3

Early Ordovician–Devonian Passive Margin Stage in the Gondwanan Units of the Iberian Massif

J. C. Gutiérrez-Marco, J. M. Piçarra, C. A. Meireles, P. Cózar,
D. C. García-Bellido, Z. Pereira, N. Vaz, S. Pereira, G. Lopes, J. T. Oliveira,
C. Quesada, S. Zamora, J. Esteve, J. Colmenar, E. Bernárdez,
I. Coronado, S. Lorenzo, A. A. Sá, Í. Dias da Silva, E. González-Clavijo,
A. Díez-Montes, and J. Gómez-Barreiro

Abstract

Progressive opening of the Rheic Ocean led to the drifting away of one or several ribbon terranes, generally ascribed to Avalonia, and inaugurated a passive margin stage on the newly formed margin of NW Gondwana. In Iberia, which remained on the Gondwanan side of the ocean, the rift to drift transition is recorded in the Ossa Morena Zone in latest Furongian times and migrated towards more internal parts of the margin during the Lower Ordovician. The passive margin stage is characterized by development of open marine platform sedimentation locally punctuated by eruption/intrusion of mainly basaltic, alkaline volcanic rocks, during transient periods of tectonic extension. A progression from outer (Ossa Morena Zone), through intermediate (Central Iberian and West Asturian-Leonese Zone, to inner (Cantabrian Zone) shelf environments can be generally established, although with significant variations related to local tectonic development. The end of the passive margin stage is marked by the formation of

---

Coordinator: J. C. Gutierrez-Marco.

J. C. Gutiérrez-Marco (✉) · P. Cózar
Instituto de Geociencias (CSIC, UCM), Severo Ochoa 7,
28040 Madrid, Spain
e-mail: jcgrapto@ucm.es

P. Cózar
e-mail: pcozar@ucm.es

J. C. Gutiérrez-Marco · P. Cózar
Departamento de Paleontología, Facultad de Ciencias Ge, José
Antonio Novais 12, 28040 Madrid, Spain

J. M. Piçarra
Laboratório Nacional de Energia e Geologia, Centro de Estudos
Geológicos e Mineiros de Aljustrel (CEGMA), Bairro da Vale d´Oca, Ap. 14, 7601-909 Aljustrel, Portugal
e-mail: jose.picarra@lneg.pt

C. A. Meireles · Z. Pereira
Laboratório Nacional de Energia e Geologia, I.P.,
Ap. 1089 4466-901, São Mamede de Infesta, Portugal
e-mail: carlos.meireles@lneg.pt

Z. Pereira
e-mail: zelia.pereira@lneg.pt

D. C. García-Bellido
School of Biological Sciences, University of Adelaide,
5005 South Australia, Australia
e-mail: Diego.Garcia-Bellido@adelaide.edu.au

N. Vaz · A. A. Sá
Departamento de Geologia, Universidade de Trás-os-Montes e
Alto Douro, 5000-801 Vila Real, Portugal
e-mail: nunovaz@utad.pt

A. A. Sá
e-mail: asa@utad.pt

N. Vaz · A. A. Sá
Centro de Geociências, Universidade de Coimbra–Pólo II,
3030-790 Coimbra, Portugal

S. Pereira
Departamento de Ciências da Terra, Faculdade de Ciências e
Tecnologia, Universidade Nova de Lisboa, Quinta da Torre,
2829-516 Caparica, Portugal
e-mail: ardi_eu@hotmail.com

J. Colmenar · Í. Dias da Silva
Departamento de Geologia and Faculdade de Ciências, Instituto
Dom Luiz, Universidade de Lisboa, 1749-016 Lisbon, Portugal
e-mail: jorgecolmenarlallena@gmail.com

Í. Dias da Silva
e-mail: ipicaparopo@gmail.com

G. Lopes
Department of Earth Science, University of Bergen,
PO box 7803 N-5020 Bergen, Norway
e-mail: gildalopes83@gmail.com

J. T. Oliveira
Laboratorio Nacional de Energia e Geologia (LNEG),
Estrada da Portela, Bairro do Zambujal, Apartado 7586-Alfragide,
2610-999 Amadora, Portugal
e-mail: josetomas.oliveira@gmail.com

C. Quesada
Instituto Geológico y Minero de España, Ríos Rosas 23 Madrid,
Spain
e-mail: quesada.cecilio@gmail.com

C. Quesada and J. T. Oliveira (eds.), *The Geology of Iberia: A Geodynamic Approach*, Regional Geology Reviews,
https://doi.org/10.1007/978-3-030-10519-8_3

syn-orogenic basins, which roughly migrate in the same direction, i.e. from external to internal parts of the margin, as a response to the propagation towards the foreland of the Variscan orogenic wedge.

3.1 Introduction

After the attenuation of the rifting event started in the early Cambrian, and which culminated with the progressive opening of the Rheic Ocean by the Early Ordovician—and the subsequent drifting away from Gondwana of the Avalonia microcontinent—, a long period (ca. 100 Ma) of relative tectonic stability was established in the Iberian marine shelf before the onset of the convergent events leading to the Variscan orogenic cycle. This passive margin stage extends from the late Early Ordovician to—at least—the Middle Devonian and is well documented in the sedimentary record, showing the influx of several paleoclimatic, depositional and tectono-sedimentary major events of regional and global significance.

The Paleozoic rocks corresponding to this phase outcrop extensively in the different areas of the Hesperian Massif (=the Iberian Massif plus its subsurface extension to the eastern border outcrops in the Demanda and Iberian Range: San José 2006), with the exception of the South Portuguese Zone, that belongs to the Avalonian paleogeographic realm. The pre-Variscan basement of the Alpine Pyrenean and Betic orogens show clear resemblance to certain Upper Ordovician to Devonian sequences of the Hesperian Massif, but is treated in a separate chapter of the volume (see Chaps. 8 and 9). Terrigenous sedimentation clearly dominated in the Ordovician and during most of the Silurian periods, whereas limestone units started to occur from the upper Silurian, became widespread in the Lower to Middle Devonian and continued in the upper Mississippian. This is a consequence of the slow movement of the Gondwana continent towards the southern hemisphere, inducing a northward drift of the entire Ibero-North African shelf, which changes from a position near the South Pole at the end of the Ordovician to more temperate and even tropical paleolatitudes, before docking with Laurussia in Variscan times.

The transition from the rift to a drift stage related with the opening of the Rheic Ocean, occurred in a complex tectonic framework that led to a long-lived magmatism (the 'Ollo de Sapo' plutonic and volcanic event), as well to graben-like subsiding zones active during the Cambrian-Ordovician transition. In the West Asturian-Leonese Zone, as well as in its southeastern extension into the Sierra de la Demanda and the Iberian Range, the Cambrian/Ordovician boundary beds are in clear stratigraphic continuity. However, both in the Cantabrian Zone and in the Ossa-Morena Zone (Estremoz-Barrancos-Hinojales sector), the oldest Ordovician sediments bearing Tremadocian fossils, paraconformably to disconformably overlie uncomplete middle to upper Cambrian successions, involving stratigraphic gaps of variable amplitude but without the development of angular unconformities. Finally, the situation in the Central Iberian Zone is even more complex, with the genesis of one or more breakup unconformities (Fig. 3.1), above which the marine shelf sedimentation typical of the passive margin setting was established. The main unconformity was alternatively interpreted as related with a crustal thickening of the Gondwana margin during a period of flat subduction, in a stage which also evolved towards the passive margin setting described below (Villaseca et al. 2016).

3.2 The Ordovician Sequence

The Lower Ordovician sequence in the Hesperian Massif is mainly represented by the ubiquitous Armorican Quartzite Formation (5–500 m thick), which gets its name from the Armorican Massif of western France (Grès Armoricain) and

---

S. Zamora
Instituto Geológico y Minero de España, Delegación en Aragón, Manuel Lasala 44-9ºB, 500006 Zaragoza, Spain
e-mail: s.zamora@igme.es

J. Esteve
Departamento de Geociencias, Universidad de Los Andes, Cra 1 No 18ª-10, AA 4976, Bogotá, Colombia
e-mail: Jv.esteve@uniandes.edu.co

E. Bernárdez
Vicerrectoría de Investigación y Posgrado, Universidad de Atacama, Avda. Copayapu 485, Copiapó, Atacama, Chile
e-mail: enrique.bernardez@uda.cl

I. Coronado
Institute of Paleobiology, ul. Twarda 51/55, PL-00-818 Warsaw, Poland
e-mail: icoronad@twarda.pan.pl

S. Lorenzo
Departamento de Ingeniería Geológica y Minera, Escuela de Ingeniería Minera e Industrial, Instituto de Geología Aplicada (IGEA, UCLM), Universidad de Castilla-La Mancha, Plaza Manuel Meca 1, 13400 Almadén, Ciudad Real, Spain
e-mail: saturnino.lorenzo@uclm.es

E. González-Clavijo · A. Díez-Montes
Instituto Geológico y Minero de España, Delegación de Salamanca, Azafranal 48, 37001 Salamanca, Spain
e-mail: e.clavijo@igme.es

A. Díez-Montes
e-mail: al.diez@igme.es

J. Gómez-Barreiro
Departamento de Geología, Universidad de Salamanca, Plaza de la Merced s/n, 37008 Salamanca, Spain
e-mail: jugb@usal.es

Fig. 3.1 Field view of the Toledanian unconformity in the norwestern bank of the Estena River near Navas de Estena (Ciudad Real Province, Cabañeros National Park). The sandstones and shales of the early Cambrian Azorejo Formation (left, vertical bedding) are onlapped in angular erosive discordance (of ∼45º) by the early Ordovician 'Intermediate Beds', the unit that underlies the Armorican Quartzite (inclined to the right in this picture). The tectonic and erosive contact is interpreted as the breakup unconformity revealing the rift-to-drift transition to the shelf sedimentation belonging to the passive margin stage. The encircled person serves as scale

typically occurs in the Central Iberian Zone and the Iberian Range, but also is known—under some local equivalent names—in the Cantabrian and West Asturian-Leonese zones. Despite a large diachroneity has been suggested in Portugal for the sedimentation of these light-colored and thick-bedded mature sandstones (references in Sá et al. 2011), the entire Armorican Quartzite of southwestern Europe is presently correlated with the single *Eremochitina brevis* chitinozoan Biozone (Paris 1990), which is broadly equivalent to a late Floian (='middle' Arenigian) age (Videt et al. 2010). However, the recent dating (Gutiérrez-Alonso et al. 2016) of a widespread K-bentonite bed occurring in the Barrios Fm, whose Tanes (=upper) member has been correlated with the Armorican Quartzite, places the Tremadocian-Floian boundary relatively close to the top of the formation in the Cantabrian Zone. This fact, and the previous paleontological dating reviewed by Sá et al. (2011), makes improbable a migration of the basal breakup discontinuity of the passive margin stage from south to north at least in inner platform zones (from the southern Central Iberian Zone to the Cantabrian Zone). Some authors (Quesada 2006; López Guijarro et al. 2007; Álvaro et al. 2014, 2018) have interpreted the unconformity at Venta del Ciervo locality in the Ossa-Morena Zone as representing the same breakup discontinuity but, there, U–Pb zircon dating of K-bentonites interbedded in quartzites yielded a ca. 489 Ma age, suggesting that the rift-to drift transition may have started earlier in the Ossa-Morena Zone (during the late Furongian).

Besides the Ollo de Sapo magmatic belt, and its coeval large volcanic event recorded in other northern Iberia localities (Gutiérrez-Alonso et al. 2016), alignments of Furongian and/or Tremadocian igneous rocks are known: (a) near the boundary with the Ossa-Morena Zone (Urra Fm., Portalegre and Carrascal granitoids); (b) in the south-central part of the Central Iberian Zone (the Beira Baixa-Central Extremadura tonalite-granodiorite belt of Rubio-Ordóñez et al. 2012), and (c) in the eastern Mounts of Toledo region

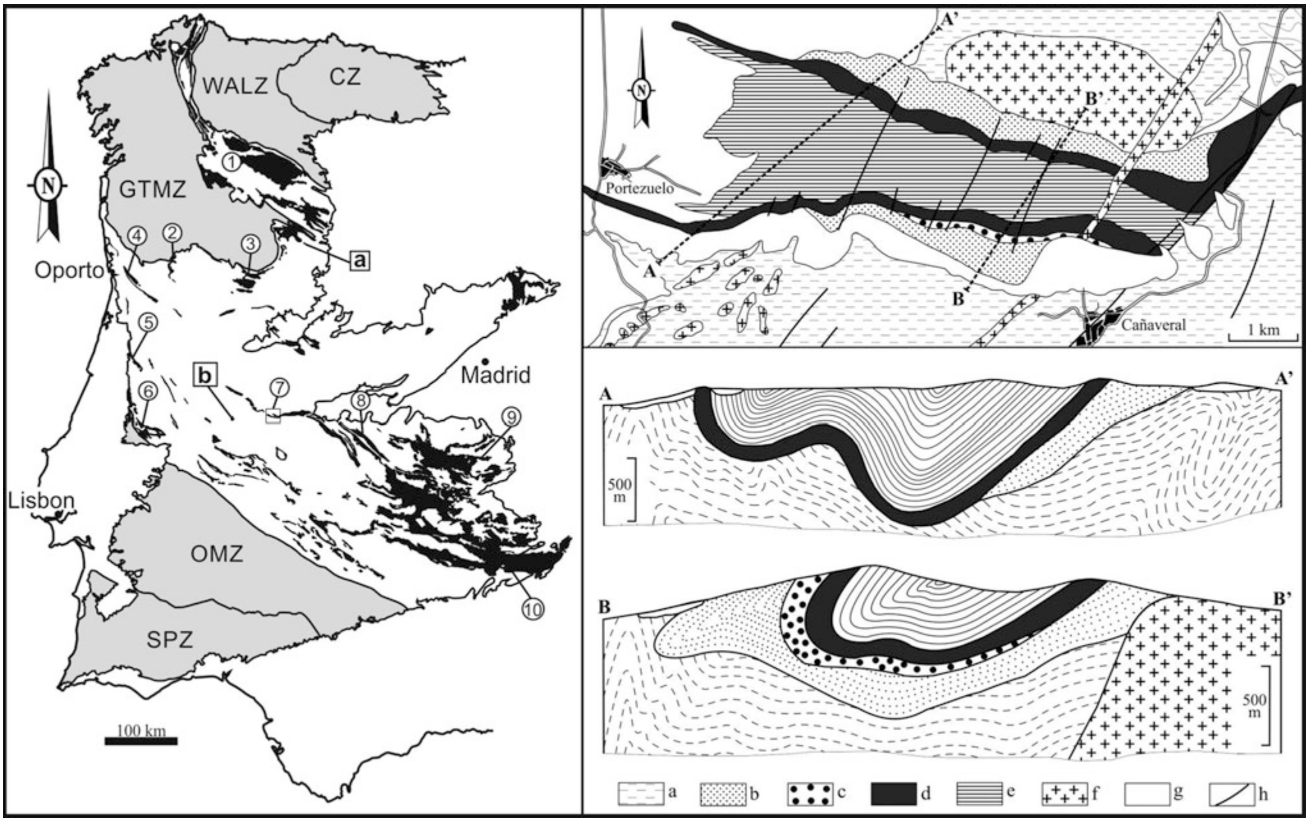

Fig. 3.2 Left: Schematic map of the Iberian Massif (left) with position of reference areas for Lower Ordovician sedimentary rocks (in black) within the Central Iberian Zone. CZ, Cantabrian Zone; WALZ, West Asturian-Leonese Zone; GTMZ, Galicia—Trás-os-Montes Zone; OMZ, Ossa-Morena Zone; SPZ, South Portuguese Zone. Localities: 1. Ollo de Sapo antiform; 2. Marão; 3. Moncorvo; 4. Valongo; 5. Buçaco; 6. Mação; 7. Cañaveral; 8. Guadarranque; 9. eastern Mounts of Toledo; 10. Despeñaperros pass (eastern Sierra Morena). a–b, outcrops of Lower Ordovician shales previously assigned to the pre-Ordovician Schist-Graywacke Complex: a, Pino del Oro schist; b, Malpica do Tejo shale (after Talavera et al. 2013). Right: detail of the Paleozoic structure in the framed area (number 7), showing part of the Cañaveral syncline just east of the Plasencia Fault. A-A′ and B-B′, underneath, correspond to the cross sections illustrating several angular unconformities between the Schist-Graywacke Complex (a. Neoproterozoic to middle Cambrian), an unnamed shale and sandstone unit (b. Tremadocian), the Serra Gorda conglomeratic beds underlying the Armorican Quartzite (c. lower Floian) and the Armorican Quartzite (d. upper Floian). Remaining symbols: e. Middle to Upper Ordovician shale and sandstone units; f. Variscan igneous rocks (Cancho García granite and Alentejo-Plasencia toleitic dyke); g. post-Paleozoic cover; h. faults. Geological map and cross sections adapted from Martín Herrero et al. (1987). Figure reproduced from (Sá et al. 2014, Fig. 1, ©Springer)

(the 'Volcano-Sedimentary Complex' of Martín Escorza 1976). As a result of the thermal subsidence and the extensional tectonics active in the Central Iberian Zone at the beginning of the Ordovician, sedimentation of unfossiliferous units of conglomerates, sandstones and shales tentatively assigned to the lower Floian and uppermost Tremadocian generally occurred in several grabens and half-grabens mostly showing Cadomian orientations. They correspond to diverse formations preceding the Armorican Quartzite (Fig. 3.2), which show great variations in thicknesses (0–450 m) and sedimentary facies, so that in short distances the sedimentation could rapidly have changed from almost continental conglomerates to fan deltas and storm-dominated shallow-marine deposits (e.g., McDougall et al. 1987). The active tectonism and the considerable paleotopography influenced the formation in the Central Iberian Zone of at least two angular unconformities (Figs. 3.2 and 3.3) and various sedimentary gaps. The main and more widespread of these is the Toledanian Unconformity, originally placed by Lotze (1956) below the Cambrian/Ordovician boundary, which has a more important structural significance and puts the Lower Ordovician sequence directly over Neoproterozoic or lower Cambrian rocks.

In the 'Ollo de Sapo' Domain, local outcrops of grey shales erroneously attributed to the Schist-Graywacke Complex by Talavera et al. 2012: (localities a–b in Fig. 3.3) were dated as late Tremadocian or even as Floian based on detrital zircons. However, in agreement with González-Clavijo (2006), these rocks clearly occur as an intercalation in the Villadepera/'Ollo de Sapo' gneisses, which are laterally correlatable with the basal Constantim member of the Angueira Fm of the Portuguese part (Meireles 2013).

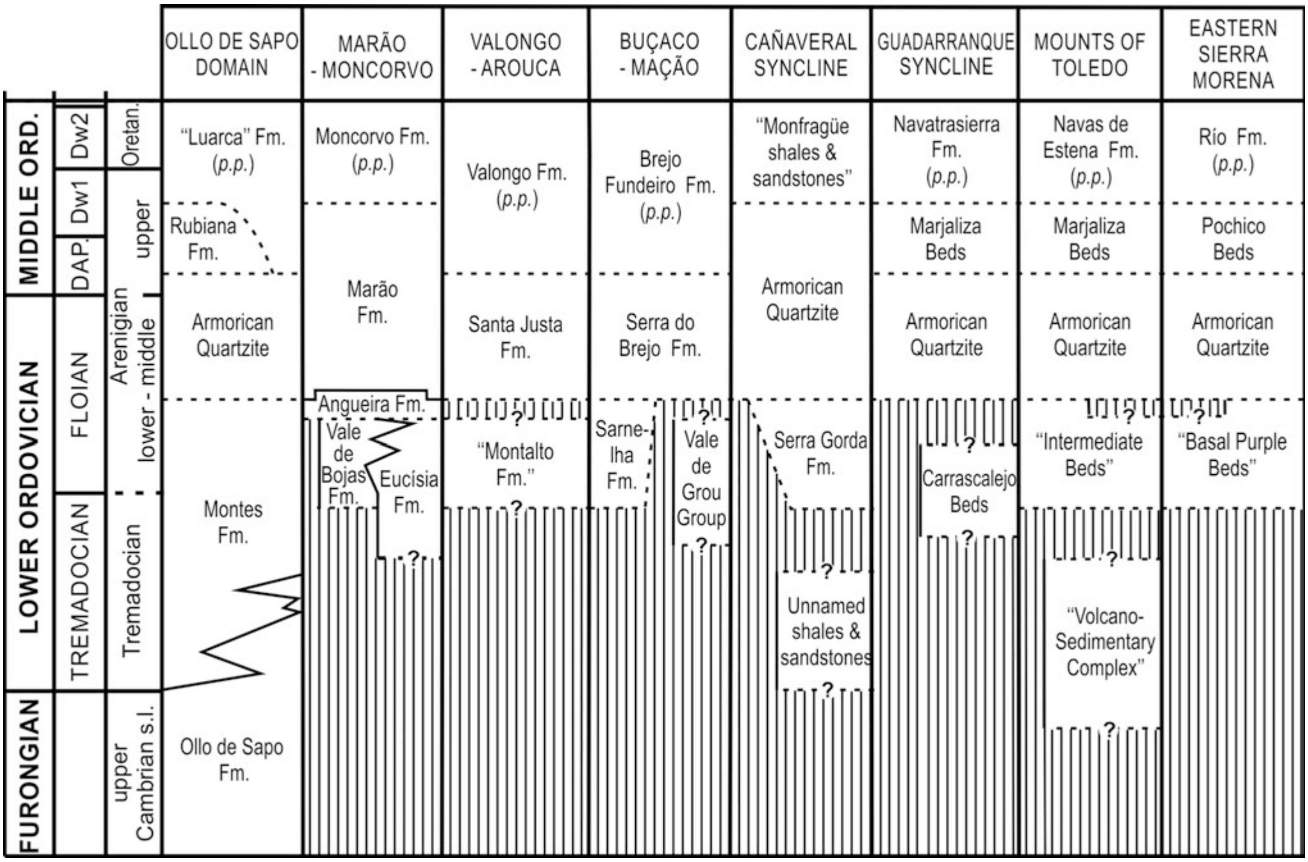

Fig. 3.3 Correlation chart of the main stratigraphic units around the Cambrian/Ordovician and Lower/Middle Ordovician boundaries in the 'Ollo de Sapo' Domain (left) and the southern Central Iberian Zone (Portugal and Spain), showing the sedimentary gaps (vertical stripes). For localization of the columns, see Fig. 3.2

The late Floian marine transgression leading to the deposition of the Armorican Quartzite operated over a huge area of SW Europe, and the unit usually ends with a variably developed succession (20–250 m) of alternating quartzites and shales, which make the transition into the Middle Ordovician shales. In some places, this alternation was incorporated as an upper member of the Armorican Quartzite sensu lato (e.g., the Fragas da Ermida Mb of the Marão Fm: Sá et al. 2005), but most frequently it was differentiated as an independent unit (e.g., Rubiana Fm, Marjaliza or Pochico 'beds'), which may extend regionally up to the lower Darriwilian. However, in some places, such as in the Portuguese inliers of Buçaco and Valongo, the top of the Armorican Quartzite grades up abruptly into dark shales already bearing Dapingian graptolites, implicating that the chronostratigraphic frame for the end of the widespread sand sedimentation is also quite complex (Gutiérrez-Marco et al. 2014a).

In the West Asturian-Leonese Zone, Lower Ordovician strata conformably succeed Cambrian formations, the bases of which discordantly overlie the Neoproterozoic. The lower limit of the Ordovician lies within the upper part of the very thick Los Cabos Group (up to 4,400 m in the Navia-Alto Sil Domain) that consists of alternating shallow marine sandstones and shales (Marcos 1973 Pérez-Estaún et al. 1990). This group extends from the Miaolingian up into the Floian in its uppermost part where sandstones closely similar to those of the Armorican Quartzite predominate.

The Lower Ordovician sequence of the Iberian Range conformably overlies a thick Cambrian succession and is subdivided into distinct formations (Wolf 1980). The base of the Ordovician, traditionally placed at the upper part of the Valconchán Formation (thick-bedded quartzites with some grey to green shaly intercalations), has been recently moved up to the upper-middle part of the succeeding Borrachón Formation (320–900 m of green to grey laminated siltstones and shales with some sandy intercalations). Above it, the sandstones and quartzites of the Deré Fm (420–850 m) are followed by green to brown siltstones and shales of the Santed Fm (200–950 m), where the Tremadocian-Floian boundary can be traced and is, in turn, overlain by the Armorican Quartzite (450–650 m).

In most regions of the Iberian Massif, the remaining Ordovician strata can be grouped into two other major sequences. The first is composed predominantly of dark mudstones and siltstones with more or less important sandstone intercalations, being roughly representative of the Middle Ordovician. The upper sequence is much less uniform and is incomplete in many areas, where it can also show internal unconformities. These Upper Ordovician strata consist of alternating mudstones, siltstones and sandstones overlain by limestone, glaciomarine diamictites and massive quartzites.

After the complete erosion of the rift shoulders flanking the Rheic Ocean opening, the compartmentalisation of the Gondwanan segment of the Iberian Massif was considerably attenuated, so that monotonous units of dark mudstones, richly fossiliferous and with a mean thickness of about 300 m (but ranging from 150 up to 1,000 m) were deposited over the areas previously reached by the Armorican Quartzite. This Middle Ordovician transgression was diachronical from the Dapingian to the late Darriwilian, starting at the base with few meters of relatively condensed strata and a widely distributed ooidal ironstone bed. The latter represents the initial deposit above a disconformity, associated with a rapid eustatic rise and showing a good development in the shallower parts of the shelf. The main ooidal ironstone bed is recorded at the base of the middle Darriwilian sequence and occurred almost synchronously over a wide area of the Central Iberian Zone, indicating uniform sedimentary conditions across large areas of a shallow, low gradient shelf (Young 1992). However, the eustatic control of the deposition of this first ooidal ironstone is not so evident in the Cantabrian Zone and in the Iberian Range, where the bed directly ovelies the Armorican Quartzite and is of a late middle Darriwilian age. This may reflect uplifting of the area by faults and generation of the corresponding paraconformity, involving an extensive sedimentary gap from the Dapingian to the lower middle Darriwilian strata.

The sedimentation of dark mudstones by the middle and early late Darriwilian is generalised in Iberia, but a regressive tendency predominates in the late Darriwilian with the record of new sandstone units. They are well-developed in the southeastern Central Iberian Zone within and above the fossiliferous mudstones discussed above, known as the so-called ‘Los Rasos’ or ‘Monte da Sombadeira Sandstone’ and ‘Quartzites inférieurs’ or ‘Botella Quartzite’, respectively. The former unit is especially interesting because this sandstone, 25–200 m thick and covering an area of approximately 75,000 km^2 in the southern Central Iberian Zone, corresponds —according to the sedimentological study of Brenchley et al. (1986)—to a single storm-generated body deposited more than 100 km from the shore. This allowed to estimate an average seaward-dip of the Ordovician Central Iberian shelf of less than 0.1º, taking into account the maximal depth known (ca. 50–80 m) in which a sediment surface above storm wave base is capable of forming hummocky cross-stratification. The thickness and the distribution of these sandstone facies, decreasing to zero northward, also indicates that the shoreline should have been positioned towards the present south and southeast, in the actual place of the Obejo-Valsequillo Domain. The latter was juxtaposed to the Central Iberian Zone in Variscan times by the Puente Génave-Castelo de Vide shear zone (Martín Parra et al. 2006). This has recently been reinterpreted as a huge rootless nappe related with an eo-Variscan continental subduction, previous to the Rheic Ocean closure, and stacked by the Late Devonian the Ossa-Morena Zone onto the Central Iberian shelf (Díez Fernández and Arenas 2015, 2016; Arenas et al. 2016).

The general deepening towards the north of the Central Iberian shelf was also confirmed by other stratigraphic evidences and by the distribution of trilobite biofacies (Hammann and Henry 1978, Rábano 1989, Robardet and Gutiérrez-Marco 1990). However, this shelf gradient is exactly inverse to the model proposed by Rubio-Ordóñez et al. (2012), which postulates an ocean over the emerged, source area for the siliciclastics, being the Beira-Extremadura belt tentatively interpreted as a continental volcanic arc in their tectonic model.

By the late middle Darriwilian (global chronostratigraphic nomenclature after Bergström et al. 2009) the whole Iberia was almost uniformly blanketed by shelf muds (e.g., Luarca, Navas de Estena, Castillejo, Sueve, Brejo Fundeiro, Moncorvo and Valongo formations). The predominantly shallow siliciclastic sedimentation without any trace of limestones, and the abundant fossil record consisting of low diversity benthic assemblages of invertebrates regarded as cold-water faunas, indicate a high paleolatitudinal position for the Iberian shelf in Gondwana. The ‘polar gigantism’ observed in some groups of Darriwilian trilobites (Gutiérrez-Marco et al. 2009) also supports the general placement of Iberia near the South Pole, as represented in most paleogeographic reconstructions for the Ordovician (e.g. Cocks and Fortey 1990, Robardet 2002, Torsvik and Cocks 2013, 2017). Also the close similarities of certain Darriwilian faunas from Ibero-Armorica to those recorded from northeast Algeria, Libya and Saudi Arabia, led Gutiérrez-Marco et al. (2002) to propose that, during Ordovician times, central Iberia was probably north of present-day Libya or Egypt instead of in the vicinity of Morocco/NW Africa. The new location, closer to the Arabian-Nubian shield and the Sahara metacraton, was later supported by isotopic and provenance studies of magmatic rocks (Bea et al. 2010, Fernández-Suárez et al. 2014), information not taken into account by Franke et al. (2017).

Paleoecological data derived from Middle Ordovician fossils confirm the general dipping of the Central Iberian shelf towards the north, with a maximal depth reached in its extension in the Navia-Alto Sil domain of the West Asturian-Leonese Zone and the Iberian Range, where some mesopelagic graptolites have been recorded (Gutiérrez-Marco et al. 1999). The Cantabrian Zone, by the way, remain emerged during much of the Middle and Late Ordovician times, with the sporadic record of some units bound by stratigraphic discontinuities in certain corridors limited by faults, within the wide uplifted area. This is the case of the Sueve Fm, yielding inshore trilobites but with some rare elements derived from offshore settings (e.g., raphiophorids: Gutiérrez-Marco and Bernárdez 2003).

The general gradient in the Ordovician shelf documented in the Central Iberian Zone would require a shoreline and an emerged area in the region presently occupied by the Obejo-Valsequillo Domain and the Ossa-Morena Zone, previous to the Variscan Orogeny. The first is a complex area of mixed paleogeographic affinities for the Lower Paleozoic, especially along the Ordovician (Gutiérrez-Marco et al. 2014b, 2016). On the other hand, the Ossa-Morena Zone clearly represents the outer and distal-shelf counterpart of the Iberian platform which was tectonically (laterally) juxtaposed to its present position during the Variscan Orogeny (Quesada 1991). The Lower Ordovician sequence starts here with offshore sediments bearing late Tremadocian mesopelagic graptolites and trilobites, followed by Floian to early Darriwilian green shales and slates, which rarely show the discontinuous ooidal ironstone bed correlatable with the widespread bed of basal middle Darriwilian age. In the Valle syncline of northern Seville, the middle Darriwilian shales yielded a fossil assemblage of Bohemian affinities, unique for Iberia and representative of deeper environments than the typical '*Neseuretus* fauna' (Gutiérrez-Marco et al. 2002, Robardet and Gutiérrez-Marco 2004). Above this unit, sedimentation proceeded with micaceous and calcareous sands continuing until the Late Ordovician.

The upper part of the Ordovician sequence generally begins with argillaceous units that, at its base or within their lower third, intercalate an ooidal ironstone bed with common phosphatic pebbles and remanié fossils. This is the so-called Favaçal or Chôsa Velha bed in Portugal, which is also widely recognized in the Cantera Shale of the Central Spain, the base of the Fombuena Fm of the Iberian Range and in the Manto de Mondoñedo Domain of the West Asturian-Leonese Zone. The age of this bed and the starting of sedimentation above it has been established as middle Berounian, by using the high-resolution biochronological scheme and the regional chronostratigraphic scale for the Mediterranean Ordovician (Gutiérrez-Marco et al. 2015, 2016, 2017). This dating is roughly equivalent to the late Sandbian–earliest Katian of the global scale and, in regional terms, is correlatable with the age of formation of the Sardic Uncorformity in SW Sardinia, that in its type area seals a sedimentary gap equivalent to the entire Middle Ordovician and part of the Early and earliest Late Ordovician (Leone et al. 1991, Pillola et al. 2008). Due to the great continuity of this 'early Caradoc' ironstone, extending even to Armorica and other places of the Mediterranean area, it has been interpreted as associated with an eustatically controlled episode of sea-level rise (Young 1989, 1992). But their coincidence in time with the Sardic movements also favoured a complementary interpretation associated to the discrete uplift of part of western Iberia as reflecting the distal echoes of the Sardic phase (Gutiérrez-Marco et al. 2002 with references). In this scenario, the minimal sedimentary gap sealed by the ooidal ironstone in Iberia varies from a partly Sandbian (late early Berounian to earliest middle Berounian) interval in the southern Central Iberian and the Iberian Range, to include part of the Middle Ordovician in north Portugal (Sá et al. 2006). The ironstone's petrographic features—more phosphatic and conglomeratic towards the south of the Central Iberian Zone—also fits with the general paleoslope of the shelf. The existence of a variable paleotopography previous to the interval or non deposition—and erosion—is demonstrated by minor uplifting areas such as the 'Dornes/Amêndoa rise' of central Portugal (Young 1989) and also by the Valongo 'rise' that emerged in the latest Darriwilian. The absence of latest Darriwilian-early Sandbian sedimentation over a large area of NW Spain (Gutiérrez-Marco et al. 1999) may also be due to the same tectonic rise, with some sin-sedimentary rifting later developed in the Truchas area (Martínez Catalán et al. 1992) and the important subsiding trough of the Navia-Alto Sil Domain of the West Asturian-Leonese Zone. Here, deep-sedimentation with up to 1,500 m-thick turbidites of the Agüeira Fm. (Pérez-Estaún and Marcos 1981) was recorded mainly along the Katian. The interpretation of the Sardic phase as a general episode of uplift (the 'Sardinian-Taurian rise' of Hammann 1992) may include also the Cantabrian Zone, that remains uplifted until the end of the Ordovician with the exception of two small fault-controlled troughs where Middle–Late Ordovician sedimentation and rare rifting-associated volcanism (in the Peñas Cape) took place. According to some authors, the Sardic Phase can be better interpreted as linked to orogenic subduction or alternatively to transtensive-transpressive modification of the Rheic Ocean opening patterns leading to the Paleotethys (Stampfli et al. 2002, Álvaro et al. 2016 and references therein).

The post-Sardic Ordovician sedimentation in Sardinia displays many facies and faunas in common with other Mediterranean settings including Iberia. Most deposits developed during the early and middle Katian (=middle–late Berounian) are thick units of alternating shales, siltstones and sandstones, with some intercalations of quartzites and dark shales, or micaceous shales with minor proportion of intercalated sandstones, within shallow shelf environments with storm influence. By the late Katian (=Kralodvorian regional stage), the global warming climatic event that preceded the Latest Ordovician glaciation (Boda Event of Fortey and Cocks 2005) favoured the arrival of warm-water taxa to south Polar Gondwana, as well as limestone deposition in several places of Iberia. The base of the limestone seems to rest conformably on middle Katian beds, but sometimes the contact is clearly disconformable (the Urbana Limestone of the southern Central Iberian Zone), or develop a ferruginous bed at the base (of the Cystoid Limestone of the Iberian Range). In the Ossa Morena Zone, a true ooidal ironstone bed marks the basal contact of the limestone which directly rests on Middle Ordovician shales (Gutiérrez-Marco et al. 2002, Robardet and Gutiérrez-Marco 2004). The basal sedimentary gap is greater in NW Iberia, where the Aquiana Limestone may even be transgressive over the Cambrian, reaching a maximum thickness of 250 m. The enormous variations of thickness observed in the late Katian limestone unit in relatively short distances (0–250 m), has been associated with the erosive processes linked to the global lowering of the sea-level induced by the Late Ordovician glaciation, perhaps combined with synsedimentary tectonics (Martínez Catalán et al. 1992, Gutiérrez-Marco et al. 2002). A Katian ooidal ironstone bed is also recorded at the base of some volcano-sedimentary units (e.g. Porto de Santa Anna Fm) that partly replaced or precluded carbonate deposition in some places of central Portugal (Buçaco).

The uppermost part of the Ordovician sequence is under the direct influx of the Hirnantian Glaciation centered in African Gondwana (Ghienne et al. 2007). This, again, demonstrates the general location of Iberia at high latitudes in the southern hemisphere during the Late Ordovician. Evidence that the main ice-sheet must have also extended to the Cantabrian Zone was presented by Gutiérrez-Marco et al. (2010), who found subglacial tunnel valleys incised on the upper part of the Barrios Fm (Armorican Quartzite). Nevertheless, the ubiquitous sediments associated with the Hirnantian Glaciation are the widespread glaciomarine diamictite formations that, under several local names, occur all over the Hesperian Massif. These deposits may be preceded by shallow sandstone-dominated sediments or, more rarely, they can show some quartzitic intercalations at its middle part (Las Majuelas Quartzite of the Gualija Fm). A terminal, overlying quartzite is rather common at the top of the Ordovician sequence (the Criadero Quartzite and equivalents such as the Luna Quartzite/La Serrona Fm of the Barrios de Luna Reservoir, previously mistaken for the Armorican Quartzite: Gutiérrez-Marco et al. 2010, Toyos and Aramburu 2014), which may extend to the Silurian. A majority of the dropstones contained in the diamictites seem to be of close provenance, but some other pebbles are striated and of clear exotic origin, having suffered a long transport by icebergs. The opportunistic *Hirnantia* Fauna, coeval with the glaciation, has been recorded so far in the Cantabrian and Central Iberian zones, as well as in the Iberian Range, associated to coarse sandstones and fine volcanoclastic sediments (Bernárdez et al. 2014). Acritarchs, trilobites and brachiopods of Hirnantian age were also recovered from central Portugal (Lopes et al. 2011, Lopes 2013, Colmenar et al. 2019).

3.3 The Silurian Sequence

The platformal sedimentation on a drifting passive margin setting prevails in the Silurian Period during spreading of the Rheic Ocean. The latitudinal position of the Iberian Massif can be estimated roughly as intermediate between the south-polar paleolatitudes of the latest Ordovician (Hirnantian glaciomarine sediments and tunnel valleys) and the warm temperate to subtropical latitudes of the Early Devonian (limestones with local reefs), with a latitudinal displacement to about 40–35º S in the latest Silurian (Robardet and Gutiérrez-Marco 2002).

The onset of the Silurian sedimentation is somewhat diachronic in the different areas of the Hesperian Massif, where strata of this system can be adscribed to two basic types of succession (Fig. 3.4). However, by the Telychian (late Llandovery) the sedimentation of graptolitic black shales constitutes an uniform event, shared with the remaining part of the Mediterranean area. This early Silurian sea-level rise was likely caused by a combination of global eustatic rise and local increased rates of tectonic subsidence.

The regional analyses show that both types of basic Silurian successions in Iberia, also associated with different faunas, probably correspond to distinct paleoenvironmental conditions and paleogeographical positions.

The first type of succession is widespread and occurs in most of the Central Iberian Zone, the Iberian Cordillera, in some units of the West Asturian-Leonese Zone (Mondoñedo) and in the Cantabrian Zone. Except in the latter, it begins with sandstone units at the Ordovician-Silurian transition. Euxinic black-shale sedimentation started generally during the late Aeronian and Telychian and persisted during the Wenlock and, in some regions, until the early Ludlow. This black-shale sequence, which received local lithostratigraphic names (e.g., Formigoso, Bádenas, Llagarinos, Guadarranquejo or 'Xistos Carbonosos' formations) was overlain by thick units of alternating sandstones, siltstones and shales of Ludlow and Pridoli age (e.g., Furada-San Pedro, Alcolea, Luesma or Sobrado formations), which are in turn overlain by other sandstone and quartzite units of the earliest Devonian. Within these sand-dominated sequences forming the upper part of the Silurian succession, the fossil record is scarce and consists mainly of shallow-water shelly faunas. The abundance of terrestrial palynomorphs and thin ooidal ironstone beds in the Furada-San Pedro Fm of the Cantabrian Zone would indicate a close proximity to the emerged source areas.

The shallow character of sedimentation of this first type of the Silurian succession is also recognised in the euxinic

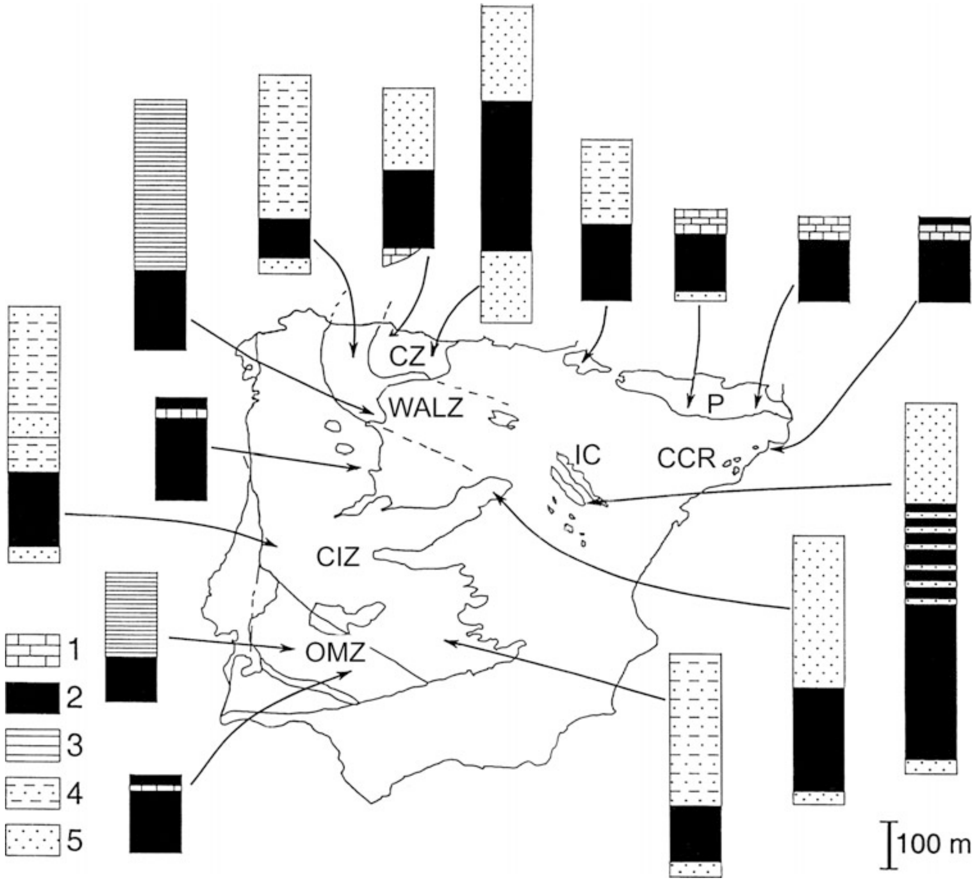

Fig. 3.4 The different types of Silurian successions in the Iberian Peninsula, reproduced from Gutiérrez-Marco et al. (1998) with permission from IGME, the copyright holder. Dominant lithofacies: 1. limestones; 2. black shales; 3. shales and siltstones; 4. alternating sandstones, siltstones and shales; 5. sandstones. Abbreviations: CZ, Cantabrian Zone; WALZ, West Asturian-Leonese Zone; CIZ, Central Iberian Zone; OMZ, Ossa-Morena Zone; IC, Iberian Range; CCR, Catalonian Coastal Ranges; P, Pyrenees. The three columns from Portugal are, from North to South, Moncorvo, Dornes-Mação and Barrancos

graptolitic facies, probably generated in areas with a stable stratification on the water masses instead of involving deep environments. This could be inferred by the presence of some Telychian graptolites listed by Robardet and Gutiérrez-Marco (2002) which are shared with those inshore environments of the pericratonic and intracratonic basins of Algeria and Libya, but that have never been found in the Ossa-Morena Zone, the northern Central Iberian Zone, the Pyrenees or the Catalonian Coastal Ranges.

In the West Asturian-Leonese Zone and the transitional area to the Central Iberian Zone, the Late Silurian sandstone-dominated sedimentation is replaced by massive chloritoid slates, extending into the Devonian, which have yielded Ludlow and Pridoli benthic and planktic elements of Bohemian type (Gutiérrez-Marco et al. 2001). The Palentian Region of the southeastern Cantabrian Zone, which probably originated in the West Asturian-Leonese Zone, also displays a lithological succession slightly different from the general scheme of the first type of Silurian succession. It starts with thick, white sandstones (Robledo Fm, Wenlock), then follows with siltstones and black shales (Las Arroyacas Fm, Wenlock to Pridoli age) and ends with sansdtones and some carbonate beds (Carazo Fm, Pridoli to Lochkovian), as indicated by García Alcalde et al. (2002). The Silurian sequences in both areas are hence representative of slightly deeper environments than those in the southern Central Iberian, Cantabrian or Iberian Range successions, as indicated also by the record of Bohemian (=Hercynian) faunas and scyphocrinoids around the Silurian/Devonian boundary beds.

The second main type of Silurian succession recorded in the Hesperian Massif is characterized by a continuous euxinic black shale or black shale-black limestone sedimentation, rather condensed (up to 200 m thick) that ranges from the basal Llandovery to the Lochkovian. It is characteristically represented in the Ossa-Morena Zone, but a similar sequence, also intercalating thin beds of black chert, occurs in the Moncorvo syncline and in the nearby autochthonous units of the northernmost part of the Central Iberian Zone in Portugal (Sarmiento et al. 1999, Meireles 2013). Because of the absence of important clastic influx of coarser terrigenous particles, it can be assumed that all these regions were situated at a distance from the terrestrial emerged land source areas, in the outer distal part of the Gondwanan marine shelf.

The Silurian-Lochkovian succession of northern Seville consists of 130–150 m of black argillaceous graptolitic shales with intercalations of siliceous slates and cherts, it is stratigraphically almost complete and fossiliferous (Jaeger and Robardet 1979, Robardet and Gutiérrez-Marco 2004, Loydell et al. 2015 with earlier references). A thin (0.5–1 m) black limestone level with orthoceratids and bivalves occurs in the Ludlow, and a thicker alternation of limestones and shales with benthic faunas of Bohemian type (the ‘*Scyphocrinites* Limestone’, 10–15 m) was intercalated on the Pridoli black shales.

Silurian limestones have never been observed in other areas of the western Ossa-Morena Zone, neither in Spain nor Portugal. In Villanueva del Fresno and Estremoz, unfossiliferous sandstones and quartzites occur in the lowermost part of the Silurian, below the graptolitic shales. The most complete succession of this system is known from the Barrancos area (Portugal), starting from the base of the Silurian according to the graptolites recognized in the uppermost levels of the Colorada Fm (Piçarra et al. 1995). This is overlain by the ‘Xistos com Nódulos’ Fm (30–50 m of black shales and thin intercalations of chert) where most of the biozones ranging from Llandovery to Ludlow strata were characterized, and by the suceeding ‘Xistos Raiados’ Fm (100 m of banded chloritoid shales and siltstones), which include successive graptolite biozones of upper Ludlow, Pridoli and Lochkovian ages (Piçarra et al. 1998, 1999, Araújo et al. 2013). The general succession of graptolite faunas from Barrancos displays a close identity with those of the Valle syncline, especially around the Homerian Lundgreni Event, with similar lithologies and non-graptolitic faunas present in both areas (Gutiérrez-Marco et al. 1996, Rigby et al. 1997, Lopes 2013).

According to Robardet and Gutiérrez-Marco (2002), there is a general trend within the Hesperian Massif, from shallow deposits in the south of the Central Iberian Zone to deeper and more distal sediments in the northern Central Iberian Zone and in the southern part of the West Asturian-Leonese Zone. To this regard, Pridolian ‘*Scyphocrinites* limestones’ occur in the Moncorvo area and at Guadramil (Portugal), in the north of the Central Iberian Zone, and Silurian successions of the Peñalba and Sil synclines are more shaly and silty, while Ludlow limestones bear trilobites of Bohemian affinities, in some way reminiscent of the Silurian of Pyrenees and Catalonia. These Hercynian magnafacies were also recognized in the Palentian Domain of the Cantabrian Zone. A different distal area of the Gondwanan platform is represented by the Ossa-Morena Zone, where the terrigenous influx was permanently weak in the Silurian and where the faunas were almost exclusively pelagic. Quesada (1991) considers these deposits as sedimented in the thinned, distalmost parts of the Gondwanan margin, before being juxtaposed tectonically to other Iberian zones that have occupied more internal parts of it. However, there is no consensus on the timing of the juxtaposition, with some authors that favoured the late Paleozoic Variscan orogeny (Simancas et al., 2001, 2003, 2005, 2006) and others who proposed a much earlier accretion during the Neoproterozoic Cadomian orogeny (Ábalos 1990, Quesada 1990a, b, 1997, 2006). The latter would require an important combination of Variscan tectonism to move the Ossa-Morena Zone to its actual position, displacing the emerged Ordovician land to the present southeast. The latter would have acted as the source area of the Central Iberian shelf during the Ordovician and Silurian, as has been repeatedly demonstrated by its general gradient indicated in both sediments and faunas (Gutiérrez-Marco et al. 2014b).

3.4 Silurian-Devonian Within-Plate Magmatism

Locally and discontinuous in time, mostly alkaline mafic intraplate volcanic and volcaniclastic rocks occur interbedded/intruded into the passive margin succession in the Iberian Massif. The most important activity was located in the southern Central Iberian Zone; e.g. Almadén area with its gigantic Hg ore deposits in Silurian and Lower Devonian times (Higueras et al. 2013 and references therein), La Codosera syncline close to the Badajoz-Córdoba shear zone (López-Moro et al. 2007) or El Castillo volcanics at the Tamames syncline.

The Almadén syncline is by far the area with more abundant and varied magmatic rocks, spanning in age from Early Silurian to Late Devonian times (Saupé 1990; Higueras 1995; Hall et al. 1997; Hernández et al. 1999; Higueras et al. 1995, 2013). Volcanic types mainly include porphyritic metabasalts but minor outcrops of differentiated rocks, such as trachyte, trachyandesite and rhyolite lavas also occur. Pyroclastic rocks are also abundant throughout the succession, among which the so-called Frailesca rock, a lapilli tuff with basaltic, sedimentary and ocassional ultramafic fragments that generally infills diatreme-like structures, has deserved special attention due to its presence in most mercury deposits in the region and its interpretation as genetically linked to their formation (Hernández et al. 1999; Jébrak et al. 1997; Higueras et al. 2011, 2013). In addition to lavas and pyroclastic rocks, mafic dolerite sills intrude the passive margin succession in this area.

In terms of composition, a spread from basanites and nephelinites, through olivine-basalts, pyroxenitic-basalts (interpreted as pyroxene cumulates), trachybasalts, trachytes, to very rare rhyolites is found. Phenocrysts comprise olivine, diopsidic pyroxene, analcite and plagioclase in the mafic rocks, biotite and plagioclase in intermediate rocks, and K-feldspar and quartz in the rare rhyolites. Late magmatic kaersutitic amphibole and Ti-rich biotite are also conspicuous in the mafic types. Textures are porphyritic, with a crystalline matrix, and often vesicular (Higueras et al. 2013). In addition to their presence as clasts in the Frailesca rock, ultramafic fragments also occur as xenoliths in the least differentiated basalts. They contain 50–80% olivine, pyroxene, and minor spinel, usually unaltered, which allows their classification as spinel lherzolites.

A peculiar characteristic of the Almadén mafic rocks is their high content in CO_2, with concentrations ranging from 8 to 15%; 20 to 30% in basalts and ultramafic xenoliths, respectively, in and around the mercury deposits (Higueras, 1995). The isotopic composition of these carbonates suggests a primary character and a probable mantle origin. Helo et al. (2011) interpreted that given its low solubility, CO_2 is the only magmatic volatile phase that may be significantly exsolved as the magmas ascend to the surface, resulting in explosive eruptions. This model could explain the explosive nature of the volcanism at Almadén as shown by the numerous Frailesca rock units and pyroclastic rocks along the stratigraphic succession (Higueras et al. 2013).

All the geochemical characteristics indicate (Higueras et al. 2013): (i) most rocks show alkaline affinities with some transitional to a tholeiite affinity; (ii) derivation from primitive mantle-derived magmas, with most rocks plotting in the alkali basalt and basanite/nephelinite fields typical of within-plate settings; and (iii) enriched nature of the mantle source, with eventual contribution from asthenospheric sources.

In the southwestern corner of the Central Iberian Zone, close to the Badajoz-Córdoba shear zone, mostly mafic magmatic rocks occur at La Codosera syncline as meter to decameter-thick sills (ocassionally reaching ca. 300 m in thickness and up to 3 km in length; López-Moro et al. 2001, 2007). The sills intrude at various levels into a metasedimentary succession which includes Lower and Upper Devonian rocks (Santos et al. 2003; López Díaz et al. 2007). López-Moro et al. (2007) published a 436 ± 17 Ma Sm–Nd isochron age (early Silurian) obtained from samples collected in four different sills. However, intrusion of these sills produced thermal metamorphic aureoles in the fossiliferous Devonian country rocks that postdate development of a first deformation fabric (Santos et al. 2003; López Díaz et al. 2007). This fact contradicts the early Silurian radiometric age obtained by López-Moro et al. (2007), casting doubts on their emplacement during the passive margin stage, and shows the need for further geochronological work. Compositionally the mafic rocks correspond to high-Mg tholeiites and tholeiitic andesites but their source is hard to characterize (López-Moro et al. 2007). On one hand, a εNd value of +6 indicates a significant mantle component; on the other hand, a moderate LREE enrichment relative to HREE and a Nb negative anomaly suggest contribution of a crustal component. To account for this apparent contradiction (López-Moro et al. 2007), inferred a hybrid mantle source with contribution of a metasomatised component and a major, depleted component.

SW of Salamanca, the El Castillo volcanics crop out in the Tamames syncline. They mainly consist of basaltic sills intruded in fossiliferous Silurian shales and minor pyroclastic rocks. Initially considered as Silurian in age (Díez Balda 1986), recent dating of a basaltic sample as Middle Devonian (394.7 ± 1.4 Ma, U–Pb zircon age, Gutiérrez Alonso et al. 2008) suggests that magmatism may have extended in this area from the Silurian, to account for the interbedded pyroclastics, into at least the Middle Devonian. According to Díez Balda (1986) both lavas and pyroclastic rocks exhibit alkaline basaltic compositions (basanites).

In addition to the above areas, Silurian and/or Devonian alkaline mafic rocks are known in many other localities across the Iberian passive margin of Gondwana; e.g. Alcañices syncline in the northern Central Iberian Zone (González-Clavijo 2006), eastern Central Iberian Zone (Ancochea et al. 1988), Ossa-Morena Zone (Piçarra 2000), and even the Cantabrian Zone, where volcanic rocks belonging to the Huergas Fm where dated at ca. 395 Ma (whole-rock Rb–Sr method; Loeschke 1983). All these volcanic manifestations attest for punctuated extensional tectonic events affecting the Iberian Gondwanan shelf during the duration of the passive margin stage.

3.5 The Devonian Sequence

The Devonian sedimentation is continuous with the Silurian in different areas of the Hesperian Massif, where the boundary between both systems is placed within certain successions dominated by sandstones or alternation of shales and sandstones, with some ooidal ironstone beds and, in the upper part, impure fossiliferous limestones that are already of Lochkovian age. These units are the Furada-San Pedro and Carazo formations of the Cantabrian Zone, the Luesma Fm of the Iberian Range, and the Seceda and Alcolea formations of the ‘Ollo de Sapo’ Domain (northern Central Iberian Zone). Above them, Devonian rocks are mostly calcareous in northern Spain with some remarkable reefal developments, especially during the late Emsian and Givetian. The greatest thicknesses of Devonian rocks recorded in the Hesperian Massif, to the north of the South-Portuguese Zone, are located in the Iberian Range (>4,000 m) and in the Cantabrian Zone (>2,000 m), essentially developed in shallow-water marine facies bearing abundant fossils. Outside these areas, Devonian outcrops are more scarce and discontinuous, with scattered occurrences in the southern Central Iberian Zone and in the Ossa-Morena Zone, which also included frequent volcanic intercalations.

In the Cantabrian Zone, Devonian rocks can be typified by two distinct marine domains: the so-called Asturo-Leonian facies, mainly representing nearshore to shallow shelf environments, and the Palentian facies, representing the offshore settings and deeper environments of the same platform. The first facies is widely distributed across the Cantabrian Zone, showing a general deepening trend towards the west and southwest, in a general regressive

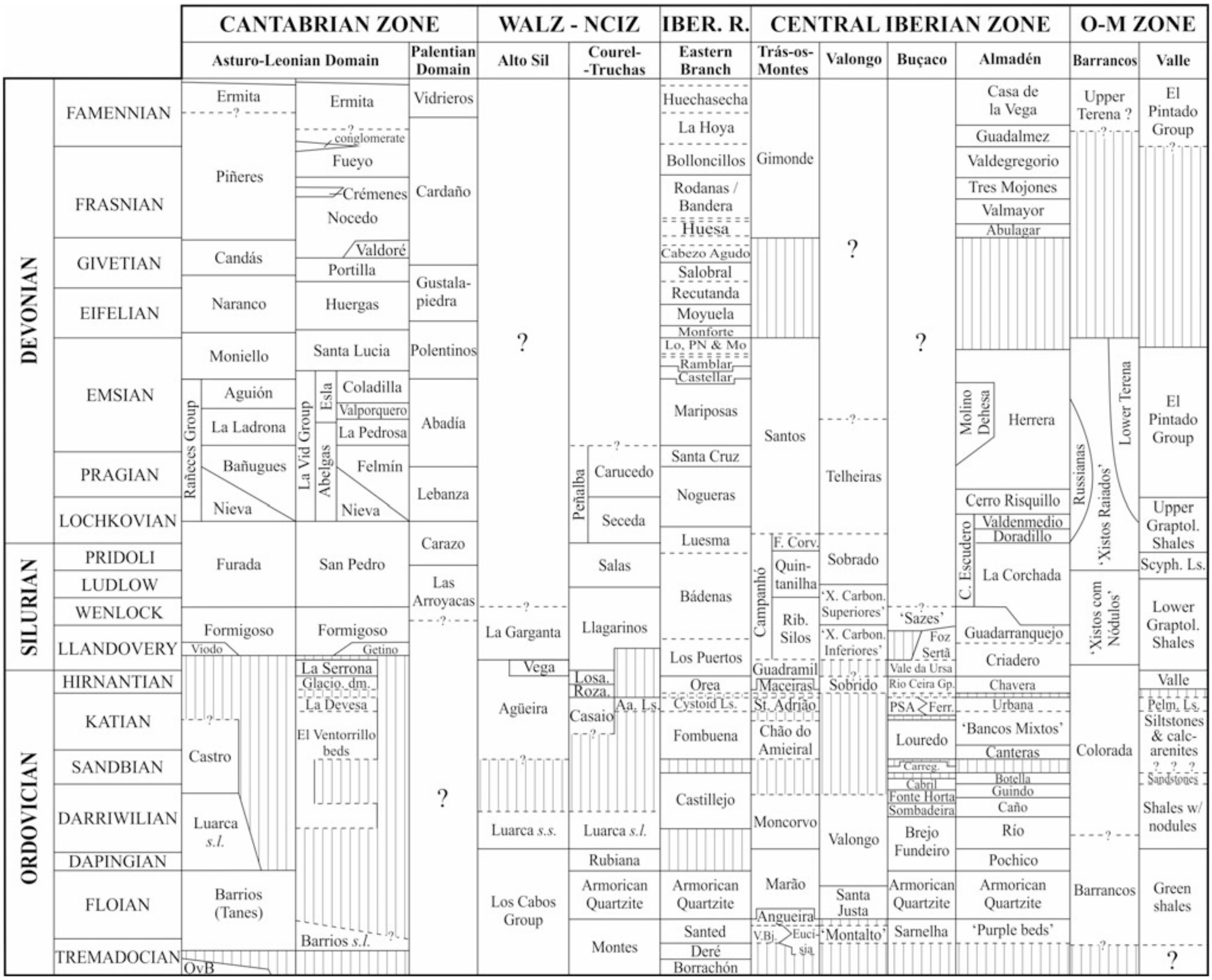

Fig. 3.5 General correlation chart of the most complete and continuous Ordovician to Devonian sedimentary units occurring in the Hesperian Massif. Devonian data mainly adapted from García Alcalde et al. (2002), Robardet and Gutiérrez-Marco (2004) and Meireles (2013). Lithostratigraphic abbreviations for formation names: Aa. Ls., La Aquiana limestone; F. Corv., Fraga dos Corvos; Ferr., Ferradosa; Glacio. Dm., unnamed glaciomarine diamictites; Losa, Losadilla; 'Lo, PN and Mo', Loscos, Peña Negra and Molino (in ascending order); OvB, Oville or lower Barrios (La Matosa Member); Pelm. Ls., Pelmatozoan limestone; PSA, Porto de Santa Anna; Rib. Silos, Ribeira de Silos; Roza, Rozadais; Sombadeira; Monte da Sombadeira; V. Bj., Vale de Bojas; 'X. Carbon.', Xistos Carbonosos; Other abbreviations: CA., Cerro; Graptol., Graptolitic; Gp., Group; Ls., limestone; O-M, Ossa-Morena; Rib., Ribeira; *s.l.*, sensu lato; *s.s.*, sensu stricto; St., Santo; WALZ—NCIZ, West Asturian-Leonese Zone

context due to regional vertical movements (García Alcalde et al. 2002). The second is restricted to an area of nappes which is thrusted over the SE of the Cantabrian Zone, probably originating in southern areas of the West Asturian-Leonese Zone (Henn and Jahnke 1984).

The Devonian succession in the Asturo-Leonian Domain is formed by an alternation of formations of either siliciclastic or carbonatic predominance, whose lithostratigraphic nomenclature shows obvious equivalences among the northern and southern slopes of the Cantabrian Ranges (Fig. 3.5). Details of the different formations have been summarized by García-Alcalde et al. (2002) and Aramburu et al. (2004), who described the continuous character of the sedimentation from the Lochkovian to the Frasnian, and the appearance of paraconformities and disconformities in the Famennian within the most complete Devonian sequences. Over an extense part of the Cantabrian Zone and towards the Asturian arc core, an important pre-upper Famennian sedimentation gap was developped, also affecting Silurian and some Ordovician strata.

The Devonian sequence of the Palentian Domain starts with shallow-water sandstones, limestones and shales that predominated in ascending order during the deposition of the early Lochkovian Carazo Fm, the late Lochkovian to Pragian

Lebanza Fm, and the Pragian to late Emsian Abadía Fm. Above the latter, the incoming of pelagic faunas of ammonoids, dacryoconarids and certain conodonts in the next four Devonian formations suggest quieter water to relatively deep conditions starting from the latest Emsian to the Famennian. To this regard, the quartz sandstones of the Murcia Fm (early Famennian) were interpreted as posible turbidites, and the reddish nodular limestones and shales of the overlying Vidrieros Fm (early Famennian to earliest Tournaisian) are representative of offshore deposits close to the slope. As in the previous case, a summary description of the formations of the Palentian Domain, including the location of the Devonian global events, was presented by García Alcalde et al. (2002), Aramburu et al. (2004).

The thick Devonian succession of the Iberian Range was deposited in an active subsiding trough presently outcropping to the west of the Datos fault, being the sedimentation continuous from the Silurian at least up to middle Famennian times. Devonian strata mostly represent shallow-water marine environments dominated by clastic sediments, richly fossiliferous, also with common thin intercalations of shelly limestones and marls. Rhythmothems due to variations in subsidence and water depth are also frequent, some of them containing pelagic faunas on black shales and limestones in alternation with neritic faunas. These pelagic faunas of dacryoconarids, ammonoids, ostracods, conodonts and epiplanktonic bivalves became relatively more abundant in the succession of the Late Devonian, where a background sedimentation of fine shale predominates. A basic study of the Devonian formations in the Iberian Range, including general aspects of correlation and paleogeographical problems, was presented by Carls (in García Alcalde et al. 2002) and Carls et al. (2004).

Scattered outcrops with Lower Devonian sedimentary rocks known from the West Asturian-Leonese Zone, other than the nappes of the Palentian Domain displaced onto the Cantabrian Zone, are only preserved in the transitional area with the 'Ollo de Sapo' Domain of the northern Central Iberian Zone. The main areas lie in the core of the Courel-Peñalba syncline, as well as in the eastern Guadarrama Sierra (García Alcalde et al. 2002). Other Devonian outcrops occurring in the autochthonous part of the Trás-os-Montes region and the Alcañices syncline are still very poorly known because of a complex tectonic overprint (González-Clavijo 2006; Meireles 2013).

The main Devonian successions of the southern Central Iberian Zone occur in the Portuguese inliers of Valongo, Marão, Dornes, Mação and Portalegre, as well as in the Spanish outcrops of the Sierra de San Pedro, Cáceres syncline, Almadén region and the eastern Sierra Morena area, each one with slightly different stratigraphical features. Nevertheless, a 'mid-Devonian stratigraphical gap' is a common feature even in the most complete successions of the domain. This involves a paraconformably contact, only detectable by biostratigraphic criteria, between successive deposits of Emsian and Frasnian (sometimes latest Givetian) ages, all developed in very similar marine facies. The 'mid-Devonian stratigraphical gap' has been interpreted as produced by an 'eo-Variscan' tectonic phase that in some parts of the southern 'Obejo-Valsequillo' Domain generates an angular unconformity of the Frasnian sandstones upon Early Devonian or earlier Paleozoic formations (Herranz Araújo 1985), being in the latter folded by a compressive/transpressive event. Oliveira et al. (1991) were the first authors who linked such tectonic episode to the initial subduction of oceanic lithosphere ('Pulo do Lobo Ocean') in the south of the Iberian Peninsula, now related with the starting of the Variscan collision and its 'echoes' in some of the apparently stable shelf areas at a wider scale.

The more complete and better-known Devonian sequences of the southern Central Iberian Zone are located in the Almadén area, lying in the core of the Herrera del Duque, Almadén and Guadalmez synclines, as well as in the Sierra de San Pedro. They are mainly composed of thick alternations of sandstones and shales, separated by metric to decametric packages of massive sandstones and quartzites. The shale-dominated formations are more frequent in the Late Devonian, whereas limestones are only recorded in the Herrera Fm (the Molino de la Dehesa Mb, Emsian) but also occur—as limestone lenses and nodules—within the Casa de la Vega Fm (early Famennian to late Tournaisian). In the Almadén syncline, a thick development of volcanic rocks (the 'Chillón Volcano-Sedimentary Complex') locally ranges along the entire Frasnian (see previous section). Details of the different Devonian formations and faunas of the southern Iberian Zone have been summarized by García Alcalde et al. (2002). In the same work the main Devonian sequences recognized in the 'Obejo-Valsequillo' Domain are also envisaged, being different from the southern Central Iberian Zone successions by a larger presence of shales and more abundant intercalations of Lower Devonian limestones (e.g. Rodríguez et al. 2010), but with some Frasnian faunas in common. Recent papers on the Devonian strata of south-central Portugal are by Gourvennec et al. (2008), Vaz (2010), Lopes (2013) and Schemm-Gregory and Piçarra (2013).

Devonian rocks have a relatively low number of well-characterised occurrences in the Ossa-Morena Zone. The better sections are located in the Zafra-Alanís and in the Barrancos-Hinojales sectors, and have been summarized by Robardet and Gutiérrez-Marco (2004). The first Unit includes the Devonian outcrops of the Valle and Cerrón del Hornillo synclines of northern Seville, where the Lochkovian graptolitic black shales, continuous with the Silurian, are conformably overlain by green to brown shales and siltst-ones of the lower part of the El Pintado Group. They have yielded brachiopods, trilobites and ostracods of the whole Pragian and the early Emsian. The upper part of the El Pintado Group concordantly overlies these Lower Devonian strata, and started with limestones and calcareous sandstones with Famennian brachiopods and conodonts, followed by black shales and black argillaceous limestones with other Famennian bivalves and conodonts. These datings demonstrate the existence of an enlarged 'mid-Devonian stratigraphical gap' within the El Pintado Group and its extension to this part of the Ossa-Morena Zone.

The Devonian sequences of the Barrancos-Hinojales sector are quite different and sparsely fossiliferous, regarding the diverse Portuguese and Spanish sections. The most complete is represented in the Barrancos area, where the 'Xistos Raiados' Fm, continuous with the Silurian, yielded Lochkovian graptolites and palynomorphs, as well as some Praguian spores at the upper beds. A lateral defined formation (Russianas Fm) composed of grey-green shales with crinoidal limestone, yielded some Pragian trilobites, brachiopods, tabulate corals, bryozoans and crinoid columnals. Above the 'Xistos Raiados' Fm and in apparent gradual to concordant basal stratigraphic contact, the Lower Terena Formation consists of greywackes and shales with conglomeratic levels. The unit yielded Lochkovian graptolites and spores from their lowermost part, and Pragian and Emsian spore assemblages from higher levels. The biostratigraphic data raise paleogeographical or structural problems because three partly coeval Early Devonian lithosomes ('Xistos Raiados', Russianas and Lower Terena) seem to occur in different parts of the Barrancos region, perhaps involving various tectonic slices (Piçarra 2000, vol. 2, p. 143).

Other interesting Lower Devonian successions in the Ossa-Morena Zone are located in the Venta del Ciervo area, where fossiliferous shales of the Verdugo Fm having yielded brachiopods, trilobites, ostracods, rugose corals and a single graptolite of Pragian-early Emsian age. Also scattered occurrences of Upper Devonian rocks considered as syn-orogenic deposits (see Chap. 11 in this volume), located in the western Beja Massif, occur in the Cabrela and Toca da Moura complexes interbedded with terrigenous sediments dated as early Carboniferous (Pereira et al. 2006a, b; Oliveira et al. 2013). The Engenharia quarry (near Montemor-o-Novo) contains calciturbidites with late Eifelian conodonts, and the limestone lenses of the Cabrela Fm yielded late Frasnian conodonts, besides some poorly preserved macrofauna of possible Late Devonian age. Mid and Late Devonian limestones are now interpreted as olistholiths dislocated from a Devonian carbonate platform, situated south of the region in present day coordinates (Pereira et al. 2006a, b). In the upper part of the Odivelas Basic Complex in the Beja Massif, the Odivelas Limestone bears Emsian-Eifelian conodonts and reefal faunas, occurring in a sequence of calciturbidites and debris-flow deposits, which include hemipelagic tufites related to a reefal system resting on top of volcanic buildings within a large volcanic complex (Machado et al. 2009, 2010).

Finally, the recent finding of Early Devonian free-living tentaculitoids and crinoid columnals, occurring in marbles belonging to the 'Volcanic-Sedimentary Complex of Estremoz', opens the possibility of a complete reconsideration of the age of one of the most distinctive units in the Paleozoic basement of soutwestern Iberia (Piçarra et al. 2014).

3.6 The Latest Devonian-Early Carboniferous Sequences

The onset of the Variscan collision between Laurussia and Gondwana in late Lower Devonian times (see Chaps. 10 and 11 in this volume) brought to an end the tectonically quiescent passive margin stage. This was specially rapid in the outer margin Gondwanan domains such as the Middle and Lower allochthons and the Parautochthon of the Galicia-Trás-os-Montes Zone, which were subducted beneath Laurussia. The associated deformation of those domains renders very difficult the identification of the passive margin record in them, reason why they are dealt with separately in the next section. Away from the orogenic hinterland, the initial expression of the collisional event is varied and diachronous. In the Ossa-Morena, Central Iberian and probably the West Asturian-Leonese zones it is expressed by the sedimentary gaps, with or without associated tilting described in the previous section (see also Fig. 3.5), but platformal sedimentary conditions resumed until the propagation of deformation towards the foreland progressively reached them during the Carboniferous.

Owing to the southeasterly escape the Ossa-Morena Zone, accommodated by sinistral displacement along the Badajoz-Córdoba shear zone since Lower Devonian times (see Chaps. 10 and 11 in this volume), a process of transpressional uflift and transtensional basin formation affected most of the Ossa-Morena and the southernmost Central Iberian Zone. Denudation of part or all the passive margin succession took place in the uplifted blocks, whereas sedimentary continuity or paraconformity happened in the subsiding basins.

The transition from the Devonian into the Carboniferous sedimentation is marked by an unconformity in the Cantabrian Zone located at the base of the Ermita Fm in the late Famennian. No true unconformity (only a disconformity or paraconformity) is recognized in the Ossa-Morena Zone, where it seems to be younger from SW to NE from the Late Devonian into the Mississippian (Oliveira et al. 1991 and references therein), nor in the southern Central Iberian Zone or Obejo-Valsequillo Domain (Fig. 3.6). Lithological

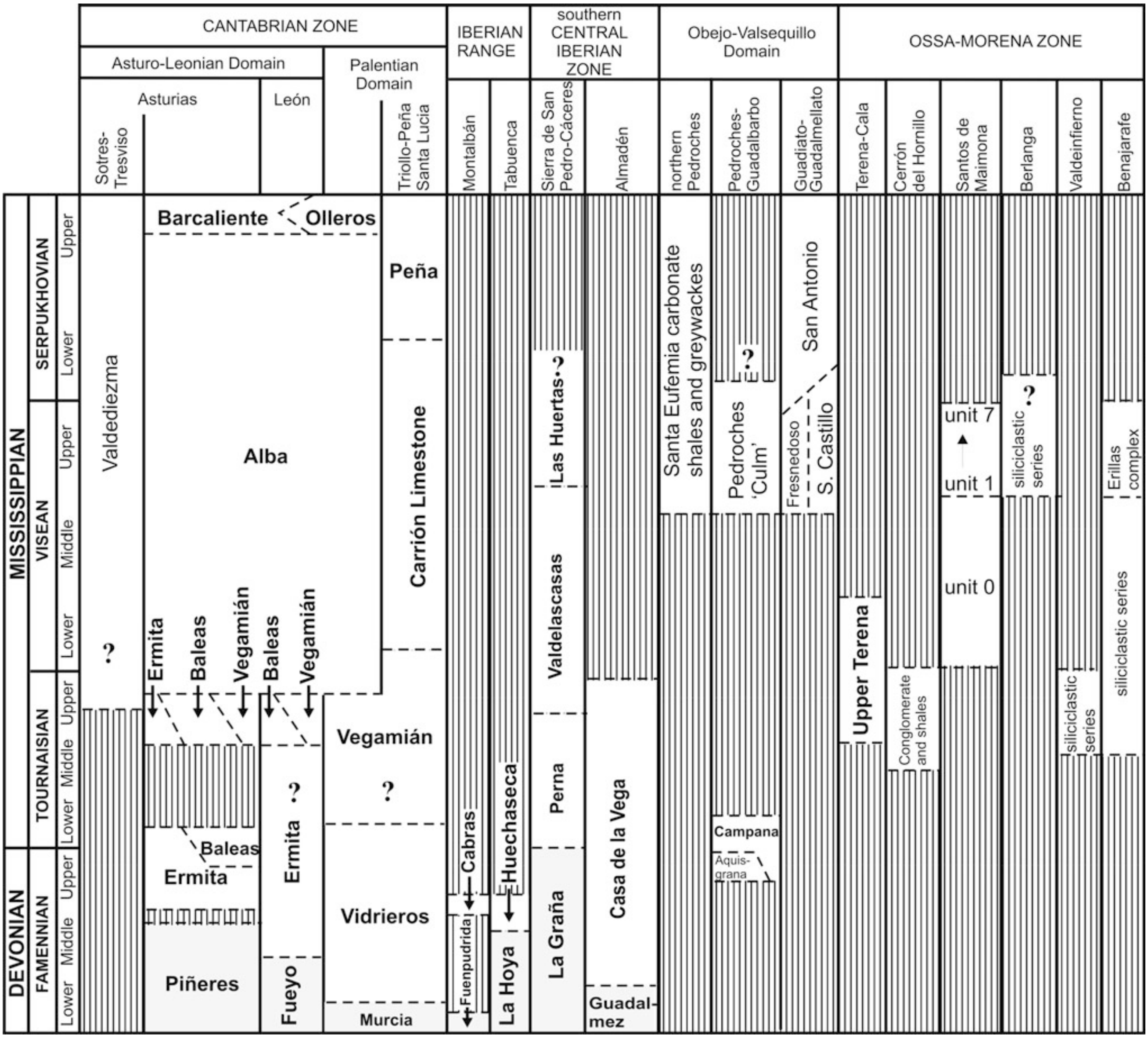

Fig. 3.6 Correlation chart of the main late Famennian and Mississippian rocks. Note that formal formations are not defined in many areas of the southern Central Iberian and Ossa-Morena zones (formal units are highlighted in bold font). Formations with grey filling are considered as pre-orogenic

descriptions are mostly based on García Alcalde et al. (2002), Colmenero et al. (2002), Fernández et al. (2004) and references therein.

In the Cantabrian Zone, the Ermita Fm is 5–75 m thick and composed of cross-bedded sandstones, siltstones, shales, and sandy limestone lenses with microconglomeratic sandstone layers. Above and laterally, it passes into sandy bioclastic packstone and grainstone limestone (mostly encrinitic) of the Baleas Fm (1–15 m thick). The overlying Vegamián Fm contains 2–5 m of black siltstones with phosphatic nodules and lydite bands with an erosive base over the Ermita Fm in some localities (Sanz-López and Blanco-Ferrera 2012). The synorogenic rocks seem to be apparently in continuity in the Palentian Domain, where the Vidrieros Fm, an ammonoid-bearing reddish nodular limestones interbedded with shales in a condensed sedimentation, and is deposited over the Murcia Fm. Laterally the Palentian Domain, Nemyrovska et al. (2011) named this formation as the Montó Fm, where it contains 30–40 m of shales and siltstones, with yellowish to pale grey nodular limestones.

There are no detailed sedimentological studies in those formations, and the Ermita Fm and lateral equivalents were interpreted as deposited in intertidal to supratidal environments, whereas the Baleas limestone was considered as submarine shoals separated by slightly deeper channels with coarser grain than the Ermita and Vegamián formations, although the presence of black shales and lydites suggest deeper water settings, and possibly anoxica. The Vidrieros Fm was interpreted as offshore deposits close to the slope. The sedimentation was continuous through the Devonian/Carboniferous boundary in the Ermita, Baleas and Vidrieros formations, although their bases and tops are not synchronous (Fig. 3.6). Another gap occurs within these formations in the Cantabrian Zone, from the lowermost Tournaisian to the upper Tournaisian (Fig. 3.6). However, it has not been demonstrated yet if it extends into the Palentian and León domains (Sanz-López and Blanco-Ferrera 2012).

The latest Devonian in the Iberian Range is limited to the Tabuenca outcrops, where a composite succession of 1,300 m was described for the Frasnian-Famennian. The succession probably ends at the late Famennian, although the area is poorly known biostratigraphically, due to it being mostly composed of pelagic shales with rather sparse fauna.

The latest Devonian is absent in most of the Central Iberian Zone, where it only occurs in the southern outcrops (Fig. 3.6). In the Almadén area, the late Famennian is represented by limestones of the Casa de Vegas Fm (early Famennian to late Tournaisian) overlying pelagic black shales and carbonate nodules of the Guadalmez Fm. In the Sierra de San Pedro, the Famennian is recognized in the La Graña Fm, mostly composed of shales with greywackes, shales and microconglomerates in its upper part. The formation passes into the Perna Fm, composed of brecciated volcanic rocks and shales, attributed to the early Tournaisian. In the Obejo-Valsequillo Domain, east of Pedroches and close to La Carolina, the 'Aquisgrana shales' are regarded as the base of the Campana Fm, which contains siltstones, shales and quartzites, with ostracods of late Famennian age.

From the late Tournaisian upwards, the succession in the Cantabrian Mountains contains the Alba Fm (late Tournaisian–late Serpukhovian) and Barcaliente Fm (latest Serpukhovian–early Baskhirian; Sanz-López et al. 2013). The Alba Fm, 20–30 m thick, is a predominantly ammonoid-bearing reddish to grey nodular limestone composed of up to 6 members (Sanz-López and Blanco-Ferrera 2012), and interpreted as a pelagic platform. However, in the Palentian Domain, Nemyrovska et al. (2005, 2011) described the Carrión Limestone and Peña formations. The former is composed of grey to yellowish nodular to well-bedded limestone (ca. 15 m thick) and it ranges from the early Visean up to the lower part of the early Serpukhovian. The Peña Fm is composed of well-bedded partly bioclastic limestones, ca. 250 m thick, and it ranges up to the earliest Bashkirian. The Carrión Limestone Fm is interpreted as a pelagic platform, whereas the Peña Fm was considered as shallow-water platform. In the core of the Picos de Europa province, the informal Valdediezma Limestone (latest Tournaisian to early Bashkirian) has been recently described (Sanz-López et al. 2018). This limestone is the result of a highly subsiding agradational platform which accumulated more than 1,200 m of massive to well-bedded limestones, mostly corresponding to microbial carbonate mounds developed in shallow-water platform, surrounded by bioclastic and oncoidal beds in the lower and upper parts of the succession. Lateral facies changes with the typical Alba and Barcaliente formations are observed in the southeastern outcrops (Sanz-López et al. 2018). The Barcaliente Fm is mostly composed of black, laminated micrites with disperse organic matter and levels with quartz grains of silt size and scattered bioclasts, interpreted as distal turbidites and deep-water background sedimentation, mostly in its lower half. This formation passes laterally to the turbiditic shales of the Olleros Fm.

The Mississippian succession is sparsely distributed in the southern Central Iberian and Ossa-Morena zones, and the Obejo-Valsequillo Domain, whereas it is absent in northern Central Iberian Zone and Iberian Range (Fig. 3.6). It is also noteworthy, that Mississippian lithostratigraphical units are rarely formally defined.

In the southwestern part of the Central Iberian Zone, in the Sierra de San Pedro, the Mississipian contains the Perna, Valedelascasas and Huertas formations (Soldevila Bartolí 1992) with a total thickness of ca. 600 m. The Perna (Tournaisian) is a volcano-sedimentary unit composed of tuffs, limrstones, shales and lydites with numerous lateral facies changes. The Valedelascasas limestones (latestTournaisian-middle Visen) are pale grey to dark limestones, very recrystallized and dolomitized. Above, extend outcrops of the shales and Huertas Fm occur, up to 400 m. The shales were compared to those of the Cáceres syncline, and assigned to the Mississipian.

In La Codosera—Puebla de Obando syncline, the Mississippian is represented by the Gévora Fm (early to late Visean), which is mostly composed of shales with interbedded sandstones, local volcanic rocks and limestone olistoliths, and may reach up to 5,000 m in thickness (Rodriguez Gonzalez et al. 2007. In the Portuguese part of the syncline, early Carboniferous palynostratigraphic data (Z. Pereira, unpublished data; Lopes 2013) have been recently recorded in the so-called Rabaça Fm (Geological Map of Portugal, sheet 6, 1: 200,000 scale, in prep.).

In the north of the Obejo-Valsequillo Domain, close to Santa Eufemia, two successions are recognized: one with massive to well-bedded limestones and shales (ca. 100 m thick) and the other composed of shales and greywackes (ca. 4,000 m thick) (Rodríguez Pevida et al. 1990). The limestone lenses were considered as olistoliths, and the alternating shales and greywackes as part of the 'culm' facies fill of the Pedroches basin. Limestone lenses were attributed to the late Visean, although the siliciclastic complex can be assigned to late Visean–earliest Bashkirian on the basis of conodonts. The Pedroches 'Culm' forms the most extensive outcrops in the Obejo-Valsequillo Domain (with a similar succession than that in the Guadalbarbo 'Culm'), where numerous folds and faults were recognized and its general thickness was estimated to be ca. 1,500 m. The base of the succession is composed of pyroclastic rocks (tuffs and volcanic ashes) interbedded with shales and carbonate breccias. Higher up in the succession, thick shale, siltstone and greywacke alternations are observed. A slope environment was proposed by Pérez-Lorente (1979). Foraminifers in the basal limestone boulders allow an assignation of the base of Pedroches "culm" to the late Visean. The upper part has not been dated as yet, but compared with neighbouring 'culm' facies in the Guadiato or Santa Eufemia, it might range into the Serpukhovian. More diverse rocks are recorded in the Guadiato and Guadalmellato areas (see Chap. 11 in this volume). Three tectonostratigraphic units were defined to characterize the Mississippian in the Guadiato area: the Fresnedoso, Sierra del Castillo and San Antonio-La Juliana units (Cózar and Rodríguez 1999). In the Fresnedoso Unit, a basal conglomerate is recorded in the so-called Alhondiguilla 'Culm' where abundant olistoliths are recorded, mostly carbonates but also fragments of nearshore sandstones and shales. The Sierra del Castillo Unit preserves fragments of the carbonate shallow-water platform. Both units were dated as late Visean. The succession during the late Visean corresponds to a deepening sequence with black shales at the top. The youngest unit, San Antonio-La Juliana Unit is composed of shales with common olistoliths and calciturbidites in a shallowing sequence reaching intertidal to supratidal carbonates interbedded with shales, veneered by deltaic conglomerates, and ranging from the early Serpukhovian to the lower part of the late Serpukhovian. The succession in the Guadalmellato area is rather similar (Cózar et al. 2006).

In the Ossa-Morena Zone some sparse marine outcrops occur (Fig. 3.6), which represent preserved parts of the infill of the syn-orogenic basins referred to above (see Chap. 11 in this volume). In the Terena-Cala area, represented by the Upper Terena Fm, the succession is composed of turbiditic shales interbedded with sandstones and conglomerates, ca. 1,000 m thick, interpreted to be deposited in a subsiding trough. In the upper part of the succession, calcareous sandstone lenses yield late Tournaisian-early Visean conodonts. The lenses were interpreted as shallow-water buildups redeposited in a toe-of-slope due to storm events. The succession in Los Santos de Maimona is composed of green shales and greywackes (rare coal) with common volcanic rocks in the lower part, followed by ca. 220 m of predominantly bioclastic and reefal limestones, and un upper part, ca. 500 m thick of siltstones, black shales, sandstones, conglomerates and some limestone olistoliths (Rodríguez 1992). The lower and upper parts of the succession were interpreted as 'culm' facies and slope deposits, whereas the limestones correspond to tidal-controlled sediments in middle and inner platform settings. The succession was assigned to the late Visean. In the area of Benajarafe, a 200–300 m thick succession is recorded, composed of conglomerates passing into marine siltstones and sandstones (with thin volcanic rocks and coal) and, in the younger part, a volcanic sequence (several hundred metres thick). In Berlanga, three units were recognized, a predominantly conglomeratic unit in the lower part (with interbedded shales and greywackes), a second shaly interval with thin sandstone beds, and the upper greywackes, interbedded with thin shales. A late Tournaisian-early Visean age was proposed for the lower part of the succession, which might range up to the late Visean. The sedimentation in Benajarafe and Berlanda were interpreted as deltaic and lagoonal (Gabaldón et al. 1985). The Cerrón del Hornillo is a poorly-known sequence, composed of a basal conglomerate, ca. 200 m of shales and rare sandy-encrinitic limestone lenses in its upper part. The lower part of the shales was assigned to the mid-late Tournaisian (Robardet et al. 1986, 1988).

3.6.1 The Drift Stage in the Upper Parautochthon of the Galicia Trás-Os-Montes Zone

Í. Dias da Silva, E. González-Clavijo, A. Díez-Montes, J. Gómez Barreiro

The drifting stage in the Upper Parautochthon (see definition in Chap. 4 of this volume) of the Galicia Trás-os-Montes Zone starts with a relatively thin (100 m) orthoquartzite unit, the Algoso Formation (Fig. 3.7; Dias da Silva 2014; Dias da Silva et al. 2014, 2016), which constitutes a reference bed suitable to unravel the Variscan structure in the Upper Parautochthon, and can be correlated to the widespread Armorican-type quartzite in Western Europe and the tectonically underlying Autochthon (Central Iberian Zone). The sedimentation of this sandy shoreline facies stratigraphic unit represents the establishment of a stable platform that culminates the regressive sequence of the stratigraphically underlying Mora-Saldanha Volcano-Sedimentary Complex (Fig. 3.7). Although no stratigraphic unconformity has been identified to date at the base of the Algoso Formation, we assume that it represents the rift-drift transition in the Upper Parautochthon stratigraphic sequence as it marks the maximum regression of the platform in the Lower Ordovician period.

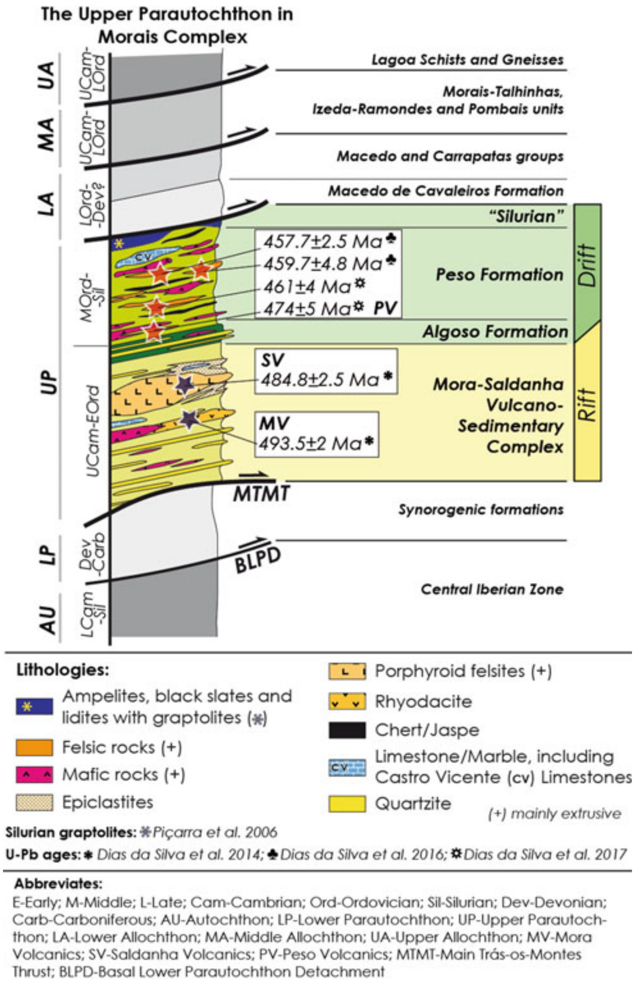

Fig. 3.7 Synthetic lithostratigraphic column of the Upper Parautochthon, in the Morais Complex, NE Portugal

The Algoso Formation is overlain by a relatively thick volcano-sedimentary unit named Peso Formation (Fig. 3.7; Dias da Silva 2014; Dias da Silva et al. 2016). It is made of black slates, locally purple probably in relation with volcanic exhalations, and includes a voluminous bimodal volcanism with abundant pyroclastic and epiclastic rocks, as well as some thin chert levels. Towards the upper part of the Peso Formation, a carbonate sedimentary unit, the Castro Vicente limestones (Pereira et al. 2006a, b), has an ambiguous stratigraphic position, pending for a better understanding of the geological structure. Meanwhile, it can be correlated to the Upper Ordovician limestones locally described at several localities of the nearby autochthonous Central Iberian Zone (Santo Adrião in Trás-os-Montes, Sá et al. 2005; and La Aquiana in the Truchas Syncline, Martínez Catalán et al. 1992). The Peso Formation volcanics include calc-alkaline rhyolites and rhyodacites, tholeiitic E-MORB basalts, and alkaline OIB basalts with locally associated plagiogranite dykes (Dias da Silva et al. 2016). Two ages of ~455 Ma were obtained in calc-alkaline rhyolites lying above the Algoso Formation (Dias da Silva et al. 2016). Together with new preliminary magmatic ages of 461 and 474 Ma found in similar rocks to the W of the Morais Complex (Dias da Silva et al. 2017), U–Pb dating confirms a Middle-Upper Ordovician age for the Peso Formation.

The volcanism of this unit shows an alkaline increase of the basaltic end-members in comparison with the Furongian Mora Volcanics. This may be an evidence of a second lithospheric stretching event as response of the extensional geodynamic setting of the N-Gondwana margin at this stage (Middle-Upper Ordovician), which ultimately led to the formation of different magmatic reservoirs/sources with a wide range of geochemical compositions (calc-alkaline, tholeiitic and alkaline) that evidence mantellic and crustal origins.

Finally, a thin unit of black ampelite and lydite beds is observed. It is gently deformed and yielded fauna with a paleogeographic affinity with the autochthonous realm, the Central Iberian Zone (Piçarra et al. 2006). This Silurian black layer is overlain by the Variscan shear zones at the top of the Upper Parautochthon, and then, by the higher metamorphic grade realm of the Lower Allochthon (Maçedo de Cavaleiros Formation, Pereira et al. 2006a, b; González-Clavijo et al. 2016).

3.6.2 Discussion of the Geodynamic Significance of the Upper Parautochthon Stratigraphic Sequence

Inside the Upper Parautochthon, no evidences of unconformities have been found. Two possibilities arise, the existence of a continuous sedimentary record from the middle Cambrian to the Silurian, as in the West Asturian-Leonese Zone (Cabos Series, Pérez-Estaún et al. 1990), or the unconformities are not recognized due to the superimposed pervasive deformation. In the second option, and comparing to what is known from the autochthonous Central Iberian Zone, two major discontinuities might be hidden. The lower one is the Toledanian unconformity (in the sense of Gutiérrez-Marco et al. 2002), that should be expected at the base of the Mora or Saldanha Volcanics, as described in the nearby CIZ in Serra do Marão, São Gabriel, Eucísia and Poiares zones, according to Sá et al. (2005), Coke et al. (2001, 2011), Gomes et al. (2009), Teixeira et al. (2013) and Dias da Silva (2014). In a higher stratigraphic position, the Sardic unconformity, would be located at the base of the Castro Vicente limestone, by correlation with the Santo Adrião Upper Ordovician limestones (Sá et al. 2005), occurring in the Autochthon, close to the Morais Complex, where this unconformity has been recently mapped (Dias da Silva 2014; Dias da Silva et al. 2010, 2011).

Assuming the simplest option, that of a continuous sedimentary sequence, the Furongian-Silurian sequence of the Upper Parautochthon correlates better to the West Asturian-Leonese Zone, starting with the Cabos Series in the middle Cambrian, than with the nearer Central Iberian Zone sequence, where the bottom of the Montes Beds is located at the Cambrian-Ordovician boundary. However, the very thick stratigraphic sequence that characterizes an Ordovician trough in the former (Marcos et al. 2004) is not identified at the Upper Parautochthon. Moreover, it is difficult to explain how, during the Variscan orogeny, a slice of a more proximal continental upper crust (West Asturian-Leonese Zone) was thrust on top of the more distal crust (Central Iberian Zone). For these reasons, it looks more realistic to envisage a wide continental shelf, with the Central Iberian Zone in an inner position and the Upper Parautochthon in a contiguous more external situation.

Thus, the Upper Parautochthon sedimentary facies could be considered similar to the nearby Central Iberian Zone and, therefore, we propose that during the Ordovician both areas were parts of a shallow shelf in the Gondwana margin, evolving to a tidal or littoral environment at the Floian (Robardet 2002). During the Middle Ordovician, sedimentation has characteristics of an anoxic distal shelf (Gutiérrez-Marco et al. 2002). The Castro Vicente limestones may have formed on top of a non-identified unconformity, occupying the upthrown block of a normal fault, as proposed by Martínez Catalán et al. (1992) for the La Aquiana limestones at the Truchas region, and by Dias da Silva (2014) for the Santo Adrião Formation in NE-Portugal. Finally, the uppermost thin Silurian black unit would indicate a starved basin in a distal shelf environment.

This paleogeographic history fits that of a passive continental margin reflecting transgressions and regressions. But the abundant and long-lasting, though episodic, volcanism suggests a more complex evolution, involving extensional deformation suitable to provide channels for the outpouring of igneous rocks, some of them of mantellic derivation. Syn-sedimentary tectonic activity during the Ordovician has been proposed also in the nearby autochthonous Central Iberian Zone (Martínez Catalán et al. 1992). The calc-alkaline affinity of the volcanism in both areas is considered inherited from the melting of Cadomian arc-related basement during rifting of the N-Gondwana margin (Bea et al. 2007; Díez-Montes et al. 2010), and is not related to an island-arc setting (Dias da Silva et al. 2014, 2015).

The Upper Parautochthon tectonic slice was part of a large N Gondwana continental shelf that underwent extension during the Furongian-Silurian period allowing profuse and long term (about 50 Ma) volcanic activity. The current structural position, on top of the autochthonous and forming part of a piggy-back nappe stack (Schermerhorn and Kotsch 1984; Dallmeyer et al. 1997), suggests that it was previously placed in a relatively distal position of the margin relative to the Central Iberian Zone. This extensional process is being related to the rifting/drifting of Gondwana resulting in the detachment of a ribbon continent including a magmatic arc, the Upper Allochthon (see Chap. 4 in this volume), produced by back-arc (hyper) extension, preserved in the Lower Allochthon (see Chaps. 2 and 4) and resulting in the formation of an intermediate ocean, partially preserved in the Middle Allochthon (Chap. 4 in this volume; Dias da Silva et al. 2014, 2016).

References

Abalos B (1990) Cinemática y mecanismos de la deformación en régimen de transpresión. Evolución estructural y metamórfica de la Zona de Cizalla Dúctil de Badajoz-Córdoba. PhD Thesis, University of the Vasque Country.

Álvaro JJ, Bellido F, Gasquet D, Pereira F, Quesada C Sánchez-García T (2014) Diachronism of late Neoproterozoic-Cambrian arc-rift transition of North Gondwana: a comparison of Morocco and the Iberian Ossa-Morena Zone. Journal of African Earth Sciences 98:113–132.

Álvaro JJ, Casas JM, Clausen S, Quesada C (2018) Early Palaeozoic geodynamics in NW Gondwana. Jour Iberian Geol 44 (4): 551–565.

Álvaro JJ, Colmenar J, Monceret E, Pouclet A, Vizcaïno D (2016) Late Ordovician (post-Sardic) rifting branches in the North Gondwanan Montagne Noire and Mouthoumet massifs of southern France, Tectonophysics 681, 111–123.

Ancochea E, Arenas R, Brandle JL, Peinado M, Sagredo J (1988) Caracterización de las rocas metavolcánicas silúricas del NO del Macizo Ibérico. Geociências, Aveiro, 3: 23–34.

Aramburu C, Méndez-Bedia I, Arbizu M, García-López S (2004) Zona Cantábrica. La secuencia preorogénica, in Geología de España (Vera JA, ed), IGME-Sociedad Geológica de España, 27–34, Madrid.

Araújo A, Piçarra Almeida J, Borrego J, Pedro J, Oliveira JT (2013) As regiões central e sul da Zona de Ossa-Morena, in Geologia de Portugal—volume I (Dias, R, Araújo A, Terrinha, P, Kullberg JC, eds), Escolar Editora, 509–549, Lisboa.

Arenas R, Díez Fernández R, Rubio Pascual FJ, Sánchez Martínez S, Martín Parra LM, Matas J, González del Tánago J, Jiménez-Díaz A, Fuenlabrada JM, Andonaegui P, García-Casco A (2016) The Galicia-Ossa-Morena Zone: Proposal for a new zone of the Iberian Massif. Variscan implications, Tectonophysics 681, 135–145.

Bea F, Montero P, González-Lodeiro F, Talavera C (2007) Zircon Inheritance Reveals Exceptionally Fast Crustal Magma Generation Processes in Central Iberia during the Cambro-Ordovician. Journal of Petrology 48:2327–2339. https://doi.org/10.1093/petrology/egm061.

Bea F, Montero P, Talavera C, Abu Anbar M, Scarrow JH, Molina JF, Moreno JA (2010) The palaeogeographic position of Central Iberia in Gondwana during the Ordovician: evidence from zircon chronology and Nd isotopes, Terra Nova 22, 341–346.

Bernárdez E, Colmenar J, Gutiérrez-Marco JC, Rábano I, Zamora S (2014) New peri-Gondwanan records of the Hirnantia Fauna in the latest Ordovician of Spain, in Gondwana 15 North meets South, Abstracts Book (Pankhurst RJ, Castiñeiras P, Sánchez Martínez S, eds), Instituto Geológico y Minero de España, 15, Madrid.

Bergström SM, Chen X, Gutiérrez-Marco JC, Dronov AV (2009) The new chronostratigraphic classification of the Ordovician System and its relations to major regional series and stages and $\delta^{13}C$ chemostratigraphy, Lethaia 42, 97–107.

Brenchley PJ, Romano M, Gutiérrez-Marco JC (1986) Proximal and distal Hummocky cross-stratified facies on a wide Ordovician Shelf in Iberia, in Shelf Sands and Sandstones (Knight RJ, McLean JR, eds), Canadian Society of Petroleum Geologists Memoir 11, 241–255, Calgary.

Carls P, Gozalo R, Valenzuela-Ríos J.I., Truyols-Massoni, M (2004) La sedimentación marina devónico-carbonífera, Cordilleras Ibérica y Costero-Catalana, in Geología de España (Vera JA, ed), Sociedad Geológica de España, Instituto Geológico y Minero de España, 475–479, Madrid.

Cocks LRM, Fortey RA (1990) Biogeography of Ordovician and Silurian faunas, in Palaeozoic Palaeogeography and Biogeography (McKerrow WS, Scotese CR, eds), Geological Society Memoir 12, 97–104, London.

Coke C, Pires CAC, Sá A, Ribeiro A (2001) O Vulcanismo na transição Câmbrico/Ordovícico da Zona Centro-Ibérica na região de Trás-os-Montes (NE Portugal) como elemento de referência estratigráfica. Cuadernos Xeolóxicos de Laxe 26:121–136.

Coke C, Teixeira RJS, Gomes MEP, Corfú F, Rubio Ordoñéz A (2011) Early Ordovician volcanism in Eucísia and Mateus areas, Central Iberian Zone, northern Portugal. Mineralogical Magazine 75 (3):685.

Colmenar J, Pereira S, Young TP, da Silva CM, Sa AA (2019) First report of Hirnantian (Upper Ordovician) high-latitude peri-gondwanan macrofossil assemblages from Portugal. Journal of Paleontology, in press, https://doi.org/10.1017/jpa.2018.88.

Colmenero JR, Fernández LP, Moreno C, Bahamonde JR, Barba P, Heredia N, González F (2002) Carboniferous, Chapter 7 in The Geology of Spain (Gibbons W, Moreno MT, eds), The Geological Society, 93–116, London.

Cózar P, Rodríguez S (1999) Propuesta de nueva nomenclatura para las unidades del Carbonífero Inferior del sector Norte del área del Guadiato (Córdoba). Boletín Geológico y Minero 110:237–254.

Cózar P, Somerville ID, Rodríguez S, Mas R, Medina-Varea P (2006) Development of a late Viséan (Mississippian) mixed carbonate/siliciclastic platform in the Guadalmellato Valley (southwestern Spain), Sedimentary Geology 183, 269–295.

Dallmeyer RD, Martínez Catalán JR, Arenas R, Gil Ibarguchi JI, Gutiérrez-Alonso G, Farias P, Aller J, Bastida F (1997) Diachronous Variscan tectonothermal activity in the NW Iberian Massif: Evidence from $^{40}Ar/^{39}Ar$ dating of regional fabrics. Tectonophysics 277:307–337. https://doi.org/10.1016/s0040-1951(97)00035-8.

Dias da Silva Í (2014) Geología de las Zonas Centro Ibérica y Galicia—Trás-os-Montes en la parte oriental del Complejo de Morais, Portugal/España, vol 45. Serie Nova Terra, vol 45. Instituto Universitario de Geología "Isidro Parga Pondal"—Área de Xeoloxía e Minería do Seminario de Estudos Galegos, Coruña.

Dias da Silva Í, González Clavijo E, Barba P, Valladares MI, Ugidos JM (2011) Geochemistry of Lower Palaeozoic shales. A case study in a sector of the Iberian Variscides. In: Gutiérrez Marco JC, Rábano I, García-Bellido D (eds), 11th International Symposium on the Ordovician System, Alcalá de Henares, 2011. Instituto Geológico y Minero de España, pp 121–125.

Dias da Silva Í, González Clavijo E, Martínez Catalán JR Evolução tectono-térmica de um sector da Zona Centro Ibérica na região do Palaçoulo (leste do Maciço de Morais, NE Portugal). In: Brilha J, Pamplona J, Valente T (eds) VIII Congresso Nacional de Geología, Braga, 2010. vol 14. e-Terra, pp 1–4.

Dias da Silva Í, Valverde-Vaquero P, González-Clavijo E, Díez-Montes A, Martínez Catalán JR (2014) Structural and stratigraphical significance of U–Pb ages from the Mora and Saldanha volcanic complexes (NE Portugal, Iberian Variscides). Geological Society, London, Special Publications 405:115–135. https://doi.org/10.1144/sp405.3.

Dias da Silva Í, Linnemann U, Hofmann M, González-Clavijo E, Díez-Montes A, Martínez Catalán JR (2015b) Detrital zircon and tectonostratigraphy of the Parautochthon under the Morais Complex (NE Portugal): implications for the Variscan accretionary history of the Iberian Massif. Journal of the Geological Society 172 (1):45–61. https://doi.org/10.1144/jgs2014-005.

Dias da Silva Í, Díez Fernández R, Díez-Montes A, González Clavijo E, Foster DA (2016) Magmatic evolution in the N-Gondwana margin related to the opening of the Rheic Ocean—evidence from the Upper Parautochthon of the Galicia-Trás-os-Montes Zone and from the Central Iberian Zone (NW Iberian Massif). International Journal of Earth Sciences 105 (4):1127–1151. https://doi.org/10.1007/s00531-015-1232-9.

Días da Silva I, González Clavijo E, Díez Montes A, Martínez Catalán JR, Gómez Barreiro J, Hoffman M, Gärtner A (2017) Furongian-Late Ordovician volcanism in the Upper Parautochthon of the Galicia-Tràs-os-Montes Zone (NE Portugal): Paleogeographic meaning and geodynamic setting. Géologie de la France 1:19–21.

Díez Balda MA (1986) El Complejo Esquisto-Grauváquico, las series paleozoicas y la estructura hercínica al Sur de Salamanca. Acta Salmanticensia 52: 1–162.

Díez Fernández R, Arenas R (2015) The Late Devonian Variscan suture of the Iberian Massif: A correlation of high-pressure belts in NW and SW Iberia, Tectonophysics 654, 96–100.

Díez Fernández R, Arenas R (2016) Reply to Comment on "The Late Devonian Variscan suture of the Iberian Massif: A correlation of high-pressure belts in NWand SW Iberia". Tectonophysics 670: 155–160. https://doi.org/10.1016/j.tecto.2015.11.033.

Díez-Montes A, Martínez Catalán JR, Bellido Mulas F (2010) Role of the Ollo de Sapo massive felsic volcanism of NW Iberia in the Early Ordovician dynamics of northern Gondwana. Gondwana Research 17:363–376. https://doi.org/10.1016/j.gr.2009.09.001.

Fernández LP, Bahamonde JR, Barba P, Colmenero JR, Heredia N, Rodríguez-Fernández LR, Salvador C, Sánchez de Posada LC, Villa E, Merino-Tomé O, Motis K (2004) Secuencia sinorogénica, in Geología de España (Vera JA, ed), Sociedad Geológica de España-Instituto Geológico y Minero de España, 34–41. Madrid.

Fernández-Suárez J, Gutiérrez-Alonso G, Pastor-Galán D, Hoffman M, Murphy JB, Linnemann U (2014) The Ediacaran–Early Cambrian detrital zircon record of NW Iberia: Possible sources and paleogeographic constraints: International Journal of Earth Sciences, https://doi.org/10.1007/s00531.

Fortey RA, Cocks RLM (2005) Late Ordovician global warming—The Boda event, Geology 33, 405–408.

Franke W, Cocks LRM, Torsvik TH, 2017, The Palaeozoic Variscan oceans revisited, Gondwana Research 48, 257–284.

Gabaldón V, Garrote A, Quesada C (1985) El Carbonífero Inferior del Norte de la Zona de Ossa-Morena (SW de España. CR 10th Int Carboniferous Congr, Madrid, 3:173–186.

García Alcalde JL, Carls P, Pardo Alonso MV, Sanz López J, Soto F, Truyols-Massoni M, Valenzuela-Ríos JL (2002) Devonian, Chapter 6 in The Geology of Spain (Gibbons W, Moreno T, eds), The Geological Society, 67–91, London.

Ghienne J-F, Le Heron DP, Moreau J, Denis M, Deynoux M (2007) The Late Ordovician glacial sedimentary system of the North Gondwana platform, in Glacial sedimentary processes and products (Hambrey MJ, Christoffersen P, Glasser NF, Hubbard B, eds), International Association of Sedimentologists, Special Publication 39, 295–319, Blackwell Publising, Oxford.

Gomes M, Coke C, Teixeira R, Azevedo M, Corfu F (2009) New insights in the Early Ordovician magmatism from the Marão anticline, Northern Portugal. Goldschmidt Conference Abstracts 2009, A450.

González-Clavijo EJ (2006) La geología del sinforme de Alcañices, Oeste de Zamora, Ediciós do Castro, Serie Nova Terra 31, 238 pp, A Coruña.

González-Clavijo E, Dias da Silva ÍF, Gutiérrez-Alonso G, Díez Montes A (2016) U/Pb age of a large dacitic block locked in an Early Carboniferous synorogenic mélange in the Parautochthon of NW Iberia: New insights on the structure/sedimentation Variscan interplay. Tectonophysics 681:159–169. https://doi.org/10.1016/j.tecto.2016.01.001.

Gourvennec R, Plusquellec Y, Pereiza Z, Piçarra JM, Le Menn, J, Robardet M, Oliveira JT (2008) A reassessment of the Lochkovian (Lower Devonian) benthic faunas and palynomorphs from the Dornes region (Southern Central Iberian Zone, Portugal). Comunicaçoes do Instituto Geológico e Mineiro 95, 5–25.

Gutiérrez-Alonso G, Murphy JB, Fernández-Suárez J, Hamilton MA (2008) Geocronología de las rocas volcánicas de El Castillo (Salamanca, Zona Centroibérica). Geogaceta 44: 3–6.

Gutiérrez-Alonso G, Gutiérrez-Marco JC, Fernández-Suárez J, Bernárdez E, Corfu F (2016) Was there a super-eruption on the Gondwanan coast 477 My ago? Tectonophysics 681, 85–94.

Gutiérrez-Marco JC, Bernárdez E (2003) Un tesoro geológico en la Autovía del Cantábrico. El Túnel Ordovícico del Fabar, Ribadesella (Asturias), Libro-catálogo de la Exposición, Ministerio de Fomento, 398 pp, Madrid.

Gutiérrez-Marco JC, Lenz AC, Robardet M, Piçarra JM (1996) Wenlock-Ludlow graptolite biostratigraphy and extinction: a reassessment from the southwestern Iberian Peninsula (Spain and Portugal), Canadian Journal of Earth Sciences 33, 656–663.

Gutiérrez-Marco JC, Robardet M, Piçarra JM (1998) Silurian Stratigraphy and Paleogeography of the Iberian Peninsula (Spain and Portugal), Temas Geológico-Mineros ITGE 23, 13–44.

Gutiérrez-Marco JC, Aramburu C, Arbizu M, Bernárdez E, Hacar Rodríguez MP, Méndez-Bedia I, Montesinos López R, Rábano I, Truyols J, Villas E (1999) Revisión bioestratigráfica de las pizarras del Ordovícico Medio en el noroeste de España (Zonas Cantábrica, Asturoccidental-leonesa y Centroibérica septentrional), Acta Geologica Hispanica 34, 3–87.

Gutiérrez-Marco JC, Sarmiento GN, Robardet M, Rábano I, Vanek J (2001) Upper Silurian fossils of Bohemian type from NW Spain and their palaeogeographical interest, Journal of the Czech Geological Society 46, 247–258.

Gutiérrez-Marco JC, Robardet M, Rábano I, Sarmiento GN, San José Lancha MA, Herranz Araújo P, Pieren Pidal AP (2002) Ordovician. Chapter 4 in The Geology of Spain (Gibbons W, Moreno T, eds), The Geological Society, 31–49, London.

Gutiérrez-Marco JC, Sá AA, García-Bellido DC, Rábano I, Valério M (2009) Giant trilobites and trilobite clusters from the Ordovician of Portugal, Geology 37, 443–446.

Gutiérrez-Marco JC, Ghienne J-F, Bernárdez E, Hacar MP (2010) Did the Late Ordovician African ice sheet reach Europe?, Geology 38, 279–282.

Gutiérrez-Marco JC, Sá AA, García-Bellido DC, Rábano I (2014a) The extent of the Middle Ordovician Dapingian Stage in peri-Gondwanan Europe and North Africa. Stratigraphic record, biostratigraphic tools, and regional chronostratigraphy, GFF 136, 90–94.

Gutiérrez-Marco JC, Sarmiento GN, Rábano I (2014b) Un olistostroma con cantos y bloques del Paleozoico Inferior en la cuenca carbonífera del Guadalmellato (Córdoba). Parte 2: Bioestratigrafía y afinidades paleogeográficas, Revista de la Sociedad Geológica de España 27, 25–43.

Gutiérrez-Marco JC, Sá AA, Rábano I, Sarmiento GN, García-Bellido DC, Bernárdez E, Lorenzo S, Villas E, Jiménez-Sánchez A, Colmenar J, Zamora S (2015) Iberian Ordovician and its international correlation, Stratigraphy 12, 257–263.

Gutiérrez-Marco JC, Lorenzo S, Rábano I, Sarmiento GN, Carlorosi J (2016) Fósiles ordovícicos del Dominio de Obejo-Valsequillo (Complejo de Ossa Morena, Zona Galicia-Ossa Morena), suroeste de España, Geotemas 16, 211–214.

Gutiérrez-Marco JC, Sá AA, García-Bellido DC, Rábano I (2017) The Bohemo-Iberian regional chronostratigraphic scale for the Ordovician System and palaeontological correlations within South Gondwana, Lethaia 50, 258–295.

Hall, C.M., Higueras, P., Kesler, S., Lunar, R., Dong, H., Halliday, A.N., 1997. Dating of alteration episodes related to mercury mineralization in the Almadén district, Spain. Earth Planet Sci Lett 148: 287–298.

Hammann W (1992) The Ordovician trilobites from the Iberian Chains in the province of Aragón, NE-Spain. I. The trilobites of the Cystoid Limestone (Ashgill Series), Beringeria 6, 3–219.

Hammann W, Henry J-L (1978) Quelques espèces de *Calymenella*, *Eohomalonotus* et *Kerfornella* (Trilobita, Ptychopariida) de l'Ordovicien du Massif Armoricain et de la Péninsule Ibérique, Senckenbergiana lethaea 59, 401–429.

Helo C, Longpré MA, Shimuzi N, Clague DA, Stix J (2011) Explosive eruptions at mid-ocean ridges driven by CO2-rich magmas. Nature Geosci 4: 260–263.

Henn A, Jahnke H (1984) Die palentinische Faziesentwicklung im Devon des Kantabrischen Gebirges, Zeitschrift der Deutschen Geologischen Gesellschaft 135, 131–147.

Hernández A, Jébrak M, Higueras P, Oyarzun R, Morata D, Munhá J (1999) The Almadén mercury mining district. Mineral Deposita 34: 539–548.

Herranz Araújo P (1985) El Precámbrico y su cobertera paleozoica en la región centro-oriental de la provincia de Badajoz, Seminarios de Estratigrafía, serie Monografías 10, 1342 pp.

Higueras P (1995) Procesos petrogenéticos y de alteración de las rocas magmáticas asociadas a las mineralizaciones de mercurio del distrito de Almadén. Ediciones de la Universidad de Castilla-La Mancha, Cuenca (Spain), 270 pp.

Higueras P, Mansilla L, Lorenzo S, Esbrí JM (2011) The Almadén mercury mining district. In: Ortiz JE, Puche O, Rábano I, Mazadiego LF (eds), History of Research in Mineral Resources. Cuadernos del Museo Geominero 13: 75–88.

Higueras P, Oyarzún R, Lillo J, Morata D (2013) Intraplate mafic magmatism, degasification, and deposition of mercury: The giant Almadén mercury deposit (Spain) revisited. Ore Geol Rev 51: 93–102.

Jaeger H, Robardet M (1979) Le Silurien et le Dévonien basal dans le Nord de la province de Séville (Espagne), Géobios 12, 687–714.

Jébrak M, Higueras P, Hernández A, Marcoux E (1997) Datos geoquímicos e isotópicos sobre el yacimiento de Nuevo Entredicho, Almadén, España. Bol Soc Esp Mineral 20ª: 87–88.

Leone F, Hammann W, Laske R, Serpagli E, Villas E (1991) Lithostratigraphic units and biostratigraphy of the post-sardic Ordovician sequence in south-west Sardinia. Bollettino della Società Paleontologica Italiana 30, 201–235.

Loeschke J (1983) Igneous and pyroclastic rocks in Devonian and Lower Carboniferous strata of the Cantabrian Mountains (NW Spain) Neues Jahrbuch für Geologie und Palaeontologie, Mh 8: 495–504.

Lopes G (2013) Investigação em palinologia e isótopos estáveis do Paleozoico da Zona Centro-Ibérica (Buçaco, Dornes, Mação e Portalegre) e Zona de Ossa-Morena (Toca da Moura e Barrancos), Portugal. Implicações paleogeográficas e paleoambientais, Ph.D. Thesis Universidade do Algarve, Faro, 678 pp.

Lopes G, Vaz N, Sequeira AJD, Piçarra J, Fernandes P, Pereira Z (2011) New insights on the palynostratigraphy of the Hirnantian of the Rio Ceira section, Buçaco, Portugal, Cuadernos del Museo Geominero 14, 313-319.

López Díaz F, Monteserín V, Pineda A et al. (2007) Mapa Geológico de España, escala 1:50000, sheet no. 728: Puebla de Obando. Instituto Geológico y Minero de España.

López-Guijarro, R., Quesada, C., Fernández-Suárez, J., Jeffries, T., Pin, C. (2007) Age of the rift–drift transition of the Rheic Ocean in the Ossa

Morena Zone: K-bentonite in the Early Ordovician succession at "Venta del Ciervo". The Rootless Variscan Suture of NW Iberia (Galicia, Spain). IGCP-497 Meeting. Abstracts and Programme. Publicaciones del Instituto Geológico y Minero de España, pp. 142–143.

López-Moro FJ, Murciego A, Rodríguez MA (2001) Aspectos estructurales, petrográficos y geoquímicos de los sills de rocas básicas e intermedias del área de Alburquerque-Villar del Rey-La Roca de la Sierra (Badajoz). Bol Soc Esp Mineral 24-A: 135–136.

López-Moro FJ, Murciego A, López-Plaza M (2007) Silurian/Ordovician asymmetrical sill-like bodies from La Codosera syncline, W Spain: A case of tholeiitic partial melts emplaced in a single magma pulse and derived from a metasomatized mantle source.

Lotze F (1956) Über sardischen Bewegungen im Spanien und ihre Beziehungen zur assynthischen Faltung, in Geotektonische Symposium zu Ehren von Hans Stille, 128–139, Stuttgart.

Loydell DK, Frýda J, Gutiérrez-Marco JC (2015) The Aeronian/Telychian (Llandovery, Silurian) boundary, with particular reference to sections around the El Pintado reservoir, Seville Province, Spain, Bulletin of Geosciences 90, 743–794.

Machado G, Hladil J, Koptíková L, Fonseca P, Rocha F, Galle A (2009) The Odivelas Limestone: evidence for a Middle Devonian reef system in western Ossa-Morena Zone (Portugal), Geologica Carpathica 60, 121–137.

Machado G, Hladil J, Slavik L, Koptikova L, Moreira N, Fonseca M, Fonseca P (2010) An Emsian-Eifelian carbonate-volcaniclastic sequence and the possible correlatable pattern of the Basal Chotec event in Western Ossa-Morena Zone, Portugal (Odivelas Limestone), Geologica Belgica 13, 431–446.

Marcos A (1973) Las series del Paleozoico inferior y la estructura herciniana del occidente de Asturias (NW de España), Trabajos de Geología Oviedo 6, 1–113.

Marcos A, Martínez Catalán JR, Gutiérrez Marco JC, Pérez Estaún A (2004). Zona Asturoccidental-Leonesa: Estratigrafía y paleogeografía. In: Vera JA (ed), Geología de España. IGME-SGE, Madrid, 49–52.

Martín Herrero D, Bascones Alvira L, Corretgé Castañón LG (1987) Mapa y Memoria Explicativa de la Hoja nº 650 (Cañaveral) del Mapa Geológico de España E. 1:50.000, IGME, 63 pp, Madrid.

Martín Escorza C (1976) Las "Capas de Transición", Cámbrico inferior y otras series preordovícicas (¿Cámbrico superior?) en los Montes de Toledo surorientales: sus implicaciones geotectónicas, Estudios Geológicos 32, 591–613.

Martín Parra LM, González Lodeiro F, Martínez Poyatos D, Matas J (2006) The Puente Génave-Castelo de Vide Shear Zone (southern Central Iberian Zone, Iberian Massif): geometry, kinematics and regional implications, Bulletin de la Société Géologique de France 177, 191–202.

Martínez Catalán JR, Hacar Rodríguez MP, Villar Alonso P, Pérez-Estaún A, González Lodeiro F (1992) Lower Paleozoic extensional tectonics in the limit between the West Asturian-Leonese and Central Iberian Zones of the Variscan Fold-Belt in NW Spain, Geologische Rundschau 81, 545–560.

McDougall N, Brenchley PJ, Rebelo JA, Romano M (1987) Fans and fan deltas—precursors to the Armorican Quartzite (Ordovician) in western Iberia. Geological Magazine 124, 347–359.

Meireles CAP (2013) Litoestratigrafia do Paleozóico do sector a nordeste de Bragança (Trás-os-Montes), Instituto Universitario de Geología Isidro Parga Pondal, Serie Nova Terra 42, 471 pp, A Coruña.

Nemyrovska TI (2005) Late Viséan/early Serpukhovian conodont succession from the Triollo section, Palencia (Cantabrian Mountains, Spain), Scripta Geologica 129, 13–89.

Nemyrovska TI, Wagner RH, Winkler Prins CF, Montañez I (2011) Conodont faunas across the mid-Carboniferous boundary from the Barcaliente Formation at La Lastra (Palentian Zone, Cantabrian Mountians, northwest Spain); geological setting, sedimentological characters and faunal descriptions, Scripta Geologica 143, 127–183.

Oliveira JT, Oliveira V, Piçarra JM (1991) Traços gerais da evolução tectono–estratigráfica da Zona de Ossa Morena, em Portugal: síntese crítica do estado actual dos conhecimentos, Comunicações dos Serviços Geológicos de Portugal 77, 3–26.

Oliveira JT, Relvas J, Pereira Z, Munhá J, Matos J, Barriga F, Rosa C (2013) O complexo vulcano-sedimentar de Toca da Moura—Cabrela (Zona de Ossa-Morena); evolução tectono-estratigráfica e mineralizações associadas, in Geologia de Portugal, vol. 1 (Dias R, Araújo A, Terrinha P, Kullberg J, eds), Escolar Editora, 621–645, Lisboa.

Paris F (1990) The Ordovician chitinozoan biozones of the Northern Gondwana Domain, Review of Palaeobotany and Palynology 66, 181–209.

Pereira E, Pereira DÍ, Rodrigues JF, Ribeiro A, Noronha F, Ferreira N, Sá CMd, Farinha Ramos J, Moreira A, Oliveira AF (2006a) Notícia Explicativa da Folha 2 da Carta Geológica de Portugal à Escala 1:200.000. 1 edn. Instituto Nacional de Engenharia, Tecnologia e Inovação, Lisboa.

Pereira Z, Oliveira V, Oliveira, JT (2006b) Palynostratigraphy of the Toca da Moura and Cabrela Complexes, Ossa Morena Zone, Portugal. Geodynamic implications, Review of Palaeobotany and Palynology 139, 227–240.

Pérez-Estaún A, Marcos A (1981) La Formación Agüeira en el sinclinorio de Vega de Espinareda: aproximación al modelo de sedimentación durante el Ordovícico superior en la zona Asturoccidental-leonesa (NW de España), Trabajos de Geología Oviedo 11, 135-145.

Pérez-Estaún A, Bastida F, Martínez Catalán JR, Gutiérrez-Marco JC, Marcos A, Pulgar JA (1990) West Asturian-Leonese Zone: Stratigraphy, in Pre-Mesozoic Geology of Iberia (Dallmeyer RD, Martínez García E, eds), Springer-Verlag, 92–102, Berlin-Heidelberg.

Pérez-Lorente F (1979) Geología de la Zona de Ossa-Morena al norte de Córdoba (Pozoblanco-Belmez-Villaviciosa de Córdoba), Tesis Doctorales de la Universidad de Granada 281, 1–340.

Piçarra JM (2000) Estudo estratigráfico do sector de Estremoz-Barrancos, Zona de Ossa Morena, Portugal, PhD Thesis Universidade de Évora, 2 vols, 95+173 pp.

Piçarra JM, Štorch P, Gutiérrez-Marco JC, Oliveira JT (1995) Characterization of the *Parakidograptus acuminatus* graptolite Biozone in the Silurian of the Barrancos region (Ossa Morena Zone, South Portugal), Comunicações do Instituto Geológico e Mineiro 81, 3–8.

Piçarra JM, Gutiérrez-Marco JC, Lenz AC, Robardet M (1998) Pridoli graptolites from the Iberian Peninsula: a review of previous data and new records, Canadian Journal of Earth Sciences 35, 65–75.

Piçarra JM, Le Menn J, Pereira Z, Gourvennec R, Oliveira JT, Robardet M (1999) Novos dados sobre o Devónico inferior de Barrancos (Zona de Ossa Morena, Portugal), Temas Geológico--Mineros ITGE 26, 628–631.

Piçarra JM, Gutiérrez-Marco JC, Sá AA, Meireles C, González-Clavijo E (2006) Silurian graptolite biostratigraphy of the Galicia-Tras-os-Montes Zone (Spain and Portugal). GFF/The Geological Society of Sweden Geologiske Föreningen/The Geological Society of Sweden, vol. 128, pp. 185–188.

Piçarra JM, Sarmiento GN, Gutiérrez-Marco JC (2014) Geochronological vs. Paleontological dating of the Estremoz Marbles (Ossa Morena Zone, Portugal)—new data and reappraisal, in Gondwana 15 North meets South, Abstracts Book (Pankhurst RJ, Castiñeiras P, Sánchez Martínez S, eds), Instituto Geológico y Minero de España, 140, Madrid.

Pillola GL, Piras S, Serpagli E (2008) Tremadoc–Lower Arenig? Anisograptid-Dichograptid fauna from the Cabitza Formation

(Lower Ordovician, SW Sardinia, Italy), Revue de Micropaléontologie 51, 167–181.

Quesada C (1990a) Precambrian terranes in the Iberian Variscan Foldbelt. In: Strachan RA, Taylor GK (Eds), Avalonian and Cadomian geology of the North Atlantic. Blackie, New York, 109–133.

Quesada C (1990b) Precambrian successions in SW Iberia: their relationship to "Cadomian" orogenic events. In: D'Lemos RS, Strachan RA, Topley CG (eds), The Cadomian Orogeny. Geol Soc, London, Sp Publ 51: 353–362.

Quesada C (1991) Geological constraints on the Paleozoic tectonic evolution of tectonostratigraphic terranes in the Iberian Massif, Tectonophysics 185, 225–245.

Quesada C (1997) Evolución geodinámica de la Zona Ossa Morena durante el ciclo Cadomiense. In: Araújo AA, Pereira MF (eds.), Estudo sobre a geología da zona de Ossa Morena (Maciço Ibérico). Livro homenagem Prof. Francisco Gonçalves, University of Évora, 205–230.

Quesada C (2006) The Ossa-Morena zone of the Iberian Massif: a tectonostratigraphic approach to its evolution. Z Deuts Gesell Geowiss 157: 585–595.

Rábano I (1989) Trilobites del Ordovícico Medio del sector meridional de la Zona centroibérica española. Parte 1, Boletín Geológico y Minero 100, 307–338.

Rigby JK, Gutiérrez-Marco JC, Robardet M, Piçarra JM (1997) First articulated Silurian sponges from the Iberian Peninsula, Spain and Portugal, Journal of Paleontology 71, 554–563.

Robardet M (2002) Alternative approach to the Variscan Belt in southwestern Europe: Preorogenic palaeobiogeographical constraints, in Variscan-Appalachian dynamics: The building of the late Paleozoic basement (Martínez Catalán JR, Hatcher RD Jr, Arenas R, Díaz-Gacía F, eds), Geological Society of America Special Paper 364, 1–15, Boulder, Colorado.

Robardet M, Gutiérrez-Marco JC (1990) Sedimentary and faunal domains in the Iberian Peninsula during Lower Paleozoic times, in Pre-Mesozoic Geology of Iberia (Dallmeyer RD, Martínez García E, eds), Springer-Verlag, 383–395, Berlin-Heidelberg.

Robardet M, Gutiérrez-Marco JC (2002) Silurian, Chapter 5 in The Geology of Spain (Gibbons W, Moreno T, eds), The Geological Society, 51–66, London.

Robardet M, Gutiérrez-Marco JC (2004) The Ordovician, Silurian and Devonian sedimentary rocks of the Ossa Morena Zone (SW Iberian Peninsula, Spain), Journal of Iberian Geology 30, 73–92.

Robardet M, Weyant M, Laveine JP, Racheboeuf P (1986) Le Carbonifère inférieur du synclinal du Cerrón del Hornillo (Province de Séville, Espagne). Révue de Paléobiologie 5/1:71–90.

Robardet M, Weyant M, Brice D, Racheboeuf P (1988) Dévonien supérieur et Carbonifère inférieur dans le nord de la province de Séville (Espagne).Âge et importance de la première phase hercynienne dans la zone d'Ossa-Morena. CR Acad Sci Paris, Série II, 307:1091–1095.

Rodríguez S (ed) (1992) Análisis Paleontológico y Sedimentológico de la cuenca carbonífera de Los Santos de Maimona (Badajoz), Coloquios de Paleontología 44, 1–232.

Rodríguez S, Fernández-Martínez E, Cózar P, Valenzuela-Ríos JI, Pardo Alonso MV (2010) Stratigraphic succession, facies and depositional environment of Emsian reefal carbonates in the Ossa-Morena Zone (SW Spain), Neues Jahrbuch für Geologie und Paläontologie Abhandlungen 257, 69–83.

Rodríguez González R, Medina Varea P, González Lodeiro F, Martín Parra LM, Martínez Poyatos D, Matas J (2007) Microflora y conodontos del Mississippiense en la Fm Gévora (núcleo del Sinforme La Codosera-Puebla de Obando, SO de la Zona Centroibérica), Revista de la Sociedad Geológica de España 20, 71–88.

Rodríguez Pevida LS, Mira López M, Ortega Gironés E (1990) Mapa Geológico de España, 1:50.000: Hinojosa del Duque 833, 15–33, Instituto Geológico y Minero de España, 1-56, Madrid.

Rubio-Ordóñez A, Valverde-Vaquero P, Corretgé LG, Cuesta-Fernández A, Gallastegui G, Fernández-González M, Gerdes A (2012) An Early Ordovician tonalitic-granodioritic belt along the Schistose-Greywacke Domain of the Central Iberian Zone (Iberian Massif, Variscan Belt), Geological Magazine 149, 927–939.

Sá AA, Meireles CA, Coke C, Gutiérrez-Marco JC (2005) Unidades litoestratigráficas do Ordovícico da região de Trás-os-Montes (Zona Centro-Ibérica, Portugal), Comunicações Geológicas 92, 31–73.

Sá AA, Meireles CA, Gutiérrez-Marco JC, Coke C (2006) A sucessão de Ordovícico Superior de Trás-os-Montes (Zona Centro-Ibérica, Portugal) e sua correlação com Valongo e Buçaco, in Resumos alargados VII Congresso Nacional de Geologia (Mirão J, Balbino A, coords) 2, 621–624, Évora.

Sá AA, Gutiérrez-Marco JC, Piçarra, JM, García-Bellido DC, Vaz N, Aceñolaza GF (2011) Ordovician vs. "Cambrian" ichnofossils in the Armorican Quartzite of central Portugal, IGME, Cuadernos del Museo Geominero 14, 483–492.

Sá AA, Gutiérrez-Marco JC, Meireles CA, García-Bellido D, Rábano I (2014) A revised correlation of Lower Ordovician sedimentary rocks in the Central Iberian Zone (Portugal and Spain), in Strati 2013, at the cutting edge of Stratigraphy (Rocha RB, Pais J, Kulberg C, Finney S, eds), Springer Geology Series, 441–446, New York.

San José MA de (2006) The kernel of the Iberian block, Zeitschrift der Deutschen Gesellschaft für Geowissenschaften 157, 529–550.

Santos JA, Apalategui O, Carvajal A et al. (2003) Mapa Geológico de España, escala 1:50000, sheet no. 751: Villar del Rey. Instituto Geológico y Minero de España.

Sanz-López J, Blanco-Ferrera S (2012) Revisión estratigráfica del Misisipiense al Pensilvaniense más bajo de la zona Cantábrica y la posición de los límites entre los pisos, Geo-Temas 13, 90 (CD annex to Geotemas 13, 163–166).

Sanz-López J, Blanco-Ferrera S, Sánchez de Posada LC (2013) Conodont chronostratigraphic resolution and *Declinognathodus* evolution close to the Mid-Carboniferous Boundary in the Barcaliente Formation type section (NW Spain), Lethaia 46, 438–453.

Sanz-López J, Cózar P, Blanco-Ferrera S (2018) Discovery of a Mississippian–early Bashkirian carbonate platform coeval with condensed cephalopod limestone sedimentation in NW Spain, Geological Journal 53:2532–2557.

Sarmiento GN, Piçarra JM, Rebelo JA, Robardet M, Gutiérrez-Marco JC, Štorch P, Rábano I (1999) Le Silurien du synclinorium de Moncorvo (NE du Portugal): biostratigraphie et importance paléógéographique. Geobios 32:749–767.

Saupé F (1990) The geology of the Almadén mercury deposit. Econ Geol 85: 482–510.

Schemm-Gregory M, Piçarra J (2013) *Astraelenia saomamedensis* n. sp.—a new gigantic rhynchonellid species and its palaeobiogeographical implications for the Portalegre syncline (Central Portugal), Rivista Italiana di Paleontologia e Stratigrafia 119, 247–256.

Schermerhorn LJG, Kotsch S (1984) First occurrence of lawsonite in Portugal and tectonic implications. Comunicações do Instituto Geológico e Mineiro 70 (1):23–29.

Simancas JF, Martínez Poyatos DJ, 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 JF, Carbonell R, González Lodeiro F, Pérez-Estaún A, Juhlin C, Ayarza P, Kashubin A, Azor A, Martínez Poyatos D, Almodóvar GR, Pascual E, Sáez R, Expósito I (2003) The crustal structure of the transpressionalVariscan Orogen of SW Iberia:

The IBERSEIS deep seismic reflection profile. Tectonics 22(6), 1062. https://doi.org/10.1029/2002tc001479.

Simancas JF, Tahiri A, Azor A, González Lodeiro F, Martínez Poyatos D, El Hadi H (2005) The tectonic frame of the Variscan-Alleghanian Orogen in Southern Europe and Northern Africa. Tectonophysics 398:181–198. https://doi.org/10.1016/j.tecto.2005.02.006.

Simancas JF, Carbonell R, González Lodeiro F, Pérez Estaún A, Juhlin C, Ayarza P, Kashubin A, Azor A, Martínez Poyatos D, Sáez R, Almodóvar GR, Pascual E, Flecha I, Martí D (2006) Transpressional collision tectonics and mantle plume dynamics: the Variscides of southwestern Iberia. In: Gee DG, Stephenson RA (eds), European Lithosphere Dynamics. Geological Society, London, Memoirs 32:345–354.

Soldevila Bartolí J (1992) La sucesión paleozoica en el sinforme de la Sierra de San Pedro (provincias de Cáceres y Badajoz, SO de España), Estudios Geológicos 48, 363–379.

Stampfli GM, von Raumer JF, Borel GD (2002) Paleozoic evolution of pre-Variscan terranes: from Gondwana to the Variscan collision, in Variscan-Appalachian dynamics: the building of the Late Paleozoic basement (Martínez Catalán JR, Hatcher RD, Arenas R, Díaz García F, eds), Geological Society of America Special Paper 364, 263–280.

Talavera C, Montero P, Martínez Poyatos D, Williams IS (2012) Ediacaran to Lower Ordovician age for rocks adscribed to the Schist-Graywacke Complex (Iberian Massif, Spain): Evidence from detrital zircon SHRIMP U-Pb geochronology, Gondwana Research 22, 928–942.

Talavera C, Montero P, Bea F, González Lodeiro F, Whitehouse M (2013) U-Pb Zircon geochronology of the Cambro-Ordovician metagranites and metavolcanic rocks of central and NW Iberia, International Journal of Earth Sciences 102, 1–23.

Teixeira RJS, Coke C, Gomes MEP, Corfu F, Dias R (2013) ID-TIMS U-Pb ages of Tremadocian-Floian ash fall tuff beds from Marão and Eucísia areas, Northern Portugal. In: William Smith Meeting 2013, London. Geological Society of London, pp 152–154.

Torsvik TH, Cocks LRM (2013) New global palaeogeographical reconstructions for the Early Palaeozoic and their generation, in Early Palaeozoic Biogeography and Palaeogeography (Harper DAT, Servais T, eds), Geological Society Memoirs 38, 5–24, London.

Torsvik TH, Cocks LRM (2017) Earth History and Palaeogeography, Cambridge University Press, 317 pp, Cambridge.

Toyos JM, Aramburu C (2014) El Ordovícico en el área de Los Barrios de Luna, Cordillera Cantábrica (NW de España), Trabajos de Geología 34, 61–96.

Vaz N (2010) Palinoestratigrafia da sequencia Ordovicico-Silúrica do Sinclinal Amêndoa-Mação, Ph.D. Thesis Universidade de trás-os--Montes e Alto Douro, Vila Real, 159 pp.

Videt B, Paris F, Rubino JL, Boumendjel K, Dabard MP, Loi A, Ghienne JF, Marante A, Gorini A (2010) Biostratigraphical calibration of third order Ordovician sequences on the northern Gondwana platform, Palaeogeography, Palaeoclimatology, Palaeoecology 296, 359–375.

Villaseca C, Merino Martínez E, Orejana D, Andersen T, Belousova E (2016) Zircon Hf signatures from granitic orthogneisses of the Spanish Central System: Significance and sources of the Cambro-Ordovician magmatism in the Iberian Variscan Belt. Gondwana Research 34, 60–83.

Wolf R (1980) The lower and upper boundary of the Ordovician System of some solected regions (Celtiberia, Eastern Sierra Morena) in Spain. Part I: The Lower Ordovician sequence of Celtiberia, Neues Jahrbuch für Geologie und Paläontologie Abhandlungen 160, 118–137.

Young TP (1989) Eustatically controlled ooidal ironstone deposition: facies relationships of the Ordovician open-shelf ironstones of Western Europe, in Phanerozoic Ironstones (Young TP, Taylor WEG, eds), Geological Society Special Publication 46, 51–63.

Young TP (1992) Ooidal ironstones from Ordovician Gondwana: a review, Palaeogeography, Palaeoclimatology, Palaeoecology 99, 321–347.