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From a bipartite Gondwanan shelf to an arcuate Variscan belt: The early Paleozoic evolution of northern Peri-Gondwana

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ABSTRACT

The Late Paleozoic Variscan Orogen of Europe and North Africa comprises reworked Neoproterozoic to Early Paleozoic crust of the northern Gondwanan shelf that collided with Laurussia. The orogen is characterized by an arcuate trend of the Rheic suture along two orthogonal orogenic arcs and an apparently arbitrary juxtaposition of contrasting paleogeographic proxies to the south of the suture. The comparison of the sedimentary provenance, paleontological, lithostratigraphic, tectonic, and magmatic record demonstrates a contiguous but bipartite, i.e. a western and an eastern, shelf to the south of the Rheic Ocean. Here we reconstruct the development and architecture of the Paleozoic shelf of northern Gondwana preceding the formation of Pangea. In the early Paleozoic both shelf segments were affected by a heterogeneous extension whereby age and composition of extension-related magmatic rocks varies systematically from Cambrian alkaline and tholeiitic rocks in the western shelf to Ordovician calc-alkaline and peraluminous rocks in the eastern shelf. The regional variation in age and composition of the magmatic rocks reflects an eastward decreasing rate of extension along northern Gondwana. The higher extension in the western shelf culminated in the formation of the Armorican Spur. The subsequent intra-Ordovician compressional event, i.e. the "Sardic phase" and the "Cenerian orogeny", exclusively affected the eastern shelf. Early Devonian collision of the Armorican Spur with Laurussia initiated the subduction accretion stage of the Variscan orogeny resulting in the formation of the Rheno-Hercynian–Moravo-Silesian Arc. At that time, the eastern shelf remained in a passive margin setting. Triggered by Late Devonian rifting along the eastern margin of Arabia, the eastern shelf decoupled from the Gondwanan plate and was displaced eastward, parallel to the northern margin of remaining mainland Gondwana. Early Carboniferous collision of the eastern shelf with the western shelf resulted in orogen wide transpressional tectonics and the formation of the Ibero-Armorican Arc. The tectonic interplay between the two Gondwanan shelf segments is the underlying cause of the final patchwork pattern of paleogeographic markers and the arcuate shape of the Variscan orogenic belt.

1. Introduction

The Acadian-Variscan-Alleghany Orogeny is the result of the Paleozoic convergence of the Gondwanan and Laurussian plates culminating in the formation of the supercontinent Pangea (Fig. 1). Exposures of the orogenic belt occur in Central and Western Europe, in parts of Morocco and Algeria to the north of the West African Craton (Michard et al., 2010) as well as in the Appalachian Mountains of northeastern America. Parts of the Variscan continental crust were overprinted and incorporated into younger orogens such as the Alps (von Raumer, 2013), the Carpatho-Balkanides (Haydoutov, 1989; Spahić and Gaudenyi, 2018), the Hellenides (Himmerkus et al., 2007), parts of the Pontides (Okay and Topuz, 2016), and the Caucasus (Mayringer et al., 2011).

There is broad consensus on the reworking of the entire Early Paleozoic shelf of northern Gondwana (i.e. northern Peri-Gondwana) by the Variscan-Alleghany Orogeny, including the Late Cambrian separation of the Avalonian plate from Gondwana with the concomitant opening of the Rheic Ocean (Cocks and Fortey, 1982; Nance et al., 2010), the subsequent Caledonian collision of Avalonia with the East European Craton (Torsvik and Rehnström, 2003) and the North American Craton (Hatcher Jr., 2010) to form Laurussia, followed by the Late Paleozoic collision of northern Peri-Gondwana with Laurussia (Franke, 2000; Matte, 2001; Kroner and Romer, 2013; Stampfli et al.,

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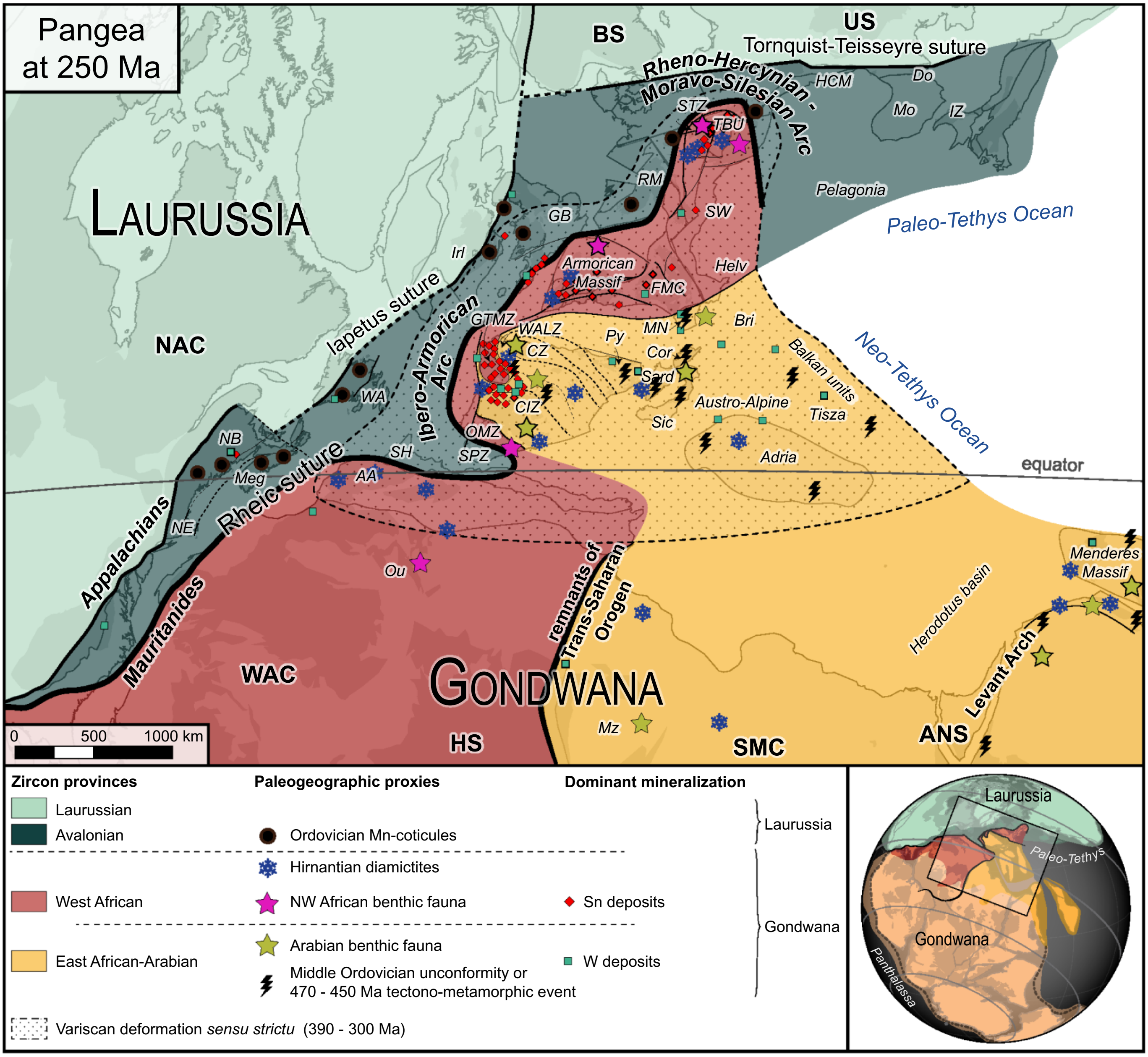

Fig. 1. Map of Pangea at ca. 250 Ma with the four zircon provenance zones Laurussia, Avalonia, West Africa, and East Africa-Arabia (Stephan et al., 2019). The dotted pattern marks the extent of pervasive Variscan crustal deformation. Note that the paleogeographic position for areas with Alpine overprint is only tentative and is modified after: Acquafredda et al. (1994); Ring et al. (1999); Dornsiepen et al. (2001); Okay et al. (2001); Zanchi et al. (2003); Topuz et al. (2006); Greiner and Neugebauer (2013); Handy et al. (2015). Abbreviations: AA – Anti-Atlas, ANS – Arabian-Nubian Shield, Bri – Briançonnais Zone (Alps), BS – Baltic Shield, CIZ – Central Iberian Zone, CZ – Cantabrian Zone, Cor – Corsica, Do – Dobrogea, GB – Great Britain, GTMZ – Galicia–Trás-os-Montes Zone, HCM – Holy Cross Mts., Helv – Helvetic nappes of the Alps, HS – Hoggar Shield, Irl – Ireland, IZ – Istanbul Zone, Meg – Meguma, MN – Montagne Noire, Mo – Moesia, Mz – Murzuq Basin, NAC – North American Craton, NB – New Brunswick, NE – New England, OMZ – Ossa-Morena Zone, Ou – Ougarta, Py – Pyrenees, RM – Rhenish Massif, Sard – Sardinia, SH – Sehoul Block (NW Morocco), Sic – Sicily, SMC – Sahara Metacraton, SPZ – South Portuguese Zone, STZ – Saxo-Thuringian Zone, SW – Schwarzwald, TBU – Teplá-Barrandian Unit, US – Ukrainian Shield, WA – West Avalonia, WAC – West African Craton, WALZ – West Asturian-Leonese Zone.

2013).

Despite the relatively simple sequence of processes that eventually led to the formation of the Variscan-Appalachian Orogen, the irregularly shaped suture between the Laurussian and the Gondwanan plates, which is expressed by two perpendicular arcs (i.e. the Rheno-Hercynian–Moravo-Silesian and the Ibero–Armorican arcs, Fig. 1), does not corroborate a simple tectonic scenario. Moreover, the irregular shape of the suture does not explain the apparently arbitrary juxtaposition of contrasting paleogeographic markers, in particular benthic faunas (Hammann, 1992; Robardet, 2003), the lithostratigraphic record (Stampfli et al., 2013; Álvaro et al., 2018; Casas and Murphy, 2018), mineral deposits (Romer and Kroner, 2015; Romer and Kroner, 2016; Ballouard et al., 2018; Romer and Cuney, 2018; Romer and Kroner, 2018), and the sedimentary provenance (Meinhold et al., 2013; Dörr et al., 2015; Henderson et al., 2016; Stephan et al., 2019).

Previous models explaining the processes leading to this complex shape of the Rheic suture and the orogenic belt are in mutual conflict because these models assume contrasting starting conditions, including (i) different initial positions of the shelf fragments along Peri-Gondwana, in particular Iberia (cf. Bea et al., 2010; Shaw et al., 2014),

(ii) the number of fragments or tectonic plates with intervening oceans (cf. Young, 1990; Robardet, 2002; Kroner and Romer, 2013), and (iii) the relative motion of the tectonic plates of Laurussia and Gondwana (cf. Stampfli et al., 2013; Torsvik and Cocks, 2013; Kroner et al., 2016).

For instance, the contrasting explanations for the various high-grade metamorphic events are reflected in models considering the Gondwana-derived units as a result of the collision of Laurussia with (i) many microplates that are separated from Gondwana by opening of small, ephemeral oceans (e.g. Matte, 1986; Franke, 2000), (ii) a ribbon-like superterrane that drifted from Gondwana by opening of the Paleo-Tethys Ocean (Stampfli and Borel, 2002; von Raumer et al., 2003; Stampfli et al., 2013), or (iii) one contiguous shelf in northern Gondwana that was juxtaposed by margin-parallel shearing (e.g. Badham, 1982; Shelley and Bossière, 2002; Martínez Catalán et al., 2007; Martínez Catalán, 2011; Casas and Murphy, 2018) or intracontinental subduction zones (Kroner et al., 2007; Kroner and Romer, 2013).

Although in mutual conflict, all geodynamic models agree that the final shape of the orogen, i.e. the existence of the two arcs, is a function of the operating tectonic processes and the pre-orogenic paleogeography of the involved crust. It is worth noting that a palinspastic reconstruction of an orogen provides crucial evidence for the relative paleogeographic positions of the involved tectonic blocks and, thus, allows for identifying, quantifying, and limiting processes that operated during the orogeny (Robardet, 2002). Such an approach, however, requires an extensive paleogeographic dataset of the entire incorporated former shelf and an understanding of the involved orogenic processes. The inferred reconstruction must not be in conflict with known starting conditions from e.g. paleontological indicators.

In this contribution, we use information from both the pre-orogenic and the synorogenic record as paleogeographic proxies to develop a generic model for the Early Paleozoic evolution of Peri-Gondwana. This model bases on (1) Early Paleozoic sediment provenance pattern and its temporal changes, (2) the distribution of benthic faunas, (3) the lithostratigraphic record, (4) the timing as well as type of Cambro-Ordovician magmatism, and (5) the tectonic and metamorphic record of the Variscan Orogen. The paleogeographic data are compared with the same dataset from equivalent rocks along north Gondwana exposed today in northern Africa and Arabia.

2. Geologic framework

The Early Paleozoic passive margin evolution of northern Gondwana commences after the termination of the Neoproterozoic to Cambrian Cadomian and Pan-African orogenies. Triggered by the subduction of the Iapetus Ocean between Laurentia and Baltica (e.g. Linnemann et al., 2007; Nance et al., 2010; Díez Fernández et al., 2012; Ilnicki et al., 2013; Hajná et al., 2018), the Cambro-Ordovician extension along the northern shelf of Gondwana is associated with locally important bimodal magmatism and the formation of graben systems (e.g. Pin and Marini, 1993; Crowley et al., 2000; Timmerman, 2008). Intracontinental extension resulted in the separation of segments of thickened Cadomian crust by segments of thinner continental crust along northern Peri-Gondwana (Kroner and Romer, 2013). Prolonged extension culminated in the formation of oceanic crust at ca. 490–480 Ma between the shelf segment “Avalonia” to the north and the extended Gondwanan shelf, i.e. the “Armorican Spur”, to the south of the evolving Rheic Ocean (Kroner and Romer, 2010). To the east of the Armorican Spur, Peri-Gondwana is flanked by the Proto-Tethys Ocean.

Later convergence between the Gondwanan and Laurussian plates eventually led to the collision of the Armorican Spur with Laurussia. Subsequent convergence during the Variscan Orogeny resulted in the closure of the Rheic Ocean to the west, the opening of the Paleo-Tethys Ocean to the east, and the destruction of the Armorican Spur by intraplate subduction and lateral escape movements (cf. Kroner and Romer, 2013).

3. Pre-orogenic constraints

3.1. Zircon provenance data

The most dominant fraction of the detrital zircon in Lower Paleozoic sedimentary rocks of north Gondwana is dated to 700–550 Ma (Suppl. 1a) and, thus, is most likely derived from the magmatic and metamorphic rocks of the Cadomian magmatic arc (ca. 650–540 Ma; Linnemann et al., 2008) and the Pan-African orogenic belt (ca. 750–550 Ma; Stern, 1994). As the Cadomian/Pan-African basement is covered by Cambrian sediments (De Wit et al., 2005; Linnemann et al., 2011; Avigad et al., 2012; Garfunkel, 2015), direct input from the Cadomian arc or the Pan-African belt is unlikely. Nevertheless, recycling of eroded material of Cadomian or Pan-African rocks may have been a potential source of the Ediacaran detrital zircon (Romer and Hahne, 2010; Henderson et al., 2016).

The pre-Cadomian/Pan-African zircon spectra (> 700 Ma) significantly differ along the shelf. Statistical analysis of U–Pb ages of detrital zircon from Lower Paleozoic sedimentary rocks revealed three contrasting provenance end-members of the former Gondwanan shelf, namely the Avalonian, West African, and East African-Arabian zircon provinces (Stephan et al., 2019). Hafnium isotopic fingerprints (Henderson et al., 2016) corroborate the provenance classification of the Gondwanan shelf.

The Avalonian Zircon Province is characterized by detritus delivered from West Gondwana (i.e. the Amazonas and West African cratons as well as adjacent orogens) with increasing input from Laurussia after the separation from Gondwana (Nance and Murphy, 1994; Zeh et al., 2001; Barr et al., 2003; Strachan et al., 2007). The West African and East African-Arabian zircon provinces received detritus from two contrasting fan systems, i.e. the West Gondwanan and East Gondwanan fan, respectively (Linnemann et al., 2004; Meinhold et al., 2013; Dörr et al., 2015; Žák and Sláma, 2017; Stephan et al., 2019). As parts of the potential source areas of the fan systems are covered by Lower Paleozoic sedimentary rocks, e.g. the West African Craton and the Sahara Metacraton (Guiraud et al., 2005; Avigad et al., 2012; Garfunkel, 2015), the main sediment supply did not directly derive from the cratonic areas. More likely the detritus derived from recycled or reworked sources such as Neoproterozoic orogenic belts that rim the cratons. Thus, the Amazonas Craton, the Trans-Saharan Orogen, and the Damara Belt represent potential sources for the Lower Paleozoic sedimentary rocks of the West African Zircon Province (Garfunkel, 2015), whereas the East African-Arabian Zircon Province was delivered by eroded material from the East African-Antarctic Orogen, the Irumide Belt, and the Kuunga Belt (Meinhold et al., 2013; Rösel et al., 2014).

In general, the zircon provenance pattern of the Gondwanan shelf sediments does not change from the Cambrian to the Early Devonian period (Suppl. 1). There are, however, some distinctive changes and significant excursions from the predominant provenance pattern:

i) In average, the Ediacaran zircon in the West African Zircon Province amounts for ca. 40% of the total detrital zircon grains dated per sample and is significantly higher in the West African Zircon Province than in the East African-Arabian Zircon Province (Fig. 2). The proportion of Ediacaran, i.e. Cadomian or Pan-African zircon, is decreasing in both provinces over time.
ii) In Middle to Upper Cambrian sedimentary rocks (510–490 Ma) of the West African Zircon Province, the relative contribution of Cadomian or Pan-African zircon decreased (Fig. 2), whereas the contribution of Eburnean zircon (2.2–2.0 Ga) increased (Suppl. 1i). Moreover, the contribution of Neoarchean zircon (2.77–2.5 Ga), which constitutes a nonsignificant fraction in the West African Zircon Province (< 5%), increased up to 40% of the total age spectra (Suppl. 1k).
iii) In the Upper Ordovician (Hirnantian) to Silurian sedimentary rocks of the West African Zircon Province zircon and rutile U–Pb ages as

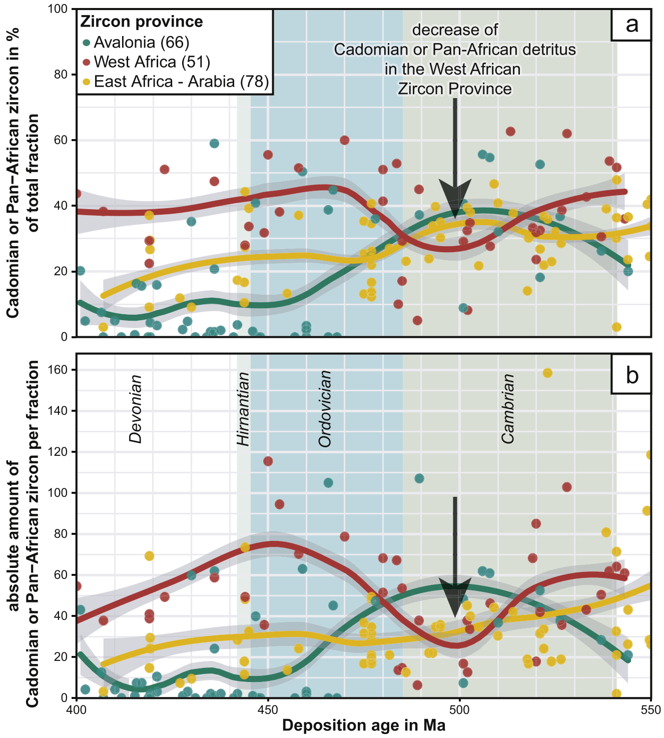

Fig. 2. Temporal variation of the contribution of Cadomian or Pan-African zircon (650–540 Ma) to the detrital zircon U–Pb age record. (a) Fit per zircon province by local regression (LOESS) of the relative Cadomian or Pan-African contribution in the age spectra per sample. (b) LOESS fit of the absolute Cadomian or Pan-African contribution in the age spectra per sample. Colors refer to the zircon provinces after Stephan et al. (2019). Gray lines refer to the 95% confidence interval of the regression. The number of samples per zircon province is given in brackets. For data sources and description of age calculation see Stephan et al. (2019).

well as zircon Hf isotopes show affinities to East African-Arabian Zircon Province (Bahlburg et al., 2010; Franz et al., 2013; Rösel et al., 2014; Ballouard et al., 2018; Rösel et al., 2018) which is interpreted as the glacial redistribution of material of contrasting sources (Rösel et al., 2018).

3.2. Lithostratigraphy of the shelf sedimentary rocks

The Lower Paleozoic sedimentary sequences of the West African and the East African-Arabian zircon provinces (sensu Stephan et al., 2019) record a similar passive margin evolution above the Cadomian/Pan-African unconformity. Nevertheless, the sequences show characteristic differences such as diachronous occurrences of carbonates, evaporites, iron oolites, volcano-clastic sequences, and stratigraphic unconformities as well as thickness of contemporaneously deposited sediments (Fig. 3). These striking lithological differences between the West African and the East African-Arabian zircon provinces allow to distinguish a western and eastern segment of the Lower Paleozoic northern Gondwanan shelf, respectively.

3.2.1. Western shelf

Cambrian and/or Ordovician strata of the West African Zircon Province unconformably rest on metasedimentary or metavolcanic sequences of the Cadomian basement. The Lower Paleozoic sedimentary rocks were deposited on a tectonically stable shelf (*sensu* Hammann, 1992) as there are no tectonic unconformities. Lower Cambrian carbonates and evaporites are overlain by Upper Cambrian mature siliciclastic, shallow marine shelf sequences that are intercalated by volcano-sedimentary sequences. Sedimentation rates steeply decline towards the Upper Cambrian and Ordovician. Locally, Middle to Upper Cambrian rocks are absent, most prominently in the Armorican Massif and the Saxo-Thuringian Zone (Doré, 1994; Robardet et al., 1994; Linnemann et al., 2007; Geyer et al., 2008). The gap may be correlative to the Furongian "Toledonian" angular unconformity of the Ossa-Morena Zone and the southern Central Iberian Zone (Hammann et al., 1982; Quesada, 1990; Gutiérrez-Marco et al., 2002; López-Guijarro et al., 2007; Álvaro et al., 2018). The marine sedimentation resumes in the Ordovician and records a progressive deepening of the shelf until the Late Devonian (Romer and Hahne, 2010). During the Hirnantian glaciation, sedimentation is either interrupted or characterized by the deposition of glaciogenic rocks, e.g. diamictites or tillites (Durand, 1985; Doré, 1994; Robardet et al., 1994; Loi and Dabard, 2002; Dabard et al., 2007; Linnemann et al., 2007; Vidal et al., 2011; Voigt and Meisel, 2014).

3.2.2. Eastern shelf

In the East African-Arabian Zircon Province, angular unconformities are significantly more abundant than in the West African Zircon Province (e.g. Hammann, 1992; Ghienne et al., 2010). Cambrian strata of the eastern shelf unconformably rest on top of Cadomian or Pan-African basement and comprise Lower Cambrian carbonates and evaporites that are overlain by siliciclastic, shallow marine shelf sediments. The successions are disrupted by Lower to Middle Cambrian erosive or angular unconformities (Fig. 3). The shelf evolution continues in the Ordovician with abundant volcanic rocks. The most prominent example is represented by the at least 600 km long zone of massive volcanic and volcano-sedimentary deposits of the Lower Ordovician "Ollo de Sapo Formation" of the Central Iberian Zone (Díez Montes, 2007; García-Arias et al., 2018). Angular or erosive unconformities also occur in Middle Ordovician strata. A major, pre-Floian unconformity is recorded in the northern Central Iberian Zone (Lotze, 1956; Gutiérrez-Marco et al., 1990; Valverde-Vaquero and Dunning, 2000), the eastern Pyrenees ("Sardic unconformity" *sensu stricto*; Casas, 2010), the Montagne Noire ("Sardic unconformity" *sensu stricto*; Robardet et al., 1994; Álvaro et al., 2016), Mouthoumet (Álvaro et al., 2016), Sardinia ("Sarrabese unconformity"; Martini et al., 1991; Cocco and Funedda, 2017), Corsica (Rossi et al., 2009), the northern Apennines (Conti et al., 1993), the Carpathians, and Turkey ("Taurinian unconformity"; Hammann, 1992; Ghienne et al., 2010). The regional importance of this erosional gap is additionally highlighted by the synchronous "pre-Hanadir unconformity" on the Arabian plate (Droste, 1997; Sharland et al., 2001; El-Khayal and Romano, 2009). This regional Middle Ordovician erosional surface is overlain by volcano-sedimentary successions or alluvial to coastal conglomerates, e.g. the Floian "Armorican Quartzite Formation" in the Central Iberian Zone (Eremochitina *brevis* biozone; Paris, 1990). These Middle to Upper Ordovician siliciclastic sedimentary units are characteristically intercalated by iron oolitic beds, e.g. in the Central Iberian, Cantabrian, and the West Asturian-Leonese Zone (Fernández and Moro, 1998; Gutiérrez-Marco et al., 2002) as well as the Carnic Alps (Schönlaub and Heinisch, 1993).

3.3. Paleontology

The Peri-Gondwanan crust is characterized by three distinctive fauna provinces, namely "Avalonia", "Armorica" (or "Cadomia"), and "Mediterranea" (e.g. Young, 1990; Robardet et al., 1994). The Avalonian faunal province records the transition from an Early Ordovician, cool water environment with Gondwanan faunal affinity to a Silurian, low latitude environment with faunas of Laurentian affinity (Boyce et al., 1991; Williams, 1993; Dean et al., 2000; Chen et al., 2001; Oczlon et al., 2007; Pollock et al., 2011). The Avalonian fauna became an independent, endemic entity after the separation of the Avalonian plate from mainland Gondwana in the Late Cambrian to Early Ordovician (Cocks and Fortey, 1982; Torsvik and Cocks, 2013).

Mainly based on neritic/benthic faunas, the Armorican or Cadomian

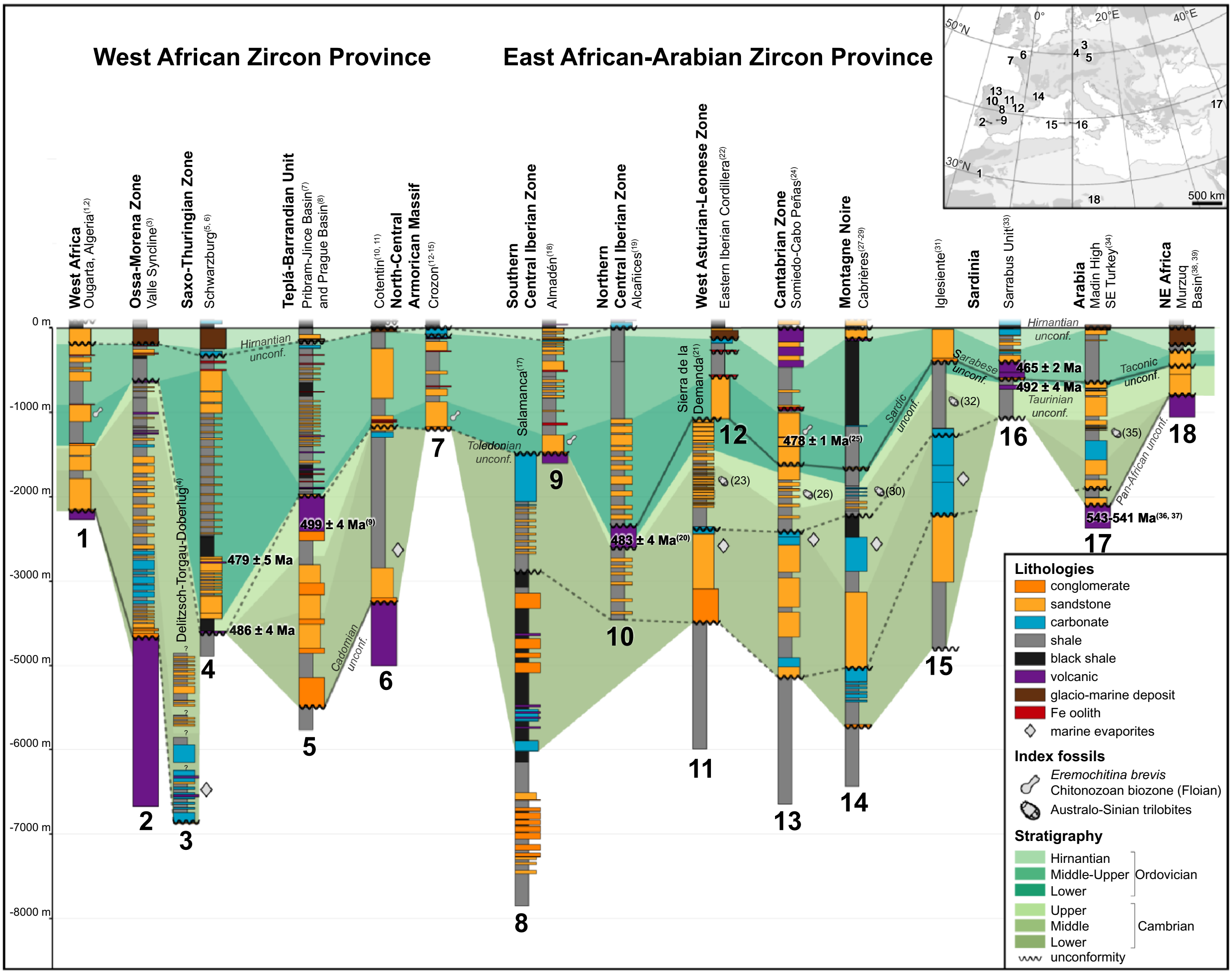

Fig. 3. Lithostratigraphic correlation chart for Lower Paleozoic Gondwanan shelf deposits. The profiles are arranged from west to east based on their sedimentary provenance. In order to show thickness variations of the Lower Paleozoic sedimentary deposits, thickness is given in meters below the Ordovician-Silurian boundary. Coloring of the various sections reflects the lithology, coloring of the field between the sections corresponds to the stratigraphic age. Number below the columns refer to the location in the map inlet. Data sources: (1) Guerrak (1987); (2) Ghienne et al. (2007); (3) Robardet and Gutiérrez-Marco (2004); (4) Geyer et al. (2008); (5) Linnemann et al. (2007); (6) Voigt and Meisel (2014); (7) Havlíček (1971); (8) Chlupáč (1993); (9) Drost et al. (2004); (10) Doré (1994); (11) Robardet et al. (1994); (12) Durand (1985); (13) Loi and Dabard (2002); (14) Dabard et al. (2007); (15) Vidal et al. (2011); (16) Gorini et al. (2008); (17) Valladares et al. (2000); (18) Saupé (1973); (19) Clavijo and Martínez Catalán (2002); (20) Montero et al. (2009); (21) Ábalos et al. (2012); (22) Gutiérrez-Marco et al. (2002); (23) Álvaro et al. (2012); (24) Aramburu et al. (2004); (25) Gutiérrez-Alonso et al. (2007); (26) Aceñolaza et al. (2014); (27) Feist (1985);(28) Colmenar et al. (2013); (29) Álvaro et al. (2014); (30) Shergold et al. (2000); (31) Pillola et al. (1998); (32) Álvaro et al. (2007); (33) Oggiano et al. (2010); (34) Ghienne et al. (2010); (35) Dean (1982); (36) Kröner and Şengör (1990); (37) Bozkaya et al. (2006); (38) Davidson et al. (2000); (39) Le Heron et al. (2013). unconf. – unconformity.

faunal province comprises the Armorican Massif (Robardet, 2003), the Teplá-Barrandian Unit (Fatka and Mergl, 2009), the Saxo-Thuringian Zone (Heuse et al., 2010), the Ossa-Morena Zone (Gutiérrez-Marco et al., 2002), and the southern part of the Central Iberian Zone (García-Alcalde et al., 2002). The faunal province shows close affinities to the Ibarmaghian faunal province of North Africa, i.e. Morocco, Algeria, and Libya (Plusquellec, 1987; Boumendjel et al., 1997). The faunal record indicates a rapid movement from peri-equatorial latitudes in the Early to Middle Cambrian towards higher latitudes in the Late Cambrian/ Early Ordovician, followed by a gradual movement from high polar latitudes in the latest Ordovician through cold and warm climatic belts to a tropical position in the Carboniferous (Robardet, 2003; Fatka and Mergl, 2009). The faunal province of Armorica and the north African part of Gondwana show similar development, which indicates a common latitudinal position close to northern parts of Gondwana at least until the Middle Devonian (Robardet, 2003).

The Mediterranean faunal province is reported for the northern Central Iberian Zone (proximal, inner shelf of Iberia), the West Asturian-Leonese, and the Cantabrian zones (both distal shelf), the Pyrenees, the Catalonian Coastal Ranges, the Montagne Noire, Sardinia, the Southern Alps, parts of the Carpathians, southern Turkey as well as Saudi Arabia (El-Khayal and Romano, 1985; Evans, 2000), and shows close similarities to faunas of Northeast Africa (e.g. Hammann, 1992; Mélou et al., 1999; Gutiérrez-Marco et al., 2002). A characteristic feature of the Ordovician strata of the Mediterranean faunal province is the influx of Australo-Asiatic taxa (Shergold et al., 1983; Gutiérrez-Marco and Rodríguez, 1987; Shergold et al., 2000; Gozalo et al., 2007). As those taxa are not known from the Armorican faunal province, the Mediterranean faunas either had exchange with an East Gondwanan marine paleocurrent system (Pohl et al., 2016) or was located at lower latitudes (Shergold et al., 2000).

3.4. Pre-Variscan tectonics and metamorphism

Although the entire northern shelf of Gondwana was affected by extension in the Early Paleozoic, the western and eastern segments of the shelf record different rates of extension and contrasting compressional phases. The western shelf is predominantly characterized by Early Paleozoic extension resulting in horst-and-graben structures and transtensional basins (Schäfer et al., 1993; Melichar, 2004; Žák et al., 2013). Lenses of mantle-derived rocks exposed in the Teplá-Barrandian Unit are interpreted to reflect localized hyperextension (Žák and Sláma, 2017). Except for an angular unconformity in the uppermost Cambrian successions (Fig. 3), there is no evidence for compressional intervals.

The eastern shelf, in contrast, records lower extension rates (no record of mantle-derived rocks) but several tectono-metamorphic events. Angular unconformities in Lower Cambrian sedimentary sequences (Fig. 3) are contemporaneous with Early Cambrian (ca. 535 Ma) HP metamorphism in the Menderes (Candan et al., 2016) and the Bitlis massifs in Turkey (Ustaömer et al., 2012). Candan et al. (2016) correlate the unconformities with tectono-metamorphic events at the East-African-Antarctic orogen in East Gondwana, e.g. *Antarctica* (Boger and Miller, 2004; Romer et al., 2009), Australia (Foster et al., 2005), and India (Santosh et al., 2009). Lower to Middle Ordovician angular unconformities correlate with a compressional or transpressive deformation event, namely the “Sardic phase” (Stille, 1939). Evidence for this compressional period is recorded in Sardinia (Carmignani et al., 1994; Franceschelli et al., 2016; Cocco and Funedda, 2017), in Corsica (Rossi et al., 2009), in the Occitan Domain (Montagne Noire and Mouthoumet massif; Álvaro et al., 2016), in the Central (Clariana et al., 2018), and Eastern Pyrenees (Laumonier, 2008; Casas, 2010), the Cantabrian (Aramburu et al., 2004), the West Asturian-Leonese (Gutiérrez-Marco et al., 2002) as well as the Central Iberian zones (Díez Balda et al., 1990; Gutiérrez-Marco et al., 2002; Correia Romão et al., 2012). Middle Ordovician angular unconformities are also observed from mainland Gondwana as far as the Taurides in southern Turkey (Ghienne et al., 2010), the Haima Supergroup of Oman (Droste, 1997; Sharland et al., 2001), and Northeast Africa (Echikh and Sola, 2000; Galadí-Enríquez et al., 2010; Le Heron et al., 2013).

The event is coeval with low-grade metamorphism in Sardinia (Franceschelli et al., 2016) and ca. 450 Ma high-grade metamorphism in the Cenerian Southern Alps (Poli and Zanferrari, 1992; Franz and Romer, 2007; Zurbriggen, 2015; Zurbriggen, 2017), the Central Alps (Gebauer, 1993; Poller et al., 1997; Schaltegger et al., 2003), the Briançonnais Zone (500–460 Ma, Gaggero et al., 2004), and the Romanian Carpathians (Balintoni et al., 2011a; Balintoni and Balica, 2013).

3.5. Magmatism

Cambro-Ordovician lithospheric extension and extensive magmatism along the northern margin of Gondwana are related to the opening of the Rheic Ocean with the separation of Avalonia from Gondwana and the formation of a wide passive margin of northern Gondwana (e.g. von Raumer and Stampfli, 2008; Nance et al., 2010; Kroner and Romer, 2013). The distribution of Cambro-Ordovician magmatic rocks (Fig. 4) shows that Cambrian magmatism exclusively occurred in the West African Zircon Province, whereas Ordovician magmatism predominated in the East African-Arabian Zircon Province. Moreover, three main groups of magmatic pulses can be distinguished (Fig. 5):

(i) In the West African Zircon Province, there are two main pulses of Cambrian bimodal, peralkaline magmatism at ca. 525 Ma and especially at 500 Ma (e.g. Avalonia, Anti-Atlas, Hoggar, Ossa-Morena Zone, Saxo-Thuringian Zone, Teplá-Barrandian Unit, and North-Central Armorican Massif).
(ii) Late Cambrian to Early Ordovician (ca. 490–480 Ma) calc-alkaline magmatism in the West African and East African-Arabian zircon provinces occurred in particular in the Central-Southern Armorican Massif and Central Iberian Zone (Ollo de Sapo Formation). The highest density of Cambro-Ordovician magmatism occurs along northern Peri-Gondwana having the same age as the final separation of Avalonia from Gondwana and the concomitant opening of the Rheic Ocean (Nance et al., 2010).
(iii) Ordovician calc-alkaline and peraluminous magmatism predominated in the East African-Arabian Zircon Province with two main pulses at ca. 470 Ma (highest frequency) and ca. 460 Ma.

There are two systematic changes in the magmatic record along the northern Gondwanan margin (i) the magmatic rocks became successively younger from the West African towards the East African-Arabian Zircon Province (Suppl. 3) and (ii) the predominant type of magmatism changed from bimodal and peralkaline magmatism in the west to calc-alkaline and peraluminous magmatism in the east (Fig. 5). Magmatism in the Avalonian Zircon Province occurred approximately coeval with magmatism in the West African Zircon Province, i.e. in the Cambrian, and terminated after the separation of Avalonia from Gondwana. The type of magmatism in Avalonia is similar to the bimodal and peralkaline magmatism in the West African Zircon Province.

4. Orogenic constraints

4.1. Variscan metamorphic age distribution as paleogeographic proxy

The age of high and ultra-high pressure (HP, UHP) metamorphism of felsic rocks closely approaches the age of subduction as these rocks are highly buoyant. As subduction occurs at the margins of continents or, in case of intracontinental subduction, between cratonic blocks, age variation among regions of (U)HP metamorphism reflects in a first approach different phases of subduction. For instance, crust in a promontory position along the subducting plate is the first to be subducted and thus yields the oldest metamorphic ages. Areas initially located in a distant position in relation to the promontory would be incorporated later into the orogen and thus give younger metamorphic ages. In case of the Variscan Orogen there are at least three regionally preserved HP metamorphic events dating to ca. 390 Ma, 360 Ma, and 340 Ma (Fig. 6). These events are interpreted to be related to three different subduction zone systems by Kroner and Romer (2013):

(i) Metamorphic rocks of the older group (ca. 390 Ma) and (ii) middle group (ca. 360 Ma) are recorded in the Galicia–Trás-os-Montes Zone (Ordóñez Casado et al., 2001; Roger and Matte, 2005; Albert et al., 2013), the Ossa-Morena Zone of Iberia (Rubio Pascual et al., 2013), the southern Armorican Massif (Bosse et al., 2005), French Massif Central (Paquette et al., 1995; Lardeaux et al., 2001; Berger et al., 2010), the Saxo-Thuringian Zone (Massonne and O'Brien, 2003; Klemd, 2010), the Mariánské Lázně Complex (Timmerman et al., 2004; Collett et al., 2018), and the Sudetes (Maluski and Patočka, 1997).
(ii) Late Variscan HP metamorphism (ca. 340 Ma) is mainly recorded from the Bohemian Massif (Klapova et al., 1998; Bröcker et al., 2009; Teipel et al., 2012; Medaris Jr et al., 2013; Tichomirowa and Köhler, 2013; Kotková and Janák, 2015), the Vosges/Schwarzwald (Kalt et al., 1994; Marschall et al., 2003), the external massifs of the Western Alps (Rubatto et al., 2010), pre-Alpine crust of Austro-Alpine units (Langone et al., 2011), the Central Spanish System (Villaseca et al., 2015), Sardinia (Di Vincenzo et al., 2004; Giacomini et al., 2005), and the Carpatho-Balkanides (e.g. Iancu et al., 1998; Medaris Jr et al., 2003; Gaggero et al., 2008; Negulescu et al., 2009; Moussallam et al., 2012).

It is worth noting that early Variscan (U)HP metamorphic rocks are exclusively exposed in the West African Zircon Province, whereas late Variscan metamorphic rocks occur in both the East African-Arabian and

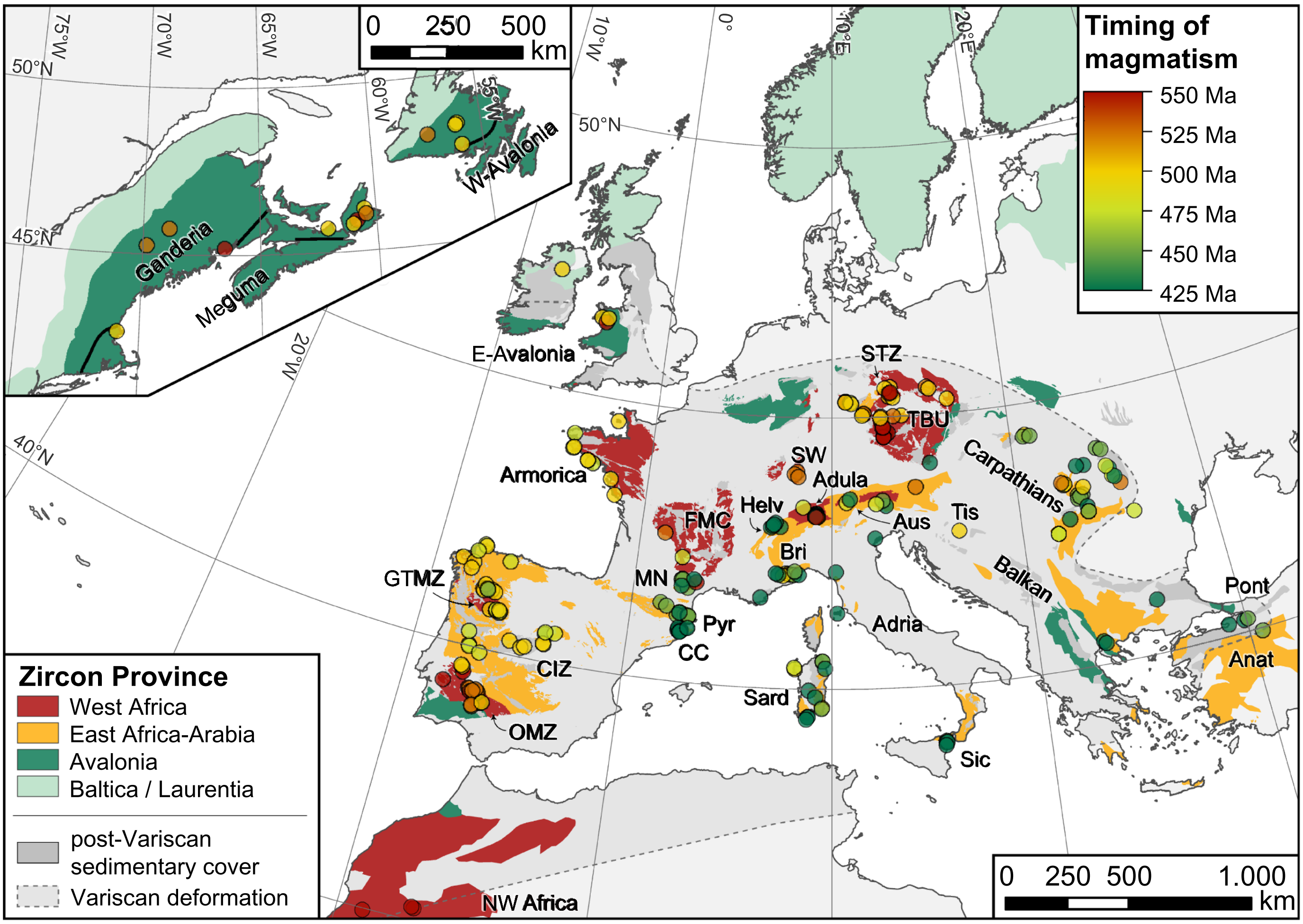

Fig. 4. Timing of Cambro-Ordovician magmatism (U–Pb zircon). The color of the Variscan massifs represents zircon provenance after Stephan et al. (2019). Abbreviations: Anat – Anatolides, Aus – Austro-Alpine nappes of the Alps, Bri – Briançonnais, CC – Catalonian Coastal Range, CIZ – Central Iberian Zone, FMC – French Massif Central, GTMZ – Galicia–Trás-os-Montes Zone, Helv – Helvetic nappes of the Alps, MN – Montagne Noir, OMZ – Ossa-Morena Zone, Pont – Pontides, Pyr – Pyrenees, Sic – Sicily, STZ – Saxo-Thuringian Zone, SW – Schwarzwald, TBU – Teplá-Barrandian Unit, Tis – Tisza. Data sources in Suppl. 2.

the West African zircon provinces (Fig. 6).

4.2. Variscan tectonic record

The Variscan Orogeny is characterized by long lasting but localized deformation. The most striking feature is an early Variscan intense deformation of the Armorican Spur (West African Zircon Province) coeval to tectonic quiescence and undisturbed voluminous marine sedimentation until the latest Devonian in the East African-Arabian Zircon Province (García-Alcalde et al., 2002; Belka and Narkiewicz, 2008). Variscan deformation can be distinguished into the following tectonic events (geographical direction given in present-day coordinates, for Permian paleogeographic position within Pangea see Fig. 7).

4.2.1. Acadian shortening (410–390 Ma)

The first contact of the continents of Gondwana and Laurussia is inferred from the early orogenic collisional event. The so-called “Acadian orogeny”, i.e. the Late Silurian/Early Devonian collision of the West African Zircon Province, including the Armorican Spur (Gondwana), with the Avalonian part of Laurussia (Dörr et al., 1999; Kroner et al., 2008) culminated in the formation of the Anglo-Brabant fold belt of Ireland, Wales, England, and Belgium (Soper and Woodcock, 2003; Meere and Mulchrone, 2006; Sintubin et al., 2009). The Acadian phase is characterized by NW–SE shortening in the northwest part (Meere and Mulchrone, 2006) and NE–SW shortening along the southeast part of the Anglo-Brabant Fold Belt (Sintubin and Everaerts, 2002). Contemporaneous subsidence and extension-related bimodal magmatism in the nearby Rheno-Hercynian Zone (Timmerman, 2008) was triggered by back-arc extension in the Laurussian upper plate (Kroner et al., 2007).

4.2.2. Nappe transport of the uppermost allochthonous units of the Armorican Spur (390–340 Ma)

The onset of Variscan collisional tectonics is reflected by the first occurrence of synorogenic sedimentary deposits in the Lower Devonian successions of the West African Zircon Province (Belka and Narkiewicz, 2008). Horizontal mineral stretching lineation, thrusting, and shearing markers from the West African Zircon Province indicate an initial SW directed tectonic transport during the Early Devonian, which is recorded in the uppermost allochthonous nappes of the Saxo-Thuringian Zone (Franke and Stein, 2000; Vollbrecht et al., 2006; Kroner et al., 2007), the Mid-German Crystalline Zone (Krohe, 1992), the Teplá Crystalline Complex (Peřestý et al., 2017), the South Armorican Shear Zone (Philippon et al., 2009), and the French Massif Central (Faure et al., 2009). Similar strain patterns occur in the upper allochthonous units of the Galicia–Trás-os-Montes Zone (Marques et al., 1992; Gil Ibarguchi et al., 1999; Rodríguez et al., 2003). As strain increments rotated during later stages of the Variscan deformation, the Galicia–-Trás-os-Montes Zone is characterized by tectonic transport parallel to

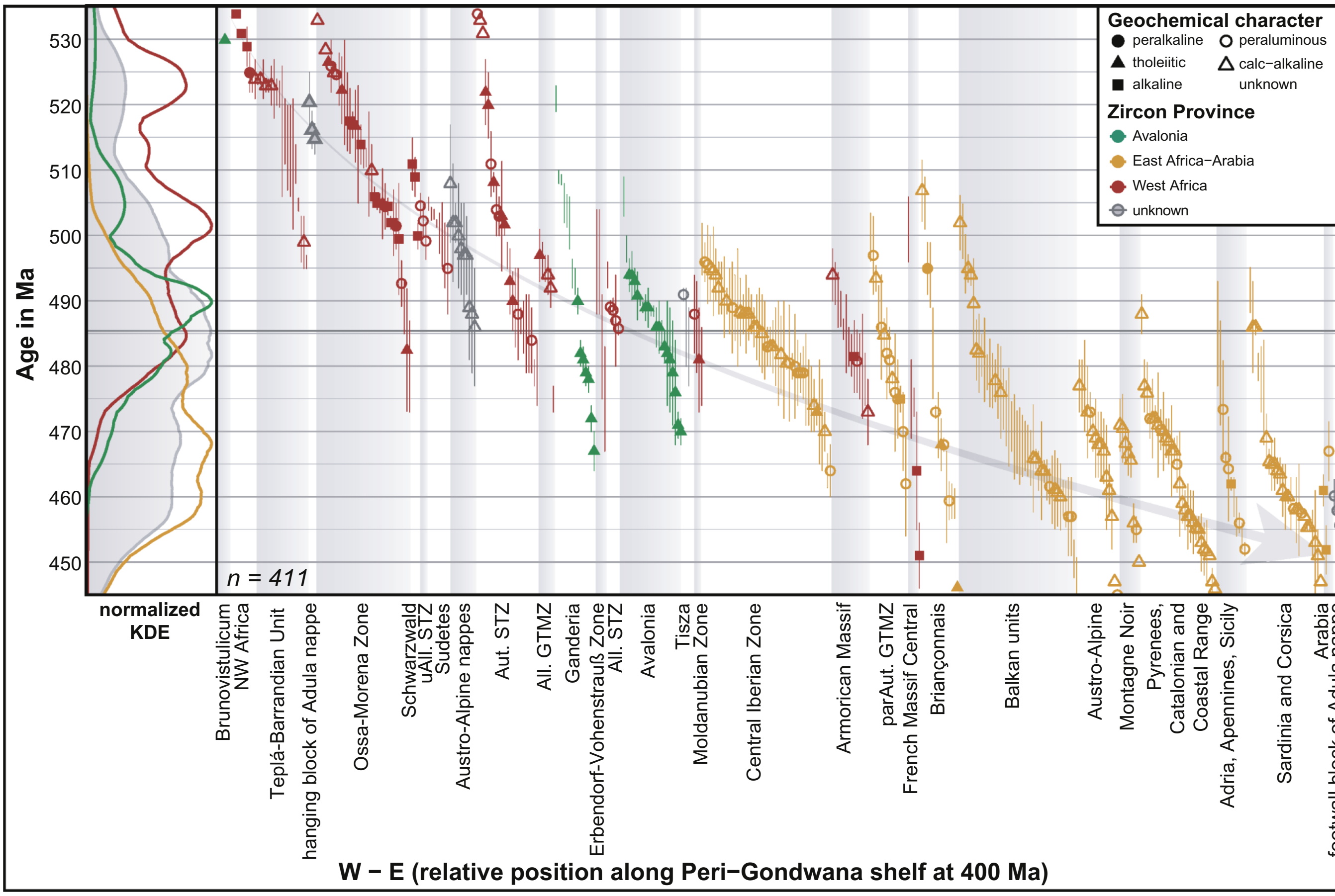

Fig. 5. Zircon U–Pb age of pre-Variscan magmatism vs. initial position along the shelf of northern Gondwana. The color of the symbol and error bar for each dated magmatic center reflects the zircon province of the sedimentary rock into which the magmatic rock had intruded, the shape of the symbols reflects the type of magmatism (no symbol means no information on dated type of magmatism). Frequency distribution (normalized kernel density estimation KDE, bandwidth: 3) of the magmatism in the Avalonian (green), West African (red), East African-Arabian (yellow) zircon provinces (after Stephan et al., 2019), and the full data set (gray). Note, the original data set had been filtered to contain only ages with 2σ uncertainty of ≤2% (as recorded in the original publication). Abbreviations: All – allochthonous, Aut – autochthonous, u – uppermost, GTMZ – Galicia–Trás-os-Montes Zone, STZ – Saxo-Thuringian Zone, n – number of samples. Location of the units is shown in Fig. 4. Age data and data sources in Suppl. 2.

the curved orogenic trend (Quesada, 1991; Rodríguez et al., 2003).

4.2.3. Nappe transport in Laurussia – the Moravian nappes (340–300 Ma)

The NE–SW compression is also reflected in the Laurussian foreland of the early Variscan Orogen, i.e. the Polish Fore-Sudetic Monocline (Żelaźniewicz et al., 2003; Jaworowski, 2010). Here, NE directed transport continued until the Carboniferous. This is also documented from the Moravian nappes (Schulmann et al., 1991; Fritz and Neubauer, 1993) and the Moravo-Silesian Zone of Laurussia (Rez et al., 2011).

4.2.4. Extension between the East African-Arabian Zircon Province and mainland Gondwana (360–340 Ma)

The compressional tectonics along the collisional zone of Laurussia and Gondwana is coeval to the formation of several horst-and-graben structures (“arch-and-basin geometry”) in Northeast Africa and Arabia (East African-Arabian Zircon Province) that are associated to significant vertical movements and horizontal extensional deformation during the Late Devonian to Early Carboniferous (Faqira et al., 2009; Frizon de Lamotte et al., 2013). The epeirogenic extension is also reflected by the occurrence of 380–370 Ma detrital zircon fission-track ages from Cambrian sedimentary rocks in the Levant Arch (Kohn et al., 1992; Vermeesch et al., 2009), ca. 357 Ma tholeiitic xenoliths from southern Syria (Stern et al., 2014), ca. 350 Ma within-plate felsic rocks, and associated gabbro underplating of the crust beneath the Levant Arch (Golan et al., 2017). Within-plate magmatism culminated at ca. 340 Ma in seafloor spreading in the Herodotus basin (today eastern Mediterranean Sea; Granot, 2016).

4.2.5. Collision of the East African-Arabian Zircon Province with the West African Zircon Province (ca. 340 Ma)

Variscan tectonics within the East African-Arabian Zircon Province did not start before the Late Devonian, as evidenced by the first occurrence of synorogenic deposits (e.g. Cassard et al., 1993; García-Alcalde et al., 2002; Gómez Barreiro et al., 2007; Belka and Narkiewicz, 2008; Faure et al., 2009; Pereira et al., 2012a). In particular in Iberia, the age of detrital zircon from synorogenic sequences reflects the West African Zircon Province as the primary source (Martínez Catalán et al., 2008; Martínez Catalán et al., 2015). Thus, the Upper Devonian to Lower Carboniferous synorogenic deposits post-date the emplacement of the allochthonous units of the Galicia–Trás-os-Montes Zone (western shelf) on top of the Central Iberian Zone (eastern shelf), i.e. the onset of collision of East African-Arabian Zircon Province with the West African Zircon Province.

Strain markers indicate E–W shortening (Fig. 6) since 340 Ma (Quesada, 1991; Dallmeyer et al., 1997; Di Vincenzo et al., 2004), which reflects nappe-stacking of the Galicia–Trás-os-Montes Zone (Gómez Barreiro et al., 2010; Díez Fernández and Martínez Catalán, 2012), sinistral shearing along the boundary between the Ossa-Morena (western shelf) and the Central Iberian zones (Burg et al., 1981; Pérez-Cáceres et al., 2016), and folding of the Central Iberian (Díez Balda

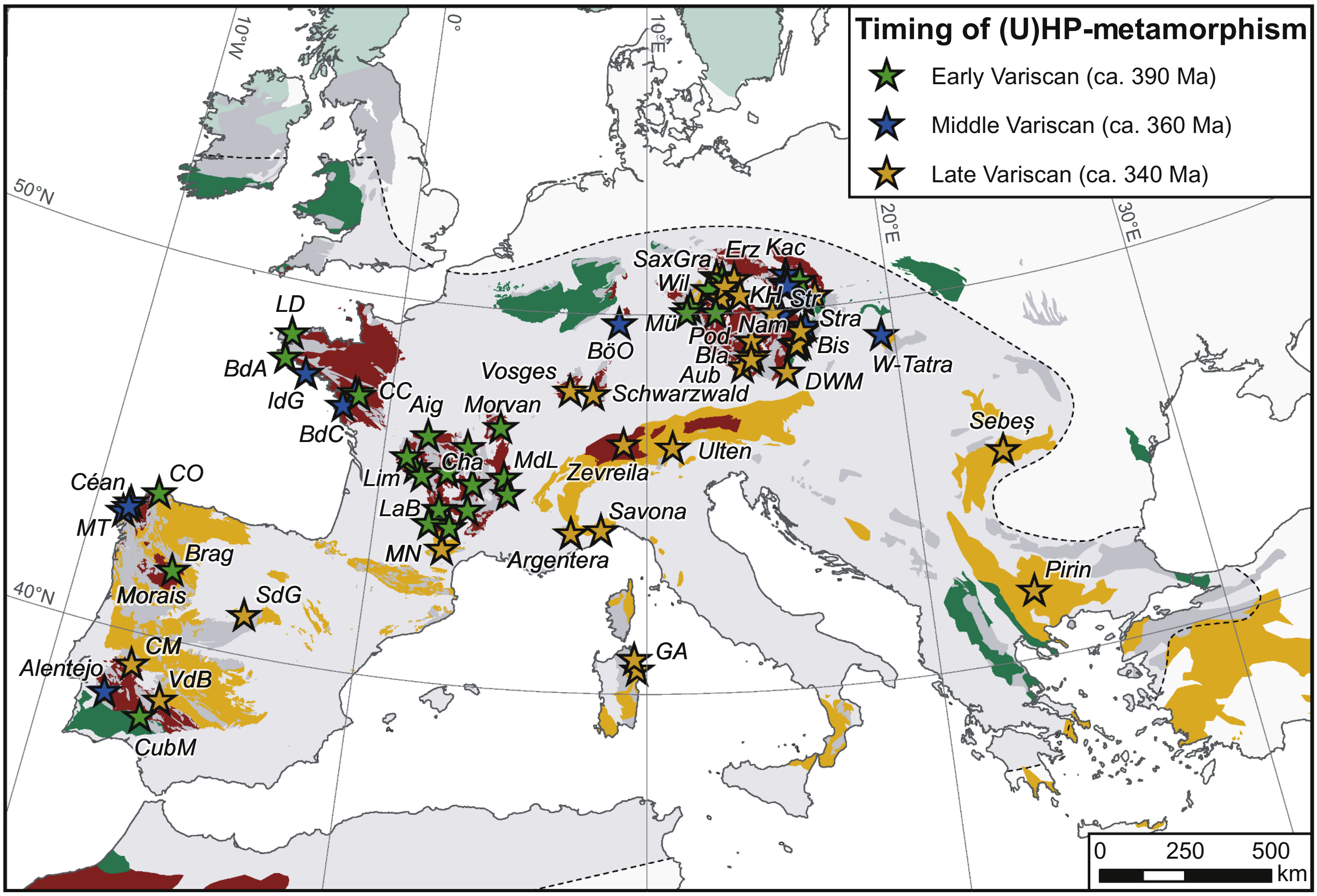

Fig. 6. Distribution and age of Variscan high-pressure events. The colors of the Variscan massifs correspond to the provenance distribution after Stephan et al. (2019), for explanations see Fig. 1. Data sources in Suppl. 4. Legend for provenance map see Fig. 1. Locations (and abbreviations): Aigurande (Aig), Alentejo, Argentera, Aubach (Aub), Baie d'Audierne (BdA), Bois de Cené (BdC), Biskupice (Bis), Blanský Les Massif (Bla), Böllsteiner Odenwald (BöO), Bragança (Brag), Champtoceaux Complex (CC), Céan, Chavanon (Cha), Campo Major (CM), Cabo Ortegal (CO), Cubito-Moura (CubM), Dunkelsteiner Wald Massif (DWM), Ergebirge (Erz), Golfo Aranci (GA), Île de Groix (IdG), Kaczawa (Kac), Kutná Hora (KH), La Bessenoits (LaB), Leon Domain (LD), Limousin (Lim), Monts du Lyonnais (MdL), Montagne Noire (MN), Morais, Morvan, Malpica-Tui (MT), Münchberg (Mü, uppermost allochthon of Saxo-Thuringian Zone), Náměšt Granulite Massif (Nam), Pirin, Podolsko Complex (Pod), Savona – Saxon Granulite Massif (SaxGra), Sierra de Guadarrama (SdG), Sebeş, Stronje (Str, Orlica-Śnieżnik Dome), Strážek granulite (Stra, Moldanubian Zone), Villafranco de los Barros (VdB), Ulten, Vosges, Western Tatra Mountains (W-Tatra), Wildenfels (Wil, uppermost allochthon of the Saxo-Thuringian Zone), Zevreila.

et al., 1990; Viruete, 1998; Jacques et al., 2018), the West Asturian-Leonese as well as the Cantabrian zones (Weil et al., 2013). Folding and thrusting in Iberia and the Southern Armorican Massif resulted in the formation of the Ibero-Armorican Arc (Matte and Ribeiro, 1975; Ballèvre et al., 2009). This strain pattern is in agreement with deformation structures from peripheral parts of the Ibero-Armorican Arc, e.g. SW directed nappe emplacement in Sardinia (Conti et al., 2001; Carosi and Palmeri, 2002; Di Vincenzo et al., 2004), E directed nappe emplacement along the offshore continental crust of Newfoundland (Lefort et al., 1993), NNE–SSW shortening in the Montagne Noire (Faure et al., 2009), and N–S shortening in the South Portuguese Zone (Onézime et al., 2003).

4.2.6. *Transpressional tectonics to the north of the East African-Arabian Zircon Province (340–300 Ma)*

In the Carboniferous, the West African Zircon Province is affected by NNW-SSE shortening forming the foreland fold-and-thrust belts along the Rheic suture zone, i.e. the Saxo-Thuringian Zone (Hahn et al., 2010; Stephan et al., 2016), the Rheno-Hercynian Zone (Oncken, 1988; Fielitz, 1992; Jacob and Franzke, 1992; Lacquement et al., 2005), and on the British Isles (Bresser and Walter, 1999; Woodcock and Rickards, 2003; Westhead et al., 2018). Thereby, the sense of transpression depends on the strike of the Rheic suture, i.e. sinistral transpression occurs along NE trending segments and dextral transpression affects NW trending segments of the suture zone. The strain partitioning resulted from the oblique reactivation of structures that developed before the formation of the orogenic wedge (Stephan et al., 2016). The final oroclinal buckling of the Ibero-Armorican Arc in the Permo-Carboniferous (ca. 300 Ma; Gutiérrez-Alonso et al., 2015) was caused by N–S directed shortening that overprinted the originally N–S trending linear belt (Weil et al., 2013; Jacques et al., 2018).

5. Discussion

5.1. *Evidence for heterogeneous extension along northern Gondwana*

The Early Paleozoic magmatic rocks along northern Gondwana predominantly include Cambrian alkaline, tholeiitic, and peralkaline rocks as well as Ordovician calc-alkaline and peraluminous rocks. As a striking feature of the Peri-Gondwanan magmatic record, the chemical character of the magmatic rocks changes abruptly at ca. 490 Ma from alkaline, tholeiitic, and peralkaline magmatism in the western shelf to calc-alkaline and peraluminous magmatism in the eastern shelf.

There is broad consensus that tholeiitic and peralkaline magmatism

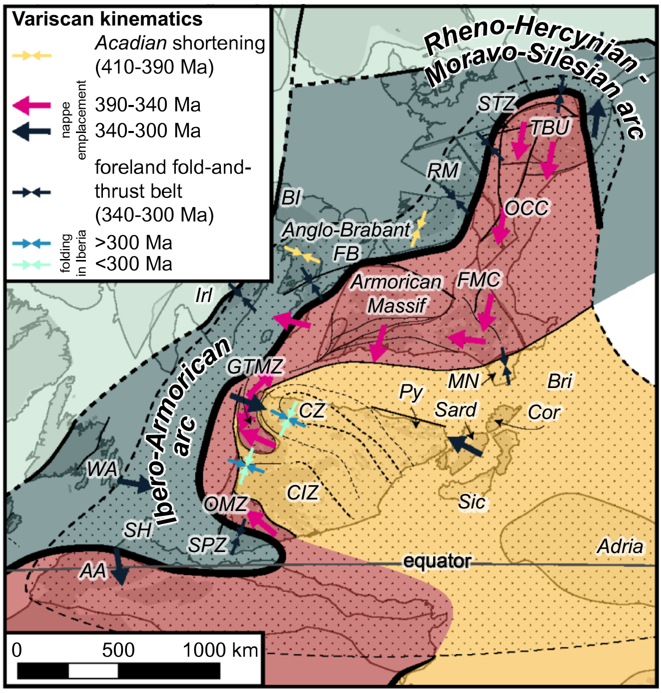

Fig. 7. Variscan kinematics shown by direction of movement of hanging wall units or maximum horizontal shortening directions. AA – Anti-Atlas, BI – British Isles, Bri – Briançonnais Zone, CIZ – Central Iberian Zone, Cor – Corsica, CZ – Cantabrian Zone, FB – fold belt, FMC – French Massif Central, GTMZ – Galicia–Trás-os-Montes Zone, Irl – Ireland, MN – Montagne Noire, OCC – Odenwald Crystalline Complex, OMZ – Ossa-Morena Zone, Py – Pyrenees, RM – Rhenish Massif, Sard – Sardinia, SH – Sehoul Block, Sic – Sicily, SPZ – South Portuguese Zone, STZ – Saxo-Thuringian Zone, TBU – Teplá-Barrandian Unit, WA – West Avalonia. See text for explanations, data sources are given in Suppl. 5.

is related to an extensional tectonic setting (e.g. McKenzie and Bickle, 1988), such as mid-ocean ridges and intracontinental rifts, respectively, whereas calc-alkaline magmatism is generally associated with subduction processes (e.g. Roberts and Clemens, 1993). As the 460 Ma pulse of the magmatism (Fig. 5) is coeval with the HP metamorphism (ca. 465 Ma) and the deformation of pre-Sardinian rocks (ca. 450–470 Ma), parts of the Ordovician calc-alkaline and peraluminous suite are likely to be derived from subduction-generated melts (Schulz et al., 2008; Cruciani et al., 2013; Cavargna-Sani et al., 2014; Zurbriggen, 2015; Díaz-Alvarado et al., 2016).

Nevertheless, vast areas of the entire northern shelf of Gondwana show no evidence for metamorphism and deformation but record calc-alkaline magmatism. The calc-alkaline chemical signature of magmatic rocks does not necessarily reflect subduction processes, but may also occur in rocks that formed in an extensional setting by assimilation or melting of basement crust (e.g. Hooper et al., 1995; Bea et al., 2007). Thus, the contrasting magmatic character between the western and the eastern shelf may reflect (i) contrasting composition of the basement and/or (ii) contrasting extent and/or speed of crustal melting, and hence contrasting contribution of assimilated country rocks. There are also differences in the Nd and/or Hf-isotopic compositions: magmatic rocks of the eastern shelf predominantly derive from a mixed source of juvenile crust and old Northeast African-Arabian basement (e.g. Bea et al., 2007; Montero et al., 2007; Talavera et al., 2013; Zlatkin et al., 2013; Lotout et al., 2016; Villaseca et al., 2016; Vozárová et al., 2017), whereas the rocks of the Avalonian and western shelf comprise predominantly juvenile crust (e.g. Archibald et al., 2013; Cambeses et al., 2016; Sagawe et al., 2016; Hajná et al., 2017). As the extension rate controls decompression of the lithospheric mantle and hence influences the volume and composition of the generated melt (Bown and White, 1994; Bown and White, 1995), the change of the chemical composition of Cambro-Ordovician extension-related magmatic rocks indicates an eastward declining rate of extension. Thereby, the higher extension rate in the western shelf allows tholeiitic melts to migrate little affected through the crust, whereas the lower extension rate in the eastern shelf forces the melt to assimilate northeast Gondwanan basement, thereby generating hybrid, calc-alkaline magmatic rocks. Local occurrence of mantle-derived lenses in the Moldanubian Zone of the Bohemian Massif (Žák and Sláma, 2017) underline high extension along the western shelf, whereas hyperextension is not known from the eastern shelf.

5.2. Diachronous subsidence and provenance changes

The coeval occurrence of Cambrian to Ordovician extension-related magmatism and extensional tectonics (Melichar, 2004; Žák et al., 2013) indicates that the subsidence is associated to the extension and subsequent cooling of the crust (Kroner et al., 2007; von Raumer and Stampfli, 2008). Cambrian and Ordovician sediments on both shelf areas have similar thickness (Fig. 3). The presence of numerous erosional unconformities in the East African-Arabian Zircon Province, however, suggests that the original thickness of Cambrian to Ordovician sediments may have been significantly higher in the eastern segment of the shelf. Moreover, the contrasting tectonic and sedimentological record on both shelf areas is related to temporary changes of detrital zircon provenance.

In the Late Cambrian (ca. 500–490 Ma), the (hyper)extended western shelf is characterized by reduced sediment influx (Fig. 3). Changes in the provenance of detrital zircon (Fig. 2, Suppl. 1) and the chemical composition of the clastic sediments (Romer and Hahne, 2010) coincide with the peak of magmatism in the western shelf (Fig. 5). This change in zircon provenance indicates a temporary shift in the source area. The small fraction of Ediacaran detrital zircon indicates that the Cadomian arc was not under erosion during the Late Cambrian (Fig. 2). Furthermore, the increase of Neoarchean detrital zircon grains (Suppl. 1k) hints to the exposure and erosion of old cratonic basement. The prolonged thermo-tectonic subsidence of the West African Craton, as demonstrated by coeval sediment accumulation on the craton (Avigad et al., 2012; Garfunkel, 2015), implies that the detritus delivered to the shelf must have been derived from more distal, interior parts of Gondwana such as the Congo and Tanzania cratons (if they were exposed), or from the recycling of eroded material from those cratons (Romer and Hahne, 2010; Stephan et al., 2019).

In the Ordovician, the sedimentation pattern on the eastern shelf changed significantly because of increasing subsidence in the eastern shelf (von Raumer and Stampfli, 2008). In contrast to the undisturbed western shelf sequences, the sedimentary successions of the eastern shelf show numerous unconformities in Cambrian and Ordovician strata. These unconformities reflect tectonic events, as demonstrated by metamorphosed and deformed rocks as well as from far field effects (Fig. 3). The unconformities indicate that there were several compressional tectonic phases in (i) the Early to Middle Cambrian and (ii) the Early to Middle Ordovician. The latter event, generally subsumed under the term “Sardic phase”, is interpreted either as a result of a far field effect due to the coeval “Caledonian” collision of Baltica with Avalonia (Franz and Romer, 2007), an Alaskan-type subduction-accretion (“Cenerian Orogeny”; Zurbriggen, 2017), or as a localized compressional expression due to strain partitioning during the Cambro-Ordovician extension (Correia Romão et al., 2012). Whatever the tectonic trigger mechanism, the temporary uplift of (parts of) the eastern shelf is associated with locally important deformation and/or gaps in the sedimentary record.

The uplift of parts of the eastern shelf is also reflected in a change of the provenance pattern as Middle Ordovician to Silurian sedimentary rocks with East African-Arabian provenance were eroded and re-deposited on the western shelf (Rösel et al., 2018). In particular in Upper Ordovician to Silurian sedimentary rocks of the Armorican

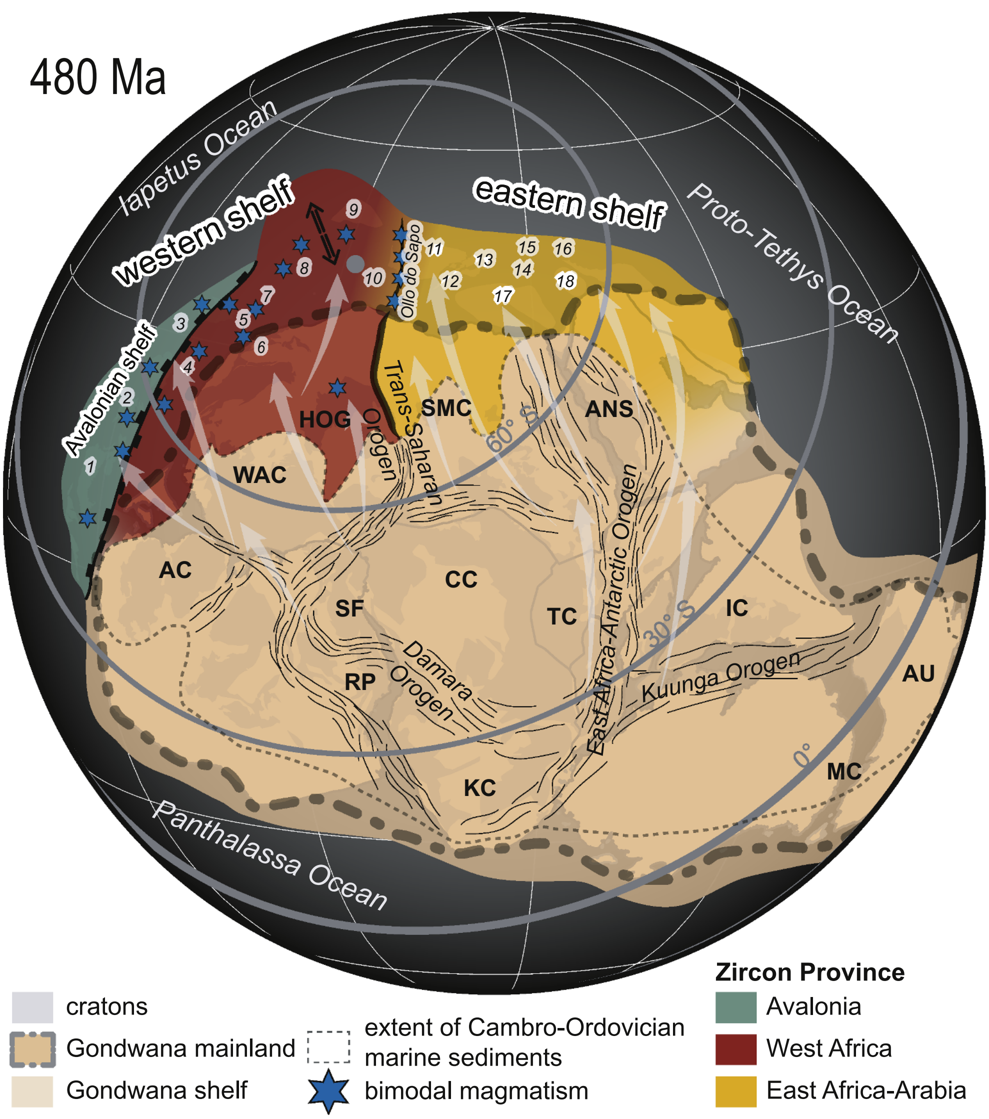

Fig. 8. Schematic reconstruction of the northern shelf of Gondwana at 480 Ma, orthographic projection. White arrows indicate possible sediment transport directions from Central Gondwana to the continental margins. South pole location bases on Torsvik et al. (2012), extent of Cambro-Ordovician sediments modified from Guiraud et al. (2005), zircon province pattern modified from Stephan et al. (2019). Abbreviations: AC – Amazonas Craton, ANS – Arabian-Nubian Shield, AU – Australia cratons, CC – Congo Craton, IC – Indian Craton, KC – Kalahari Craton, MC – Mawson Craton, SF – São Francisco Craton, SMC – Sahara Metacraton, RP – Rio Plato Craton, TC – Tanzania Craton, WAC – West African Craton, 1 – West Avalonia, 2 – East Avalonia, 3 – Far-East Avalonia, 4 – Ossa-Morena Zone, 5 – Teplá-Barrandian Unit, 6 – Anti-Atlas, 7 – Galicia–Trás-os-Montes Zone, 8 – Lausitz Block (Saxo-Thuringian Zone), 9 – Armorican Massif, 10 – French Massif Central, 11 – Iberia (Central Iberian Zone, West Asturian-Leonese Zone, Cantabrian Zone), 12 – Sardinia-Corsica, 13 - Briançonnais, 14 – Balkan units, 15 – Montagne Noir-Pyrenees-Catalonian Coastal Range, 16 – Proto-Alps, 17 – Adria-Apennines-Sicily, 18 – Menderes Massif.

Massif and the Saxo-Thuringian Zone (western shelf), the East African-Arabian provenance of detrital zircon (Bahlburg et al., 2010; Franz et al., 2013; Rösel et al., 2014; Ballouard et al., 2018) is underlined by the occurrence of detrital rutile with ca. 460–470 Ma ages (Rösel et al., 2018) that correspond to the Sardic magmatic or metamorphic event in the eastern shelf.

Despite the redistribution of the Sardic detritus from the eastern shelf to the western shelf and the reduced extension, which implies a lower potential for tectonic subsidence, the eastern shelf records higher sediment influx (up to 6000 m) than the western shelf (Fig. 3). The two shelf segments, furthermore, received sediments from contrasting Gondwanan source areas (Stephan et al., 2019) that were subjected to contrasting potential for erosion. The source area of the West African Zircon Province (western shelf) comprises predominantly old crust (e.g. the West African Craton, the Amazonian Craton, and the Congo Craton), while the source area of East African-Arabian Zircon Province (eastern shelf) is characterized by predominantly young orogens, such as the Kuunga Belt and the East African-Antarctic Orogen (Meinhold et al., 2013; Rösel et al., 2014; Rösel et al., 2018). Whereas cratons were subjected to long-lasting erosion and hence have a low relief, younger orogens are likely to have a higher relief and hence a significant higher potential for erosion (Cawood et al., 2012; Cawood et al., 2013; Hawkesworth et al., 2013). In addition, both source areas are affected by contrasting climatic conditions. The source area of the East African-Arabian Zircon Province, i.e. East Gondwana, was located in lower latitudes during the Cambrian-Ordovician. In contrast, the source area of West African Zircon Province, i.e. West Gondwana, was located in polar regions and was partly covered by the Hirnantian ice sheet (Fig. 8).

In summary, the contrasting sedimentary and tectonic records of the two shelf segments are the result of contrasting sediment sources and heterogeneous extension along Peri-Gondwana. The tectonic inheritance, i.e. the shelf-wide Cambro-Ordovician lithospheric-scale rifting, strike-slip, and compression, has produced important and heterogeneously distributed mechanical anisotropies that in part were reactivated during the Variscan Orogeny.

5.3. Architecture of northern Peri-Gondwana: evidence for a contiguous but bipartite shelf

Paleogeographic proxies, including zircon provenance, the timing and type of Cambro-Ordovician magmatism, and the age of Variscan tectono-metamorphic overprint provide constraints for reconstructing relative positions of the pre-orogenic units along northern Gondwana (Table 1). There is broad consensus about the Cambrian paleogeographic position of Avalonia close to the South American part of West Gondwana because of dominant detritus from the Amazonas Craton (Nance and Murphy, 1994; Collins and Buchan, 2004; Balintoni et al., 2011b; Willner et al., 2013; Zlatkin et al., 2014). Due to coeval

Table 1
Paleogeographic features of northern Peri-Gondwana.

	Western Gondwanan shelf	Eastern Gondwanan shelf
Detrital zircon province[1]	West African Zircon Province, (Avalonian Zircon Province)	East African–Arabian Zircon Province
Benthic and neritic fauna[2]	Northwest African taxa (“Ibarmaghian faunal province”)[3]	Arabian taxa with rare occurrences of Australo-Asiatic taxa (“Mediterranean faunal province”)[4]
Magmatism[5]	* ca. 520 Ma and ca. 500 Ma bimodal, alkaline or tholeiitic magmatism * ca. 490 Ma calc-alkaline magmatism	* ca. 490 Ma calc-alkaline magmatism * ca. 470 Ma and ca. 460 Ma calc-alkaline and peraluminous magmatism
Lower Paleozoic angular unconformities[6]	* Cadomian/Pan-African unconformity (Neoproterozoic to Lower Cambrian) * Upper Cambrian * Hirnantian	* Cadomian/Pan-African unconformity (Neoproterozoic to Lower Cambrian) * Lower Cambrian * Middle Cambrian * Lower/Middle Ordovician (“Sardinian”, “Sarabese”, or “Taurinian” unconformity above ca. 470–450 Ma deformed rocks) * Hirnantian
Pre-Variscan metamorphism and deformation	not recorded	* ca. 535 Ma HP metamorphism (e.g. the Menderes and the Bitlis massifs)[7] * ca. 470–450 Ma high-grade metamorphism (“Cenerian Orogeny”)[8]
Variscan HP metamorphism[9]	ca. 390–340 Ma	ca. 340–300 Ma
Oceanic realm	Rheic Ocean	Proto − / Paleo-Tethys Ocean

[1] Provenance classification after Stephan et al. (2019).
[2] Lower Paleozoic.
[3] Sources: Young (1990); Plusquellec and Hladil (2001); Gutiérrez-Marco et al. (2002); Robardet (2002); Fatka and Mergl (2009).
[4] Sources Shergold et al. (1983); Gutiérrez-Marco and Rodríguez (1987); Hammann (1992); Mélou et al. (1999); Shergold et al. (2000); Gutiérrez-Marco et al. (2002).
[5] Data sources see Tab. Suppl. 2.
[6] Data sources see Fig. 3.
[7] Ustaömer et al. (2012); Candan et al. (2016).
[8] Sources: Poli and Zanferrari (1992); Gebauer (1993); Poller et al. (1997); Schaltegger et al. (2003); Gaggero et al. (2004); Franz and Romer (2007); Balintoni et al. (2011a); Balintoni and Balica (2013); Zurbriggen (2015); Franceschelli et al. (2016); Zurbriggen (2017).
[9] Source: Kroner and Romer (2013), for more details see Suppl. 5.

magmatism and sediment mixture with West African detritus (Stephan et al., 2019), Avalonia was part of the western shelf prior to its separation from Gondwana at ca. 480 Ma (Fig. 8).

South of the Rheic Ocean the constant Gondwana-derived detritus to the shelf (e.g. Linnemann et al., 2004; Žák and Sláma, 2017; Stephan et al., 2019), the generally similar sedimentary evolution (Fig. 3), and the benthic-faunal similarities across the supposed sutures (e.g. Young, 1990; Robardet, 2002) provide ample evidence for a contiguous shelf of northern Gondwana prior to the Early Devonian onset of the Variscan Orogeny. The shelf-parallel variations of geological features (sedimentary provenance, benthic faunas, and timing of magmatism), however, point to a bipartite nature of northern Peri-Gondwana, i.e. a western and an eastern shelf (Table 1). Temporary changes in the provenance pattern, i.e. the mixture of West Gondwanan with East Gondwanan detritus, indicate sediment exchange between parts of both shelf segments. The sediment exchange between the two shelf segments precludes the existence of a sharp boundary, e.g. a topographic high or seafloor spreading, between the two parts of the shelf prior to the onset of the Variscan Orogeny.

The transition between the two segments of the northern shelf of Gondwana is located between the Armorican Massif and the Central Iberian Zone (Fig. 8) because of similarities in the faunal (Gutiérrez-Marco et al., 2002; Robardet, 2003), lithostratigraphic (Fig. 3), and magmatic record (Fig. 5) but contrasting detrital zircon provenance (Henderson et al., 2016; Stephan et al., 2019). The transition may be associated with the probably most extensive magmatic zone of Peri-Gondwana, i.e. the Ollo de Sapo Formation within Central Iberia.

On northern Africa as part of mainland Gondwana, the boundary between both zircon provinces follows the boundary between the West African Craton and the Saharan Metacraton, i.e. the Trans-Saharan Belt (Henderson et al., 2016; Stephan et al., 2019). Assuming that remnants of the Trans-Saharan Belt have served as watershed for the sediment supply, the boundary between the western and eastern shelf was located along the northward extension of that orogenic belt (Fig. 8).

The bipartite shelf architecture incorporates the contemporaneous existence of the Rheic and the Proto-Tethys oceans to the north of the passive margin of Gondwana with the western and eastern shelf related to the Rheic and Proto-Tethyan realm, respectively (Table 1, Fig. 8).

5.4. Implications for the Variscan Orogeny

This study distinguished two segments of contrasting development for the contiguous but bipartite shelf of northern Gondwana. Earlier tectonic models (e.g. Matte, 2001; Kroner et al., 2007; Franke et al., 2017) and paleogeographic reconstructions (e.g. Stampfli and Borel, 2002; Stampfli et al., 2013) did not take into consideration this important feature. The here presented Permian reconstruction of the Variscan Orogen shows the juxtaposition of tectonic blocks that are derived from Avalonia, the western and eastern shelf of northern Gondwana eventually resulted in the formation of the Rheno-Hercynian–Moravo-Silesian and the Ibero-Armorican arcs (Fig. 1). The Rheno-Hercynian–Moravo-Silesian Arc is the result of early Variscan (ca. 390 Ma) NE–SW directed collision of the rigid Teplá-Barrandian and Lausitz blocks (Armorican Spur) with the Rheno-Hercynian–Moravo-Silesian back arc basin of East Avalonia (Kroner et al., 2008) (Figs. 9 & 10). The collision followed the Acadian (ca. 400 Ma) accretion of the Armorican block with the Midland Microcraton, i.e. Avalonia (Rolet et al., 1994; Leloix et al., 1999; Soper and Woodcock, 2003; Leveridge and Shail, 2011). The eastern shelf of northern Gondwana remained in a passive continental margin setting until the Late Devonian opening of the Paleo-Tethys Ocean (García-Alcalde et al., 2002).

The prolonged compressional events in the eastern shelf (360–340 Ma) are coeval with extensional magmatism along the Herodotus rift at the western rim of the Arabian plate (Granot, 2016; Golan et al., 2017). As there is no Variscan tectonic overprint recorded to the east of this structure, i.e. Turkey, Arabia, and Northeast Africa (Fig. 1), we propose that a segment of the eastern shelf had decoupled from mainland Gondwana in course of prolonged extension along the Herodotus rift prior to 340 Ma (Fig. 10) and successively collided with the already accreted western shelf, i.e. the Armorican Spur (Fig. 11). This decoupling probably reflects plate tectonic reorganization due to

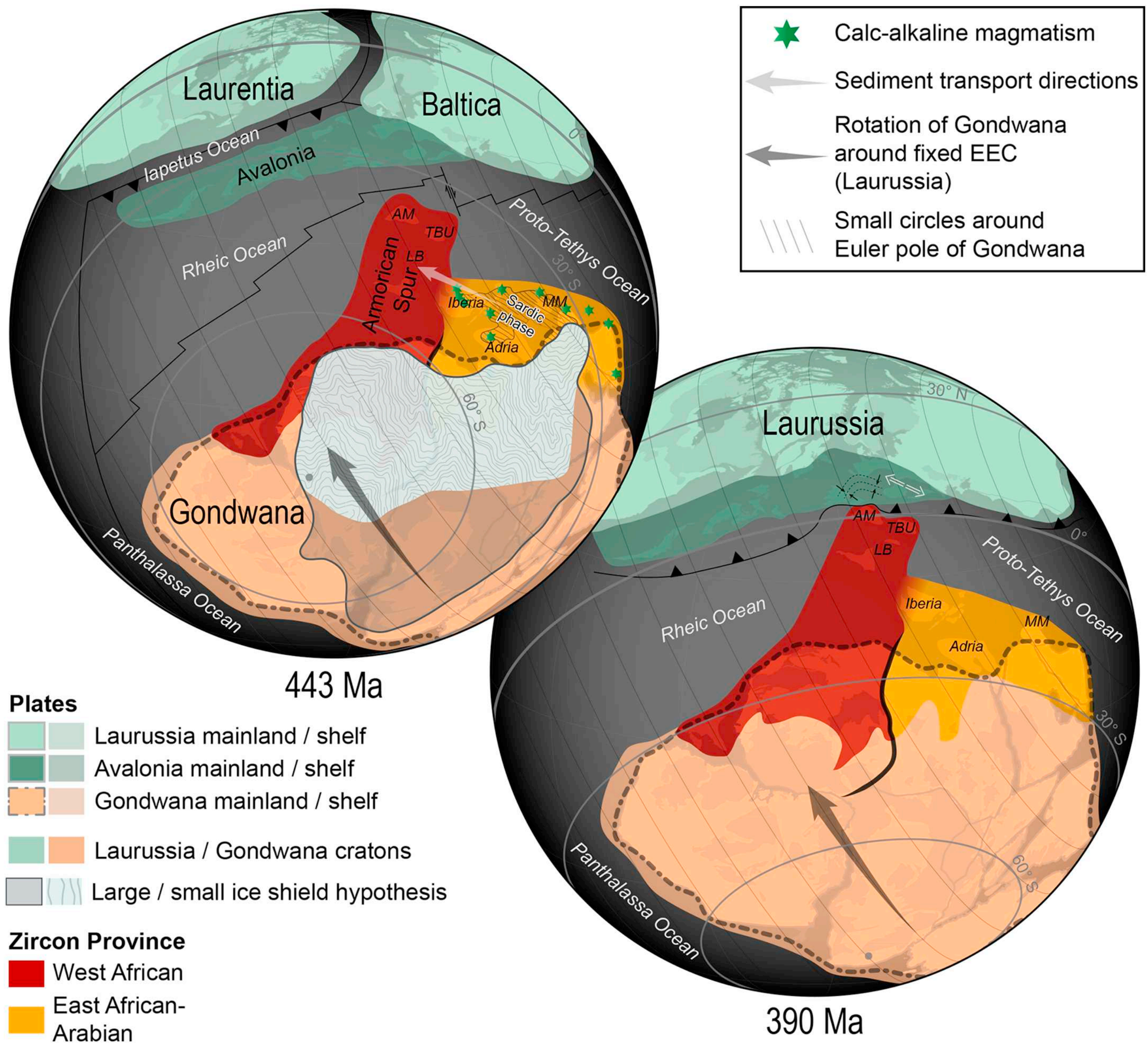

Fig. 9. Model for the evolution of Peri-Gondwana from 443 Ma to 390 Ma (orthographic projection). 443 Ma: Ordovician (Sardinian/Cenerian) tectono-metamorphic event is coeval with calk-alkaline magmatism that exclusively occurs in the eastern shelf of northern Gondwana. The extent of the Hirnantian ice shield is modified from Le Heron and Dowdeswell (2009). The glacially redistributed detritus from the East African-Arabian Zircon Province to the West African Zircon Province led to short-termed, mixed zircon provenance signatures. 390 Ma: The initial collision of the western segment of the Gondwanan shelf with Laurussia resulted in the Acadian Orogeny and back-arc extension in the Rheno-Hercynian–Moravo-Silesian shelf of Laurussia. For additional explanations see text. Relative to the fixed East European Craton, motion of Gondwana to Laurussia between 370 and 250 Ma is consistent with the Euler pole reconstruction of Kroner et al. (2016); the motion of non-Variscan terranes (e.g. China blocks) is not illustrated; the reconstruction is modified after Kroner and Romer (2013); Kroner et al. (2016); Romer and Kroner (2018); the extent of Cambro-Ordovician marine sediments is based on Guiraud et al. (2005); zircon provinces are modified after Stephan et al. (2019). Abbreviations: AM – Armorican Massif, IB – Iberia, LB – Lausitz Block (autochthonous Saxo-Thuringia), MM – Menderes Massif, TBU – Teplá-Barrandian Unit.

the change in the rotation of the Gondwanan plate after the accretion of the Armorican Spur to Laurussia, which resulted in the opening of the Paleo-Tethys Ocean (Kroner et al., 2016). The decoupling of the eastern shelf from mainland Gondwana may have reactivated ancient mechanical anisotropies such as the Cambrian and Ordovician inherited structures and culminated in westward extrusion of the detached segment of the eastern shelf.

The collision of the eastern with the western shelf segment is recorded in the Iberian Variscides culminated in the formation of the Ibero-Armorican Arc (Fig. 11). This collisional event is reflected by 340 Ma wrench tectonics along the Coimbra-Cordoba shear zone between the Ossa-Morena (western shelf) and the Central Iberian zones (westernmost promontory of the eastern shelf; Pereira et al., 2012b; Rojo-Pérez et al., 2019), the thrusting of the allochthonous units of the Galicia–Trás-os-Montes Zone (western shelf) on top of the Central Iberian Zone (Gómez Barreiro et al., 2007), and the accretion of the Montagne Noire (eastern shelf) to the northern part of the French Massif Central (western shelf) as indicated by Late Variscan pervasive deformation in the southern part of the French Massif Central (Cassard et al., 1993; Faure et al., 2009). Coeval transpressional tectonics and

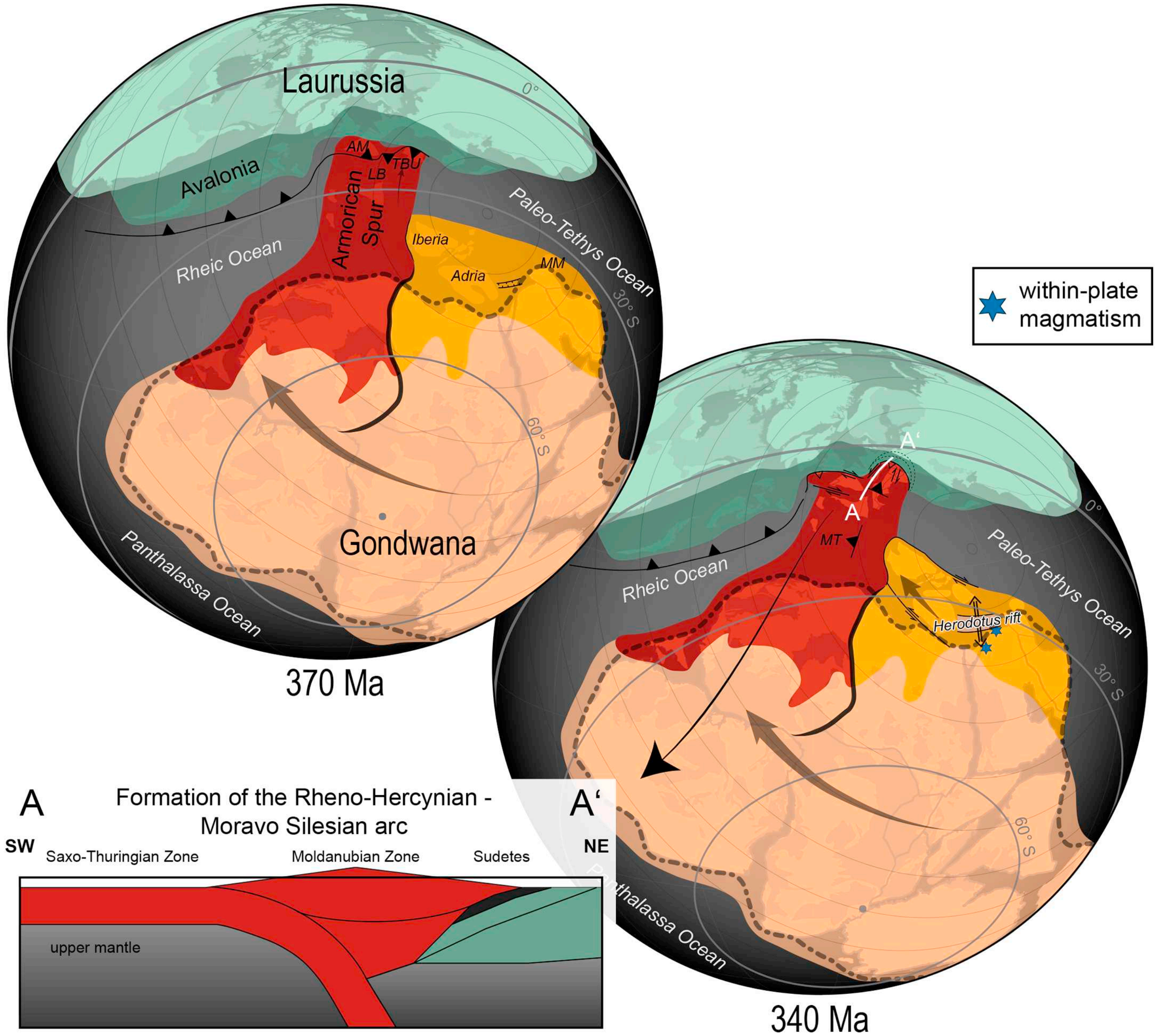

Fig. 10. Model for the evolution of Peri-Gondwana from 370 Ma to 340 Ma. 370 Ma (orthographic projection): 370 Ma: The subduction of the leading edge of the Armorican Spur is associated with NE–SW shortening. The opening of the Paleo-Tethys Ocean resulted in rifting at the western margin of the Arabian plate. 340 Ma: The formation of the Rheno-Hercynian–Moravo-Silesian Arc is due to the accretion of the western shelf of northern Gondwana to Laurussia. Prolonged extension along the Herodotus rift resulted in the decoupling of the eastern shelf from northern Gondwana by reactivating Ordovician mechanical anisotropies. Section A is modified after Kroner et al. (2007); orientation of the sections given in present coordinates. Abbreviations: AM – Armorican Massif, IB – Iberia, LB – Lausitz Block, MM – Menderes Massif, MT – Malpica-Tui, TBU – Teplá-Barrandian Unit. For further explanations see Fig. 9.

lateral escape movements in the western shelf (Kroner et al., 2007; Stephan et al., 2016) may be triggered by the oblique indention of the eastern shelf. Prolonged convergence between the Laurussian and Gondwanan plates resulted in the oroclinal buckling of the initial collision zone of the two shelf fragments eventually forming the “Cantabrian orocline” within the Ibero-Armorican Arc (Weil et al., 2000; Weil et al., 2013).

6. Conclusions

Differences in sediment provenance, benthic faunas, age and type of magmatic rocks, and the tectono-metamorphic as well as lithostratigraphic record reveal the bipartite nature of the northern shelf of Gondwana prior to the Variscan Orogeny. The Early Paleozoic Gondwanan shelf is distinguished into a western and eastern segment that are separated by remnants of the Trans-Saharan Orogen:

(i) The detrital zircon record indicates a West Gondwanan and a Central-East Gondwanan source for the western and eastern shelf, respectively. Both shelf segments received sedimentary input from two independent Gondwanan super-fan systems separated by the Trans-Saharan watershed. The contrasting source areas and thus the contrasting potential for erosion control the sediment subsidence of the shelf segment. Except for the short-termed detrital redistribution during the Hirnantian glaciation, the super-fan systems remained stable during the entire time (Cambrian to Early Devonian) as demonstrated by the detrital zircon spectra. Short-term sediment exchange between the two shelf segments in the

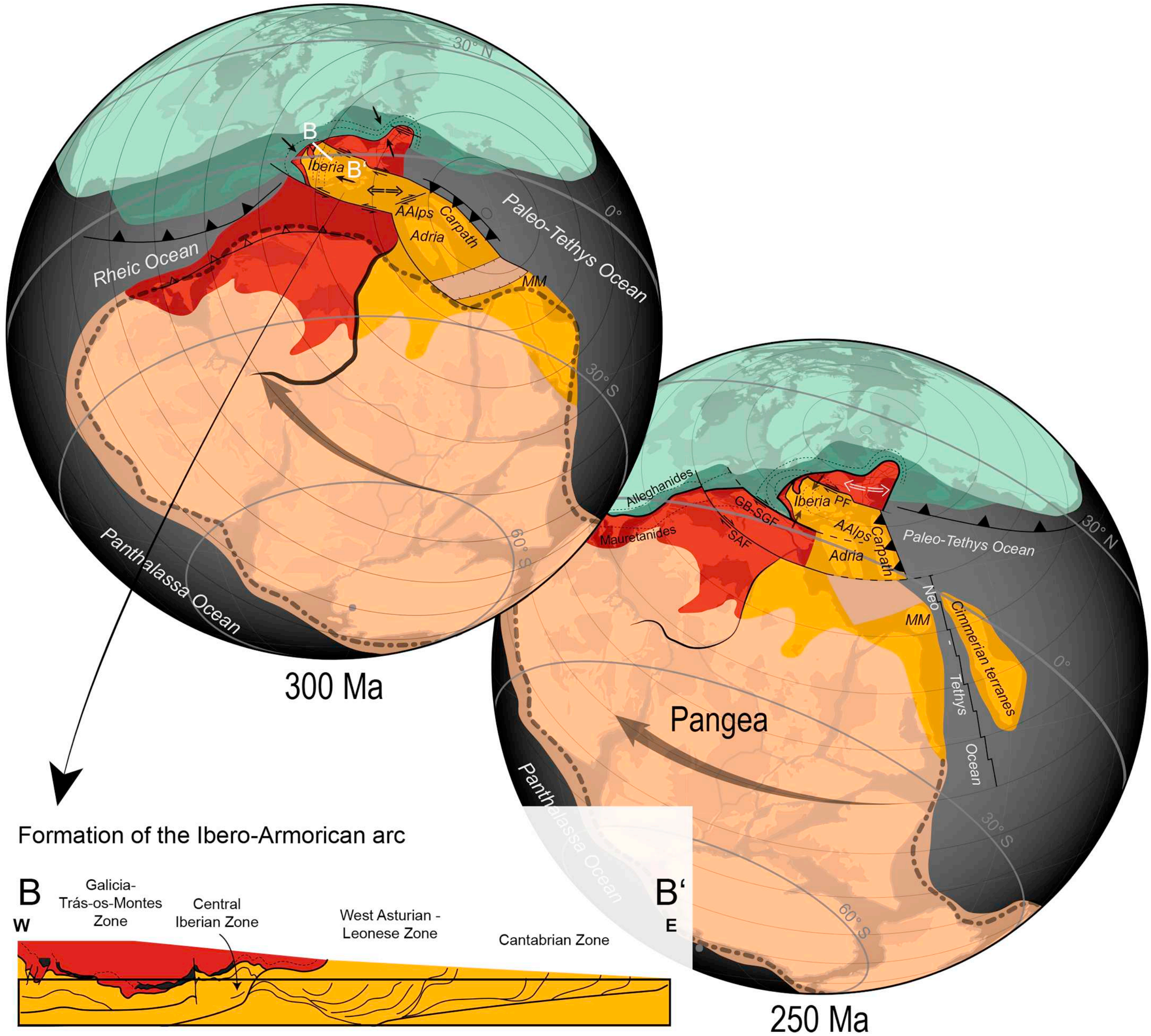

Fig. 11. Model for the evolution of Peri-Gondwana from 300 Ma to 250 Ma (orthographic projection). 300 Ma: The formation of the Ibero-Armorican Arc was coeval to transpressional tectonics in the Armorican Spur. 250 Ma: Final oroclinal bending in Iberia marks the end of the Variscan Orogeny that is followed by the transformation of Central Europe into an extensional province. Gondwana decoupled from Laurussia (incl. accreted western and eastern shelf) along the South Atlas Fault and the prolonged plate convergence culminates in the final closure of remaining parts of the Rheic Ocean. The collisional tectonics related to the formation of the Mauretanides, the Alleghanides, and the Ouachita-Marathon-Sonora Belt to the west of Gondwana resulted in the final amalgamation of Pangea. The clockwise motion of Gondwana is related to the separation of the Cimmerian terranes by opening the Neotethys Ocean to the east of Gondwana (modified after Dornsiepen et al., 2001; Greiner and Neugebauer, 2013; Handy et al., 2015); polar wander after Torsvik et al. (2012); section B is modified after Martínez Catalán et al. (2009); orientation of the sections given in present coordinates. Abbreviations: AAlps – Austro-Alpine, Carpath – Proto-Carpathians, GB-SGF – Grand Bank–Straits of Gibraltar Fault, MM – Menderes Massif. PF – Pyrenean Fault, SAF – South Atlas Fault. For further explanations see Fig. 9.

Ordovician and Silurian precludes the existence of a tectonic boundary, a topographic high or seafloor spreading between the two parts of the shelf prior to the onset of the Variscan Orogeny.

(ii) Both shelf segments record a similar Cambro-Ordovician shelf evolution but diachronous occurrence of angular unconformities: Lower Paleozoic sediments of the western shelf show tectonically undisturbed sedimentation in a setting of steady subsidence. In contrast, the evolution of the eastern shelf is characterized by numerous compressional tectonic events that are locally associated with high-grade metamorphism.

(iii) Different latitudinal positions and/or access to marine paleocurrent systems resulted in the development of contrasting benthic and neritic faunas in both shelf segments. This is demonstrated by the exclusive occurrence of West African faunas in the western shelf and East Gondwanan taxa in the eastern shelf.

(iv) There is ample evidence for heterogeneous extension along northern Peri-Gondwana as demonstrated by contrasting subsidence patterns, the temporal provenance changes, the tectonic record, and the type of magmatism. The diachronous magmatism along the northern margin of Gondwana includes Cambrian tholeiitic and alkaline magmatism in the western shelf and Ordovician calc-alkaline and peraluminous magmatism in the eastern shelf.

This east-ward propagation of the magmatic activity can be used as paleogeographic proxy for the relative position of the tectonic units along the pre-orogenic Gondwanan shelf.
(v) The diachronous, shelf-wide Cambro-Ordovician lithospheric-scale rifting event as well as strike-slip and compressional tectonics in the eastern shelf (e.g. "Sardic phase" and "Cenerian Orogeny") have created important mechanical anisotropies that were reactivated during the Variscan Orogeny.

Based on the pre-Variscan paleogeographic constraints, we present implications for the Variscan Orogeny that are in agreement with the Variscan tectonic and metamorphic record. The Late Paleozoic tectonometamorphic record reveals that tectonic blocks from both shelf segments were incorporated diachronously into the Variscan Orogen: (i) The western shelf was extended during the Cambrian and formed a Gondwanan promontory, namely the Armorican Spur, that collided and accreted to Laurussia in the Early Devonian. (ii) The eastern shelf remained in an undisturbed position until the Late Devonian. Triggered by Late Devonian rifting along the eastern margin of Arabia, the eastern shelf decoupled from mainland Gondwana along reactivated Ordovician lithospheric-scale faults followed by Early Carboniferous westward movement and collision with the western shelf that had been accreted before.

The Rheno-Hercynian–Moravo-Silesian Arc is the final result of the Devonian indention of the Armorican Spur into the Laurussian plate and Early Carboniferous transpressional overprint. Lateral escape of the accreted spur is triggered by the Early Carboniferous collision of the eastern shelf and resulted in the formation of the Ibero-Armorican Arc. Variscan oroclinal buckling is the direct result of prolonged plate convergence between Gondwana and Laurussia.

The bipartite nature of the northern shelf of Gondwana provides crucial constraints for the Early Paleozoic paleogeography of pre-Variscan units. Vice versa, it offers new implications for the Variscan juxtaposition of tectonic blocks of contrasting paleogeographic affinities. Thus, the interplay between the two Gondwanan shelf segments is seen as the underlying cause of the final patchwork pattern of paleogeographic markers and the arcuate shape of the Variscan orogenic belt.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.earscirev.2019.03.012.

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