmatismo de la Zona Centroibérica: consideraciones generales y ensayo de correlación. In: Vera, J. (Ed.), Geología de España. SGE-IGME, Madrid, pp. 128–133.

Behr, H.J., Engel, W., Franke, W., Giese, P., Weber, K., 1984. The Variscan belt in Central Europe: main structures, geodynamic implications, open questions. Tectonophysics 109, 15–40.

Bernardin, C., Cornée, J.J., Corsini, M., Mayor, S., Muller, J., Tayebi, M., 1988. Variations d'épaisseur du Cambien moyen en Meseta marocaine occidentale: signification géodynamique des données de surface et de subsurface. Canadian Journal of Earth Sciences 25, 2104–2117.

Berthelsen, A., 1992. Mobile Europe. In: Blundell, D., Freeman, R., Mueller, S. (Eds.), A Continent Revealed. The European geotraverse. Cambridge University Press, Cambridge, UK, pp. 11–32, 153–164.

Bossière, G., 1980. Un complexe métamorphique polycyclique et sa blastomylonitisation. Etude pétrologique de la partie occidentale du massif de Grande Kabylie (Algérie). PhD thesis, University of Nantes, France.

Bossière, G., Peucat, J.J., 1986. Structural evidence and Rb–Sr, 39–40 Ar mica age relationships for the existence of an Hercynian deep crustal shear zone in Grande Kabilie (Algeria) and its Alpine reworking. Tectonophysics 121, 277–294.

Bouabdelli, M., 1994. La Tectonique de l'Est du Massif hercynien central (zone d'Azrou-Khénifra). Géologie du Paléozoique du Maroc central et de la Meseta orientale, Bulletin de l'Institut Scientifique (Rabat) Numero Spécial, vol. 18, pp. 145–168.

Bouillin, J.P., Bossière, G., Bourrouilh, R., Coutelle, A., Durand-Delga, M., 1984. Mise au point sur l'âge des socles métamorphiques kabyles (Algérie). Comptes Rendus de l'Académie des Sciences Paris, Série II 298, 655–660.

Boulin, J., Bouabdelli, M., Houicha, E., 1988. Evolution paléogéographique et géodynamique de la chaîne paléozoïque du

Moyen Maroc: un essai de modélisation. Comptes Rendus de l'Académie des Sciences Paris 306 (II), 1501–1506.

Burg, J.P., Iglesias, M., Laurent, Ph., Matte, Ph., Ribeiro, A., 1981. Variscan intracontinental deformation: the Coimbra–Córdoba Shear zone (SW Iberian Peninsula). Tectonophysics 78, 161–177.

Castro, A., Fernández, C., de la Rosa, J., Moreno Ventas, I., Rogers, G., 1996. Significance of MORB-derived amphibolites from the Aracena metamorphic belt, southwest Spain. Journal of Petrology 37, 235–260.

Chalouan, A., Michard, A., 1990. The Ghomarides nappes, Rif Coastal Range, Morocco: a Variscan chip in the Alpine Belt. Tectonics 9, 1565–1583.

Cook, C.A., Holdsworth, R.E., Styles, M.T., 2002. The emplacement of peridotites and associated oceanic rocks from the Lizard Complex, southwest England. Geological Magazine 139, 27–45.

Crespo Blanc, A., Orozco, M., 1988. The Southern Iberia Shear Zone: a major boundary in the Hercynian folded belt. Tectonophysics 148, 221–227.

Crowley, Q.G., Floyd, P.A., Winchester, J.A., Franke, W., Holland, J.G., 2000a. Early Palaeozoic rift-related magmatism in Variscan Europe: fragmentation of the Armorican Terrane Assemblage. Terra Nova 12, 171–180.

Crowley, Q.G., Floyd, P.A., Stodrá, V., Winchester, J.A., Holland, J.G., 2000b. The Mariánské–Lázne Complex: Remnants of a Subducted Early Palaeozoic Seaway. Program and Abstracts of the 15th International Conference on Basement Tectonics, Galicia 2000, Variscan–Appalachian Dynamics: The Building of the Upper Paleozoic Basement, A Coruña (Spain), pp. 86–89.

Dallmeyer, R.D., Martínez Catalán, J.R., Arenas, R., Gil Ibarguchi, J.I., Gutiérrez Alonso, G., Farias, P., Bastida, F., Aller, J., 1997. Diachronous Variscan tectonothermal activity in the NW Iberian Massif: evidence from ^{40}Ar/^{39}Ar dating of regional fabrics. Tectonophysics 277, 307–337.

Demange, M., 1994. Antevariscan evolution of the Montagne Noire (France): from a passive margin to a foreland basin. Comptes Rendus de l'Académie des Sciences Paris 318 (II), 921–933.

Destombes, J., Jeannette, A., 1966. Mémoire explicatif de la carte géotechnique de la Méséta Côtière à l'Est de Casablanca au 1/50,000. Notes et Mémoires Service géologique Maroc 180. 104 pp.

Eden, C., Andrews, J., 1990. Middle to Upper Devonian melanges in SW Spain and their relationship to the Meneage formation in south Cornwall. Proceedings of the Ussher Society 7, 217–222.

El Hadi, H., Tahiri, A., Reddad, A., 2003. Les granitoïdes hercyniens post-collisionnels du Maroc oriental: une province magmatique calco-alcaline à shoshonitique. Comptes Rendus Geoscience 335, 959–967.

El Hassani, A., 1991. La Zone de Rabat-Tiflet: bordure nord de la chaîne calédono-hercynienne du Maroc. Bulletin de l'Institut Scientifique (Rabat) 15, 1–134.

Expósito, I., Simancas, J.F., González Lodeiro, F., Azor, A., Martínez Poyatos, D., 2002. La estructura de la mitad septentrional de la Zona de Ossa–Morena. Deformación en el bloque de muro de un cabalgamiento cortical de evolución compleja. Revista de la Sociedad Geológica de España 15, 3–14.

Fernández-Suárez, J., Corfu, F., Arenas, R., Marcos, A., Martínez Catalán, J.R., Díaz García, F., Abati, J., Fernández, F.J., 2002. U–Pb evidence for a polyorogenic evolution of the HP–HT units of the NW Iberian Massif. Contributions to Mineralogy and Petrology 143, 236–253.

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

Fonseca, P., Ribeiro, A., 1993. Tectonics of the Beja–Acebuches Ophiolite: a major suture in the Iberian Variscan Foldbelt. Geologische Rundschau 82, 440–447.

Fonseca, P., Munhá, J., Pedro, F., Rosas, J., Moita, P., Araujo, A., Leal, N., 1999. Variscan ophiolites and high-pressure metamorphism in southern Iberia. Ofioliti 24, 259–268.

Franke, W., 1989. Tectonostratigraphic units in the Variscan belt of central Europe. Special Paper-Geological Society of America 230, 67–90.

Franke, W., 2000. The mid-European segment of the Variscides: tectonostratigraphic units, terrane boundaries and plate tectonic evolution. In: Franke, W., Haak, V., Oncken, O., Tanner, D. (Eds.), Orogenic Processes: Quantification and Modelling in the Variscan Belt. Special Publication-Geological Society of London, vol. 179, pp. 35–61.

Franke, W., Engel, W., 1982. Variscan sedimentary basins on the continent and relations with south–west England. Proceedings of the Ussher Society 5, 259–269.

Gallastegui, G., Suárez, O., Cuesta, A., 2004. Zona Cantábrica. Magmatismo. In: Vera, J. (Ed.), Geología de España. SGE-IGME, Madrid, pp. 47–49.

Gómez-Pugnaire, M.T., Azor, A., Fernández Soler, J.M., López Sánchez-Vizcaíno, V., 2003. The amphibolites from the Ossa–Morena/Central Iberian Variscan suture (Southwestern Iberian Massif): geochemistry and tectonic interpretation. Lithos 68, 23–42.

Hatcher, R.D., 1987. Tectonics of the southern and central Appalachian internides. Annual Review of Earth and Planetary Sciences 15, 337–362.

Herbig, H.G., 1985. An upper Devonian limestone slide block near Marbella (Betic Cordillera, Southern Spain) and the palaeogeographic relations between Malaguides and Menorca. Acta Geologica Hispanica 20, 155–178.

Herbig, H.G., Stattegger, K., 1989. Late Palaeozoic heavy minerals and clast modes from the Betic Cordillera (southern Spain): transition from a passive to an active continental margin. Sedimentary Geology 63, 93–108.

Hoepffener, Ch., 1987. La tectonique hercynienne dans l'Est du Maroc. PhD thesis Université Louis Pasteur, Strasbourg, France. 276 pp.

Hoepffener, Ch., 1994. La zone de Midelt–Tazekka–Bsabis, le domaine interne de la chaine varisque et ses relations avec le Massif hercynien central. Géologie du Paléozoique du Maroc central et de la Meseta orientale. Bulletin de l'Institut Scientifique (Rabat) Numero Spécial, vol. 18, pp. 169–190.

Holder, M.T., Leveridge, B.E., 1986. Correlation of the Rhenohercynian Variscides. Journal of the Geological Society (London) 143, 141–147.

Houari, M.R., Hoepffener, Ch., 2003. Late Carboniferous dextral wrench-dominated transpression along the North African craton margin (Eastern High-Atlas, Morocco). Journal of African Earth Sciences 37, 11–24.

Karbouch, F., 1994. Le volcanisme dévono-dinantien du Massif central et de la Meseta orientale. Géologie du Paléozoique du Maroc central et de la Meseta orientale. Bulletin de l'Institut Scientifique (Rabat) Numero Spécial, vol. 18, pp. 191–199.

Kemnitz, H., Romer, R.L., Oncken, O., 2002. Gondwana break-up and the northern margin of the Saxothuringian belt (Variscides of Central Europe). International Journal of Earth Sciences (Geologische Rundschau) 91, 246–259.

Keppie, D., 1982. Terranes in the Northern Appalachians. Maps 1: 5,000,000 and Charts. Nova Scotia Department of Mines and Energy, Canada.

Kreuzer, H., Muller, P., Reinecke, T., Wissman, G., 1984. Petrography and K–Ar Dating of the Mazagan Granodiorite DSDP Leg 79, Holes 544A and 544B. Initial Reports DSDP 79, Washington (US Government Printing Office), pp. 543–549.

Lefort, J.P., Ben Salmia, A., 1992. Les accrétions laurentiennes et al propagation de l'effet de coin grenvillien. Comptes Rendus de l'Académie des Sciences Paris 315 (II), 623–627.

Lefort, J.P., Ben Salmia, A., Miller, H.G., 1996. Age and mode of emplacement of the Collector Anomaly (Canada): is it the northwestern boundary of Gondwana? Journal of Geodynamics 21, 177–190.

Le Pichon, X., Sibuet, J.C., Francheteau, J., 1977. The fit of the continents around the North Atlantic Ocean. Tectonophysics 38, 169–209.

Liñán, E., Quesada, C., 1990. The Ossa–Morena Zone. Rift phase (Cambrian). In: Dallmeyer, R.D., Martínez García, E. (Eds.), Pre-Mesozoic Geology of Iberia. Springer-Verlag, Berlin, pp. 259–266.

López Sánchez-Vizcaíno, V., Gómez Pugnaire, M.T., Azor, A., Fernández Soler, J.M., 2003. Phase diagram sections applied to amphibolites: a case study from the Ossa–Morena/Central Iberian Variscan suture (Southwestern Iberian Massif). Lithos 68, 1–21.

Mahmood, A., Bennani, A., 1984. S-type characteristics of the Hercynian granitoids of the Central Palaeozoic Massif, Morocco. Geological Magazine 121, 301–309.

Martínez Catalán, J.R., Pérez Estaún, A., Bastida, F., Pulgar, J.A., Marcos, A., 1990. The west Asturian–Leonese zone. Structure. In: Dallmeyer, R.D., Martínez García, E. (Eds.), Pre-Mesozoic Geology of Iberia. Springer-Verlag, Berlin, pp. 103–114.

Martínez Catalán, J.R., Arenas, R., Díaz García, F., Rubio Pascual, F.J., Abati, J., Marquínez, J., 1996. Variscan exhumation of a subducted Paleozoic continental margin: the basal units of the Ordenes Complex, Galicia, NW Spain. Tectonics 15, 106–121.

Martínez Catalán, J.R., Arenas, R., Díaz García, F., Abati, J., 1997. Variscan accretionary complex of northwest Iberia: terrane correlation and succession of tectonothermal events. Geology 25, 1103–1106.

Martínez Catalán, J.R., Díaz García, F., Arenas, R., Abati, J., Castiñeiras, P., González Cuadra, P., Gómez Barreiro, J., Rubio Pascual, F.J., 2002. Thrust and detachment systems in the Ordenes Complex (northwestern Spain): implications for the Variscan–Appalachian geodynamics. In: Martínez Catalán, J.R., Hatcher, R., Arenas, R., Díaz García, F. (Eds.), Variscan–Appalachian Dynamics: The Building of the Late Paleozoic Basement. Special Paper-Geological Society of America, vol. 364, pp. 163–182.

Martínez Catalán, J.R., Arenas, R., Díaz García, F., Abati, J., Sánchez Martínez, S., Fernández-Suárez, J., 2004. Zona de Galicia-Trás-Os-Montes. Terrenos e historia acrecionaria. In: Vera, J. (Ed.), Geología de España. SGE-IGME, Madrid, pp. 162–165.

Matte, Ph., 1986. Tectonics and plate tectonic model for the Variscan belt of Europe. Tectonophysics 126, 331–334.

Matte, Ph., 1991. Accretionary history and crustal evolution of the Variscan belt in Western Europe. Tectonophysics 196, 309–337.

Matte, Ph., 2001. The Variscan collage and orogeny (480–290 Ma) and the tectonic definition of the Armorica microplate: a review. Terra Nova 13, 122–128.

Matte, Ph., 2002. Variscides between the Appalachians and the Urals; similarities and differences between Paleozoic subduction and collision belts. In: Martínez Catalán, J.R., Hatcher, R., Arenas, R., Díaz García, F. (Eds.), Variscan–Appalachian Dynamics: The Building of the Late Paleozoic Basement, Special Paper-Geological Society of America, vol. 364, pp. 239–251.

Matte, Ph., Burg, J.P., 1981. Sutures, thrusts and nappes in the Variscan arc of western Europe: plate tectonic implications. In: McClay, K., Price, N.J. (Eds.), Thrust and Nappe Tectonics, Special Publication-Geological Society of London, vol. 9, pp. 353–358.

Matte, Ph., Ribeiro, A., 1975. Forme et orientation de l'ellipsoide de déformation dans la virgation hercynienne de Galicia: relation avec le plissement et hypothèses sur la gènese de l'arc Ibéro–Armoricain. Comptes Rendus de l'Académie des Sciences Paris 280 (D), 2825–2828.

McKerrow, W.S., Mac Niocaill, C., Ahlberg, P.E., Clayton, G., Cleal, C.J., Eagar, R.M.C., 2000. The Late Palaeozoic relations between Gondwana and Laurussia. In: Franke, W., Haak, V., Oncken, O., Tanner, D. (Eds.), Orogenic Processes: Quantification and Modelling in the Variscan Belt. Special Publication-Geological Society of London, vol. 179, pp. 9–20.

Murphy, J.B., Fernández-Suárez, J., Keppie, J.D., Jeffries, T.E., 2004. Contiguous rather than discrete Paleozoic histories for the Avalon and Meguma terranes based on detrital zircon data. Geology 32, 585–588. doi:10.1130/G20351.1.

Neubauer, F., 2002. Evolution of late Neoproterozoic to early Paleozoic tectonic elements in Central and Southeast European Alpine mountain belts: review and synthesis. Tectonophysics 352, 87–103.

Neubauer, F., Handler, R., 2000. Variscan Orogeny in the Eastern Alpine–Mediterranean Mountain belts: how does it relate with extra-Alpine Variscides? Program and Abstracts of the 15th International Conference on Basement Tectonics, Galicia 2000, Variscan–Appalachian Dynamics: The Building of the Upper Paleozoic Basement, A Coruña (Spain), p. 17.

Nysæther, E., Torsvik, T.H., Feist, R., Walderhaug, H.J., Eide, E.A., 2002. Ordovician palaeogeography with new palaeomagnetic data from the Montagne Noir (Southern France). Earth and Planetary Science Letters 203, 329–341.

Oliveira, J.T., Horn, M., Paproth, E., 1979. Preliminary note on the stratigraphy of the Baixo Alentejo Flysch Group, Carboniferous of Southern Portugal, and on the palaeogeographic development, compared to corresponding units in Northwest Germany. Comunicações dos Serviços Geológicos de Portugal 65, 151–168.

Ordóñez Casado, B., 1998. Geochronological Studies of the Pre-Mesozoic Basement of the Iberian Massif: The Ossa–Morena Zone and the Allochthonous Complexes within the Central Iberian Zone. PhD thesis, ETH, Zurich. 235 pp.

Ouali, H., Briand, J.L., Bouchardon, P., Capiez, P., 2003. Le volcanisme cambrien du Maroc central: implications géodynamiques. Comptes Rendus. Geoscience 335, 425–433.

Pérez Estaún, A., Bastida, F., 1990. The Cantabrian zone. Structure. In: Dallmeyer, R.D., Martínez García, E. (Eds.), Pre-Mesozoic Geology of Iberia. Springer-Verlag, Berlin, pp. 55–69.

Pérez Estaún, A., Bastida, F., Martínez Catalán, J.R., Gutiérrez Marco, J.C., Marcos, A., Pulgar, J.A., 1990. The West-Asturian Leonese zone. Stratigraphy. In: Dallmeyer, R.D., Martínez García, E. (Eds.), Pre-Mesozoic Geology of Iberia. Springer-Verlag, Berlin, pp. 92–102.

Pérez Estaún, A., Martínez Catalán, J.R., Bastida, F., 1991. Crustal thickening and deformation sequence in the footwall to the suture of the Variscan belt of northwest Spain. Tectonophysics 191, 243–253.

Peucat, J.J., Bossière, G., 1991. Age U–Pb fini-hercynien de la ceinture mylonitique de haute pression-haute température en Grande Kabylie (Algérie). Comptes Rendus de l'Académie des Sciences Paris 313 (II), 1261–1267.

Piqué, A., 1979. Evolution structurale d'un segment de la chaine hercynienne: la Meseta marocaine nord-occidentale. PhD thesis, Université de Strasbourg (Sciences Géologiques Mémoires) 56. 243 pp.

Piqué, A., 1981. Northwestern Africa and the Avalonian plate: relations during late Precambrian and late Paleozoic time. Geology 9, 319–322.

Piqué, A., 1994. Géologie du Maroc. Marrakech, Pumag. 240 pp.

Piqué, A., Michard, A., 1989. Moroccan Hercynides. A synopsis. The Palaeozoic sedimentary and tectonic evolution at the northern margin of west Africa. American Journal of Science 289, 286–330.

Piqué, A., Jeannette, D., Michard, A., 1980. The Western Meseta Shear Zone, a major and permanent feature of the Hercynian belt of Morocco. Journal of Structural Geology 2, 55–61.

Piqué, A., Bossière, G., Bouillin, J.P., Chalouan, A., Hoepffener, Ch., 1993. Southern margin of the Variscan belt: the northwestern Gondwana mobile zone (eastern Morocco and Northern Algeria). Geologische Rundschau 82, 432–439.

Piqué, A., Bouabdelli, M., Darboux, J.R., 1995. Le rift cambrien du Maroc occidentale. Comptes Rendus de l'Académie des Sciences Paris 320 (II), 1017–1024.

Quesada, C., Fonseca, P., Munhá, J., Oliveira, J.T., Ribeiro, A., 1994. The Beja–Acebuches ophiolite (Southern Iberia Variscan fold belt): geological characterization and geodynamic significance. Boletín Geológico y Minero 105, 3–49.

Ribeiro, A., Pereira, E., Severo, L., 1980. Análise da deformaçao da zona de cisalhament Port-Tomar na transversal de Oliveira de Azeméis. Comunicações dos Serviços Geológicos de Portugal 66, 3–9.

Ribeiro, A., Dias, R., Brandao Silva, J., 1995. Genesis of the Ibero–Armorican arc. Geodinamica Acta 8, 173–184.

Ricou, L.E., 1994. Tethys reconstructed: plates, continental fragments and their boundaries since 260 Ma from Central America to South-Eastern Asia. Geodinamica Acta 7, 169–218.

Robardet, M., 2002. Alternative approach to the Variscan Belt in southwestern Europe: pre-orogenic paleobiogeographical constraints. In: Martínez Catalán, J.R., Hatcher, R., Arenas, R., Díaz García, F. (Eds.), Variscan–Appalachian Dynamics: The Building of the Late Paleozoic Basement. Special Paper-Geological Society of America, vol. 364, pp. 1–15.

Robardet, M., 2003. The Armorica "microplate": fact or fiction? Critical review of the concept and contradictory palaeobiogeographical data. Palaeogeography, Palaeoclimatology, Palaeoecology 195, 125–148.

Robardet, M., Gutiérrez Marco, J.C., 1990. Sedimentary and faunal domains in the Iberian Peninsula during Lower Paleozoic times. In: Dallmeyer, R.D., Martínez García, E. (Eds.), Pre-Mesozoic Geology of Iberia. Springer-Verlag, Berlin, pp. 385–395.

Robardet, M., Blaise, J., Bouyx, E., Gourvennec, R., Lardeux, H., Le Herissé, A., Le Menn, J., Melou, M., Paris, F., Plusquellec, Y., Poncet, J., Renault, S., Rioult, M., Weyant, M., 1993. Paléogeographie de l'Europe occidentale de l'Ordovicien au Dévonien. Bulletin de la Societé Géologique de France 164, 683–695.

Rodgers, J., 1982. The life history of a mountain range. The Appalachians. In: Hsü, K.J. (Ed.), Mountain Building Processes. Academic Press, London, pp. 229–241.

Sánchez Carretero, R., Eguiluz, L., Pascual, E., Carracedo, M., 1990. Part V: Ossa–Morena Zone. In: Dallmeyer, R.D., Martínez García, E. (Eds.), Pre-Mesozoic Geology of Iberia. Springer-Verlag, Berlin, pp. 292–313.

Sanz de Galdeano, C., Andreo, B., García-Tortosa, F.J., López-Garrido, C., 2001. The Triassic palaeogeographic transition between the Alpujarride and Malaguide complexes. Betic-Rif Internal Zone (S Spain, N Morocco). Palaeogeography, Palaeoclimatology, Palaeoecology 167, 157–173.

Schäfer, H.J., Gebauer, D., Nagler, T.F., 1991. Evidence for Silurian eclogite and granulite facies metamorphism in the Badajoz–Córdoba Shear belt, SW Spain. Terra Abstracts Supplement 6 to Terra Nova 3, 11.

Schenk, P.E., 1997. Sequence stratigraphy and provenance on Gondwana's margin: the Meguma zone (Cambrian–Devonian) of Nova Scotia, Canada. Geological Society of America Bulletin 109, 395–409.

Silva, J.B., Oliveira, J.T., Ribeiro, A., 1990. South Portuguese Zone, structural outline. In: Dallmeyer, R.D., Martínez García, E. (Eds.), Pre-Mesozoic Geology of Iberia. Springer-Verlag, Berlin, pp. 348–362.

Simancas, J.F., Martínez Poyatos, D., Expósito, I., Azor, A., González Lodeiro, F., 2001. The structure of a major suture zone in the SW Iberian Massif: the Ossa–Morena/Central Iberian contact. Tectonophysics 332, 295–308.

Simancas, J.F., Expósito Ramos, I., Martínez Poyatos, D., Azor, A., González Lodeiro, F., 2002. Opposite subduction polarities connected by transform faults in the Iberian Massif and west-European Variscides. In: Martínez Catalán, J.R., Hatcher, R., Arenas, R., Díaz García, F. (Eds.), Variscan–Appalachian Dynamics: The Building of the Late Paleozoic Basement. Special Paper-Geological Society of America, vol. 364, pp. 253–262.

Simancas, J.F., Carbonell, R., González Lodeiro, F., Pérez Estaún, A., Juhlin, C., Ayarza, P., Kashubin, A., Azor, A., Martínez Poyatos, D., Almodóvar, G.R., Pascual, E., Sáez, R., Expósito, I., 2003. Crustal structure of the transpressional Variscan orogen of SW Iberia: SW Iberia deep seismic reflection profile (IBERSEIS). Tectonics 22 (6), 1062. doi:10.1029/2002TC001479.

Suppe, J., 1985. Principles of Structural Geology (Chapter 12). Prentice Hall, New Jersey.

Tahiri, A., 1991. Le Maroc central septentrional: stratigraphie, sédimentologie et tectonique du Paléozoïque; un exemple de passage des zones internes aux zones externes de la chaîne hercynienne du Maroc. PhD thesis, Université de Bretagne occidentale, Brest. 311 pp.

Tahiri, A., 1994. Tectonique hercynienne de l'anticlinorium de Khouribga-Oulmès et du synclinorium de Fourhal. Géologie du Paléozoique du Maroc central et de la Meseta orientale, Bulletin de l'Institut Scientifique (Rabat) Numero Spécial, vol. 18, pp. 125–144.

Tait, J.A., Bachtadse, V., Franke, W., Soffel, H.C., 1997. Geodynamic evolution of the European Variscan fold belt: palaeomagnetic and geological constraints. Geologische Rundschau 86, 585–598.

Tapponier, P., Peltzer, G., Le Dain, A.Y., Armijo, R., Cobbing, P., 1982. Propagating extrusion tectonics in Asia: new insights from simple experiments with plasticene. Geology 10, 611–616.

Torsvik, T.H., Smethurst, M.A., Briden, J.C., Sturt, B.A., 1990. A review of Palaeozoic palaeomagnetic data from Europe and their palaeogeographic implications. In: McKerrow, W.S., Scotese, C.R. (Eds.), Palaeogeography and Biogeography. Special Publication-Geological Society of London, vol. 12, pp. 25–41.

Truyols, J., Arbizu, M.A., García Alcalde, J.L., García López, S., Méndez Bedia, I., Soto, F., Truyols Massoni, M., 1990. The Asturian–Leonese domain (Cantabrian Zone). In: Dallmeyer, R.D., Martínez García, E. (Eds.), Pre-Mesozoic Geology of Iberia. Springer-Verlag, Berlin, pp. 10–19.

Vauchez, A., 1975. Tectoniques tangentièlles superposées dans le segment hercynien Sud-Ibérique: Les nappes et plis couchés de la region d'Alconchel–Fregenal de la Sierra (Badajoz). Boletín Geologico y Minero 86, 573–580.

Vegas, R., Medialdea, T., Muñoz, M., Díaz del Rio, V., Somoza, L., 2004. Nature and tectonic setting of the Guadalquivir Bank (Gulf of Cadiz, SW Iberian Peninsula). Revista de la Sociedad Geológica de España 17, 49–60.

Weil, A.O., Van der Voo, R., van der Plujim, B.A., 2001. Oroclinal bending and evidence against the Pangea megashear: the Cantabria–Asturias arc (northern Spain). Geology 29, 991–994.

Winchester, J.A., The PACE TMR Network Team, 2002. Palaeozoic amalgamation of Central Europe: new results from recent geological and geophysical investigations. Tectonophysics 360, 5–21.

Zahraoui, M., 1994. Le Silurian. Le Dévonian inférieur et moyen. Géologie du Paléozoique du Maroc central et de la Meseta orientale, Bulletin de l'Institut Scientifique (Rabat) Numero Spécial, vol. 18, pp. 38–56.