100 Ma cycles of oceanic lithosphere generation in peri-Gondwana: Neoproterozoic to Devonian ophiolites from the NW African-Iberian margin of Gondwana and the Variscan Orogen

Ricardo Arenas[1]*, Sonia Sánchez Martínez[1], Richard Albert[2], Faouziya Haissen[3], Javier Fernández-Suárez[1], Núria Pujol-Solà[4], Pilar Andonaegui[1], Rubén Díez Fernández[5], Joaquín A. Proenza[4], Antonio Garcia-Casco[6] & Axel Gerdes[2]

[1]Departamento de Mineralogía y Petrología and Instituto de Geociencias (UCM, CSIC), Universidad Complutense. 28040 Madrid, Spain.

[2]Institut für Geowissenschaften, Goethe-University Frankfurt, 60438 Frankfurt, Germany.

[3]LGAGE, Département de Géologie, Université Hassan-II de Casablanca, Casablanca, Morocco.

[4]Departament de Mineralogia, Petrologia i Geologia Aplicada, Universitat de Barcelona. 08028 Barcelona, Spain.

[5]Departamento de Geodinámica, Estratigrafía y Paleontología, Universidad Complutense. 28040 Madrid, Spain.

[6]Departamento de Mineralogía y Petrología and Instituto Andaluz de Ciencias de la Tierra (UGR, CSIC), Universidad de Granada. 18071 Granada, Spain.

**Corresponding author (e-mail: rarenas@ucm.es)*

E-mail addresses:

arenas@geo.ucm.es(Ricardo Arenas, corresponding author)

s.sanchez@geo.ucm.es (Sonia Sánchez Martínez)

r.albert@geo.ucm.es (Richard Albert)

faouziya.haissen@gmail.com (Faouziya Haissen)

jfsuarez@geo.ucm.es (Javier Fernández-Suárez)

nurpss@gmail.com (Núria Pujol-Solà)

andonaeg@geo.ucm.es(Pilar Andonaegui)

rudiez@ucm.es(Rubén Díez Fernández)

japroenza@ub.edu (Joaquín A. Proenza)

agcasco@ugr.es (Antonio Garcia-Casco)

gerdes@em.uni-frankfurt.de (Axel Gerdes)

Abstract

The Variscan Orogen in Iberia and the Anti-Atlas mountains in Morocco contains a set of ophiolites formed between Neoproterozoic and Devonian times, during the complex evolution of the NW African-Iberian margin of Gondwana. During this time interval the margin evolved from an active margin (c. 750-500 Ma, the Reguibat-Avalonian-Cadomian arc), to the final collision with Laurussia in Devonian times to form Pangea. In this context, one of the oldest recognized ophiolite is the Bou Azzer Ophiolite from the Anti-Atlas, dated at c. 697 Ma and containing two types of mafic rocks, the youngest of which have boninitic composition. To the North, in the SW Iberian Massif, the Calzadilla Ophiolite contains mafic rocks also of boninitic composition dated at c. 598 Ma. Farther North, in the NW Iberian Massif, the Vila de Cruces Ophiolite is formed by a thick sequence of mafic rocks with arc-tholeiitic composition and minor alternations of tonalitic orthogneisses dated at c. 497 Ma. In the same region, the Bazar Ophiolite has a similar age of c. 495 Ma. Also in NW Iberia there is a group of ophiolites with varied lithologies and dominant mafic rocks with arc-tholeiitic composition (ophiolites of Careón, Purrido and Moeche), dated at c. 395 Ma. The composition of all these peri-Gondwanan ophiolites is of supra-subduction zone type showing no evidence for

preserved MORB-type oceanic lithosphere. Consequently, these ophiolites were generated in the peri-Gondwanan realm during the opening of fore-arc or back-arc basins. Fore-arc oceanic lithosphere was promptly obducted or accreted to the volcanic arc, but the oceanic or transitional lithosphere generated in back-arc settings was preserved until the assembly of Pangea. Based on the ages of the described ophiolites, the peri-Gondwanan realm has been a domain where generation of oceanic or transitional lithosphere seems to have occurred at intervals of c. 100 Ma. These regularly spaced time intervals may indicate cyclic events of mantle upwelling in the peri-Gondwanan mid-ocean ridges, with associated higher subduction rates at the peri-Gondwanan trenches and concomitant higher rates of partial melting in the mantle wedges involved. The origin of the apparent cyclicity for mantle upwelling in the peri-Gondwanan ocean ridges is unclear, but it could have been likely related to episodic deep mantle convection. Cycles of more active deep mantle convection can explain episodic mantle upwelling, transition from low to fast spreading type mid-ocean ridges and finally the dynamic context for the episodic generation of new supra-subduction zone type oceanic peri-Gondwanan lithosphere.

Introduction

The NW African-Iberian margin of Gondwana (including proto-Gondwana) was characterized by a protracted evolution since Neoproterozoic times until the final assembly of Pangea in Devonian and Carboniferous times. Between c. 780 Ma (Cryogenian) and c. 500 Ma (Late Cambrian), it represented an active margin with generation of abundant and rather continuous magmatism (Fuenlabrada et al., 2010, 2020; Albert et al., 2015). Later on, since Late-Cambrian to Early Ordovician times, frontal subduction and/or slab roll-back and trench retreat favored extension in the upper plate lithosphere and, hence, rifting and subsequent drift of peri-Gondwanan terranes. The most prominent separation was that of the Avalonian terrane and the associated opening of the Rheic Ocean at its wake (Nance et al., 2010).

Thick sedimentary series were deposited on the Gondwanan margin between Cryogenian and Ordovician times. Tectonically alternating with these series, several obducted mafic-ultramafic units (ophiolites) account for the opening and closure of some minor oceanic or transitional domains. The presence of these ophiolites suggests that the evolution of the margin was complex and controlled by variable interactions between the subducting peri-Gondwanan oceanic lithosphere, the magmatic arcs, and the mainland. During Early-Middle Devonian times, dextral convergence between Gondwana and Laurussia resulted in the consumption of the Rheic Ocean and continental collision that led to the final amalgamation of Pangea. Two events of high-P metamorphism separated in time (at c. 400 and 370 Ma) clearly indicate that this collision was complex, and contractional events alternated with lithospheric extension and the opening of new ephemeral oceanic domains (Fernández-Suárez et al., 2007; Abati et al., 2010; Arenas et al., 2014a; Díez Fernández et al., 2020). Remnants of these oceanic domains are preserved as ophiolitic units along the Variscan Orogen (Arenas and Sánchez Martínez, 2015).

The mafic-ultramafic units preserved in these ophiolites are remnants of deep dynamics processes associated with the protracted evolution of the NW African-Iberian margin of Gondwana. The ophiolites currently appear in the Anti-Atlas Domain of Morocco and in many of the massifs that define the Variscan Orogen, notably in the Iberian Massif. During the past twenty years, knowledge about these ophiolites has increased substantially, including their existence, distribution, geochemical characteristics, and chronology. Dating of mafic-ultramafic sequences is difficult as these lithologies contain no or scarce zircon, the most amenable mineral to obtain precise U-Pb ages for the protoliths. However, the chronology of the protoliths of these oceanic sequences is now well constrained. Also, significant data exist that allow reconstructing parts of their obduction chronology and the primary location of the oceanic or transitional domains. Dates of the ophiolitic units have revealed an apparent cyclicity in the opening of oceanic or transitional domains along the peri-Gondwanan realm. The origin and meaning of this cyclicity is yet unclear, but its

existence indicates that repetitive major-scale processes have significantly conditioned the evolution of the peri-Gondwanan realm.

This work presents a review of the available U-Pb age data that support the existence of cyclicity in the development of the mafic-ultramafic sequences of Morocco and the Iberian Massif. The main geochemical features of the mafic rocks are also presented in order to extract inferences pertaining to the tectonic setting of generation of the different oceanic or transitional domains. Possible geodynamic scenarios that could have favored this cyclicity are discussed, although we are still probably far from a detailed understanding of the processes involved. However, the mere discovery of this cyclicity is a solid first step towards some kind of understanding of the processes involved.

Geological Setting

The reconstruction of Pangea at the end of the Paleozoic (Fig. 1) shows the position of the Anti-Atlas Domain in relation to the Iberian Massif. The pre-Pangean location of both regions in the margin of Gondwana is difficult to reconstruct, due to both the oroclinal folding and the long strike-slip shear zones that characterize the Variscan Orogen (Martínez Catalán et al., 2007, 2011; Weil et al. 2013; Gutiérrez-Alonso et al., 2015) that may have probably produced large displacements in the initial location of some regions. However, based on their present location (Fig. 1), the original pre-Variscan distance between the Anti-Atlas and the southern (non-Avalonian) part of the Iberian Massif, can be estimated at least in c. 1500-2000 km. Consequently, this large spatial separation and the long time interval recorded in the associated stratigraphic record, make the studied section a representative domain of the large-scale dynamic evolution of the NW African-Iberian margin of Gondwana.

Located to the South of the High Atlas Mountain Range, the Anti-Atlas Domain contains the northernmost outcrops of formations equivalent to those found further South in the realm of the West African Craton (Michard et al., 2010; Brahimi et al., 2018; Soulaimani et al., 2019). Several tectonic windows or inliers show Paleoproterozoic (c. 2.2-2 Ga) to Late Ediacaran formations which are overlain by thick Paleozoic series (Fig. 2). In the Bou Azzer inlier, a large unit of mafic-ultramafic rocks represents the only coherent ophiolite described so far in NW Africa. The c. 700 Ma Bou Azzer Ophiolite has been described as a peri-proto-Gondwanan ophiolite tectonically emplaced above continental rifting series formed at c. 750-700 Ma and unconformably covered by siliciclastic sedimentary rocks, the Tiddiline unit (Leblanc, 1976; Ahmed et al., 2005; El Hadi et al., 2010). The ophiolite is intruded by two groups of arc-related granitic rocks. A first suite of syn-kinematic diorite-tonalite plutons dated at c. 653-640 Ma, followed by late-kinematic granodiorite plutons dated at c. 579-578 Ma (Inglis et al., 2004). The age of the syn-kinematic granitoids is also considered the obduction age of the ophiolite onto the continental margin (El Hadi et al., 2010).

The Iberian Massif is characterized by the presence of large allochthonous complexes which appear in the uppermost structural positions and were thrust above parautochthonous and autochthonous domains during the Variscan Orogeny (Fig. 3; see Arenas et al., 2016a and Díez Fernández et al., 2016 for review). Similar allochthonous complexes can be found along other regions of the Variscan Orogen (Fig. 1; Ballèvre et al., 2014; Martínez Catalán et al., 2020). These complexes contain a thick stack of terranes with different origin and tectonothermal evolution. They include a variety of ophiolitic units that appear emplaced between continental or arc-derived terranes affected by two different Variscan high-P metamorphic events dated at c. 400 and 370 Ma (Arenas et al., 2014a). The presence of these ophiolites has allowed the identification of more than one suture in the Iberian Massif, with ages ranging between Ediacaran to Devonian.

In the SW Iberian Massif, forming part of the Ossa-Morena Complex, the c. 600 Ma Calzadilla Ophiolite occurs as tectonic slices imbricated with Ediacaran siliciclastic rocks of the so called Serie Negra Group (Fig.3). Both the ophiolite and the surrounding metasedimentary series have been interpreted as the remnants of an Ediacaran fore-arc basin opened in the most external section of the active margin of Gondwana (Arenas et al., 2018). The imbrication and final obduction of the ophiolite above the continental margin probably occurred in the Ediacaran – Early Cambrian boundary (Arenas et al., 2018; Díez Fernández et al., 2019).

In the NW of the Iberian Massif, the ophiolites considered in this work form part of the Órdenes and Cabo Ortegal allochthonous complexes. Equivalent ophiolites are present in the allochthonous complexes located more to the SE in the Portuguese region of Trás-os-Montes (Fig. 3; Martínez Catalán et al., 2020). Two ophiolitic units dated at c. 500 Ma have been described in the large Órdenes Complex of Galicia (Fig. 3). In the western part of this complex, the Bazar Ophiolite is defined by a mafic-ultramafic sequence characterized by a large geochemical variation. This unit was described as a ridge-derived ophiolite accreted below a dissected peri-Gondwanan volcanic arc in Early Ordovician times (Sánchez Martínez et al., 2012). Low-P granulite facies metamorphism recognized in the mafic rocks was dated at c. 475 Ma and is considered an indication of ridge-subduction. In the eastern part of the Órdenes Complex, the c. 500 Ma Vila de Cruces Ophiolite consists of a thick imbricate unit of greenschist facies mafic rocks, schists and phyllites, with a few levels of orthogneisses and serpentinites in the upper part of the unit. This Cambrian ophiolite was interpreted as a typical back-arc ophiolite based on its characteristic geochemical pattern (Arenas et al., 2007; Arenas and Sánchez Martínez, 2015). However, unlike the ophiolites described before, no evidence of a pre-Variscan obduction was found in the Vila de Cruces ophiolite. The tectonic fabrics dated in this ophiolite (c. 363-367 Ma, $^{40}Ar/^{39}Ar$ dating; Dallmeyer et al., 1997) indicate the accretion to an orogenic crust and the final subsequent obduction onto a

192 continental margin during the main Variscan orogenic events. These data seem to indicate
193 that large back-arc basins existed for a long period in the peri-Gondwanan realm.
194
195 Three different Middle Devonian ophiolites (c. 400 Ma) are mentioned in this work: the
196 Careón Ophiolite, in the eastern section of the Órdenes Complex, and the Purrido and
197 Moeche ophiolites, in the western and eastern parts of the Cabo Ortegal Complex,
198 respectively (Fig. 3). The Careón Ophiolite was the first ophiolite dated in the Iberian Massif,
199 and probably also the first ophiolite presented as a supra-subduction zone type in the
200 Variscan Orogen (Díaz García et al., 1999; Sánchez Martínez et al., 2007). Similar ages and
201 classification emerged successively for the Purrido and Moeche ophiolites (Arenas and
202 Sánchez Martínez, 2015). The protoliths of these ophiolites were generated in between the
203 two high-P metamorphic events characteristic of the Variscan Orogen. Considering this
204 chronology and the presence of very old zircon remnants in these ophiolites (Sánchez
205 Martínez et al., 2011), they were probably formed during the opening of an ephemeral
206 synorogenic basin during the main events of the Pangea assembly, either of pull-apart
207 (Arenas et al., 2014a) or supra-subduction zone type (Díez Fernández et al., 2020). This
208 buoyant oceanic lithosphere was likely obducted soon after its generation, as suggested by
209 $^{40}Ar/^{39}Ar$ ages of the amphibolite facies foliation of the Careón and Purrido ophiolites ranging
210 between c. 391 and 377 Ma (Peucat et al., 1990; Dallmeyer et al., 1997).
211
212 It is also relevant to note that a younger ophiolite (not considered in this work) has
213 been described in the Iberian Massif, the Beja-Acebuches Ophiolite, dated at c. 340-332 Ma
214 (Azor et al., 2008). This ophiolite is located at the northern boundary of the South Portuguese
215 Zone (Fig. 3). This boundary is considered the true main suture developed during the final
216 assembly of Pangea, because it separates Gondwana from the southern margin of Laurussia
217 (Figs. 1 and 3). Consequently, it represents the original location of the Rheic Ocean suture,
218 but this region was strongly reworked during the Variscan deformation which caused the

opening of a new syn-orogenic basin and the final obduction of a Carboniferous ophiolite (Díez Fernández et al., 2016).

Ophiolite sequences

Representative columns that show the architecture of the ophiolites described in this work can be seen in Figure 4. With the exception of the Bou Azzer Ophiolite, the mafic-ultramafic sequences considered in the peri-Gondwanan realm do not show typical mid-ocean ridge architectures. On the contrary, they appear as alternations of ultramafic units with other sections formed by gabbroic rocks and/or their metamorphic products, either amphibolites, greenschists or rare granulites. In these plutonic sections, tonalitic compositions are very rare, although they do exist. Typical mid-ocean ridge sections characterized by the presence of volcanic rocks and a sheeted dyke complex are in general absent. The general architecture of these ophiolites strongly suggests that they were formed in a tectonic setting different to that of mid-ocean ridges, probably in supra–subduction zone regions.

The architecture of the c. 700 Ma Bou Azzer Ophiolite described in Figure 4 is based on the map and cross sections presented by El Hadi et al. (2010). It is composed of a single c. 5-6 km thick ophiolite column lacking tectonic imbrications. However, the existence of internal imbrication cannot be ruled out because the ophiolite is unusually thick. In the ophiolite, a lower unit of ultramafic rocks, dominated by serpentinites, is followed by a plutonic unit of variably deformed gabbros and layered gabbros metamorphosed under amphibolite facies conditions. An upper section of undifferentiated volcanic rocks and dykes has been described in this ophiolite, immediately below the basal unconformity of the Tiddiline siliciclastic formation. Moreover, a set of scarce doleritic dykes intrude the peridotitic and gabbroic units, indicating a second magmatic event.

The column of the c. 600 Ma Calzadilla Ophiolite is characterized by a c. 1 km thick lower mafic-ultramafic unit and some upper imbrications of serpentinites and Ediacaran metagreywackes of the Serie Negra Group (Fig. 4; Arenas et al. 2018). The c. 800 m thick basal ultramafic section is composed of harzburgites, dunites, amphibole-bearing peridotites and some pyroxenites, which show moderate serpentinization. Distributed in the host dunites, some sectors contain abundant high-Al podiform chromitites (Merinero et al., 2013), typical of the mantle-crust transition zone (Moho discontinuity). These rocks may therefore be related to the contact between the ultramafic unit and the c. 200 m thick plutonic unit. The latter is exclusively formed by medium-coarse metagabbros metamorphosed under amphibolite facies conditions.

The c. 500 Ma Bazar Ophiolite is composed of two main slices with a total thickness of c. 5 km (Fig. 4; Sánchez Martínez et al., 2012). However, taking into account that the thickness of this ophiolite is significant, internal imbrications cannot be discarded, especially in the thicker mafic unit. The upper slice is the thickest and includes a lower section of moderately serpentinized ultramafic rocks which appear in complex alternations with a large diversity of gabbros, leucogabbros and tonalitic stocks. These plutonic rocks indicate high intrusive activity over the upper section of the lithospheric mantle. The mafic section is formed by gabbros, melagabbros, high-T amphibolites and common amphibolites. In the less deformed sectors, lens-shaped bodies of low-P mafic granulites account for an initial high-T metamorphic event affecting this unit.

The c. 500 Ma-aged Vila de Cruces Ophiolite consists of an imbrication of several slices that include mafic rocks, schists and phyllites (Arenas et al., 2007). The mafic rocks consist of highly sheared greenschists that, in the upper part of the unit, include some alternations of thin tonalitic orthogneisses and serpentinites. Distributed within the

greenschists, a few remnants of low to moderately sheared metagabbros can also be locally observed.

The Careón Ophiolite is the most representative unit for the c 400 Ma ophiolites, and also the one that was first dated and described in some detail (Díaz García et al., 1999; Sánchez Martínez et al., 2007). It consists of three slices that apparently repeat an oceanic mantle-crust transition zone. This paleo Moho region locally shows the development of metamorphic soles with evidence of high-T metamorphism. The larger intermediate slice, the Careón slice (Fig. 4), reaches a thickness of c. 1000 m, being constituted by a lower ultramafic section and an upper plutonic section, both with a similar thickness. The ultramafic section contains serpentinized peridotites, intruded by frequent stocks of gabbros, pegmatoid gabbros and doleritic dykes. The plutonic section is constituted by gabbros, layered gabbros and pegmatoid gabbros, which also appear intruded by numerous doleritic dykes (Díaz García et al., 1999). Included also in this group, the Purrido and Moeche ophiolites comprise thinner sequences of common metagabbroic amphibolites and sheared greenschists with some alternations of phyllites and minor serpentinites, respectively (Arenas and Sánchez Martínez, 2015).

Zircon U-Pb ages and Hf isotope composition

U-Pb ages and isotopic Hf data of 258 zircons from the investigated ophiolites are plotted in the U-Pb age (Ma) versus εHf(t) diagram of Figure 5. In this plot, the $^{206}Pb/^{238}U$ ages (of concordant analyses) were preferred for representation. This data collection contains all the published geochronological and isotopic information available for the ophiolites considered in this work. The data presented in Figure 5 clearly show the four age groups separated by c. 100 Ma gaps. The protoliths of these peri-Gondwanan ophiolites

were formed in the Neoproterozoic and the Paleozoic in four main events of generation of oceanic or transitional lithosphere, at c. 700, 600, 500 and 400 Ma.

Data from the Neoproterozoic c. 700 Ma-aged Bou Azzer Ophiolite are taken from the U-Pb data (SHRIMP) of a gabbro dated at 697 ± 6 Ma (El Hadi et al., 2010). However, isotopic Hf data were not obtained for zircon in this ophiolite and therefore it is not possible to make deductions about the associated isotopic sources. Just in order to plot the U-Pb ages in this diagram and compare the number of analyses, we have assigned arbitrarily depleted mantle εHf(t) values (Fig. 5). In the case of the c. 600 Ma Calzadilla Ophiolite, U-Pb ages (SHRIMP) and isotopic Hf (LA-ICP-MS) were obtained in a metagabbro dated at c. 598 ± 10 Ma (Arenas et al., 2018). εHf(t) values are in general higher than 10 and indicate a juvenile origin for the gabbroic protoliths (Fig. 5). However, scarce zircon data with εHf(t)< 8 may suggest limited isotopic mixing and interaction with older isotopic sources, which is in agreement with a peri-continental or peri-arc setting for this ophiolite.

Considered as a whole, the U-Pb zircon ages (LA-ICP-MS) of the Cambrian Bazar and Vila de Cruces ophiolites show an average age at c. 500 Ma (Fig. 5). In the Bazar Ophiolite, these ages correspond to an ophiolitic metagabbro dated at 495 ± 2 Ma (Sánchez Martínez et al., 2012). Data for the Vila de Cruces Ophiolite has been obtained in a metagabbro and three tonalitic orthogneisses (Sánchez Martínez et al., 2020, this volume). All εHf(t) data plot around the depleted mantle evolution trend, suggesting juvenile or near-juvenile isotopic sources for the protoliths, even in the case of the tonalitic rocks (Fig. 5). One of this tonalitic orthogneisses yielded the first U-Pb age for this ophiolite at c. 497 ± 4 Ma (TIMS; Arenas et al., 2007).

The available age data for the Devonian ophiolites are based on the U-Pb zircon dating of a leucocratic metagabbro of the Careón Unit (395 ± 2 Ma, TIMS; Díaz García et al., 1999), two metagabbroic amphibolites of the Purrido Unit (395 ± 2 Ma, SHRIMP; Sánchez

Martínez et al., 2011) and a mylonitic greenschist of the Moeche Unit (400 ± 3 Ma, LA-ICP-MS; Arenas et al., 2014b). The isotopic Hf zircon data in these ophiolites (Purrido and Moeche ophiolites; LA-ICP-MS) show two different populations, with contrasted εHf(t) values (Fig. 5). A first group of zircons with rather high εHf(t) values reveals the presence of juvenile magmas in the origin of these Devonian ophiolites. However, another group of zircons show negative εHf(t) values, which indicate the participation of older isotopic sources. Taken together, the isotopic Hf data define a marked mixing line that should have been active during the generation and emplacement of the original mafic magmas (Fig. 5). This evolution can only be generated during the interaction of the mafic protoliths with a region characterized by the presence of old isotopic sources, i.e. a continental domain or a volcanic arc rooted by an old continental basement.

Immobile trace element geochemistry and geodynamic setting

The geochemistry of immobile elements has proven to be the most efficient tool to decipher the dynamic setting of ophiolite generation (Pearce and Cann, 1971; Pearce, 1996, 2014). The origin of the described ophiolites has been investigated using a database of 117 chemical analyses of immobile trace elements. The database is sourced from published information, with the exception of the analyses of the Bou Azzer Ophiolite, which were obtained for this study. The database includes: 12 analyses from the Bou Azzer Ophiolite, including gabbros (6 samples) and doleritic dykes (6 samples); 10 analyses of gabbros from the Calzadilla Ophiolite (Arenas et al., 2018); 16 analyses from the Bazar Ophiolite (Sánchez Martínez et al., 2012), including metagabbros (5 samples), amphibolites (7 samples) and mafic granulites (4 samples); 16 analyses from the Vila de Cruces Ophiolite (Arenas et al., 2007), including metagabbros (4 samples) and greenschists (12 samples); 32 analyses from the Careón Ophiolite (Sánchez Martínez et al., 2007), including gabbros (15 samples), doleritic dykes (9 samples) and amphibolites (8 samples); 18 amphibolites from the Purrido

357 Ophiolite (Sánchez Martínez et al., 2011) and 13 greenschists from the Moeche Ophiolite
358 (Arenas et al., 2014b).
359
360 The Nb/Yb versus Th/Yb diagram (Fig. 6) separates the field of mafic magmas
361 generated in non-subduction settings (N-MORB-OIB array), from the domain where the
362 magmas derived from supra-subduction zone settings. These regions are characterized by
363 mantle modification by subduction-derived fluids and the composition of melts is displaced
364 towards higher Th/Yb ratios (Pearce, 2014). Magmas modified by assimilation of continental
365 crust form diagonal lines in which both Th and Nb are modified. These lines define trends
366 that extend from the N-MORB-OIB array into the island-arc or continental-arc fields. These
367 magmas can also show a characteristic high dispersion in this diagram. This geochemical
368 pattern is considered a diagnostic feature for back-arc basin settings and has also been
369 described in ridge subduction and, more rarely, in continental margin settings (Pearce,
370 2014). The distribution of the peri-Gondwanan ophiolitic basaltic rocks in this diagram clearly
371 shows that most of them, if not all, pertain to supra-subduction type ophiolites. These
372 ophiolites are hence derived from oceanic or transitional lithosphere formed above peri-
373 Gondwanan subduction zones, after partial melting of mantle wedges modified by the ascent
374 fluids generated during dehydration of the subducted slab. The mafic rocks of the Bou Azzer,
375 Calzadilla and Vila de Cruces ophiolites plot far from the MORB-OIB array, in regions typical
376 of magmas formed in supra-subduction zone settings (SSZ), near volcanic arcs (Fig. 6). The
377 geochemistry of the Bazar Ophiolite is much more complex because it is characterized by
378 the presence of different magma types and larger dispersion (Fig. 6). This pattern has been
379 described in magmas formed in settings characterized by ridge subduction (Pearce, 2014).
380 This was the dynamic setting initially suggested for the Bazar Ophiolite, based on the
381 accretion of this ophiolite immediately following the generation of the mafic protoliths, with
382 the development of a prograde low to intermediate-P granulite facies metamorphism
383 (Sánchez Martínez et al., 2012). The composition of the Devonian Careón, Purrido and
384 Moeche ophiolites is also indicative of their generation in a supra-subduction zone setting.

Taking together, these three coeval ophiolites show a projection characterized by a large dispersion (Fig. 6). Moreover, the plotted analyses define diagonal lines passing from the MORB-OIB array to the SSZ field, which is compatible with assimilation of continental material during the ascent of the mafic magmas in a supra-subduction zone setting (Pearce, 2014).

The Ti versus V diagram (Fig. 7) can be used to refine the origin of mafic magmas previously characterized as SSZ types in the Nb/Yb vs. Th/Yb diagram (Shervais, 1982; Pearce, 2014). Excluding the unusual composition of the mafic rocks of the Bazar Ophiolite, most of the data plot in the field of basalts generated in slab-distal regions, either in back-arc basin or fore-arc basin settings, although the rocks of the Vila de Cruces Ophiolite are divided into slab-proximal and slab-distal fields (Fig. 7). Additionally, the rocks of the Ediacaran Calzadilla Ophiolite appear as typical boninites, according to the previous classification of the mafic rocks of this ophiolite (Arenas et al., 2018). In the case of the older Bou Azzer ophiolite, the group of mafic rocks that correspond to boninite compositions (Fig. 7) includes the younger doleritic dykes that intrude all levels of the ophiolite, including the harzburgitic mantle. Boninitic magmas are considered to be generated from ultra-depleted harzburgitic sources, which result from previous melting events that removed most of the incompatible elements (Dobson et al., 2006). Repetitive melting affects a stable mantle wedge, i.e. a mantle section not affected by significant convection. The Bou Azzer Ophiolite shows the characteristics of a subduction-initiation ophiolite, where magmas in this diagram evolve from MORB-like when subduction begins, to more boninite-like as subduction proceeds (Pearce, 2014).

Discussion

SSZ ophiolite: the common ophiolitic type in the peri-Gondwanan realm

Taking into account the distribution of the investigated ophiolites in Iberia and the Anti-Atlas domain, their lithological constitution, chronology and geochemistry, it can be concluded that the SSZ ophiolite type represents the most characteristic ophiolitic type in the NW African-Iberian peri-Gondwanan realm. Consequently, the NW African-Iberian margin of Gondwana was a large region where new oceanic or transitional lithosphere was generated in successive events in SSZ contexts (Fig. 8). This conclusion is in good agreement with previous studies pointing out that the NW African-Iberian margin of Gondwana was an active margin at least between Cryogenian and Cambrian times, i.e. a large region where subduction was active during a long time (Pereira et al., 2012; Linnemann et al., 2014; Albert et al., 2015; Fuenlabrada et al., 2016, 2020; Rojo-Pérez et al., 2019). There is not clear evidence for typical MORB compositions in the mafic rocks of the considered peri-Gondwanan ophiolites. The cold and dense lithosphere of the peri-Gondwanan oceans was continuously subducted, without any detected MORB remains in the investigated ophiolites. Conversely, the newly created SSZ oceanic lithospheres were characterized by buoyant nature in relation to accretionary processes. In the cases were the new oceanic lithosphere was generated in fore-arc realms, it was rapidly transferred to the peri-Gondwanan volcanic-arc system. On the contrary, the oceanic lithosphere generated in back-arc basins was preserved with little change and progressively covered by thick sedimentary series. These back-arc domains were finally deformed and obducted during the assembly of Pangea.

It has been proposed that the obduction of the Bou Azzer Ophiolite took place in the context of a basin located in between the proto-Gondwanan mainland and a volcanic arc at c. 579-578 Ma (El Hadi et al., 2010). The generation in Neoproterozoic times (at c. 700 Ma) of the oceanic lithosphere represented by this ophiolite, occurred near the most external section of Reguibat, in the NE margin of the West African Craton. This location and the generation of boninitic magmas following the extrusion of common SSZ basalts, suggest a typical external fore-arc domain as the most probable dynamic setting for the formation of the

441 Bou Azzer Ophiolite (Fig. 8). This ophiolite was likely generated above the peri-proto-
442 Gondwanan trench where the litosphere of the Pharusian Ocean was subducted (Fig. 8).
443 This ophiolite was likely obducted onto a section of the West African Craton covered by
444 rifting-related sedimentary series (El Hadi et al., 2010). A similar fore-arc generation has
445 been proposed for the Calzadilla Ophiolite, where the composition of the gabbroic rocks is
446 also boninitic (Fig. 8). This ophiolite was probably obducted onto the continental margin at c.
447 540 Ma, according to U-Pb zircon age and detailed structural data that allow reconstructing
448 the tectonothermal evolution underwent by this ophiolite (Arenas et al., 2018; Díez
449 Fernández et al., 2019). In the case of the c. 500 Ma ophiolites, the scenario seems more
450 varied. The Bazar Ophiolite was probably also generated in a fore-arc setting, according to
451 its geochemical characteristics and prompt accretion at c. 475 Ma (Sánchez Martínez et al.,
452 2012). However, the Vila de Cruces Ophiolite is characterized by a thick sedimentary cover
453 and was not apparently affected by deformation and metamorphism until the onset of the
454 Variscan deformation. This suggests that the protoliths of this ophiolite were preserved in a
455 long-lasting stable back-arc basin (Fig. 8).
456
457 The generation of the Devonian ophiolites appears to have been much more
458 complex. The protoliths of these ophiolites were generated in between the two high-P
459 Variscan metamorphic events dated at c. 400 and 370 Ma (Arenas et al., 2014a). Their
460 chronology (c. 400 Ma) hence implies that they were generated in relation to some type of
461 basin opened in the middle of the already assembled Pangea (Fig. 9). Pull-apart or supra-
462 subduction zone models have been considered for the opening of this basin (Arenas et al.,
463 2014a; Díez Fernández et al., 2020). However, our current knowledge may not be detailed
464 enough yet to decipher the tectonic context where this basin was generated. Different
465 possibilities for related subduction and/or strike-slip tectonics exist. Besides, the generation
466 of this SSZ oceanic crust in the middle of Pangea in Devonian times, implies participation of
467 a mantle section that was previously hydrated during long subduction. This mantle section

was apparently located in the distal margin of Gondwana that was affected by collision with Laurussia (Arenas et al., 2016; Díez Fernández et al., 2016).

100 Ma cycles of mantle upwelling

The NW African-Iberian margin of Gondwana faced an ocean for a long time, probably before the amalgamation of Rodinia (Torsvik, 2003). During most of this period, peri-Gondwanan subduction zones were active, favoring continuous hydration and episodic partial melting of the related mantle wedges. This margin was also characterized by a dynamic setting where frequent generation of new supra-subduction oceanic or transitional oceanic crust occurred (Fig. 8). According to the chronology of the peri-Gondwanan ophiolites, new oceanic lithospheres were generated in cycles separated by c. 100 Ma. The reason for this cyclicity is unclear, but in any case the peri-Gondwanan ophiolites clearly highlight these cycles and are therefore a key starting point in furthering our understanding of the scenarios involved.

First, it can be proposed that each new event of generation of oceanic lithosphere was triggered by increasing rates of partial melting in the mantle wedge above the subduction zone. These episodic events occurred in the context of the large peri-Gondwanan arc-system, giving rise to more or less ephemeral fore-arc or back-arc basins with SSZ type oceanic or transitional lithosphere. The activation of higher rates of mantle partial melting can be related to accelerate fluid percolation in the mantle wedge, which in turn indicates increasing subduction rates. Variable subduction rates can be caused by changes in the intensity of mantle upwelling in the central ridges of the peri-Gondwanan oceans. Since we have found no trace of MORB-type lithosphere in the peri-Gondwanan ophiolites, it can be concluded that the whole peri-Gondwanan oceans were entirely consumed by subduction. However, these were probably large oceans with central ridges active during a long period,

according to the activity of the peri-Gondwanan volcanic-arc systems. The origin of the revealed cyclicity of mantle upwelling in the peri-Gondwanan oceans ridges can be related to deep episodic mantle convection (Richter, 1973; Coltice et al., 2019). Cycles of more active deep mantle convection can explain episodic mantle upwelling, transition from low to fast type mid-ocean ridges, higher subduction rates, and finally, the dynamic context for the episodic generation of new supra-subduction zone type oceanic or transitional peri-Gondwanan lithosphere in regions undergoing extension. The causes for these evenly spaced c. 100 Ma fast-ridge cycles may be connected with secular long term heat exchange between the outer core and the lower mantle. Different long-term and short-term cycles of mantle activity since Paleoproterozoic times have been recently revealed on Earth (Li et al., 2019; Mitchell et al., in press). The cyclicity discovered in the generation of new oceanic crust in the peri-Gondwanan realm, provides first order evidence to further understanding mantle cycles since Neoproterozoic times. In this context, the peri-Gondwanan ophiolites appear as key units that can unexpectedly provide valuable information on this question.

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775
776 **Figure captions**
777
778 **Fig. 1**. Reconstruction of a part of Pangea at the end of the Paleozoic with the distribution of
779 orogens in the Baltica-Laurentia-Avalonia-Gondwana junction. The general structure and
780 domains of the Variscan Orogen is shown, as well as the location of the ophiolites
781 described in this work (stars): 1) Bou Azzer Ophiolite; 2) Calzadilla Ophiolite; 3) Villa de
782 Cruces Ophiolite; 4) Bazar Ophiolite; 5) Careón Ophiolite; 6) Purrido Ophiolite; 7) Moeche
783 Ophiolite. Pangea map based on Martínez Catalán et al. (2009) and Díez Fernández and
784 Arenas (2015).
785
786 **Fig. 2**. General map of the Anti-Atlas Domain showing the location of the Neoproterozoic
787 Bou Azzer Ophiolite. This region represents the northern boundary of the West African
788 Craton. Several tectonic windows or inliers contain Paleoproterozoic (2200-2000 Ma) to
789 Late Ediacaran formations, which occur below unconformable thick Paleozoic series
790 (Michard et al., 2010; Brahimi et al., 2018; Soulaimani et al., 2019). The eastern part of
791 the Anti-Atlas Domain is affected by Variscan deformation that developed a generation of
792 large folds with axial traces trending NE-SW. Modified after Michard et al. (2010).
793
794 **Fig. 3**. Terrane distribution and geotectonic zones in the Iberian Massif (Díez Fernández and
795 Arenas, 2015; Arenas et al., 2016b), and location of the Neoproterozoic and Paleozoic

ophiolites described in this work. Abbreviations: AF, Azuaga Fault; BAO, Beja-Acebuches Ophiolite; CA, Carvalhal Amphibolites; CF, Canaleja Fault; CMU, Cubito-Moura Unit; BCU, Badajoz-Córdoba Unit; ET, Espina Thrust; HF, Hornachos Fault; IOMZO, Internal Ossa-Morena Zone Ophiolites; LLF, Llanos Fault; MLF, Malpica-Lamego Fault; OF, Onza Fault; OVD, Obejo-Valsequillo Domain; PG-CVD, Puente Génave-Castelo de Vide Detachment; PRF, Palas de Rei Fault; PTF, Porto-Tomar Fault; RF, Riás Fault; VF, Viveiro Fault.

Fig. 4. Representative schematic columns for some of the Neproterozoic and Paleozoic ophiolites of the Moroccan Anti-Atlas and the Iberian Massif.

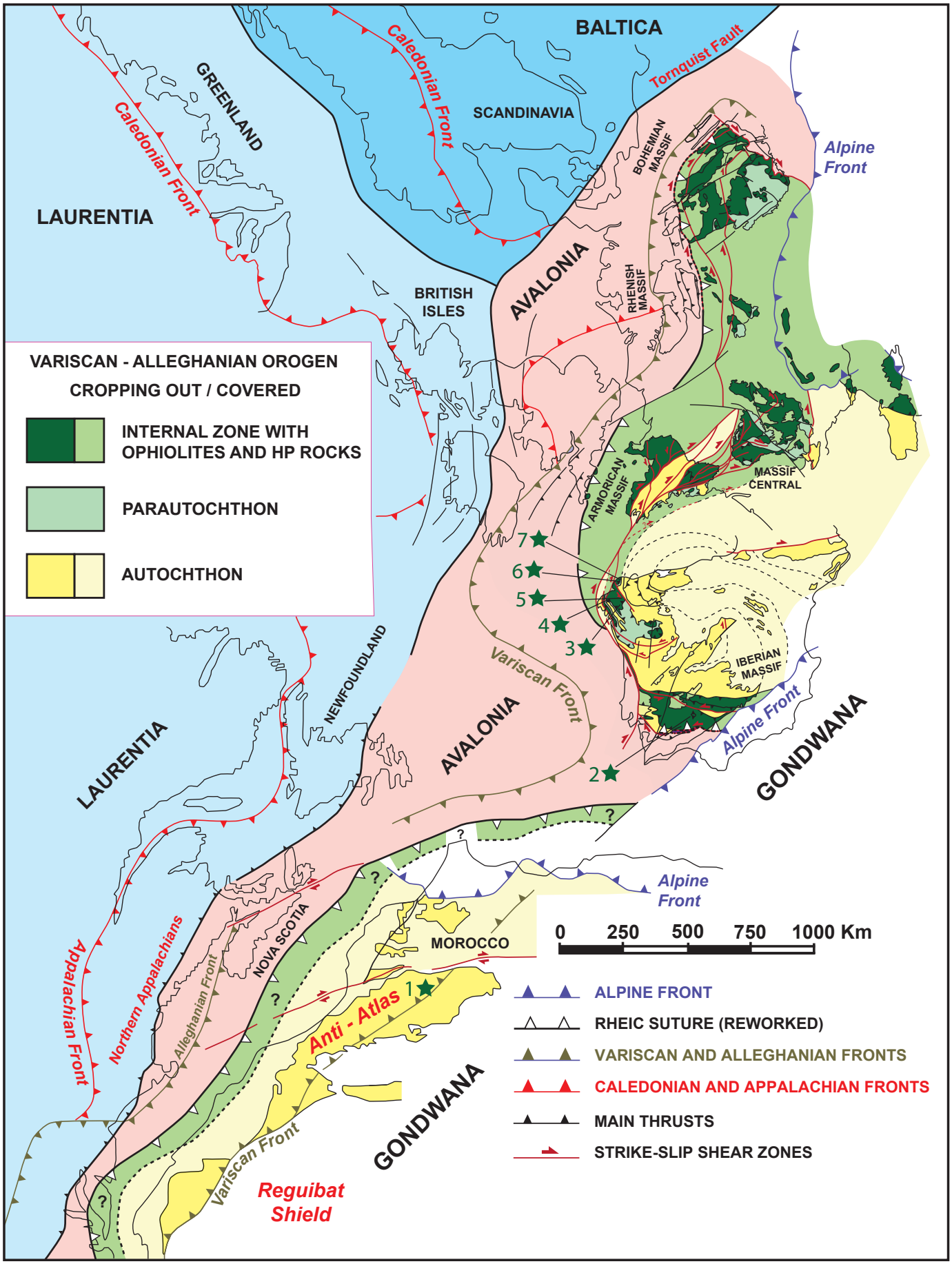
Fig. 5. Hf isotope evolution diagram showing combined U-Pb and Lu-Hf data of all available zircon analyses in the described ophiolites. $\varepsilon Hf_{(t)}$ values were considered close DM for the c. 700 Ma Bou Azzer Ophiolite, as isotopic Hf analyses in zircon have not been published. Oblique colored bands represent crustal evolution trends for Eburnean and Cadomian DM derived rocks. Adaptive Kernel Density Estimation of analyzed zircon with Lu-Hf systematics is represented in grey, with binwidth of histograms built at 20 Ma (Density Plotter5.0 software; Vermeesch, 2012). CHUR, chondritic uniform reservoir; DM, depleted mantle; MORB, mid-ocean ridge basalt. DM, MORB and crustal trends were calculated as described by Albert et al, 2015.

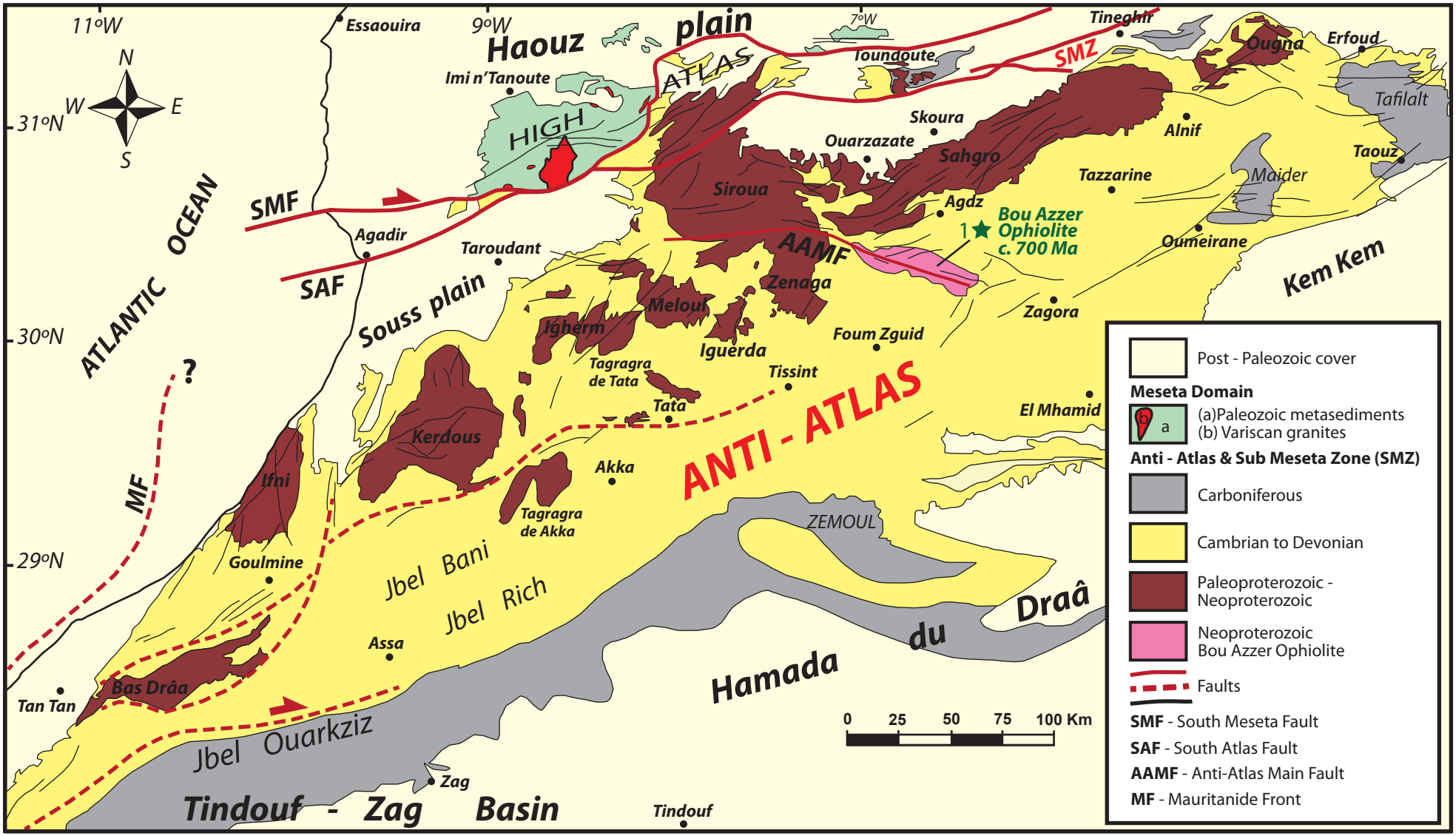
Fig. 6. Th/Yb versus Nb/Yb diagram (Pearce 2008, 2014) for the ophiolites described in this work (geochemical data from 117 mafic samples). This diagram allows differentiate the tectonic settings in which the ophiolites were generated. The compositions of mid-ocean ridge ophiolites follow the N-MORB-OIB array. However, supra-subduction zone ophiolites are distributed above this array in the regions where oceanic or continental arcs compositions are represented.

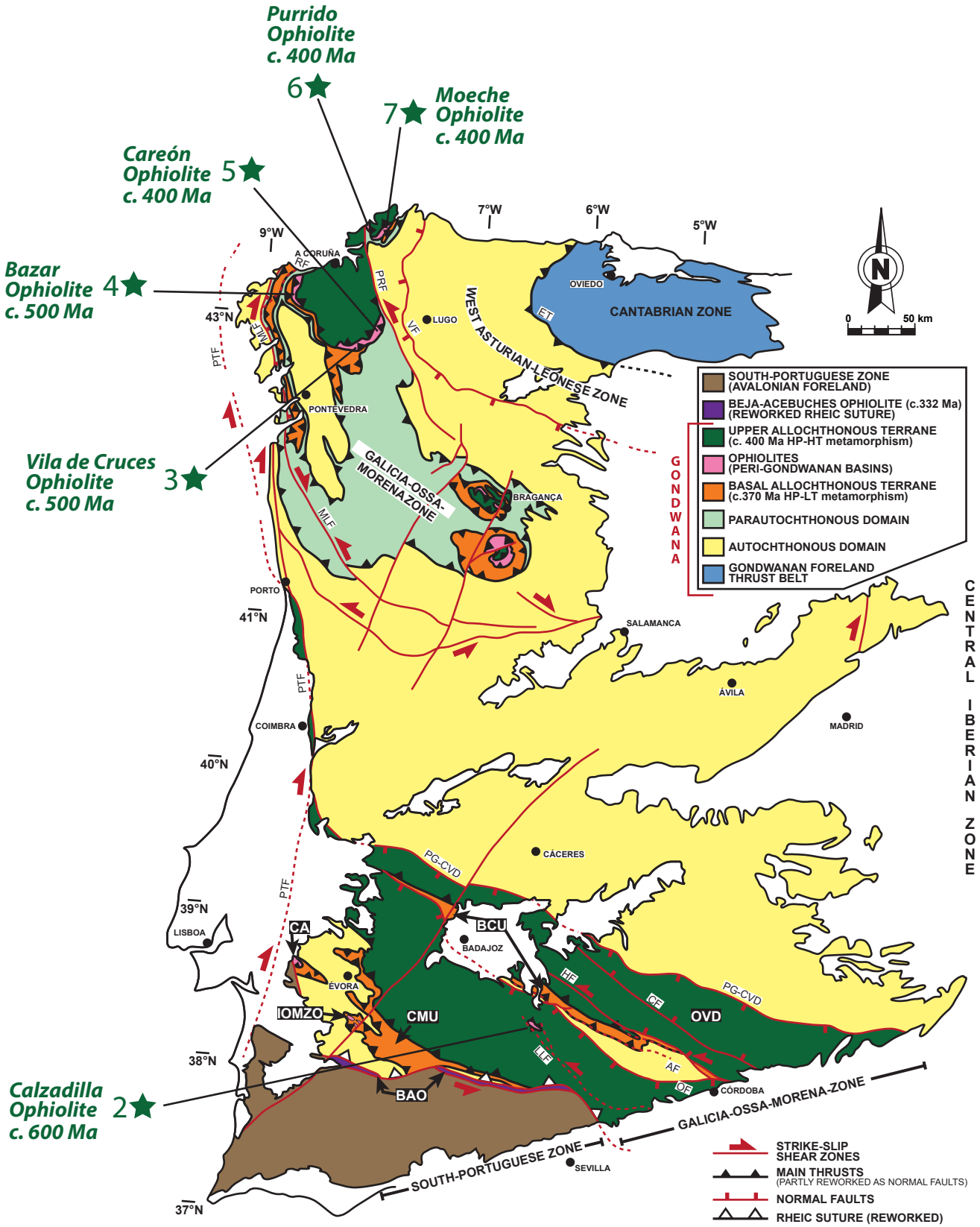
824 **Fig. 7**. Ti-V plot (Shervais, 1982; Pearce, 2014) for the composition of the ophiolites
825 described in the text (n = 117). This diagram is used to differentiate mid-ocean ridge
826 basalts (MORB), island arc tholeiites (IAT) and boninite magma types. However, used
827 after the previous Th/Yb versus Nb/Yb diagram (Fig. 6), once the existence of MORB
828 compositions has been ruled out, this diagram allows to recognize the composition of
829 back-arc basin or fore-arc basin basalts (BABB and FAB) generated in slab-proximal or
830 slab-distal settings.
831
832 **Fig. 8.** Paleogeographic context in the periphery of NW African-Iberian Gondwana and proto-
833 Gondwana between c. 700 Ma and c. 500 Ma. A) Opening of the Reguibat fore-arc basin
834 above the associated Reguibat trench, in the western branch of the Pharusian Ocean
835 (Stampfli et al., 2013). The Reguibat fore-arc basin is considered the dynamic setting for
836 the generation of the mafic protoliths of the Bou Azzer Ophiolite. B) Obduction of the Bou
837 Azzer Ophiolite at c. 653-640 Ma (El Hadi et al., 2010) occurred during the closure of the
838 Pharusian Ocean and the development of the Trans Saharan Orogen (Brahimi et al.,
839 2018). This Pan-African Orogen is part of the complex interactions between crustal blocks
840 that finally assembled Gondwana at c. 600 Ma. In the NW African-Iberian margin of
841 Gondwana, subduction of the lithosphere of the Panafrican Ocean probably caused the
842 development of a long Cadomian fore-arc basin, associated with the long well-dated peri-
843 Gondwanan volcanic arc (Linnemann et al., 2014; Albert et al., 2015). This fore-arc basin
844 is considered the dynamic context where the protoliths of the Calzadilla Ophiolite were
845 generated. C) Obduction of the Calzadilla Ophiolite in the Ediacaran–Early Cambrian
846 boundary occurred during complex interaction between the fore-arc basin and the volcanic
847 arc (Arenas et al., 2018; Díez Fernández et al., 2019). Later on, at c. 500 Ma, a back-arc
848 basin opened along the external margin of Gondwana pulling away sections of the
849 volcanic arc, still active for some time in both sides of this basin (Arenas et al., 2007).
850 Generation of this back-arc basin was associated with the pronounced extensional event
851 that affected the peri-Gondwana domain, which finally caused the rifting of the Avalonian

terrane and the opening of the Rheic Ocean (Nance et al., 2010). The protoliths of the Vila de Cruces Ophiolite represent the oceanic or transitional lithosphere generated in this back-arc basin.

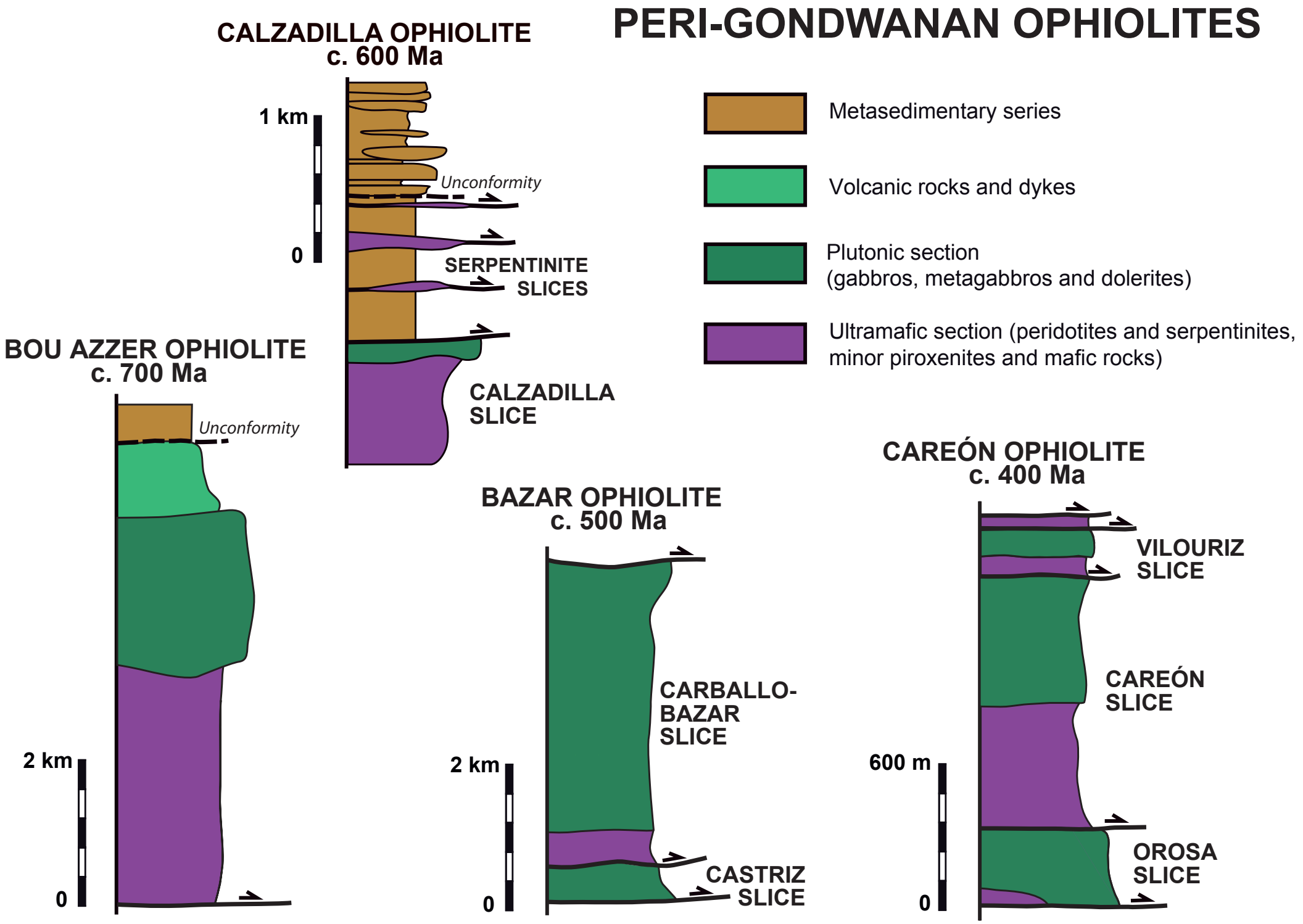
Fig. 9. Highly schematic reconstruction of the Anti Atlas–Iberia domain showing the probable distribution of the peri-Gondwanan ophiolites at the beginning of the Variscan deformation. The ophiolites dated at c. 400 Ma represent an ephemeral intraorogenic basin opened at c. 395 Ma and shortly accreted to the early Variscan orogenic wedge at c. 385-380 Ma (Arenas et al., 2014a; Díez Fernández et al., 2020). The back-arc basin represented by the Vila de Cruces Ophiolite was affected later by the advancing deformation and its lithologies were incorporated to the orogenic wedge in a lower position (Arenas et al., 2016a; Díez Fernández et al., 2016). Continuity of the ophiolites in the intermediate section between Avalonia and the Anti Atlas is speculative as the most internal Variscan domain is actually submerged in this region. However the westward continuation of the most deformed sectors of the Variscan Orogen, those including ophiolites and high-P units, can be expected according to the position of the boundary between Avalonia and the margin of Gondwana. This boundary represents the Rheic Ocean Suture. The origin of the described ophiolites, all of them derived from long fore-arc or back-arc basins, suggests that its initial geometry in the Variscan Orogen should correspond to units with significant extent along the strike of the Gondwana margin. These ophiolitic units were accreted to the orogenic wedge in between others continental terranes which represent different sections of the Gondwana margin. The location of the Visean Beja-Acebuches Ophiolite in SW Iberia is also shown. The position of Iberia, British Isles and Anti Atlas is only a reference and does not represent their exact location at the end of the Pangea assembly (Variscan Orogeny in this region).

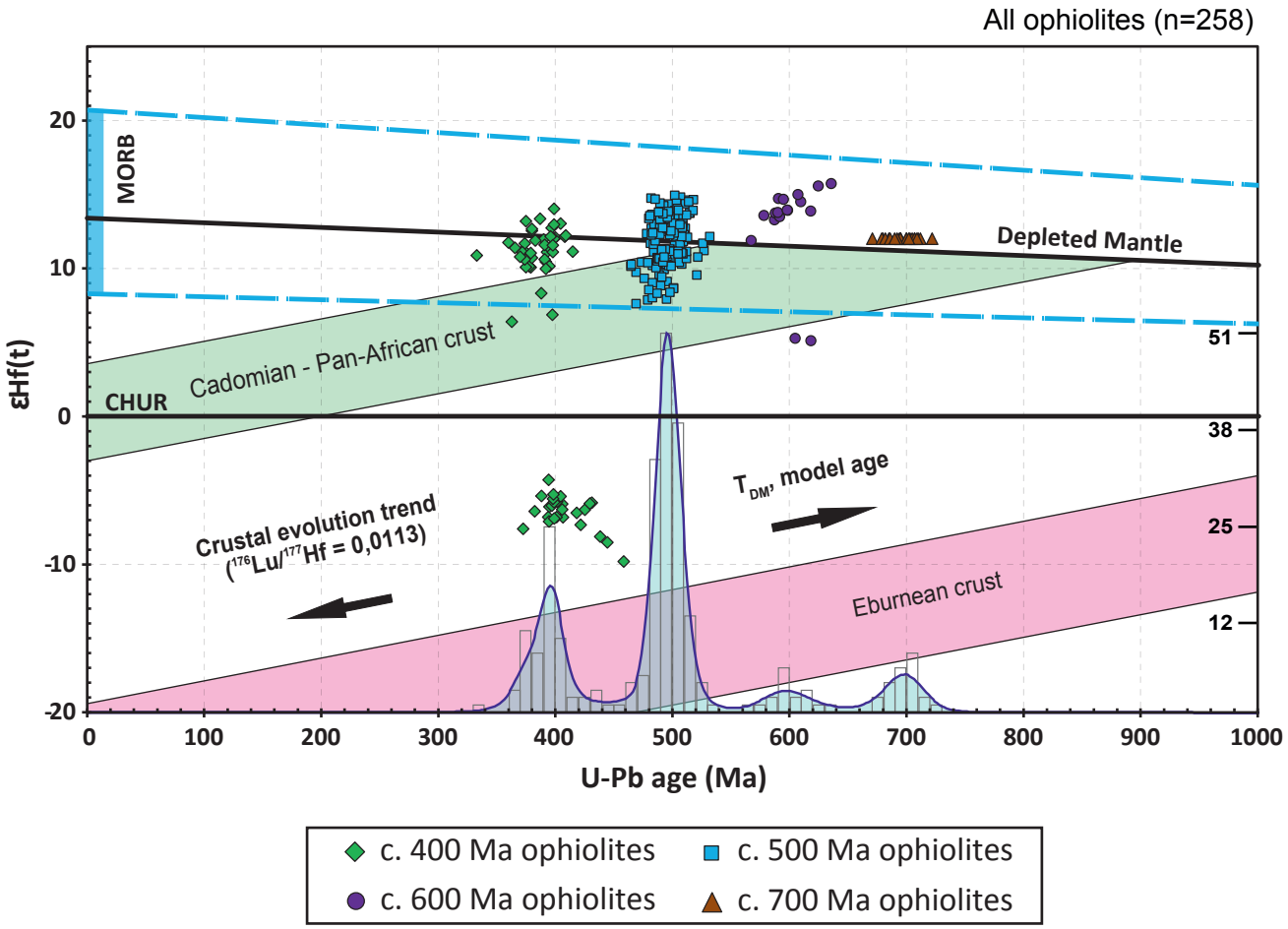

BALTICA
Tornquist Fault
Caledonian Front
SCANDINAVIA
GREENLAND
Caledonian Front
LAURENTIA
BRITISH ISLES
AVALONIA
BOHEMIAN MASSIF
RHENISH MASSIF
Alpine Front
ARMORICAN MASSIF
MASSIF CENTRAL
IBERIAN MASSIF
Variscan Front
Alpine Front
GONDWANA
VARISCAN - ALLEGHANIAN OROGEN
CROPPING OUT / COVERED
INTERNAL ZONE WITH OPHIOLITES AND HP ROCKS
PARAUTOCHTHON
AUTOCHTHON
7
6
5
4
3
2
1
NEWFOUNDLAND
LAURENTIA
AVALONIA
GONDWANA
Alpine Front
MOROCCO
NOVA SCOTIA
Appalachian Front
Northern Appalachians
Alleghanian Front
Anti - Atlas
Variscan Front
Reguibat Shield
0 250 500 750 1000 Km
ALPINE FRONT
RHEIC SUTURE (REWORKED)
VARISCAN AND ALLEGHANIAN FRONTS
CALEDONIAN AND APPALACHIAN FRONTS
MAIN THRUSTS
STRIKE-SLIP SHEAR ZONES


11°W
9°W
7°W
31°N
30°N
29°N
N
S
W
E
Essaouira
Haouz plain
ATLAS
Imi n'Tanoute
HIGH
Toundoute
SMZ
Tineghir
Ougna
Erfoud
Tafilalt
Skoura
Ouarzazate
Sahgro
Alnif
Taouz
Tazzarine
Maider
Siroua
Agdz
Bou Azzer Ophiolite c. 700 Ma
Oumeirane
Kem Kem
SMF
AAMF
Agadir
Taroudant
SAF
Souss plain
ATLANTIC OCEAN
Zenaga
Melouk
Igherm
Zagora
Foum Zguid
Iguerda
Tagragra de Tata
Tissint
Tata
El Mhamid
ANTI - ATLAS
Kerdous
Akka
Ifni
MF
Tagragra de Akka
ZEMOUL
Goulmine
Jbel Bani
Jbel Rich
Draâ
Assa
Hamada du
Bas Drâa
Tan Tan
Jbel Ouarkziz
Zag
Tindouf - Zag Basin
Tindouf
0 25 50 75 100 Km
Post - Paleozoic cover
Meseta Domain
(a)Paleozoic metasediments
(b) Variscan granites
Anti - Atlas & Sub Meseta Zone (SMZ)
Carboniferous
Cambrian to Devonian
Paleoproterozoic - Neoproterozoic
Neoproterozoic Bou Azzer Ophiolite
Faults
SMF - South Meseta Fault
SAF - South Atlas Fault
AAMF - Anti-Atlas Main Fault
MF - Mauritanide Front


Purrido
Ophiolite
c. 400 Ma
6
7
Moeche
Ophiolite
c. 400 Ma
Careón
Ophiolite
c. 400 Ma
5
Bazar
Ophiolite
c. 500 Ma
4
Vila de Cruces
Ophiolite
c. 500 Ma
3
Calzadilla
Ophiolite
c. 600 Ma
2
9°W
7°W
6°W
5°W
43°N
41°N
40°N
39°N
38°N
37°N
A CORUÑA
LUGO
OVIEDO
PONTEVEDRA
PORTO
COIMBRA
LISBOA
SALAMANCA
ÁVILA
MADRID
CÁCERES
BADAJOZ
ÉVORA
SEVILLA
CÓRDOBA
BRAGANÇA
CANTABRIAN ZONE
WEST ASTURIAN-LEONESE ZONE
GALICIA-OSSA-MORENA ZONE
SOUTH-PORTUGUESE ZONE
CENTRAL IBERIAN ZONE
GONDWANA
PRF
VF
ET
MLF
PTF
PG-CVD
CA
BCU
IOMZO
CMU
BAO
OVD
HF
CF
LF
AF
OF
0
50 km
SOUTH-PORTUGUESE ZONE (AVALONIAN FORELAND)
BEJA-ACEBUCHES OPHIOLITE (c.332 Ma) (REWORKED RHEIC SUTURE)
UPPER ALLOCHTHONOUS TERRANE (c. 400 Ma HP-HT metamorphism)
OPHIOLITES (PERI-GONDWANAN BASINS)
BASAL ALLOCHTHONOUS TERRANE (c.370 Ma HP-LT metamorphism)
PARAUTOCHTHONOUS DOMAIN
AUTOCHTHONOUS DOMAIN
GONDWANAN FORELAND THRUST BELT
STRIKE-SLIP SHEAR ZONES
MAIN THRUSTS
(PARTLY REWORKED AS NORMAL FAULTS)
NORMAL FAULTS
RHEIC SUTURE (REWORKED)

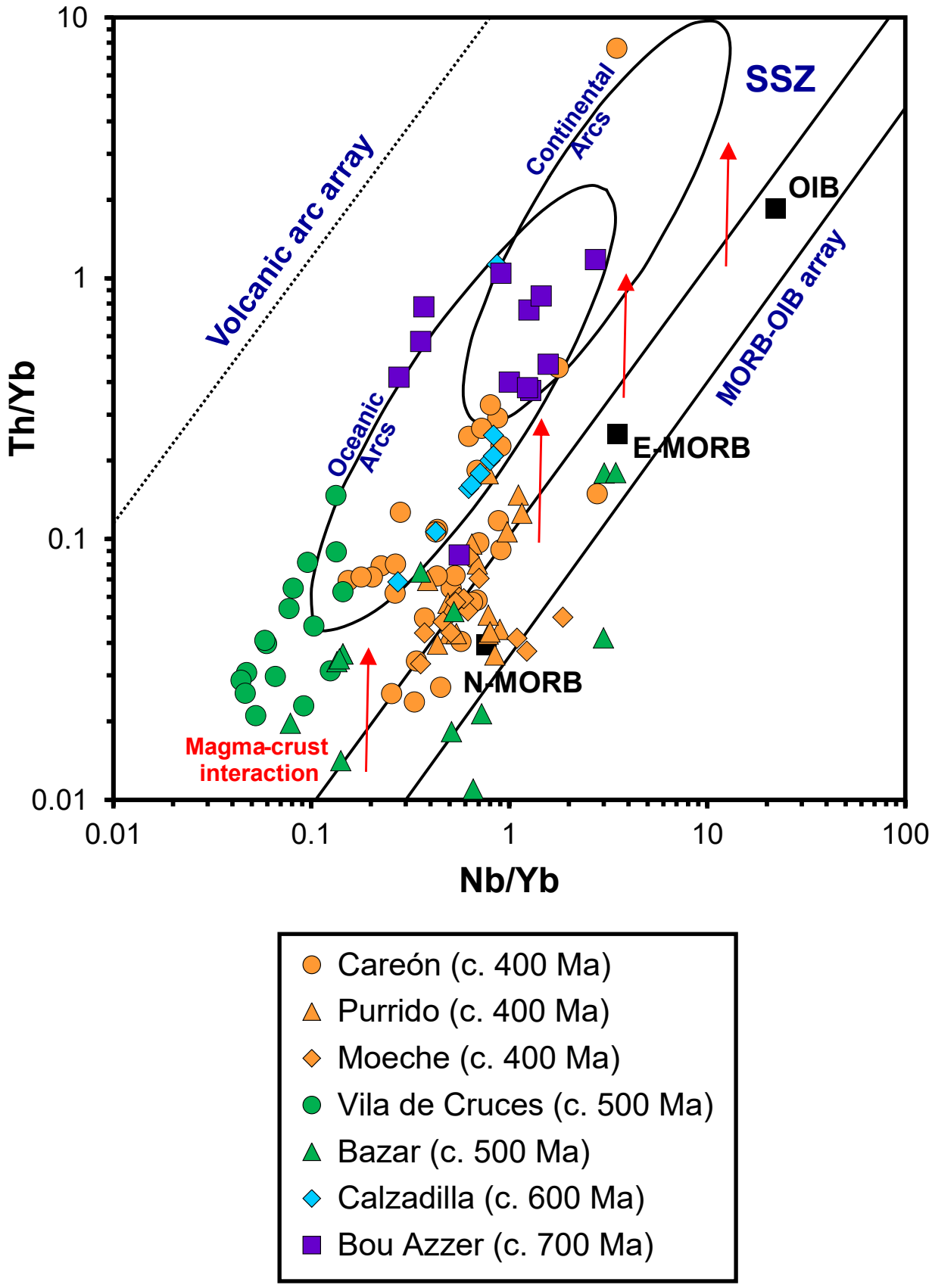
PERI-GONDWANAN OPHIOLITES



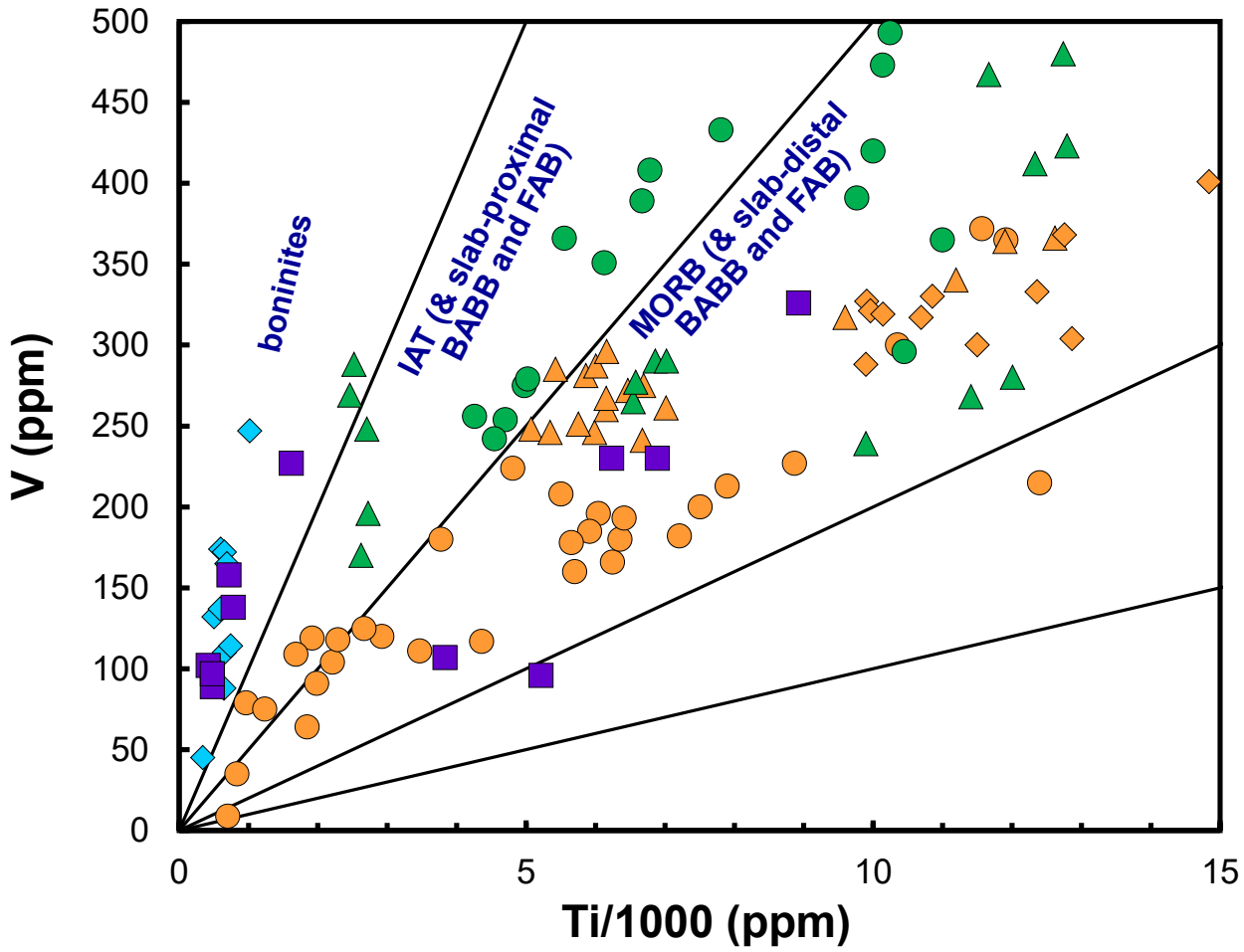


◆ c. 400 Ma ophiolites ■ c. 500 Ma ophiolites

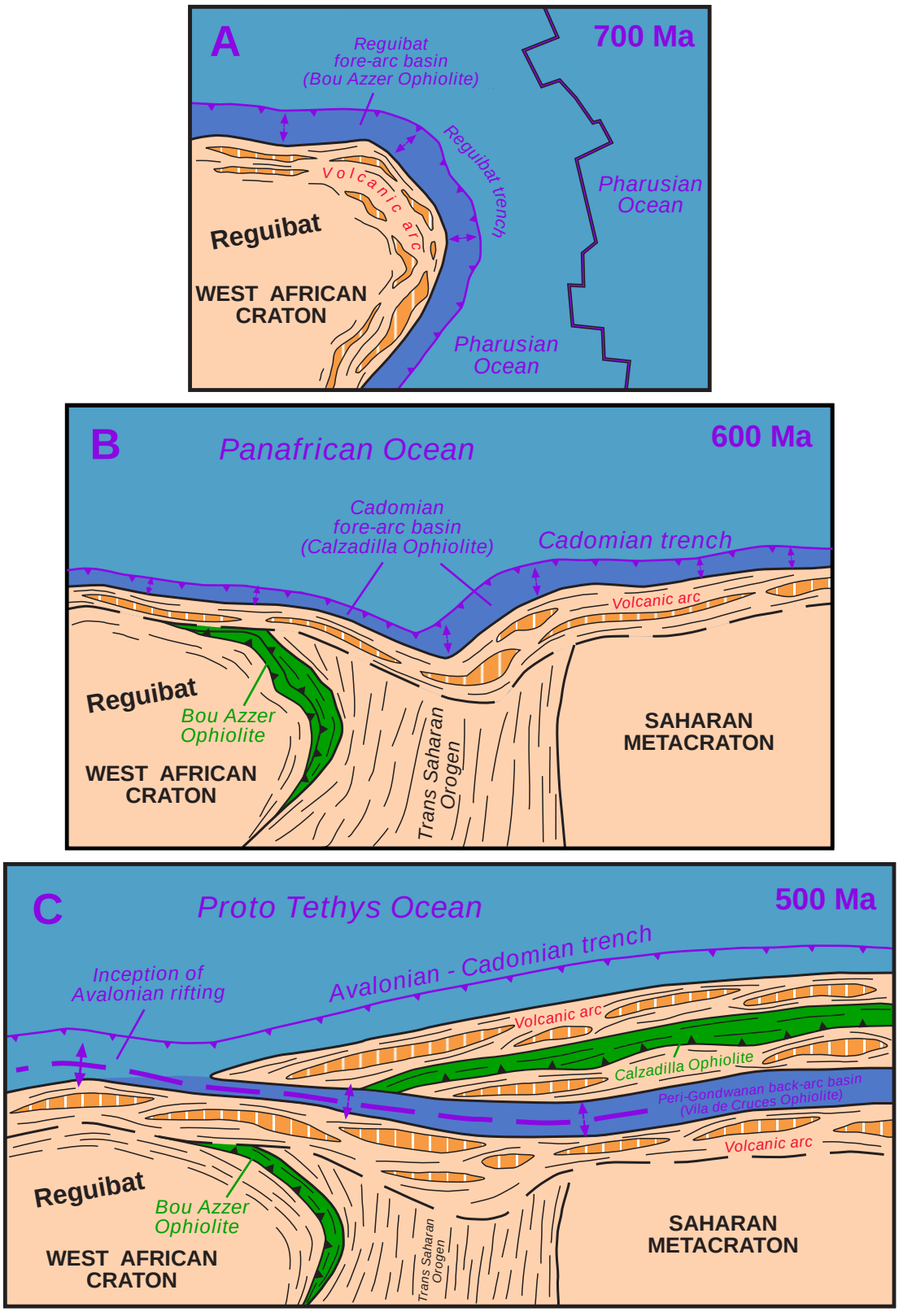
● c. 600 Ma ophiolites ▲ c. 700 Ma ophiolites

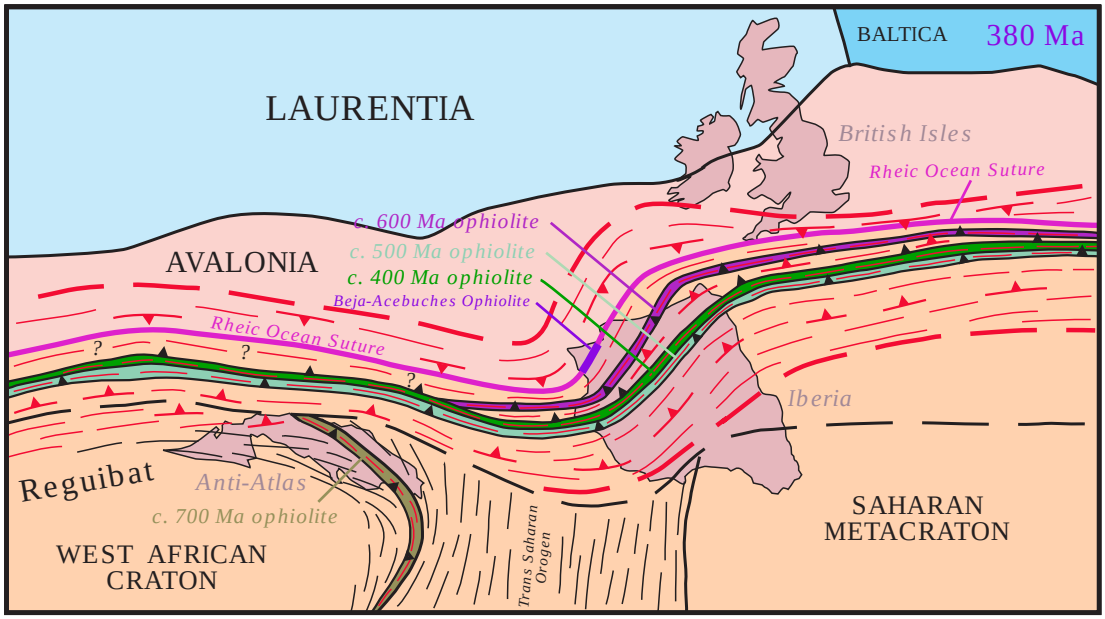


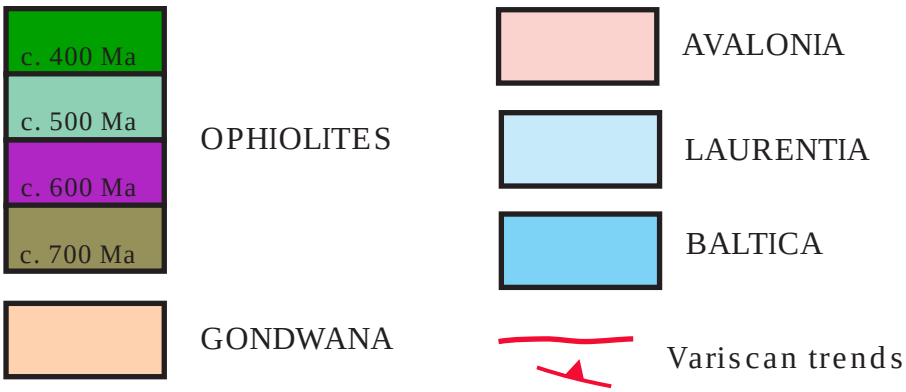
- Careón (c. 400 Ma)
- Purrido (c. 400 Ma)
- Moeche (c. 400 Ma)
- Vila de Cruces (c. 500 Ma)
- Bazar (c. 500 Ma)
- Calzadilla (c. 600 Ma)
- Bou Azzer (c. 700 Ma)



- Careón (c. 400 Ma)
- Purrido (c. 400 Ma)
- Moeche (c. 400 Ma)
- Vila de Cruces (c. 500 Ma)
- Bazar (c. 500 Ma)
- Calzadilla (c. 600 Ma)
- Bou Azzer (c. 700 Ma)


A
700 Ma
Reguibat
fore-arc basin
(Bou Azzer Ophiolite)
Reguibat trench
Volcanic arc
Reguibat
WEST AFRICAN
CRATON
Pharusian
Ocean
Pharusian
Ocean
B
Panafrican Ocean
600 Ma
Cadomian
fore-arc basin
(Calzadilla Ophiolite)
Cadomian trench
Volcanic arc
Reguibat
Bou Azzer
Ophiolite
WEST AFRICAN
CRATON
Trans Saharan
Orogen
SAHARAN
METACRATON
C
Proto Tethys Ocean
500 Ma
Inception of
Avalonian rifting
Avalonian - Cadomian trench
Volcanic arc
Calzadilla Ophiolite
Peri-Gondwanan back-arc basin
(Vila de Cruces Ophiolite)
Volcanic arc
Reguibat
Bou Azzer
Ophiolite
WEST AFRICAN
CRATON
Trans Saharan
Orogen
SAHARAN
METACRATON
OPHIOLITES
VOLCANIC ARCS
FORE-ARC & BACK-ARC
BASINS
CONTINENTS
OCEANS
Trenches & ridges
Tectonic trends


BALTICA
380 Ma
LAURENTIA
British Isles
Rheic Ocean Suture
c. 600 Ma ophiolite
c. 500 Ma ophiolite
c. 400 Ma ophiolite
Beja-Acebuches Ophiolite
AVALONIA
Rheic Ocean Suture
?
?
?
Iberia
Reguibat
Anti-Atlas
c. 700 Ma ophiolite
WEST AFRICAN
CRATON
Trans Saharan
Orogen
SAHARAN
METACRATON


c. 400 Ma
c. 500 Ma
c. 600 Ma
c. 700 Ma
OPHIOLITES
GONDWANA
AVALONIA
LAURENTIA
BALTICA
Variscan trends