Rheic Ocean ophiolitic remnants in southern Iberia questioned by SHRIMP U-Pb zircon ages on the Beja-Acebuches amphibolites

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[1] The Rheic Ocean was a major oceanic domain between Avalonia and Gondwana in Ordovician-Silurian times. Most of the Paleozoic plate reconstructions assume that the Rheic Ocean suture lies within southern Iberia, coinciding with the contact between the South Portuguese Zone and the Ossa-Morena Zone. This paper reports four Sensitive High Resolution Ion Micro-Probe (SHRIMP) U-Pb zircon ages from mid-ocean ridge basalt (MORB)-featured rocks of the Beja-Acebuches Amphibolite unit, which crops out along the boundary between the Ossa-Morena and the South Portuguese Zone, and is considered its most conspicuous suture unit. The obtained ages range from 332 ± 3 to 340 ± 4 Ma, corresponding to the crystallization of the mafic protoliths. These Early Carboniferous ages for the Beja-Acebuches amphibolites imply that this unit can no longer be viewed as an ophiolite belonging to the Rheic Ocean suture, since this oceanic domain was presumably closed in Devonian times. Tectonic reconstructions joining in a single suture line the Beja-Acebuches Amphibolite unit in southern Iberia to either the Devonian Lizard ophiolite in southern England or the root zone of the Devonian/Ordovician ophiolitic units in northwest Iberia must be therefore reconsidered because of the age difference. We interpret the Beja-Acebuches Amphibolite unit to represent a narrow and very ephemeral realm of oceanic-like crust that opened in Early Carboniferous times, after total consumption of the Rheic Ocean. We suggest that a mantle plume underneath southern Iberia in Early Carboniferous times is the most plausible large-scale geodynamic scenario for the formation of these MORB-featured rocks. **Citation:** Azor, A., D. Rubatto, J. F. Simancas, F. González Lodeiro, D. Martínez Poyatos, L. M. Martín Parra, and J. Matas (2008), Rheic Ocean ophiolitic remnants in southern Iberia questioned by SHRIMP U-Pb zircon ages on the Beja-Acebuches amphibolites, *Tectonics*, *27*, TC5006, doi:10.1029/2008TC002306.

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1. Introduction

[2] Remnants of oceanic lithosphere, namely, ophiolites, obducted and welded in between continental lithosphere during collision can be preserved within mountain belts, marking preexisting oceanic domains as suture zones. Thus, identification and characterization of ophiolitic units is one of the main targets of studies focused on the tectonic evolution of orogens. In fact, plate tectonic reconstructions, particularly for pre-Mesozoic times, are primarily based on the suture lines recognizable within mountain belts. Nevertheless, recognizing suture zones in orogens is not a simple task, because ophiolites may be missing or may be highly dismembered. This makes it difficult to distinguish different oceanic realms, from true oceans to ephemeral basins. The Late Paleozoic Variscan-Alleghanian Orogen (Figure 1a) is an example of region where the origin of ophiolitic remnants remains unclear, thus emphasizing the need for multisource data (paleomagnetic, paleontological/stratigraphical, structural/tectonometamorphic and geochronological/geophysical) to evaluate conflicting paleogeographic models.

[3] There are substantial controversies and uncertainties concerning the timing, location, extent and continuity of oceanic domains sutured along the vast Variscan-Alleghanian Orogen [e.g., *Tait et al.*, 2000; *Matte*, 2001; *Nysæther et al.*, 2002; *Linnemann et al.*, 2004]. This orogen appears as dispersed outcrops in western Europe, northwest Africa and northeast America (Figure 1a). Despite uncertainties regarding its evolution, some general aspects of the kinematics of continental blocks from Early to Late Paleozoic times leading to the Variscan-Alleghanian orogeny are well established. In a simplistic way, the Carboniferous Variscan-Alleghanian collision was preceded by the following plate dispersal and accretion episodes [e.g., *Matte*, 2001]: (1) Cambrian to Ordovician rifting along the northern Gondwana margin formed Avalonia as a separate microplate and a number of peri-Gondwana terranes [*Cocks and Torsvik*, 2006], usually grouped under the term Armorica microplate; (2) Rheic Ocean formation in Ordovician-Silurian times between the drifting Avalonia and Armorica (Figure 1b); and (3) consumption of the Rheic Ocean in Devonian time and initial collision of Gondwana, Gondwana-related terranes (Armorica) and Avalonia in Devonian–Early Carboniferous times.

[4] Most of the paleotectonic reconstructions available assume the Rheic Ocean suture to crop out in southern

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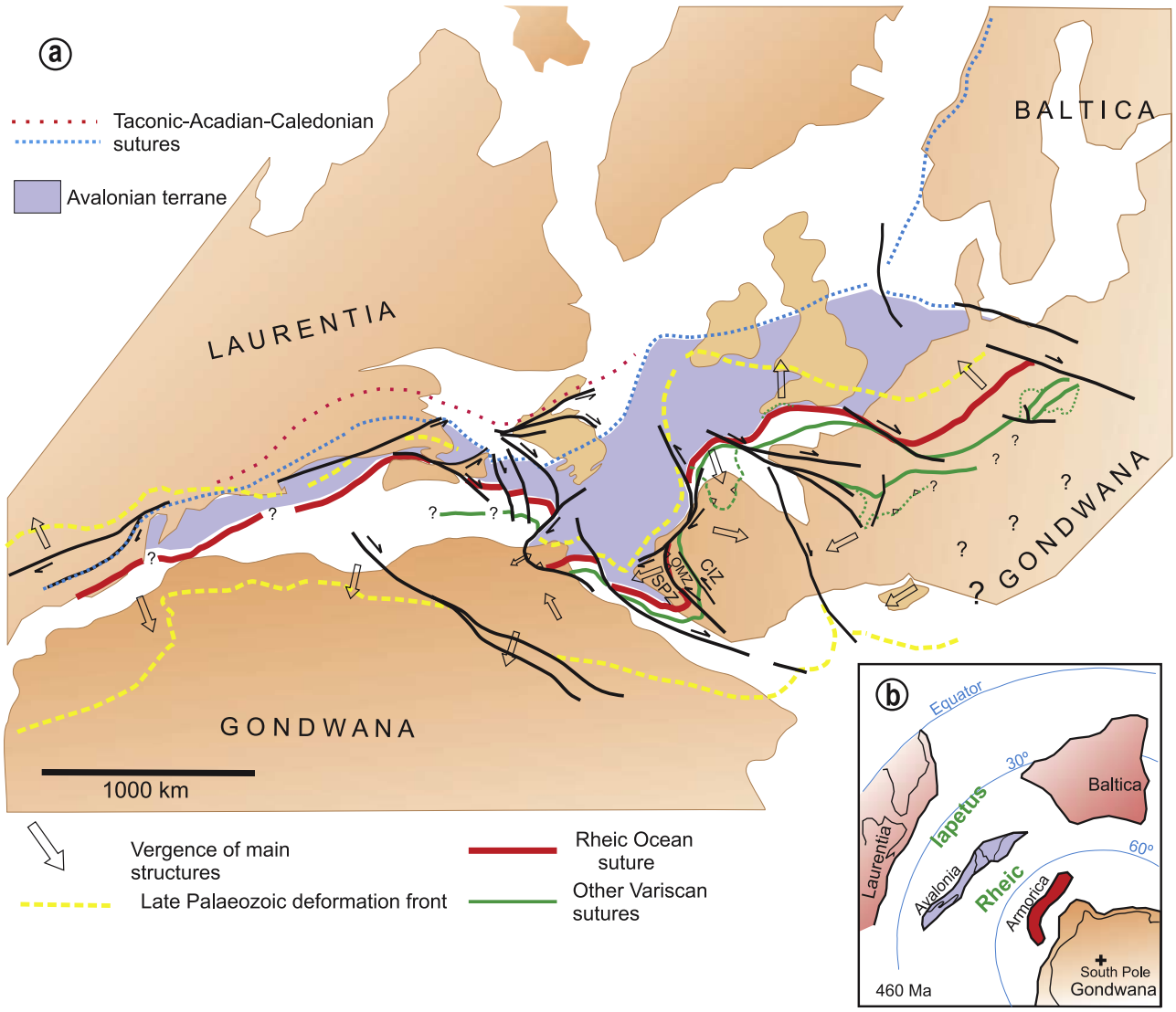

Figure 1. (a) Late Carboniferous reconstruction of the Variscan-Alleghanian Orogenic Belt (slightly modified from *Simancas et al.* [2005, and references therein]). The inferred positions of the Rheic Ocean suture and other Variscan second-order sutures have been depicted. CIZ, Central Iberian Zone; OMZ, Ossa-Morena Zone; SPZ, South Portuguese Zone. (b) Middle Ordovician paleogeographic reconstruction of Gondwana, Gondwana-related terranes (Armorica), Avalonia, Baltica, and Laurentia with the oceanic domains open in between (slightly modified from *Nysæther et al.* [2002]).

Iberia, coinciding with the contact between the South Portuguese Zone (SPZ) and the Ossa-Morena Zone (OMZ) [e.g., *Matte*, 2001] (Figures 1a and 2). This paper aims to refine the meaning and time correlation of Variscan suture contacts in southern Iberia. We present the first U-Pb ion microprobe ages on zircons from mafic rocks generally attributed to the Rheic Ocean suture. Our results point to a new interpretation for these rocks, which questions essential aspects of the paleotectonic reconstructions available.

2. Geological Setting

[5] The Iberian Massif (Figure 2a) in western Europe constitutes the largest and by far the most representative outcrop in the Variscan Orogen, with several suture-related units, some of them containing rocks with oceanic affinity [e.g., *Martínez Catalán et al.*, 1997; *Matte*, 2001; *Araújo et al.*, 2005; *Simancas et al.*, 2005; *Pin et al.*, 2006]. Variscan Iberia has been classically divided into two transects: (1) a northern one consisting of an east vergent orogenic wedge developed on the paleopassive margin of Gondwana, which is overthrust to the west by a pile of allocthonous tectonic units, some of them with high-pressure metamorphism and/or ophiolitic rocks [e.g., *Pérez-Estaún et al.*, 1991; *Arenas et al.*, 2007a]; and (2) a southern one with a predominant southwest vergence [e.g., *Simancas et al.*, 2001], which includes three continental blocks (SPZ, OMZ, and Central

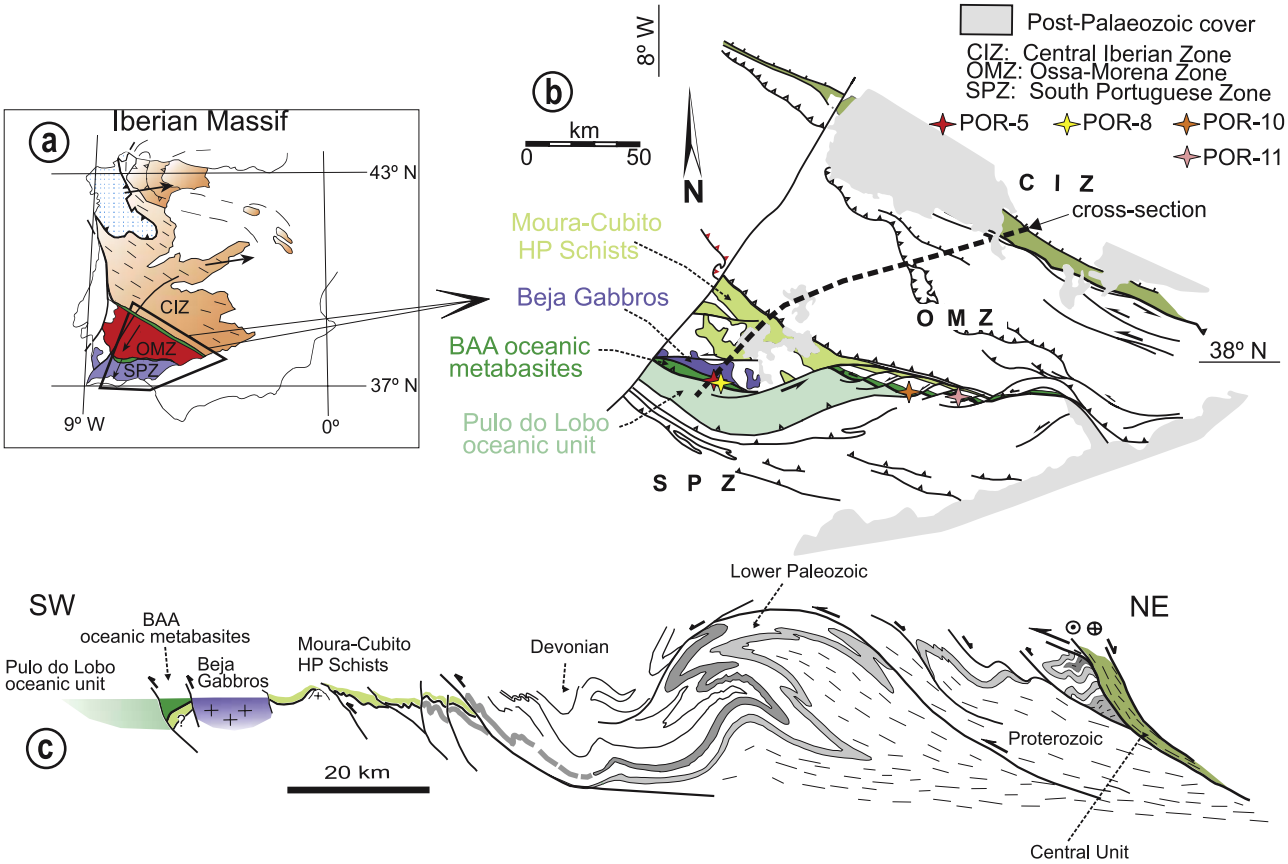

Figure 2. (a) Variscan tectonic zones in the Iberian Massif with location of putative suture-related units in southern Iberia (green). The blue dotted pattern corresponds to the NW Iberia allochthonous tectonic units containing ophiolitic rocks. The zones in the Iberian Massif have been marked with the same colors as in Figure 1b according to their attribution to Gondwana, Armorica, and Avalonia. CIZ, Central Iberian Zone; OMZ, Ossa-Morena Zone; SPZ, South Portuguese Zone. (b) Geological sketch of southern Iberia, where the different units shaping the boundary between the Ossa-Morena and South Portuguese zones have been depicted. The samples studied are located by stars. (c) Schematic cross section of southern Iberia (see location in Figure 2b). The southern part of the cross section is based on work by *Fonseca and Ribeiro* [1993] and *Araújo et al.* [2005].

Iberian Zone (CIZ)) with inferred suture contacts in between (Figure 2).

[6] The OMZ/CIZ boundary is marked by a complex tectonic unit, namely, the Badajoz-Córdoba Shear Zone or Central Unit (Figure 2) [*Burg et al.*, 1981; *Azor et al.*, 1994]. This unit includes metasediments, orthogneisses, and amphibolites with scarce eclogite relics [*Abalos et al.*, 1991; *López Sánchez-Vizcaíno et al.*, 2003]. This boundary has been interpreted either as a suture of the Late Paleozoic Variscan Orogen, where at least some of the allochthonous ophiolitic units of NW Iberia would be rooted [e.g., *Matte*, 2001; *Simancas et al.*, 2005; *Pin et al.*, 2006], or as a suture of the Late Precambrian Cadomian Orogen, later reactivated as an intracontinental left-lateral shear zone during the Variscan Orogeny [e.g., *Abalos et al.*, 1991; *Quesada*, 1991]. The radiometric ages available point, however, to a Lower Paleozoic age for some amphibolite protoliths and an Early Carboniferous age for the high-grade metamorphism [*Ordóñez-Casado*, 1998], thus favoring the interpretation of this boundary as a Variscan suture. Some of the amphibolites (the Early Paleozoic ones) feature an oceanic geochemical signature [*Ordóñez-Casado*, 1998; *Gómez-Pugnaire et al.*, 2003], thus supporting the interpretation of existence along this boundary of very dismembered ophiolitic rocks, representing some sort of oceanic domain (Figures 1 and 2) that was closed during the Variscan Orogeny. Paleontological/faunistic data [*Robardet*, 2003] argue against the existence of a wide ocean between the CIZ and the OMZ at Ordovician to Devonian times. Therefore, this suture would represent most probably the relics of a relatively narrow oceanic realm developed during the Lower Paleozoic between Gondwana (CIZ) and Armorica (OMZ) (Figure 1b).

[7] The most compelling evidence for interpreting the OMZ/SPZ contact as the Rheic Ocean suture (Figure 1) has been the existence of a continuous band of amphibolites with oceanic affinity, namely, the Beja-Acebuches Amphibolite (BAA) unit (Figure 2) [*Bard*, 1977; *Bard and Moine*,

1979; *Fonseca and Ribeiro*, 1993; *Quesada et al.*, 1994; *Castro et al.*, 1996]. Additionally, south of the BAA unit, metasedimentary rocks with some metabasalt intercalations of normal mid-ocean ridge basalt (NMORB) oceanic signature (the Pulo do Lobo Unit; Figures 2b and 2c) have been interpreted as an accretionary prism related to a north dipping subduction zone [*Eden and Andrews*, 1990]. Finally, north of the BAA unit, the Moura-Cubito Schists (Figures 2b and 2c) intercalate slices of basic rocks, partly with oceanic affinity. These schists show high-pressure/low-temperature metamorphism [*Booth-Rea et al.*, 2006] with eclogite facies relics in some of the amphibolite intercalations [*Fonseca et al.*, 1999]. Accordingly, the Moura-Cubito Schists have been interpreted as an obducted accretionary complex rooted to the south in the suture zone [*Araújo et al.*, 2005].

3. Beja-Acebuches Amphibolites and Beja Gabbros

[8] We report here new geochronological data from the BAA unit, which has been interpreted by some authors as a dismembered ophiolite [*Fonseca and Ribeiro*, 1993; *Quesada et al.*, 1994]. The BAA unit crops out for 200 km along of the OMZ/SPZ boundary (Figure 2b) with a thickness of 500–2000 m. To the east, in the Spanish sector, the BAA unit is made up of medium- and fine-grained amphibolites, likely derived from gabbros and maybe some basalts, with medium-grained ones dominating toward the structural top (north) and fine-grained ones becoming dominant toward the structural bottom (south) [*Quesada et al.*, 1994]. To the west in the Portuguese sector, a sequence including serpentinites, dunites, amphibolites/gabbros and basalts has been reconstructed from scattered outcrops [*Fonseca and Ribeiro*, 1993].

[9] Geochemical data from the BAA are abundant, though their interpretation is far from being straightforward. *Bard* [1977] proposed that the BAA unit may represent either the very early stages of development of a marginal volcanic arc or a very ephemeral and narrow oceanic basin (intracontinental rifting). *Quesada et al.* [1994] interpreted the BAA unit as representing an oceanic lithosphere formed within an intra-arc or back-arc marginal basin. *Castro et al.* [1996] envisaged a mid-ocean ridge setting as the most probable for the generation of the BAA unit. Finally, *Pin et al.* [1999] shown that metagabbros and metabasalts from the BAA unit have very different ε_{Nd} values, thus concluding that the gabbroic and basaltic rocks may not be cogenetic; they also pointed out that only some of the metabasalts display ε_{Nd} values similar to NMORBs, with most of them showing significant interaction with continental components.

[10] The main deformational fabric in the BAA unit indicates oblique left-lateral top-to-the-SW ductile shearing [*Crespo-Blanc and Orozco*, 1991] occurred at mainly low-pressure amphibolite to greenschist facies conditions [*Bard and Moine*, 1979; *Castro et al.*, 1996]. Some authors [e.g., *Fonseca and Ribeiro*, 1993] recognize an early high-temperature low-pressure (granulite facies?) north directed ductile shearing, which is interpreted as related to ophiolite obduction. Metamorphic ages in the BAA unit were obtained by *Dallmeyer et al.* [1993] and *Castro et al.* [1999] using the $^{40}Ar/^{39}Ar$ method on amphibole concentrates; these ages, which are thought to constrain cooling below 500°C, range from 328 to 346 Ma.

[11] In Portugal, the BAA unit is bounded to the north by the undeformed Beja Gabbros (Figures 2b and 2c). Conventional U-Pb zircon dating of these gabbros yielded an age of ≈350–352 Ma [*Pin et al.*, 1999], while Sensitive High Resolution Ion Micro-Probe (SHRIMP) U-Pb on zircons has provided an age of 342 Ma [*Jesus et al.*, 2007]. These ages are consistent with those previously obtained by $^{40}Ar/^{39}Ar$ on amphibole concentrates from the gabbros (≈339 Ma [*Dallmeyer et al.*, 1993]). Unfortunately, the relationships between the Beja Gabbros and the BAA unit cannot be discerned in the field, since they are separated by faults. Thus, in the Beja Gabbros the lack of the tectonic fabric that pervades the BAA rocks has been taken as evidence for a pre-Carboniferous age of the BAA unit.

4. Sample Description and U-Pb Ages

[12] We report the first protolith ages on the BAA unit. We collected 20 samples, selecting the ones containing zircons for the geochronological study. Three of the zircon-bearing samples are coarse-grained metabasites (POR-5, POR-8, and POR-10), while the fourth is a fine-grained metabasite (POR-11) (Figure 2b).

[13] Sample POR-5 is a medium-grained light colored gabbro with a nearly isotropic fabric. It contains plagioclase, clinopyroxene, ore minerals, accessory zircon and rare secondary chlorite. Zircon crystals are transparent, pink, clear, and appear as rounded fragments of larger grains. In cathodoluminescence (CL), most crystals display a broad banded oscillatory zoning pattern with an irregular, small (10–40 μm across) and CL-bright rim in a few crystals. The zoned zircons have medium to low U and Th contents (Th/U 0.3–0.4) and yield a concordia age of 340 ± 4 Ma (Figure 2 and Table 1), which is interpreted as dating the intrusion of the gabbroic protolith. Three other analyses, one of them on a bright rim, yielded apparent younger ages down to 219 Ma, which are suspected of Pb loss, possibly related to metamorphism. This sample also contains a few smaller (<100 μm) zircon grains (5% of the total) with euhedral faces and a complex oscillatory zoning. One of these grains yielded an age of 533 ± 7 Ma (Figure 3 and Table 1), suggesting a xenocrystic or inherited origin.

[14] Sample POR-8 is a medium-grained dark colored amphibolite with a planar fabric related to tectonic deformation. It contains plagioclase, amphibole, ore minerals, accessory zircon and secondary chlorite. The zircons recovered from this sample have external features, internal zoning and U-Th composition similar to the main zircon population in sample POR-5. The zircons yielded a concordia age of 337 ± 5 Ma (Figure 3 and Table 1).

[15] Sample POR-10 is a strongly foliated medium-grained amphibolite consisting of plagioclase, amphibole,

Table 1. SHRIMP U-Pb-Th Analyses

Spot	^{206}Pb (%)	U (ppm)	Th (ppm)	Th/U	^{207}Pb/^{235}U	Error (%)	^{206}Pb/^{238}U	Error (%)	Error Correlation	^{206}Pb/^{238}U Age	± 1σ
POR5-1.1[a]	0.35	134	42	0.31	0.3229	7.67	0.04939	1.50	0.195	310.8	4.5
POR5-4.1[a]	0.49	111	34	0.31	0.3151	8.75	0.05167	1.50	0.172	324.8	4.8
POR5-5.1[a]	0.35	225	96	0.43	0.3702	2.73	0.05201	1.36	0.500	326.8	4.3
POR5-10.1	0.22	88	24	0.28	0.3348	7.58	0.05328	1.52	0.201	334.7	5.0
POR5-2.1	0.51	266	118	0.44	0.3642	4.10	0.05332	1.36	0.333	334.8	4.5
POR5-2.2	0.40	104	31	0.29	0.4334	2.88	0.05335	2.20	0.764	335.1	7.2
POR5-6.2	0.24	139	44	0.31	0.3418	7.34	0.05335	1.45	0.198	335.1	4.7
POR5-7.1	0.32	197	87	0.44	0.4043	1.96	0.05387	1.38	0.702	338.2	4.5
POR5-3.1	0.13	242	99	0.41	0.3869	2.46	0.05419	1.36	0.551	340.2	4.5
POR5-13.1	0.40	123	44	0.36	0.3432	6.62	0.05460	1.46	0.220	342.7	4.9
POR5-11.1	0.14	452	117	0.26	0.4149	1.60	0.05482	1.33	0.830	344.1	4.5
POR5-8.1	0.01	263	76	0.29	0.3760	3.59	0.05496	1.36	0.380	344.9	4.6
POR5-9.1	0.39	114	37	0.32	0.3350	6.17	0.05514	1.46	0.237	346.0	4.9
POR5-12.1 inh[b]	0.16	764	185	0.24	0.6795	1.59	0.08622	1.36	0.851	533.1	6.9
POR8-8	0.76	122	33	0.27	0.3509	5.93	0.05235	1.71	0.288	328.9	5.5
POR8-6	0.34	268	81	0.30	0.3720	3.14	0.05290	1.53	0.488	332.3	5.0
POR8-4	0.11	249	89	0.36	0.3851	2.56	0.05374	1.54	0.601	337.4	5.1
POR8-11	0.47	261	63	0.24	0.3603	3.80	0.05376	1.72	0.453	337.6	5.7
POR8-9	0.34	253	81	0.32	0.3841	3.21	0.05390	1.54	0.481	338.4	5.1
POR8-7	0.37	204	49	0.24	0.3563	4.45	0.05411	1.57	0.353	339.7	5.2
POR8-10	0.06	446	114	0.26	0.3955	2.08	0.05415	1.50	0.718	339.9	5.0
POR8-2	0.16	227	91	0.40	0.3933	2.81	0.05451	1.54	0.549	342.1	5.1
POR8-1.1	0.11	335	122	0.36	0.3927	2.34	0.05484	1.51	0.645	344.1	5.1
POR10-4A[a]	2.85	31	15	0.48	0.2125	25.20	0.05008	1.82	0.072	315.0	5.6
POR10-11[a]	2.80	27	14	0.52	0.1931	38.61	0.05015	2.09	0.054	315.4	6.4
POR10-18	0.16	755	706	0.94	0.3732	2.18	0.05135	1.85	0.853	322.8	5.8
POR10-13	1.96	36	20	0.54	0.2950	14.37	0.05137	1.69	0.117	322.9	5.3
POR10-3	0.70	53	18	0.34	0.3454	14.10	0.05140	1.62	0.115	323.1	5.1
POR10-1	1.82	65	29	0.44	0.2925	15.33	0.05153	1.54	0.101	323.9	4.9
POR10-6	0.00	114	66	0.58	0.4017	6.55	0.05192	1.34	0.204	326.3	4.3
POR10-2	0.00	23	10	0.43	0.3856	4.52	0.05246	1.68	0.373	329.6	5.4
POR10-9	0.86	89	34	0.38	0.3527	7.76	0.05254	1.48	0.191	330.1	4.8
POR10-15	0.65	118	86	0.73	0.3511	6.89	0.05258	1.44	0.209	330.3	4.6
POR10-19	0.00	52	31	0.58	0.4161	2.92	0.05273	1.39	0.476	331.3	4.5
POR10-7	2.17	50	25	0.49	0.2659	16.98	0.05290	1.57	0.092	332.3	5.1
POR10-14	0.73	117	27	0.23	0.3570	5.83	0.05292	1.29	0.221	332.5	4.2
POR10-10	0.30	188	50	0.26	0.3693	3.56	0.05301	1.30	0.366	333.0	4.2
POR10-5	0.18	136	34	0.25	0.3792	3.70	0.05315	1.25	0.338	333.8	4.1
POR10-17	0.77	41	18	0.44	0.3485	18.74	0.05348	1.80	0.096	335.9	5.9
POR10-12	0.25	136	63	0.47	0.3908	3.59	0.05382	1.53	0.427	337.9	5.0
POR10-16	0.01	1247	1934	1.55	0.3949	1.29	0.05384	1.14	0.884	338.1	3.8
POR10-20	0.03	177	58	0.33	0.4001	2.52	0.05420	1.33	0.527	340.2	4.4
POR10-8	0.09	427	427	1.00	0.3988	1.76	0.05421	1.17	0.662	340.3	3.9
POR11A-12.1[a]	1.94	198	75	0.38	0.2680	8.95	0.04721	1.26	0.141	297.4	3.7
POR11A-15.1[a]	0.89	1647	1054	0.64	0.3631	2.15	0.05084	1.03	0.478	319.7	3.2
POR11A-2.2[a]	0.31	592	342	0.58	0.3699	2.45	0.05134	1.06	0.434	322.8	3.3
POR11-14.1	1.37	450	305	0.68	0.3265	4.65	0.05189	1.10	0.237	326.1	3.5
POR11-3.1A	0.36	615	297	0.48	0.3783	2.21	0.05193	1.06	0.478	326.4	3.4
POR11A-18.1	1.81	525	515	0.98	0.3557	6.52	0.05213	1.13	0.173	327.6	3.6
POR11-18.1	0.63	505	215	0.43	0.3771	2.82	0.05214	1.08	0.382	327.6	3.4
POR11-13.2	2.28	290	14	0.05	0.3302	10.30	0.05219	1.22	0.118	327.9	3.9
POR11-12.1	0.56	534	286	0.53	0.3612	2.74	0.05259	1.07	0.391	330.4	3.4
POR11-16.1	0.91	275	131	0.48	0.3428	5.60	0.05269	1.17	0.209	331.0	3.8
POR11A.17.1	1.53	313	342	1.09	0.3514	6.42	0.05274	1.18	0.183	331.3	3.8
POR11-6.1	0.70	434	319	0.74	0.3594	3.48	0.05297	1.10	0.318	332.8	3.6
POR11-2.2	0.79	339	173	0.51	0.3729	4.02	0.05303	1.13	0.281	333.1	3.7
POR11-17.1	1.00	362	185	0.51	0.3419	5.04	0.05306	1.23	0.244	333.3	4.0
POR11A-10.1	5.84	760	696	0.92	0.3908	6.67	0.05327	1.21	0.181	334.5	3.9
POR11-5.2	0.45	672	327	0.49	0.3728	2.49	0.05328	1.05	0.423	334.6	3.4
POR11A-14.1	4.61	1004	612	0.61	0.3508	11.97	0.05335	1.25	0.105	335.1	4.1
POR11A-4.2	0.38	333	246	0.74	0.3903	3.95	0.05341	1.55	0.392	335.4	5.1
POR11-8.1	0.48	674	332	0.49	0.3838	2.22	0.05360	1.12	0.507	336.6	3.7
POR11-10.1	1.02	249	204	0.82	0.3343	5.97	0.05371	1.18	0.198	337.3	3.9
POR11-9.1	2.69	132	92	0.70	0.2523	18.44	0.05376	1.47	0.080	337.6	4.8
POR11-1.1	0.35	831	494	0.59	0.3740	2.14	0.05397	1.04	0.486	338.8	3.4
POR11A-13.1	1.36	746	757	1.01	0.3832	3.83	0.05402	1.07	0.279	339.1	3.5
POR11A-8.2	1.05	291	92	0.32	0.3515	5.17	0.05404	1.15	0.223	339.3	3.8
POR11A-16.1	0.99	362	166	0.46	0.3732	3.92	0.05404	1.14	0.289	339.3	3.8

Table 1. (continued)

Spot	^{206}Pb (%)	U (ppm)	Th (ppm)	Th/U	^{207}Pb/^{235}U	Error (%)	^{206}Pb/^{238}U	Error (%)	Error Correlation	^{206}Pb/^{238}U Age	± 1σ
POR11A-9.1	0.61	598	615	1.03	0.3858	3.26	0.05482	1.07	0.328	344.1	3.6
POR11-11.1	1.20	237	138	0.58	0.3487	5.99	0.05487	1.39	0.232	344.4	4.7
POR11-15.1 inh[b]	0.59	399	489	1.23	0.7941	3.44	0.09820	1.09	0.317	604	6
POR11-13.1 inh[b]	1.67	106	64	0.60	0.6786	6.02	0.10010	1.30	0.216	615	8
POR11-4.2 inh[b]	0.58	40	38	0.95	4.3167	2.94	0.30446	1.48	0.503	1713	22
POR11-7.2 inh[b]	0.11	659	243	0.37	16.3442	1.25	0.51729	1.03	0.823	2688	23

[a]Data excluded from the age calculation because of suspected Pb loss.
[b]Here inh indicates inherited core.

clinopyroxene, and accessory titanite, apatite and zircon. The zircons recovered have a more complex internal structure compared to the other samples. The zoning is predominantly broadband oscillatory, but CL-dark and U-rich cores (500–1000 ppm), often motted and fracture-rich are present in many grains. Thin and CL-bright rims are also occasionally present. Regardless of the zoning, most analyses define a concordia age of 332 ± 3 Ma (Figure 3 and Table 1).

[16] Sample POR-11 is a strongly foliated fine-grained amphibolite made up of amphibole, plagioclase and quartz, with titanite, ore minerals and zircon as accessory phases; sericite, actinolite, and epidote are secondary phases. The

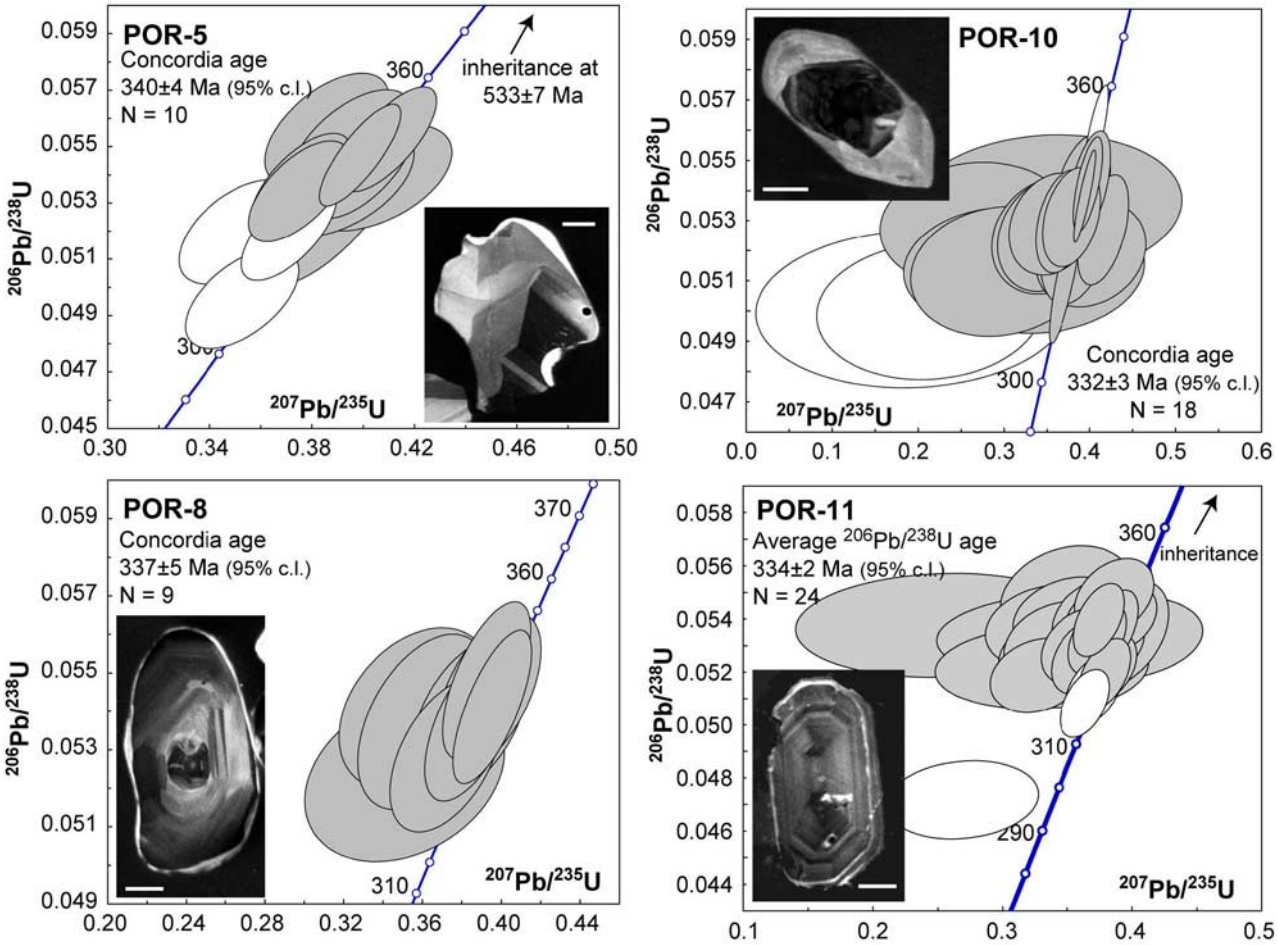

Figure 3. Concordia diagrams for the SHRIMP zircon U-Pb analyses of the four samples. Concordia and average ages are calculated from the analyses plotted as gray ellipses. White ellipses represent analyses suspected of Pb loss during metamorphism. Data point error ellipses are 2 sigma. The inset in each diagram is a cathodoluminescence image of a representative zircon crystal in the corresponding sample. The scale bar corresponds to 20 μm.

zircon crystals have color and shape similar to the other samples, with a prevalence of euhedral grains. CL zoning varies from broad to fine oscillatory, with a few grains displaying sector zoning and others preserving distinct cores. Occasionally, CL-dark rims are preserved, whose size is, however, below the resolution of SHRIMP analysis. The zircons generally have medium to high U and Th contents (Table 1) with Th/U in the range 0.4–1.1. Most analyses cluster in a group plotted slightly off the Concordia, possibly because of an analytical offset in measuring the $^{207}Pb/^{235}U$ ratio. Therefore, the average $^{206}Pb/^{238}U$ age of 334 ± 2 Ma (Figure 3) is taken here as the best estimate of the crystallization of the protolith. A few grains with poor zoning yielded slightly younger ages, while the distinct cores yielded inherited ages (0.6 to 2.5 Ga, Table 1).

5. Discussion

[17] The geochronological data obtained in this work provide a time framework for the MORB-featured amphibolitic unit that constitutes the boundary between the OMZ and SPZ, thus questioning the correlation of ophiolitic units along the Variscan-Alleghanian Orogen. In sections 5.1–5.4, we tackle the implications of our new ages for the timing of MORB-featured mafic magmatism and low-pressure metamorphism in southern Iberia, the Rheic Ocean reconstructions and the correlation of Variscan ophiolitic units. Finally, we propose an evolutionary model for southern Iberia during the Late Paleozoic, integrating these new radiometric ages with the geological and geophysical data available.

5.1. Timing of Mafic Magmatism and Low-Pressure Metamorphism

[18] The zircons dated show the typical internal zoning (broadband oscillatory) and chemistry (high Th/U of 0.3–1.1) commonly observed in magmatic zircons from mafic rocks [e.g., *Rubatto and Gebauer*, 2000; *Corfu et al.*, 2003]. Therefore we interpret the ages obtained from the main population of zircon grains as dating the crystallization of the BAA protoliths. A limited number of analyses recording apparent younger ages (Figure 3 and Table 1) likely represent a partial disturbance of the U-Pb system during the later amphibolite facies metamorphism. Our data do not offer however any further constraints on the timing of metamorphism. It is worth noting that some of the samples (POR-5 and POR-11) contain a few older zircon grains or cores. These zircons either have a xenocrystic origin (isolated grains incorporated into the gabbroic rocks by assimilation of host rocks during magma ascent) or are inherited from the magma source (cores overgrown by magmatic zircons). Such contamination of the magmatic zircon population, as well as the eventual Pb loss associated with metamorphism, would not be easily detected by isotope dilution analyses of zircon grains. This fact justifies by itself the use of SHRIMP microanalysis, despite the possible detriment of precision.

[19] The ages obtained for the protoliths of the BAA unit range from 340 ± 4 to 332 ± 3 Ma. Independently of the precise tectonic scenario invoked (arc-related basin, mid-ocean ridge, or even intracontinental magmatism during extensional tectonics), these protolith ages allow the conclusion that the BAA gabbroic rocks correspond to an Early Carboniferous magmatic event and not to the Ordovician-Devonian Rheic Ocean, which, in turn, has a number of important consequences.

[20] The ages reported here (340–332 Ma) are only in part younger than the ones available for the Beja Gabbros (352–342 Ma [*Pin et al.*, 1999; *Jesus et al.*, 2007]). The shift toward older ages in the first geochronology done on the Beja Gabbro (350–352 Ma [*Pin et al.*, 1999]) is probably due to the presence of some inheritance (as observed in our study on the BAA unit) not detected by conventional isotope dilution analysis. The combined data open the possibility that the BAA unit, the Beja Gabbros and other plutonic rocks of the same age in the OMZ may be part of the same magmatic event. Moreover, the Early Carboniferous period in southern Iberia is characterized by abundant bimodal volcanism hosting massive sulphide deposits in the so-called Iberian Pyrite Belt of the SPZ [*Schermerhorn*, 1971; *Leistel et al.*, 1997; *Nesbitt et al.*, 1999; *Sáez et al.*, 1999] and thick flysch sedimentation both in the southern part of the CIZ and the whole SPZ [*Oliveira*, 1990; *Giese et al.*, 1994; *Martínez Poyatos et al.*, 1995]. Accordingly, the general tectonic regime in southern Iberia at Early Carboniferous times seems to be an extensional/transtensional one (see below), where volcanism, gabbroic magma formation (Beja Gabbros), ephemeral oceanic crust generation (BAA unit) and deep-water marine sedimentation would have occurred on a thinned continental crust.

[21] The metamorphism ages available for the BAA unit, which likely date the amphibolite to greenschist facies event affecting it, span a time period between 342 and 328 Ma [*Dallmeyer et al.*, 1993; *Castro et al.*, 1999]. Therefore, the older metamorphism ages seem to be unrealistic, since they overlap with our protolith ages. On the contrary, the younger metamorphism ages are compatible with our protolith ages, indicating that deformation/metamorphism of the BAA rocks occurred shortly after its formation.

5.2. Implications for the Rheic Ocean Paleogeography

[22] The geochemical signature of the BAA rocks has been mostly attributed to an origin in a back-arc or intra-arc basin developed in a suprasubduction zone setting [*Quesada et al.*, 1994], although a mid-ocean ridge has also been suggested [*Castro et al.*, 1996]. The latter scenario is very unlikely due to the short time span between the formation of the BAA unit (circa 332–340 Ma, this work) and its exhumation (circa 330 Ma, considering as valid the youngest $^{40}Ar/^{39}Ar$ ages [*Castro et al.*, 1999]). As for the back-arc or intra-arc basin in a suprasubduction zone setting, the Early Carboniferous ages reported here might be interpreted as being related to the very final stages of Rheic Ocean consumption. Nevertheless, the palynological content of Upper Devonian and Lower Carboniferous sediments at both sides of the BAA unit is similar [*Pereira et al.*, 2006], thus, suggesting that the OMZ and SPZ were already welded in Late Devonian times. This implies that the Rheic

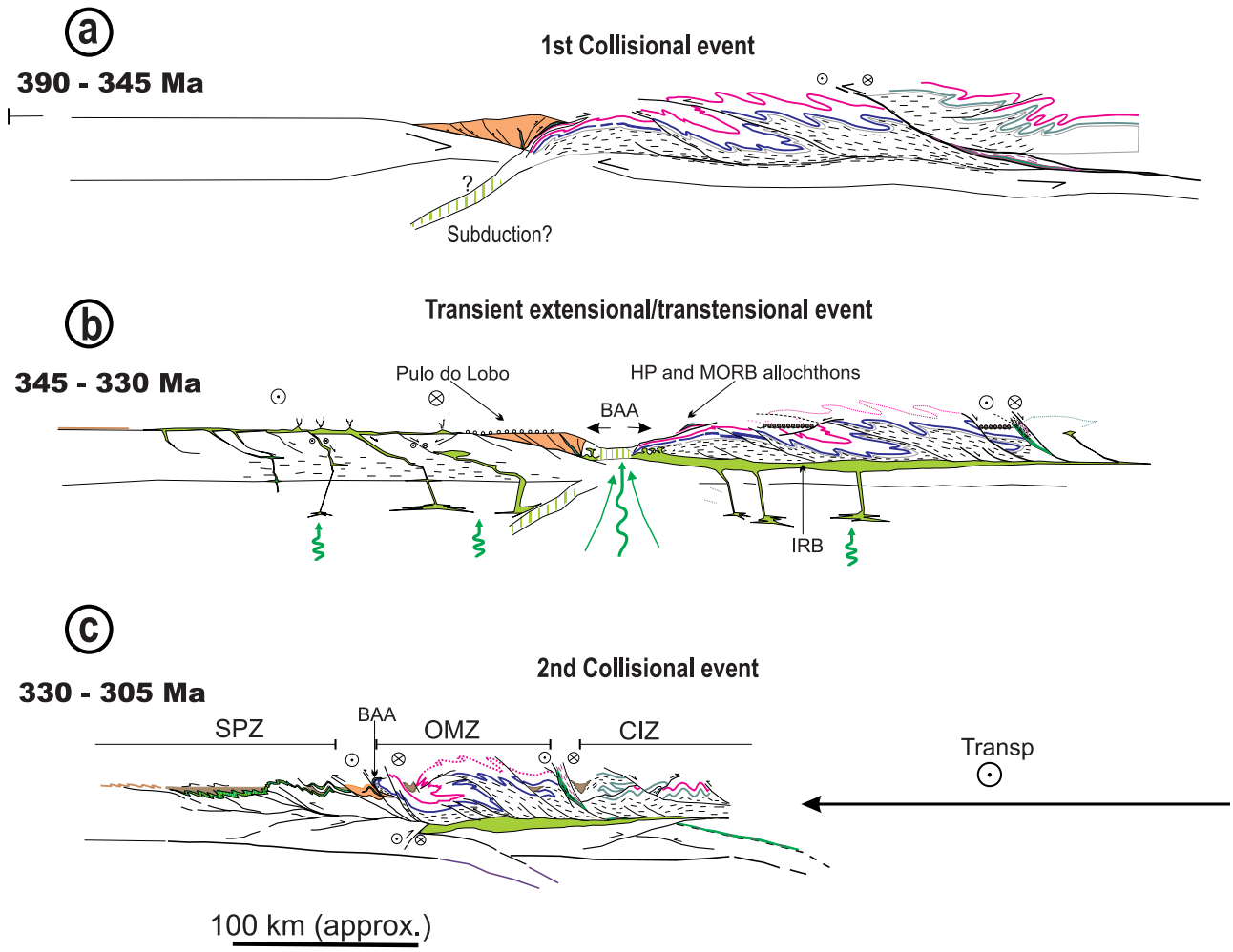

Figure 4. Evolutionary model for southern Iberia from Middle-Late Devonian to Late Carboniferous. (a) The first collisional event propagated NE and SW from the boundary between the Central Iberian and Ossa-Morena zones giving way to recumbent folds and thrusts in the upper crust. (b) The Early Carboniferous transient extensional/transtensional event was characterized by abundant mafic magmatism and thick flysch sedimentation. During this stage a huge volume of mafic rocks were trapped in the middle crust of the Ossa-Morena Zone, generating an irregular highly reflective body, namely, the Iberian reflective body (IRB). Intense and localized extension in the boundary between the Ossa-Morena and South Portuguese zones was responsible for the formation of the MORB-featured Beja-Acebuches amphibolites (BAA). (c) Renewal of the shortening during the second collisional event in Late Carboniferous times under a transpressional tectonic regime produced the final crustal geometry of southern Iberia. This cross section has been depicted taking into account the surface geology data and the seismic image provided by IBERSEIS.

Ocean, if present along this boundary, must have been consumed previously. In other words, the BAA unit cannot represent an oceanic realm related to the Rheic Ocean. Therefore, we favor the interpretation of the BAA unit as a narrow and very ephemeral realm of oceanic-like crust, independent from the Rheic Ocean and generated after its consumption (Figure 4). The extreme narrowness of this domain is favored by the palynological data [*Pereira et al.*, 2006] and indirectly by the presence of Cambrian inherited zircons in one of the dated gabbros, which could have been assimilated from surrounding continental rocks. In the same way, the geochemical data provided by *Pin et al.* [1999], which were interpreted in terms of a mixture of rocks with different origins, are now well understood in this context where oceanic and continental rocks could have been easily amalgamated.

[23] Our new data show that the Rheic suture is not represented at all in the BAA unit and cast some doubts on the tectonic meaning of the OMZ/SPZ boundary. Nevertheless, the OMZ/SPZ might still represent a criptic Rheic suture, the BAA unit having been formed after the total consumption of the Rheic Ocean. On this view, the small

and dispersed fragments of MORB-featured mafic rocks both to the north (in southwest OMZ) and south (in the Pulo do Lobo unit) of the BAA unit remain as putative Rheic-related suture rocks. However, no absolute ages are available on these MORB-featured rocks.

5.3. Correlations With Other Variscan Ophiolites

[24] Up to now, Variscan ophiolites across Europe have been arranged into two groups according to their ages: Early Paleozoic ophiolites (≈470–497 Ma [e.g., *Ordóñez-Casado et al.*, 2001; *Arenas et al.*, 2007b]) and Devonian ophiolites (≈395–400 Ma [e.g., *Díaz García et al.*, 1999; *Nutman et al.*, 2001; *Pin et al.*, 2006]). Early Paleozoic ophiolites may attest the Rheic Ocean opening, while Devonian ophiolites may attest minor (mostly suprasubduction) oceanic realms formed during intraoceanic subduction of the Rheic Ocean [*Sánchez Martínez et al.*, 2007; *Arenas et al.*, 2007b]. The Early Carboniferous ages reported here for the BAA unit are the youngest ones among the Variscan ophiolites, thus preventing direct correlation with any other ophiolites in this orogen. Similarly, the tectonic models joining in a single suture line the BAA unit in southern Iberia to either the Lizard ophiolite in southern England [e.g., *Crespo-Blanc and Orozco*, 1991; *Matte*, 2001] or the root zone of the allochthonous ophiolitic units in northwest Iberia [e.g., *Ribeiro et al.*, 2007] must be reconsidered because of the above mentioned age difference.

5.4. Integrating the Beja-Acebuches Amphibolites in the Southern Iberia Tectonic Evolution

[25] The Early Carboniferous ages of the BAA protoliths, together with their oceanic affinity and temporal coincidence with conspicuous basic magmatism and thick sedimentation throughout all southern Iberia, constitute main fundamentals when trying to establish a reliable tectonic scenario. An extensional/transtensional setting unrelated to any putative pre-Carboniferous suprasubduction zone context seems the most plausible one (see below). Such extensional/transtensional Early Carboniferous stage would have been preceded by an essentially Middle-Late Devonian collisional event characterized by the formation of kilometer-scale recumbent folds (Figure 4a) affecting the entire OMZ and the southern part of the CIZ [*Simancas et al.*, 2001, 2003; *Expósito et al.*, 2002]. This first collisional event propagated from the OMZ/CIZ contact both to the north (southern part of the CIZ) and south (OMZ), thus attesting continental subduction of the OMZ crust underneath the CIZ crust (Figure 4a) as shown in the seismic profile IBERSEIS [*Simancas et al.*, 2003]. Pre-Devonian evolution of this boundary is inferred from geochronology and geochemistry of the amphibolites intercalated in the Central Unit, which suggest the existence of a narrow oceanic domain in Early Paleozoic times between OMZ and CIZ continental blocks, which would have been consumed by subduction previously to the continental subduction and collision. As for the OMZ/SPZ contact, two possible scenarios are plausible in Middle-Late Devonian: (1) the final stages of Rheic ocean consumption were occurring as suggested in Figure 4a; the remnants of this subduction would not be the BAA ophiolitic unit, though the MORB-featured basalts included in the Pulo do Lobo unit to the south of the OMZ/SPZ contact and the slices of mafic rocks with high-pressure metamorphism and/or ophiolitic affinity to the north of the OMZ/SPZ contact may well attest the Rheic Ocean subduction; and (2) the Rheic Ocean was not present between the OMZ and SPZ, being both part of a single continental block with two domains, one affected by the OMZ/CIZ collision to the north (OMZ) and one another not affected by the southward propagation of this collision (SPZ); in this second scenario the SPZ would record a continuous marine sedimentation all along the Devonian in a passive continental margin. The lack of protolith ages in the suspected Rheic Ocean remnants makes it impossible to discard one of these two options.

[26] The extensional/transtensional event responsible for the formation of the BAA ophiolitic unit may represent a transient stage after the first collisional stage. Thus, the BAA MORB-featured unit could have been generated in a very ephemeral and narrow oceanic domain open during this extensional/transtensional event (Figure 4b). This event could also have been responsible for the abundant mafic magmatism both in the OMZ (plutonic rocks) and SPZ (mainly volcanic rocks with associated massive sulfide deposits in the so-called Iberian Pyrite Belt), as well as thick flysch sedimentation both in the SPZ and the southern part of the CIZ. The interpretation proposed here for the BAA unit is in some ways similar to that made by *Bard* [1977], who envisaged intracontinental rifting as a possible setting of this unit.

[27] To find the reason for the change in the tectonic regime from compression to extension/transtension, one needs to consider together surface geology data and deep crustal features. The IBERSEIS seismic profile provides an image of southern Iberia crust in a SW-NE transect. The most striking seismic structure imaged in the OMZ is a long, thick, irregular, strongly reflective band in the middle crust, namely, the IBERSEIS Reflective Body (IRB, Figures 4b and 4c). This band contains small domains of layered reflectivity interfingering at different dips, which have been interpreted as an Early Carboniferous rock layering of differentiated mafic igneous bodies intruding rocks with different degrees of assimilation [*Simancas et al.*, 2003, 2006]. A mantle plume affecting all of the European Variscan Belt and maybe the northern Appalachians [*Murphy and Keppie*, 2005] in Early Carboniferous times is the most plausible large-scale geodynamic scenario for all the above mentioned features, including the formation of MORB-featured rocks.

[28] Variscan collisional tectonics resumed after the Early Carboniferous transient extensional/transtensional stage. This second collisional stage had a general transpressional character in southern Iberia [e.g., *Simancas et al.*, 2006], with the strain partitioned among upright folds, oblique thrusts and left-lateral strike-slip faults (Figure 4c). Thus, the very narrow oceanic domain represented by the BAA unit was closed and exhumed shortly after formation by the renewal of the convergence, generating the penetrative

planar-linear fabric affecting the rocks of this unit. Accordingly, the formation of the BAA rocks and the intrusion of the Beja Gabbros, as well as the high-temperature/low-pressure metamorphism and the shear zone affecting the BAA unit, occurred within a short-lived 20 Ma long episode in Early Carboniferous times.

[29] The evolution envisaged here in southern Iberia can be compared with the one of the central European Variscides. The OMZ/SPZ contact has been correlated with the Rheno-Hercynian/Saxo-Thuringian boundary in central Europe, where after Middle Devonian consumption of the Rheic Ocean in between these two zones, extensional tectonics gave way to a bimodal volcanism and the opening of a new small ocean, namely, the Rheno-Hercynian Ocean [*Franke*, 2000], which, in turn, was closed in earliest Carboniferous times. According to the ages reported here, the BAA unit of southern Iberia cannot be the equivalent of any of the suture units found in the Rheno-Hercynian/Saxo-Thuringian boundary. Interestingly, the Rheno-Hercynian zone itself, which represents the foreland of the Variscan Belt in Germany (Avalonia), contains Early Carboniferous tholeiitic E-type MORB-featured mafic pillow lavas. These volcanics are clearly unrelated to a suprasubduction zone scenario, since the Devonian Rheno-Hercynian Ocean was already being subducted southward in Early Carboniferous times under one of the fragments of the Armorica microplate. Therefore, they might be associated with the magmatic event responsible for the formation of the BAA unit and other mafic rocks in southern Iberia.

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