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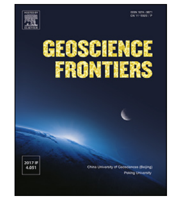

Focus Paper

Early Paleozoic accretionary orogens along the Western Gondwana margin

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A B S T R A C T

Early Paleozoic accretionary orogens dominated the Western Gondwana margin and were characterized by nearly continuous subduction associated with crustal extension and back-arc basin development. The southwestern margin is represented by Famatinian and Pampean basement realms exposed in South America, both related to the protracted Paleozoic evolution of the Terra Australis Orogen, whereas the northwestern margin is mainly recorded in Cadomian domains of Europe and adjacent regions. However, no clear relationships between these regions were so far established. Based on a compilation and reevaluation of geological, paleomagnetic, petrological, geochronological and isotopic evidence, this contribution focuses on crustal-scale tectonic and geodynamic processes occurring in Western Gondwana accretionary orogens, aiming at disentangling their common Early Paleozoic evolution. Data show that accretionary orogens were dominated by high-temperature/low-pressure metamorphism and relatively high geothermal gradients, resulting from the development of extended/hyperextended margins and bulk transtensional deformation. In this sense, retreating-mode accretionary orogens characterized the Early Paleozoic Gondwana margin, though short-lived pulses of compression/transpression also occurred. The existence of retreating subduction zones favoured mantle-derived magmatism and mixing with relatively young (meta)sedimentary sources in a thin continental crust. Crustal reworking of previous forearc sequences due to trenchward arc migration thus took place through assimilation and anatexis in the arc/back-arc regions. Therefore, retreating-mode accretionary orogens were the locus of Early Paleozoic crustal growth in Western Gondwana, intimately associated with major flare-up events, such as those related to the Cadomian and Famatian arcs. Slab roll back, probably resulting from decreasing convergence rates and plate velocities after Gondwana assembly, was a key factor for orogen-scale geodynamic processes. Coupled with synchronous oblique subduction and crustal-scale dextral deformation, slab roll back might trigger toroidal mantle flow, thus accounting for bulk dextral transtension, back-arc extension/transtension and a large-scale anticlockwise rotation of Gondwana mainland.

1. Introduction

Accretionary orogens form along convergent margins as the result of subduction and comprise forearc, arc and back-arc domains (Cawood et al., 2009 and references therein). In continental margins, they represent key areas for growth of the continental crust by addition of juvenile mantle-derived magmas in the arc and back-arc areas, or accretion of oceanic rocks (e.g., island arcs, seamounts) along the trench, thus contrasting with collisional orogens dominated by crustal reworking processes (Clift et al., 2009; Scholl and von Huene, 2009; Stern and Scholl, 2010; Collins et al., 2011; Stern, 2011; Spencer et al., 2019). Depending on the plate convergence rates, accretionary orogens can be divided into

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advancing and retreating types (Cawood et al., 2009): advancing orogens are characterized by crustal thickening due to compression/transpression, whereas retreating orogens undergo crustal thinning as the result of extension/transtension (Collins, 2002; Cawood et al., 2009).

The Late Neoproterozoic – Early Cambrian is a critical period in the Earth's evolution in terms of crustal-scale tectonometamorphic and magmatic processes, since the protracted Brasiliano – Pan-African Orogeny that led to the assembly of Gondwana was partially coeval with the development of accretionary orogens along the southern and northern Gondwana margins (Cawood, 2005; Cawood and Buchan, 2007; Murphy et al., 2011, 2013; Oriolo et al., 2017). The southern Gondwana margin recorded subduction along the proto-Pacific margin giving rise to the Paleozoic Terra Australis Orogen (Fig. 1; Cawood, 2005), which is particularly well-documented in western South America and southern Africa (Fig. 2). In these regions, nearly continuous subduction and arc magmatism alternated with discrete orogenic pulses related to the assembly of microplates (Ramos et al., 1986; Rapela et al., 1998a; Rapalini, 2005; Ramos, 2009; Casquet et al., 2012a; Chew et al., 2016), culminating with widespread tectonometamorphic, magmatic and sedimentary processes related to the Late Carboniferous–Permian Gondwanide Orogeny (Trouw and De Wit, 1999; Kleiman and Japas, 2009; Mišković et al., 2009; Spalletti et al., 2010; Maksaev et al., 2014; Chew et al., 2016; del Rey et al., 2016; Castillo et al., 2017; Oriolo et al., 2019). On the other hand, the northwestern Gondwana margin, which essentially comprises northern Africa and Avalonian-Cadomian domains of Europe and North America (Figs. 1 and 3), not only record Paleozoic continental arc magmatism but also crustal extension and oceanic basin

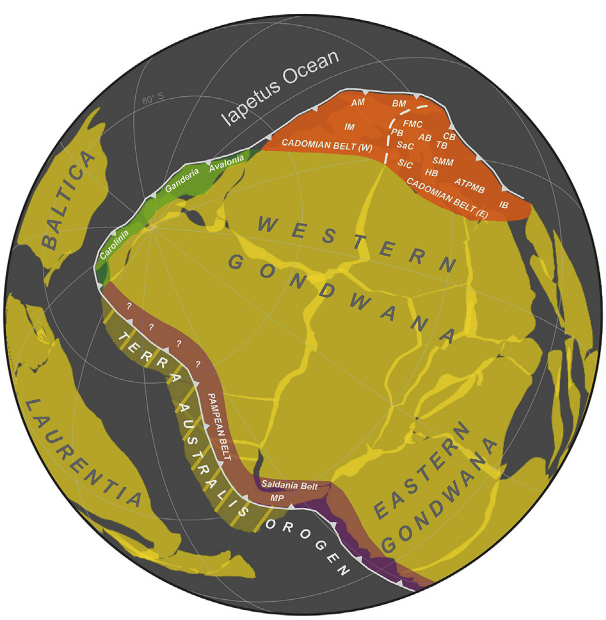

Fig. 1. Paleogeographic reconstruction of Western Gondwana at ca. 540 Ma using GPlates 2.2 (Müller et al., 2018) and the paleomagnetic database of Scotese (2016). Distribution of Carolinia, Avalonia, Ganderia and Cadomian domains modified after Linnemann et al. (2007), Nance et al. (2010), Stampfli et al. (2011), van Staal et al. (2012), von Raumer et al. (2015) and Stephan et al. (2019a). Correlations of the Pampean Belt with the Saldania Belt following Casquet et al. (2018). Potential location of the Malvinas Plateau based on Ramos et al. (2017). Western (W) and Eastern (E) sectors of the Cadomian margin after Stephan et al. (2019b). See text for further paleogeographic constraints. Striped areas along the Terra Australis Orogen schematically represent post-Cambrian orogens and accreted terranes. AB: Alpine basement, AM: Armorican Massif, ATPMB: Anatolides-Taurides-Pontides-Menderes Massif-Bitlis Massif, BM: Bohemian Massif, CB: Carpathian basement, FMC: French Massif Central, HB: Hellenides basement, IB: Iranian basement, IM: Iberian Massif, MP: Malvinas Plateau, PB: Pyrenean basement, SaC: Sardinia-Corsica, SiC: Sicily-Calabria, SMM: Serbo-Macedonian Massif, TB: Tisia Block.

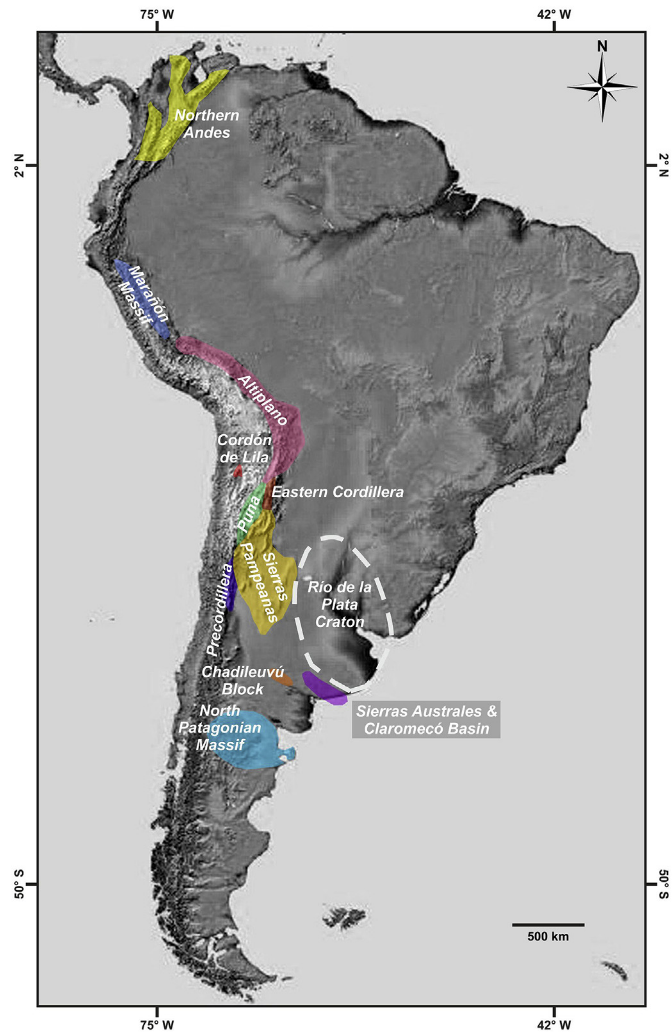

Fig. 2. Sketch map showing main areas hosting Late Ediacaran–Ordovician rocks in South America related to the southwestern Gondwana margin (modified after Pankhurst et al., 2016; Ramos, 2018).

development (Stampfli et al., 2002; Nance et al., 2010, 2012; Murphy et al., 2011, 2013; von Raumer et al., 2013, 2015; Garfunkel, 2015; Stephan et al., 2019a). This Early to Middle Paleozoic record is, however, largely overprinted by Late Paleozoic Variscan to Meso–Cenozoic orogenic processes (e.g., von Raumer et al., 2003).

During the Late Ediacaran–Cambrian, most regions of southwestern Gondwana recorded subduction along main cratonic blocks (e.g., Aceñolaza, 2003; Steenken et al., 2011; Ramos et al., 2014; Greco et al., 2017; Ortiz et al., 2017; Prezzi et al., 2018). In the Sierras Pampeanas (Argentina), this active margin recorded a first orogenic event, the Pampean Orogeny, at ca. 540–530 Ma (Rapela et al., 1998b; Sims et al., 1998; Siegesmund et al., 2010; Steenken et al., 2011; Casquet et al., 2018; López de Luchi et al., 2018). Subduction continued afterwards, being ubiquitously recorded along the proto-Andean margin of South America (Ramos, 2018, and references therein). This protracted Late Cambrian to Ordovician active margin records a major pulse of orogenic and magmatic activity at ca. 486–465 Ma, attributed to the Famatinian Orogeny (González et al., 2004; Steenken et al., 2006, 2011; Cristofolini et al., 2014; López de Luchi et al., 2018; Ramos, 2018; Rapela et al., 2018; Otamendi et al., 2020).

In a similar way to the South American Brasiliano record, the Pan-African amalgamation of crustal blocks in northern Africa gave rise to several Ediacaran orogenic belts (Liégeois et al., 2013, and references therein), which were the source of detritus for subsequent Early

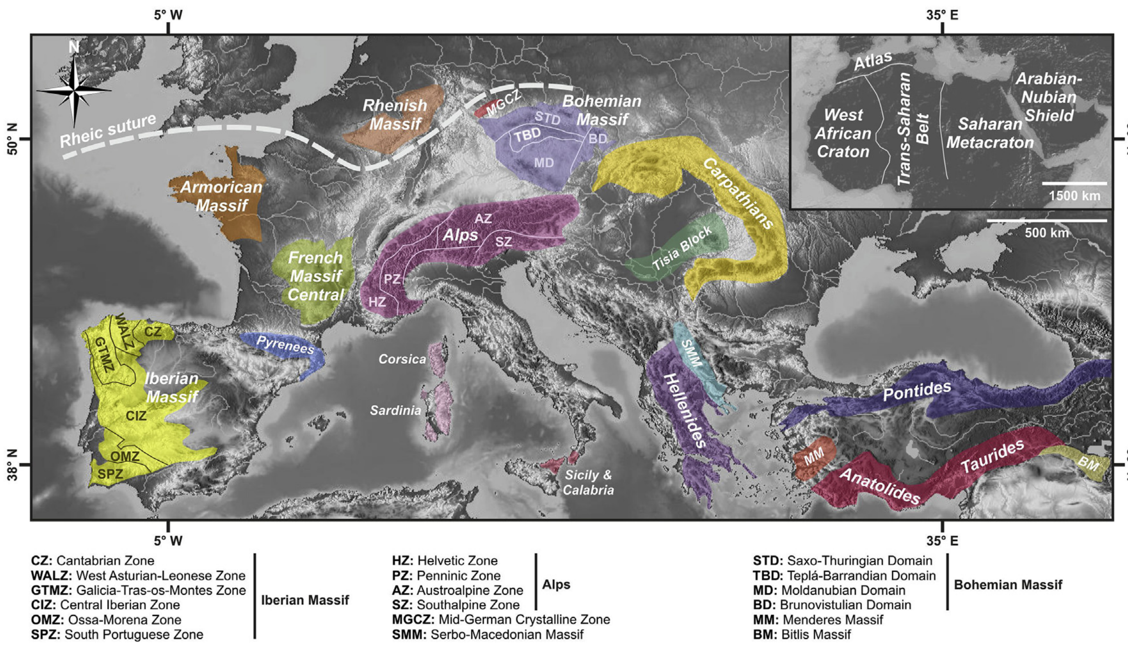

Fig. 3. Sketch map showing main areas hosting Late Ediacaran–Ordovician rocks in Europe and adjacent regions related to the northwestern Gondwana margin (modified after Rossi et al., 2009; Nance et al., 2010; Ustaömer et al., 2012; Fiannacca et al., 2013; von Raumer et al., 2013; Ballèvre et al., 2014; Martínez Catalán et al., 2014; Balen et al., 2015; Antić et al., 2016). Inset shows key tectonostratigraphic units of northern Africa (modified after Brahimi et al., 2018).

Paleozoic shelf deposits along northwesternmost Gondwanan regions (Avigad et al., 2005; Squire et al., 2006; Meinhold et al., 2013; Veevers, 2017; Stephan et al., 2019a, 2019b). However, Avalonian–Cadomian terranes record coeval Late Ediacaran–Ordovician metamorphism and magmatism, interpreted as the result of complex extensional and arc-related processes (e.g., Linnemann et al., 2007, 2014; Schulz et al., 2008; von Raumer et al., 2015; Henriques et al., 2017; Koglin et al., 2018). Though diachronous, these processes were associated with development of the Avalonian–Cadomian continental arc, and the opening of the Rheic and Paleotethys oceans during the Early and early Middle Paleozoic, respectively (Stampfli et al., 2002, 2011; Linnemann et al., 2008; Nance et al., 2010, 2012; von Raumer et al., 2013).

In last years, several contributions have revised the Early Paleozoic geological record to reconstruct the paleogeography and tectonic evolution of the southern and northern Gondwana margins (e.g., Nance et al., 2010, 2012; Stampfli et al., 2011; Meinhold et al., 2013; von Raumer et al., 2015; Ramos, 2018; Rapela et al., 2018; Weinberg et al., 2018; Stephan et al., 2019a, 2019b). Nevertheless, both regions have been commonly treated separately and no clear relationships were so far established between them. For this reason, this contribution aims at disentangling the common Early Paleozoic tectonic and geodynamic evolution of the northern and southern Gondwana margins, with emphasis in Western Gondwanan regions (i.e., South America, Africa and related blocks), based on a compilation of geological, paleomagnetic, structural, petrological, geochronological and isotopic evidence. Specific aspects related to the local evolution of particular areas are beyond the scope of this contribution, which is focused on major tectonic and geodynamic processes occurring in accretionary orogens.

2. The southwestern margin and the Early Paleozoic evolution of the Terra Australis Orogen

The Paleoproterozoic Rio de la Plata Craton represents the main cratonic area of southern South America (e.g., Oyhantçabal et al., 2011, 2018). Along its western margin, mostly represented by the Sierras Pampeanas and Puna regions (Argentina), Early Paleozoic accretionary orogens are best exposed and have been more extensively studied, though they are also present further north, particularly in the case of the Famatinian orogen (Fig. 2; e.g., Ramos, 2018). Sparse basement inliers comprise mostly Paleoproterozoic and Mesoproterozoic rocks, attributed to different blocks that were accreted to the Rio de la Plata Craton margin during the Paleozoic (Ramos et al., 1986, 2010; Loewy et al., 2004; Ramos, 2004, 2008; Casquet et al., 2010, 2012a; Cordani et al., 2010; Rapela et al., 2010; Varela et al., 2011).

In the Sierras Pampeanas, the onset of subduction along the continental margin is constrained at ca. 577 Ma based on U–Pb SHRIMP zircon data of calc-alkaline diatexites (Schwartz et al., 2008; Siegesmund et al., 2010). However, arc-related calc-alkaline felsic to intermediate intrusions and subordinated volcanic rocks are widespread between ca. 553 Ma and 531 Ma, as indicated by U–Pb SHRIMP, LA-ICP-MS, SIMS and TIMS zircon data (Schwartz et al., 2008; Iannizzotto et al., 2013; von Gosen et al., 2014; Dahlquist et al., 2016), whereas post-orogenic felsic magmatism is well-constrained at ca. 531–519 Ma (Iannizzotto et al., 2013; von Gosen et al., 2014; Ramos et al., 2015). Further north, U–Pb LA-ICP-MS, SHRIMP and TIMS zircon ages constrain the timing of comparable magmatism at ca. 541–523 Ma in the Eastern Cordillera, where widespread coeval low-grade metasiliciclastic sequences are also exposed (Fig. 2; Aceñolaza and Aceñolaza, 2007; Drobe et al., 2009; Hongn et al., 2010; Adams et al., 2011; Aparicio González et al., 2011; Escayola et al., 2011; Hauser et al., 2011). Comparable metasedimentary units are also recorded in the Sierras Pampeanas (e.g., Aceñolaza and Aceñolaza, 2007; Drobe et al., 2009; Cristofolini et al., 2012; Perón Orrillo et al., 2019). Though uncertain (e.g., González et al., 2020), a similar evolution could be tentatively suggested for the southern margin of the Rio de la Plata Craton between the Claromecó Basin and the North Patagonian Massif based on the timing and geochemical fingerprint of Cambrian magmatic units (Tohver et al., 2012; Rapalini et al., 2013; Pankhurst et al., 2014; Greco et al., 2015, 2017; González et al., 2018) and geophysical evidence (Prezzi et al., 2018).

Crustal anatexis and high-grade metamorphism is well-documented during the main phase of the Pampean Orogeny mostly at ca. 554–526 Ma, contemporaneously with calc-alkaline magmatism, as indicated by U–Pb SHRIMP zircon/monazite and LA-ICP-MS zircon ages of anatectic melts and metamorphic overgrowths in migmatites, gneisses and granulites (Rapela et al., 1998b; Sims et al., 1998; Siegesmund et al., 2010; Murra et al., 2016; Tibaldi et al., 2019). In addition, U–Pb and Pb/Pb stepwise leaching titanite and U–Pb SHRIMP monazite ages of ca. 509–506 Ma indicate subsequent retrograde metamorphism in marbles and granulites, respectively (Fantini et al., 1998; Siegesmund et al., 2010). Peak metamorphic conditions obtained by conventional thermobarometry indicate dominantly high-temperature and low- to medium-pressure conditions of ca. 800–850 °C and 6–8 kbar, respectively, in the sillimanite stability field (Rapela et al., 1998b, 2002; Otamendi et al., 1999, 2005; Martino et al., 2010), suggesting relatively high geothermal gradients of ca. 30–35 °C/km (Fig. 4). Subsequent retrograde amphibolite-facies metamorphism at ca. 650–750 °C and 4–6 kbar is also recorded (Rapela et al., 1998b; Otamendi et al., 1999; Martino et al., 2010). On the other hand, structural data point to pure-shear-dominated dextral transpression during peak metamorphic conditions, succeeded by late simple-shear-dominated dextral deformation (Martino, 2003; Simpson et al., 2003; Piñán-Llamas and Simpson, 2006; Martino et al., 2010; von Gosen and Prozzi, 2010; von Gosen et al., 2014; Tibaldi et al., 2019).

Several authors emphasized the existence of a magmatic lull at ca. 520–500 Ma, towards the end of the Pampean Orogeny and the onset of the Famatinian Orogeny (e.g., Pankhurst and Rapela, 1998; Weinberg et al., 2018). Tough scarce, felsic magmatism is recorded at ca. 521–509 Ma in the Sierras Pampeanas, Puna, Sierras Australes and North Patagonian Massif (Rapela et al., 2003; Tohver et al., 2012; Greco et al., 2015; Ramos et al., 2015), possibly related to post-orogenic Pampean crustal extension (Ramos et al., 2015; Greco et al., 2017; Prezzi et al., 2018). Further evidence is provided by Late Cambrian to Ordovician metasedimentary units, where detrital zircons yielding U–Pb ages of ca. 520–500 Ma derived from Pampean magmatism are well-documented, resulting from exhumation and unroofing of the Pampean Orogen (Hauser et al., 2011; Cristofolini et al., 2012; Augustsson et al., 2016; Perón Orrillo et al., 2019). A major change attributed to the onset of Famatinian subduction (e.g., Cristofolini et al., 2012; Ducea et al., 2015) is subsequently recorded at ca. 495–490 Ma based on deformation of Cambrian low-grade metasedimentary units, which are overlain by Lower Ordovician successions (Collo and Astini, 2008). The trenchward migration of the locus of arc magmatism (Mannheim, 1993) favoured burial of Cambrian sedimentary sequences, which acted as the host rock of Ordovician magmatism, i.e., the Cambrian accretionary prism occupied a magmatic arc position during the Ordovician (Cristofolini et al., 2012; Otamendi et al., 2020).

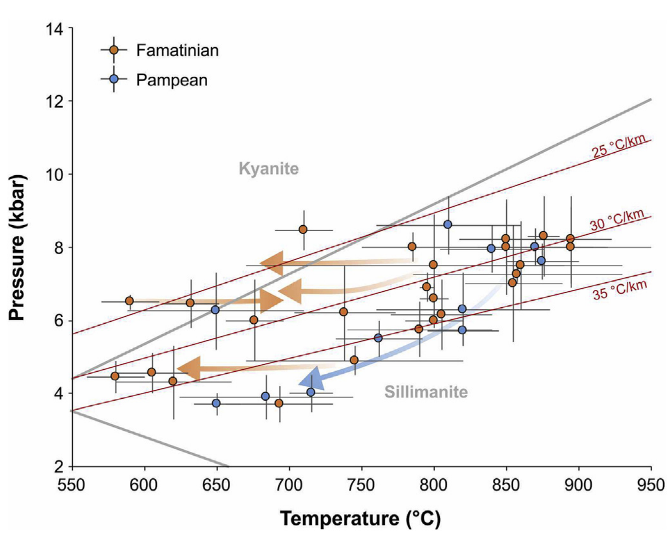

Fig. 4. Metamorphic conditions of southwestern accretionary orogens (forearc/accretionary prism conditions not included). Arrows schematically indicate prograde and retrograde paths. See Section 2 for further details. Data from Rapela et al. (1998b, 2002), Otamendi et al. (1999, 2005, 2008), González et al. (2004), Murra and Baldo (2006), Castro de Machuca et al. (2008), Tibaldi et al. (2009, 2011, 2013, 2016), Martino et al. (2010), de los Hoyos et al. (2011), Larrovere et al. (2011) and Sola et al. (2017).

In the Sierras Pampeanas, the Famatinian magmatic arc is characterized by voluminous meta- to peraluminous calc-alkaline magmatism (e.g., Pankhurst et al., 1998, 2000; Otamendi et al., 2010, 2012, 2020; Ducea et al., 2015) and was mostly built up between ca. 486 Ma and 463 Ma, with a main peak of magmatic activity at ca. 472–468 Ma, well-recorded by LA-ICP-MS, SHRIMP and CA-TIMS zircon data (e.g., Pankhurst et al., 2000; Fanning et al., 2004; Dahlquist et al., 2008, 2012, 2013; Ducea et al., 2010, 2017; Otamendi et al., 2017; Rapela et al., 2018). Comparable intrusions yielding U–Pb SHRIMP zircon ages of ca. 476–466 Ma are exposed in the North Patagonian Massif (Pankhurst et al., 2006; Rapalini et al., 2013) and the Chadileuvú Block (Chernicoff et al., 2010), whereas K-bentonites are recorded at ca. 470 Ma immediately west in the Precordillera terrane, indicating derivation of ashes from the proximal Famatinian arc (Astini and Dávila, 2004; Fanning et al., 2004). In the Puna region, dominantly granitic to granodioritic calc-alkaline magmatism is documented at ca. 488–462 Ma by U–Pb LA-ICP-MS and TIMS zircon data (Viramonte et al., 2007; Insel et al., 2012; Bahlburg et al., 2016), together with coeval bimodal felsic and OIB-/MORB-type mafic volcanism that extends up to the northwesternmost Sierras Pampeanas and Eastern Cordillera (Coira et al., 2009; Hauser et al., 2011; Cisterna et al., 2017).

Famatinian relics were also reported in the Cordón de Lila, where felsic intrusions and volcanic rocks yielded U–Pb SHRIMP and LA-ICP-MS zircon ages of ca. 480–463 Ma (Zimmermann et al., 2010; Pankhurst et al., 2016). Further north, Ordovician sedimentary sequences with minor volcanic intercalations are well-exposed in the Altiplano (Bahlburg et al., 2006; Ramos, 2008), whereas U–Pb SIMS, LA-ICP-MS and TIMS zircon ages of ca. 478–444 Ma constrain the timing of crystallization of orthogneisses in the Marañón Massif (Chew et al., 2007; Cardona et al., 2009). In a similar way, Famatinian magmatism is recorded by amphibolites and meta- to peraluminous orthogneisses and granitoids exposed in the basement of the Northern Andes, which yield U–Pb LA-ICP-MS zircon ages of 488–444 Ma (Tazzo-Rangel et al., 2019; van der Lelij et al., 2019).

This main stage of magmatism was coeval with the peak of the Famatinian tectonometamorphic event. As in the case of the Pampean Orogen, thermobarometric data of the Famatinian arc indicate high-temperature and low- to medium-pressure conditions of mostly ca. 800–850 °C and 5–8 kbar, respectively (González et al., 2004; Murra and Baldo, 2006; Castro de Machuca et al., 2008; Otamendi et al., 2008; de los Hoyos et al., 2011; Larrovere et al., 2011; Tibaldi et al., 2011, 2013, 2016; Sola et al., 2017). In contrast, high-pressure/low-temperature gradients characterize lower plate metamorphic conditions recorded in the westernmost Sierras Pampeanas (e.g., Varela et al., 2011; Mulcahy et al., 2014). High-temperature metamorphism and associated crustal anatexis under relatively high geothermal gradients of ca. 30–35 °C/km (Fig. 4) lasted for more than ca. 50 Myr in the Famatinian arc and back-arc, as indicated by monazite, titanite and zircon geochronological data (Steenken et al., 2006; Finch et al., 2017; Weinberg et al., 2019; Wolfram et al., 2019), thus contrasting significantly with the relatively short-lived Pampean event (Rapela et al., 1998a). On the other hand, contemporaneous transpressional deformation was characterized by reverse-slip-dominated shear zones, which also favoured the subsequent Middle to Late Paleozoic exhumation of the Famatinian arc (Martino, 2003; Simpson et al., 2003; Whitmeyer and Simpson, 2003; González et al., 2004; Cristofolini et al., 2010, 2013, 2017; Steenken et al., 2010; Mulcahy et al., 2011; Castro de Machuca et al., 2012; Demartis et al., 2017; Löbens et al., 2017).

3. The northwestern margin and the Early Paleozoic evolution of Cadomian domains

From west to east, the northern African margin comprises the West African Craton, the Saharan Metacraton and the Arabian-Nubian Shield, separated by Pan-African belts (e.g., Abdelsalam et al., 2002; Liégeois et al., 2003; Ennih and Liégeois, 2008; Stern et al., 2010). These northern African blocks of Gondwana represented the mainland and main source of detritus for shelf deposits of most Cadomian domains, which were located to the north (Avigad et al., 2005; Squire et al., 2006; Meinhold et al., 2013; Veevers, 2017; Stephan et al., 2019a, 2019b). In contrast to the southwestern Gondwana margin, which records a relatively common evolution (Section 2), the reconstruction of pre-Variscan tectonic processes in these regions is more complicated, since basement exposures are isolated and largely overprinted by Late Paleozoic to Cenozoic orogenic processes (e.g., von Raumer et al., 2003, 2013). The first stage in the evolution of the northwestern Gondwana margin is essentially related to the Ediacaran–Cambrian Cadomian Orogeny (e.g., D'Lemos et al., 1990; Brun et al., 2001; Chantraine et al., 2001; Linnemann et al., 2008). Since the timing of the earliest tectonomagmatic processes in Cadomian domains overlaps with the Pan-African Orogeny at ca. 630–600 Ma (Linnemann et al., 2000; Dörr et al., 2002; Soejono et al., 2017), it is thus difficult to establish the main geodynamic setting, i.e., Pan-African collisional vs Cadomian accretionary processes. For this reason, the following review focuses on Late Ediacaran–Early Cambrian processes (< ca. 600 Ma) that can be attributed to the Cadomian Orogeny sensu stricto (e.g., Linnemann et al., 2007).

The type locality of the Cadomian Orogeny is located in the North Armorican Domain of the Armorican Massif in France (Fig. 3). The southern parts were severely overprinted by Early Palaeozoic rifting and oceanic spreading, documented by ophiolites (Paquette et al., 2017), which were later involved into the subduction and collision stages of the Variscan orogeny (Ballèvre et al., 2009). Granitic magmatism was recorded at ca. 602–533 Ma together with coeval volcano-sedimentary sequences, as indicated by U–Pb TIMS and Pb/Pb evaporation zircon data (Chantraine et al., 2001, and references therein). Based on the similar detrital zircon fingerprint of Ediacaran to Early Paleozoic metasedimentary rocks (Gerdes and Zeh, 2006; Ballouard et al., 2018; Dörr and Stein, 2019), basement relics of the Mid-German Crystalline Zone have been correlated with the Armorican Massif at the western part of the shelf (Fig. 1), further supported by the presence of Cadomian magmatism at ca. 566–542 Ma (Dörr and Stein, 2019).

In the westernmost part of the margin (Fig. 1), U–Pb detrital zircon data of the Iberian Massif (i.e., Ossa-Morena, Central Iberian, Galicia-Tras-os-Montes, West Asturian-Leonese and Cantabrian Zones, and Variscan allochthonous units; Fig. 3) place the most likely source of detritus along the northwestern African margin, between the West African Craton and the westernmost Saharan Metacraton (Fernández-Suárez et al., 2002a, 2014; Linnemann et al., 2008; Pereira et al., 2008, 2012a, 2012b; Díez Fernández et al., 2010; Talavera et al., 2012, 2015; Albert et al., 2015; Orejana et al., 2015; Pereira, 2015; Cambeses et al., 2017; Naidoo et al., 2018). In the Ossa-Morena Zone, the earliest arc-related magmatic activity is recorded at ca. 610–580 Ma by E-MORB amphibolites (Sánchez-Lorda et al., 2014, 2016), succeeded by the intrusion of deformed diorites and granites at ca. 578–573 Ma (U–Pb SHRIMP and TIMS zircon data; Bandrés et al., 2004). Comparable U–Pb LA-ICP-MS zircon ages were also obtained for the protoliths of high-pressure Variscan metabasites and metagranitoids (Abati et al., 2018). Younger peraluminous calc-alkaline orthogneisses and amphibolites were reported as well, yielding U–Pb TIMS zircon ages of ca. 569–548 and 539 Ma, respectively (Henriques et al., 2015). Late Ediacaran calc-alkaline granitoids and coeval felsic volcanism were also documented in the West Asturian-Leonese and Cantabrian Zones at ca. 605–557 Ma by U–Pb LA-ICP-MS and TIMS zircon data (Fernández-Suárez et al., 1998; Gutiérrez-Alonso et al., 2004; Rubio-Ordóñez et al., 2015).

The Bohemian Massif, comprising the Saxo-Thuringian, Moldanubian, Teplá-Barrandian and Brunovistulian Domains (Fig. 3), records a protracted Ediacaran to Ordovician tectonomagmatic evolution, closely located to the Iberian Massif (Fig. 1). U–Pb detrital zircon evidence of all domains indicates that Ediacaran to Ordovician metasedimentary rocks essentially received detritus from the West African Craton and Trans-Saharan Belt, with a large contribution of Pan-African/Cadomian magmatic sources (Linnemann et al., 2004, 2007, 2014; Bahlburg et al., 2010; Drost et al., 2011; Mazur et al., 2012; Žáčková et al., 2012; Hajná et al., 2013, 2017; Košler et al., 2014; Kurzweil et al., 2015; Žák and Sláma, 2018). In the Saxo-Thuringian Domain, two main pulses of continental arc felsic magmatism yield U–Pb SHRIMP/LA-ICP-MS and Pb/Pb evaporation zircon ages of ca. 577–550 Ma and 540–530 Ma, and are separated by the Cadomian unconformity (Linnemann et al., 2000, 2008; Buschmann et al., 2001; Tichomirowa et al., 2001). Mafic to felsic orthogneisses also record calc-alkaline magmatism at ca. 550 Ma in the Münchberger Massif nappes (i.e., allochthonous units of the Saxo-Thuringian Domain), as constrained by LA-ICP-MS U–Pb zircon and geochemical data (Koglin et al., 2018). In the Moldanubian Domain, metarhyolites and metabasites yield U–Pb SHRIMP zircon ages of ca. 555–549 Ma (Teipel et al., 2004), whereas U–Pb TIMS zircon data of the Teplá-Barrandian Domain constrains the timing of felsic volcanism at ca. 585–568 Ma and subsequent felsic to mafic intrusions at ca. 540–523 Ma (Dörr et al., 2002, and references therein). Finally, U–Pb LA-ICP-MS and geochemical data of the Brunovistulian Domain indicate the presence of calc-alkaline arc-related granitic magmatism at ca. 601–568 Ma (Finger et al., 2000; Soejono et al., 2017).

The paleogeographic position of the French Massif Central constrained by detrital zircon data of Ediacaran metasedimentary rocks is controversial and has been alternatively interpreted as the result of a western vs eastern position along the shelf (Melleton et al., 2010; Chelle-Michou et al., 2017; Couzinié et al., 2019; Stephan et al., 2019a, 2019b). Ediacaran to Cambrian orthogneisses are present in the French Massif Central as well, yielding U–Pb SHRIMP and LA-ICP-MS zircon crystallization ages of 550–525 Ma (Alexandrov et al., 2001; Melleton et al., 2010; Chelle-Michou et al., 2017). Further east (Fig. 1), the Austroalpine basement records a protracted Ediacaran to Ordovician tectonomagmatic evolution, similarly to adjacent Alpine basement domains (e.g., Manzotti et al., 2015; Maino et al., 2019). Late Ediacaran to Ordovician metasedimentary rocks south of the Tauern Window were mostly derived from the northeastern Saharan Metacraton and the northern Arabian-Nubian Shield (Sinai), with a significant contribution of detritus derived from continental arc rocks (Heinrichs et al., 2012; Siegesmund et al., 2018). Intercalated Ediacaran to Early Cambrian metabasic rocks with N-MORB and volcanic arc geochemical fingerprint yielded Pb/Pb evaporation zircon ages of ca. 590 Ma and 550–530 Ma, respectively (Schulz and Bombach, 2003; Schulz et al., 2004). The latter are also coeval with basaltic magmatism in the Tauern Window, constrained at ca. 549 Ma by U–Pb SHRIMP zircon data (Eichhorn et al., 1999), and calc-alkaline gabbroic to dioritic gneisses yielding U–Pb LA-ICP-MS zircon ages of ca. 544–533 Ma in nappes of the Central Alps (Bussien et al., 2011). Slightly younger calc-alkaline metagabbros and metatonalites with U–Pb TIMS zircon ages of ca. 524–522 Ma were reported for the Silvretta Nappe of the Austroalpine basement (Schaltegger et al., 1997).

On the other hand, Early Paleozoic metasedimentary rocks of the Eastern Pyrenees basement record a detrital zircon fingerprint comparable to that of the Austroalpine coeval units, suggesting a similar paleogeographic position along the shelf (Margalef et al., 2016; Stephan et al., 2019a). U–Pb SHRIMP and LA-ICP-MS zircon data of metatuffs, metaignimbrites and orthogneisses constrain the timing of felsic magmatism at ca. 577–548 Ma, attributed to a continental arc setting based on their geochemical signature (Cocherie et al., 2005; Castiñeiras et al., 2008; Casas et al., 2015). The metamorphic basement of the Peloritani Mountains of Sicily and Calabria shows a similar evolution (Fig. 1), constrained by U–Pb SHRIMP detrital zircon data of metasedimentary rocks (Williams et al., 2012) and crystallization ages of ca. 565–545 Ma recorded by U–Pb SHRIMP zircon data in felsic calc-alkaline orthogneisses (Fiannacca et al., 2013), though slightly younger intrusions up to ca. 526 Ma are suggested by U–Pb TIMS zircon data (Micheletti et al., 2007).

Late Ediacaran to Cambrian sedimentation derived from the northeastern Gondwana mainland (Fig. 1) and coeval magmatism is also recorded in the External Hellenides, as indicated by U–Pb detrital zircon data of metasedimentary rocks and orthogneisses yielding U–Pb TIMS zircon ages between ca. 556 Ma and 511 Ma, respectively (Romano et al., 2004; Dörr et al., 2015). U–Pb LA-ICP-MS detrital zircon data suggest a similar paleogeographic position of the Serbo-Macedonian Massif, further supported by the presence of arc-related granitoids and subordinated gabbros of ca. 562–521 Ma (Antić et al., 2016). Detrital zircon data suggest a similar provenance for most domains of the Carpathians, though some regions may have a more likely western shelf affinity (Balintoni et al., 2014, and references therein). In addition, orthogneisses yielding U–Pb LA-ICP-MS zircon crystallization ages of ca. 588 and 549 Ma were reported as well (Balintoni et al., 2010a).

A location along the eastern part of the shelf (sensu Stephan et al., 2019a) was indicated for the Taurides-Pontides basement as well as for the Menderes and Bitlis Massifs based on U–Pb LA-ICP-MS detrital zircon data of Ediacaran to Early Paleozoic metasedimentary rocks (Ustaömer et al., 2012; Zlatkin et al., 2013; Abbo et al., 2015; Avigad et al., 2016). Arc-related magmatism is well-recorded, as indicated by the presence of calc-alkaline metagranitoids and subvolcanic rocks yielding U–Pb LA-ICP-MS and SHRIMP zircon crystallization ages of ca. 590–530 Ma, being coeval with high- to medium-grade regional metamorphism (Gessner et al., 2004; Ustaömer et al., 2009, 2012; Koralay et al., 2012; Zlatkin et al., 2013; Şahin et al., 2014; Abbo et al., 2015; Koralay, 2015; Beyarslan et al., 2016). However, tholeiitic magmatism is also documented in the Menderes Massif by metagabbros yielding U–Pb LA-ICP-MS zircon crystallization ages of ca. 565–555 Ma, which record high-pressure metamorphism at ca. 535 Ma (Candan et al., 2016). In a similar way (Fig. 1), U–Pb LA-ICP-MS zircon data of Ediacaran to Early Paleozoic sedimentary rocks of the Iranian blocks suggest a provenance from the northeasternmost part of Western Gondwana (Horton et al., 2008; Etemad-Saeed et al., 2016; Honarmand et al., 2016). Associated calc-alkaline subduction-related metagranitoids and subordinated metabasites and volcanic rocks are also well-recorded, yielding U–Pb LA-ICP-MS, SIMS and TIMS zircon ages of ca. 601–522 Ma (Hassanzadeh et al., 2008; Azizi et al., 2011; Jamshidi Badr et al., 2013; Moghadam et al., 2015, 2016, 2017, 2018, 2019).

Cadomian metamorphism is well-documented in the Armorican Massif, with pressure-temperature conditions of ca. 600–800 °C and 3–6 kbar obtained for migmatites yielding U–Pb TIMS zircon ages of ca. 550–535 Ma (Peucat, 1986; Ballèvre et al., 2001). Th–U–Pb EPMA monazite ages of ca. 552–517 Ma constrain the timing of high temperature/low-pressure regional metamorphism in the northern part of the Cadomian Domain (Schulz et al., 2007; Schulz, 2013), being comparable with Ar/Ar muscovite and amphibole ages reported further southeast (Ballèvre et al., 2001, and references therein). Further relics of Cadomian metamorphism are exposed in the Iberian Massif (Fig. 5), indicating low-pressure (<4 kbar) and high-temperature (ca. 450–650 °C) conditions for rocks of the central Ossa-Morena Zone (Eguíluz and Abalos, 1992). In addition, pseudosection modelling yielded pressure-temperature conditions of ca. 7–8 kbar and 640–660 °C for amphibolites and orthogneisses at the contact between the Ossa Morena and the Central Iberian Zones, constrained at ca. 540 Ma by U–Pb TIMS zircon, monazite and titanite data (Henriques et al., 2015). Similar Th–U–Pb EPMA monazite ages of ca. 551–540 Ma were reported for high-grade metamorphism in the Teplá-Barrandian Domain by Zulauf et al. (1999). Likewise, deformation triggered the development of a sedimentary hiatus, referred to as the Cadomian unconformity. In the Saxo-Thuringian Domain, U–Pb zircon ages of volcano-sedimentary sequences underlying the unconformity provide a maximum age of ca. 543 Ma for the onset of deformation (Linnemann et al., 2008, and references therein), whereas the age of the hiatus is constrained at ca. 544–539 Ma in the Ossa-Morena Zone based on detrital zircon data of underlying and overlying units (Pereira et al., 2012a). In the Central Iberian Zone, the gap is roughly constrained by U–Pb detrital zircon between ca. 576 Ma and 555 Ma, most likely at ca. 560–550 Ma, as suggested by Ar/Ar data of metasedimentary rocks (Talavera et al., 2015, and references therein). In a similar way, U–Pb LA-ICP-MS zircon ages of ca. 566 Ma and 542 Ma were reported for deformed magmatic rocks and crosscutting dykes in the Mid-German Crystalline Zone, respectively, further supporting a Late Ediacaran age for the Cadomian deformation (Dörr and Stein, 2019).

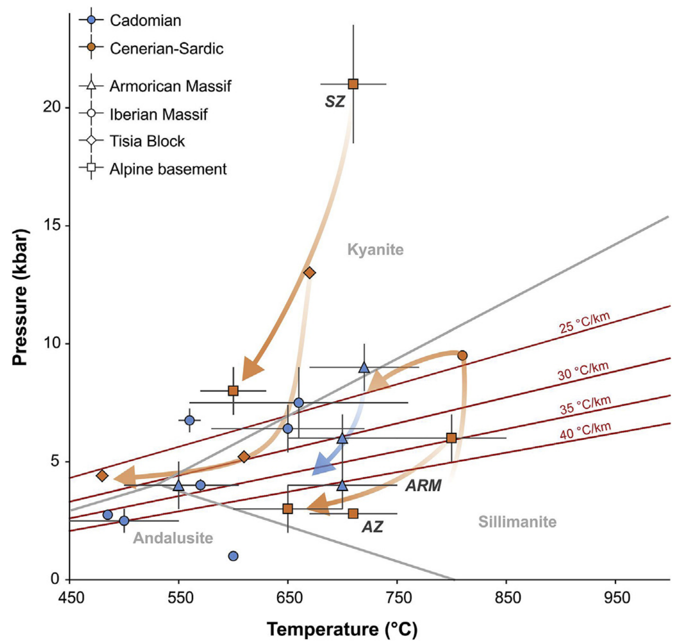

Fig. 5. Metamorphic conditions of northwestern accretionary orogens. Arrows schematically indicate prograde and retrograde paths. See Section 3 for further details. Data from Eguíluz and Abalos (1992), Ballèvre et al. (2001), Abati et al. (2003), Franz and Romer (2007), Thöny et al. (2008), Schulz and von Raumer (2011), Balen et al. (2015) and Henriques et al. (2015). SZ: Southalpine Zone (Strona-Ceneri Zone), AZ: Austroalpine Zone, ARM: Aiguilles Rouges Massif (External Alpine domain).

The Late Cambrian post-orogenic Cadomian evolution records the local occurrence of further calc-alkaline magmatism at ca. 530–490 Ma (e.g., Chen et al., 2000; Linnemann et al., 2000; Tichomirowa et al., 2001; Dörr et al., 2002; Andonaegui et al., 2012, 2016; Mandl et al., 2018; Zieger et al., 2018). However, the Late Cambrian–Ordovician evolution is intimately related to crustal extension and the opening of the Rheic Ocean, and the existence of coeval subduction along the peri-Gondwanan is still under debate (see Section 5; Nance et al., 2010, 2012; Álvaro et al., 2018; García-Arias et al., 2018; Stephan et al., 2019a).

In the Ossa-Morena Zone of the Iberian Massif, U–Pb TIMS zircon ages of ca. 517–502 Ma constrain the timing of mostly bimodal, alkaline to subalkaline volcanism (Sánchez-García et al., 2008). Calc-alkaline peraluminous felsic orthogneisses yield U–Pb SHRIMP zircon crystallization ages of ca. 527–505 Ma, being possibly coeval with tholeiitic metabasites (Chichorro et al., 2008), whereas alkaline to peralkaline syenites yielding U–Pb LA-ICP-MS zircon ages of ca. 490–470 Ma are exposed as well (Díez Fernández et al., 2015). On the other hand, calc-alkaline peraluminous felsic magmatism yielded U–Pb SIMS, LA-ICP-MS and SHRIMP zircon ages of ca. 492–470 Ma in the Central Iberian Massif (Bea et al., 2006; Montero et al., 2007, 2009; Navidad and Castiñeiras, 2011) and ca. 498–458 Ma in the Galicia-Tras-os-Montes Zone (Talavera et al., 2013; Dias da Silva et al., 2016). In addition, tholeiitic metabasites with a U–Pb SHRIMP crystallization age of ca. 473 Ma were reported in the Central Iberian Massif (Villaseca et al., 2015). In allochthonous Iberian units, U–Pb SHRIMP zircon ages of ca. 489 Ma and 475–470 Ma constrain the timing of granodioritic and alkaline/peralkaline granitic intrusions (Díez Fernández et al., 2012).

In the Bohemian Massif, U–Pb LA-ICP-MS and Pb/Pb evaporation zircon data of mostly peraluminous, felsic magmatism of the Saxo-

Thuringian Domain yielded ages of ca. 504–503 Ma and 488–484 Ma, respectively (Linnemann et al., 2000; Tichomirowa et al., 2001; Zieger et al., 2018). Similar results were obtained for the protoliths of felsic orthogneisses in allochthonous units of the Saxo-Thuringian Domain, characterized by dominantly peraluminous calc-alkaline compositions and U–Pb LA-ICP-MS/SHRIMP and Pb/Pb evaporation zircon ages of ca. 505–450 Ma (Mingram et al., 2004; Sagawe et al., 2016; Koglin et al., 2018). In a similar way, protoliths of orthogneisses of the Moldanubian Domain have meta- to peraluminous high-K calc-alkaline granitic compositions and U–Pb LA-ICP-MS/SHRIMP zircon ages of ca. 492–480 Ma (Friedl et al., 2004; Teipel et al., 2004; Soejono et al., 2019). Further U–Pb SHRIMP zircon ages of ca. 491–457 Ma and 481 Ma constrain the timing of leucosome crystallization after crustal anatexis and eclogitic amphibolite crystallization (Teipel et al., 2004). In contrast, magmatism in the Teplá-Barrandian Domain is dominantly older, as documented by U–Pb TIMS zircon ages of ca. 524–522 Ma of gabbroic to granodioritic intrusions and a U–Pb SHRIMP zircon age of ca. 499 Ma of rhyolites (Dörr et al., 2002; Drost et al., 2004). The latter are associated with basalts defining a bimodal, dominantly subalkaline association, though some alkaline features are also present (Drost et al., 2004). Finally, metabasites with MORB geochemical signature yielded U–Pb LA-ICP-MS zircon ages of ca. 530–590 Ma in the Brunovistulian Domain (Soejono et al., 2010).

Felsic metavolcanic rocks and orthogneisses of the Armorican Massif have U–Pb SHRIMP and LA-ICP-MS zircon ages of 494–472 Ma and, similarly to coeval felsic magmatism reported in other peri-Gondwanan regions, peraluminous calc-alkaline compositions (Ballèvre et al., 2012; El Korh et al., 2012). Nearly coeval U–Pb LA-ICP-MS zircon ages of ca. 493–467 Ma were obtained for the crystallization of metamafic rock protoliths (Faure et al., 2010; Paquette et al., 2017). Comparable mafic magmatism at ca. 475 Ma is recorded in the French Massif Central (Paquette et al., 2017), where orthogneisses yielding U–Pb LA-ICP-MS zircon ages of ca. 475–451 Ma were also documented (Melleton et al., 2010).

In the Austroalpine basement south of the Tauern Window, Ordovician felsic magmatism is also well-documented by the presence of dominantly peraluminous calc-alkaline orthogneisses and metaporphyroids yielding Pb/Pb evaporation and U–Pb SHRIMP ages of ca. 477–448 Ma (Schulz and Bombach, 2003; Schulz et al., 2004, 2008; Siegesmund et al., 2007). Further east, basement relics of the Austroalpine Silvretta-Seckau Nappe System host peraluminous metagranitoids with U–Pb LA-ICP-MS zircon ages of ca. 508–486 Ma (Mandl et al., 2018), whereas slightly younger U–Pb LA-ICP-MS zircon ages of ca. 485–467 Ma were reported in the Central Alps for comparable peraluminous orthogneisses (Bussien et al., 2011). In the Adula nappe, U–Pb LA-ICP-MS zircon data documents the presence of mafic magmatism at ca. 521–515 Ma and 445 Ma, and felsic peraluminous intrusions at ca. 459–445 Ma (Cavargna-Sani et al., 2014). U–Pb LA-ICP-MS zircon ages of ca. 505 Ma and 482 Ma were obtained for felsic magmatic rocks in the Siviez-Mischabel nappe basement (Scheiber et al., 2014). To the west, high-K to shoshonitic peraluminous granitoids yielding U–Pb SHRIMP zircon ages of ca. 465–456 Ma are exposed in the Grand St Bernard-Briançonnais nappe system (Bergomi et al., 2018), whereas crystallization of metabasic and metadacitic rocks is constrained at ca. 457 Ma and 443 Ma, respectively, by U–Pb SHRIMP zircon ages in the Argentera Massif (Rubatto et al., 2001). The latter are similar to the U–Pb LA-ICP-MS zircon ages of ca. 464–455 Ma of metabasic rocks and orthogneisses of the Aiguilles Rouges Massif (Bussy et al., 2011). In the Ligurian Alps, felsic volcanic and plutonic activity is well-constrained at ca. 507–446 Ma by U–Pb SHRIMP, LA-ICP-MS and TIMS zircon data (Maino et al., 2019), whereas a U–Pb LA-ICP-MS zircon age of ca. 468 Ma was obtained for basic magmatism (Giacomini et al., 2007).

Ordovician, dominantly felsic calc-alkaline magmatism is well-recorded in the Pyrenees, with U–Pb SHRIMP, LA-ICP-MS and TIMS zircon ages spanning between ca. 488 Ma and 446 Ma (Cocherie et al., 2005; Castiñeiras et al., 2008; Casas et al., 2010; Navidad et al., 2010; Liesa et al., 2011; Martínez et al., 2011; Mezger and Gerdes, 2016; Martí et al., 2019). Contemporaneous peraluminous rhyolitic metaporphyroids yielding U–Pb TIMS zircon ages of ca. 456–452 Ma were reported in the Peloritani Mountains of Sicily (Trombetta et al., 2004). In a similar way, calc-alkaline felsic metagranitoids and metavolcano-sedimentary sequences are well-constrained at ca. 492–440 Ma by U–Pb SHRIMP, LA-ICP-MS and TIMS zircon data in Sardinia and Corsica (Helbing and Tiepolo, 2005; Giacomini et al., 2006; Rossi et al., 2009; Oggiano et al., 2010; Pavanetto et al., 2012; Cruciani et al., 2013), though tholeiitic mafic protoliths yielding U–Pb LA-ICP-MS zircon ages of ca. 460 Ma were also recognized (Giacomini et al., 2005).

In the Serbo-Macedonian Massif, U–Pb LA-ICP-MS zircon ages of ca. 462–456 Ma were obtained for tholeiitic amphibolites, whereas ages of ca. 522–521 Ma, 490–472 Ma and 443–426 Ma were reported for felsic calc-alkaline metagranitoids (Himmerkus et al., 2009; Antić et al., 2016). Contemporaneous metagranitoids were also recognized in the Tisia Block at ca. 491–483 Ma (U–Pb LA-ICP-MS zircon data; Starijaš et al., 2010) and Carpathians at ca. 495–448 Ma (U–Pb LA-ICP-MS zircon data; Balintoni et al., 2010a, 2010b; Balintoni and Balica, 2013). In the latter, metabasic intrusions and dominantly peraluminous, calc-alkaline rhyolitic to andesitic volcanism yielding U–Pb LA-ICP-MS and SHRIMP zircon ages of ca. 478 Ma and 496–447 Ma, respectively, were documented as well (Balintoni et al., 2010b; Vozárová et al., 2010, 2017). Though sparse, Ordovician granitic magmatism is also present in the Taurides-Anatolides, as indicated by Pb/Pb evaporation and U–Pb SIMS zircon ages of ca. 467 Ma and 446 Ma, respectively (Okay et al., 2008; Özbey et al., 2013). In a similar way, a U–Pb TIMS zircon age of ca. 471 Ma was reported for a gabbro in northeastern Iran basement rocks (Moghadam et al., 2018).

In the Ossa-Morena Zone, the timing of the Late Cambrian–Ordovician tectonometamorphic event is constrained between ca. 532 Ma and 480 Ma, as indicated by U–Pb TIMS ages of an orthogneiss and an undeformed granite, respectively (Expósito et al., 2003), whereas allocthonous units of the Iberian Massif record coeval granulite facies metamorphism and associated crustal anatexis at ca. 498–486 Ma constrained by U–Pb TIMS monazite and SHRIMP zircon data (Abati et al., 1999, 2007; Fernández-Suárez et al., 2002b). During this high-grade event, peak conditions of ca. >800 °C and 9.5 kbar were attained following an anticlockwise trajectory (Abati et al., 2003). In the Austroalpine basement, high-temperature/low-pressure metamorphic conditions are documented in migmatites of the Ötztal Complex, which record ca. 670–750 °C and <2.8 kbar constrained at ca. 441 Ma by EPMA Th–U–Pb monazite ages (Thöny et al., 2008; Rode et al., 2012). In addition, a U–Pb TIMS metamorphic zircon age of ca. 490 Ma provides further evidence for Early Paleozoic anatexis of this migmatitic complex (Klötzli-Chowanetz et al., 1997). In the Central Alps, U–Pb TIMS zircon data of ca. 478 Ma provides a maximum age for high-pressure metamorphism, succeded by high-temperature metamorphism and anatexis at ca. 456–445 Ma (Schaltegger, 1993; Schaltegger et al., 2003). Eclogite facies metamorphism under ca. 740–680 °C and 23.5–18.5 kbar is constrained at ca. 457–448 Ma by U–Pb TIMS ages of metamorphic zircon and rutile in the Strona-Ceneri Zone of the Southern Alps, succeded by Barrovian metamorphism at ca. 630–570 °C and 7–9 kbar (Franz and Romer, 2007), whereas younger EPMA Th–U–Pb monazite ages of ca. 445–400 Ma were obtained for the Alpine External Aiguilles Rouges Massif under peak conditions of ca. 800 °C and 6 kbar (Schulz and von Raumer, 2011). Finally, an orthogneiss of the Tisia Block yielded peak metamorphic conditions of ca. 670 °C and 13 kbar at ca. 490 Ma, succeeded by an evolution from ca. 610 °C and 5.2 kbar to 480 °C and 4.4 kbar between ca. 490 Ma and 465 Ma, as indicated by EPMA Th–U–Pb monazite ages (Balen et al., 2015).

In addition to the presence of metamorphism, some regions also record coeval Ordovician deformation. In the Ligurian Alps, Ordovician folding is constrained between ca. 494 Ma and 467 Ma, as indicated by U–Pb LA-ICP-MS and TIMS zircon ages of pre- and post-deformation magmatic rocks (Maino et al., 2019, and references therein). Ordovician folding is also well-documented in the Pyrenees and Sardinia by

Cambrian–Early Ordovician sequences, which are unconformably overlained by Late Ordovician conglomerates ("Sardic" unconformity; Casas and Fernández, 2007; Casas, 2010; Puddu et al., 2018, 2019; Cocco and Funedda, 2019). U–Pb LA-ICP-MS zircon ages of ca. 480 Ma and 465 Ma corresponding to pre-Sardic and cross-cutting magmatic units, respectively, constrain the timing of this event in Sardinia (Oggiano et al., 2010). In the Pyrenees, Late Ordovician magmatism is well-constrained by U–Pb SHRIMP, SIMS and LA-ICP-MS zircon ages of ca. 462–446 Ma, overlying the Sardic unconformity, which may be restricted to the Early–Middle Ordovician (Casas et al., 2010; Martínez et al., 2011; Martí et al., 2019; Puddu et al., 2019).

4. The isotopic record

In order to evaluate the role of tectonomagmatic processes in the Early Paleozoic crustal growth of Western Gondwana, coupled U–Pb and Lu–Hf zircon data were compiled (Fig. 6). Data include both magmatic and detrital zircons from late Neoproterozoic to Ordovician units of the southwestern and northwestern margins. With few exceptions (see below), magmatic and detrital zircons show a similar trend, though the former are relatively scarce for the late Neoproterozoic.

Interestingly, the South American Lu–Hf record all along the proto-Andean margin shows a nearly homogenous fingerprint characterized by ε_{Hf} values mostly between ca. +1 and −6 at ca. 650–440 Ma, shared by the Sierras Pampeanas, Patagonia, Eastern Cordillera, Puna, northern Chilean basement, Méridas Andes and Santander Massif (Fig. 6a). Magmatic zircons older than ca. 580–550 Ma are scarce and only documented as inherited xenocrysts in younger units, though detrital Ediacaran zircons show the nearly chondritic to slightly subchondritic Lu–Hf composition (Reimann et al., 2010; Hauser et al., 2011; Augustsson et al., 2016). The first peak of magmatic zircons is recorded at ca. 550–510 Ma (Hauser et al., 2011; Bahlburg et al., 2016; Dahlquist et al., 2016; Ortiz et al., 2017), being thus coeval with the timing of the Pampean Orogeny (see Section 2). The magmatic and detrital zircon record is scarce at ca. 510–500 Ma, suggesting minimum magmatic activity that could be attributed to the timing of trenchward migration of the magmatic arc locus between the Pampean and Famatinian events (Cristofolini et al., 2012; Weinberg et al., 2018) or, alternatively, to changes in subduction zone configuration due to ridge-trench interaction (see Section 5.1; Otamendi et al., 2020).

Magmatic zircons record a large cluster at ca. 500–440 Ma, coincident with the timing of the Famatinian arc. In particular, the main peak is recorded at ca. 485–465 Ma, contemporaneously with the Famatinian Orogeny (e.g., Ducea et al., 2010, 2017; Otamendi et al., 2017; Rapela et al., 2018), and shows a larger spread in ε_{Hf} values, mostly between +8 and −12. The Lu–Hf signature of the Famatinian magmatism is almost comparable all along the South American margin, from the Mérida Andes to Patagonia (Chernicoff et al., 2010; Hauser et al., 2011; Dahlquist et al.,

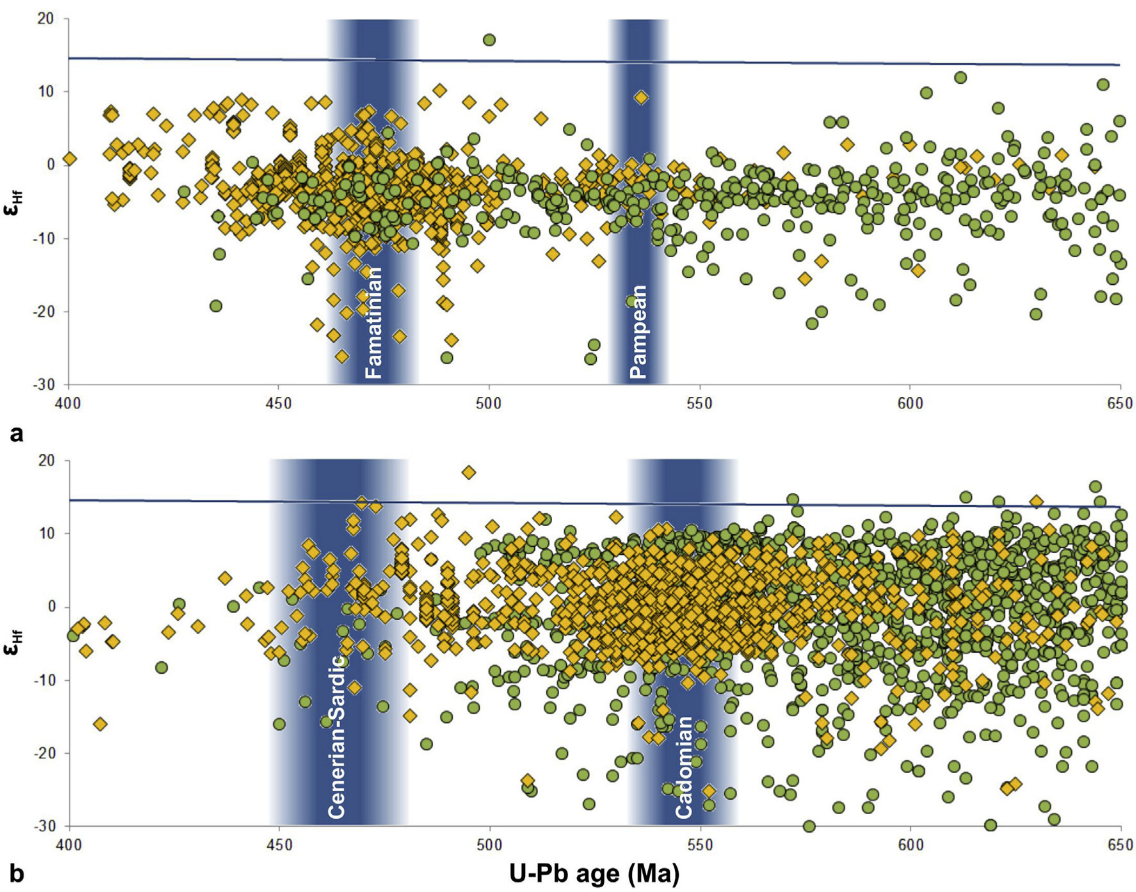

Fig. 6. U–Pb vs. ε_{Hf} magmatic (yellow) and detrital (green) zircon data of Ediacaran to Early Paleozoic units of southwestern (a) and northwestern (b) Gondwana accretionary orogens. Data were recalculated considering a constant decay $\lambda^{176}Lu = 1.867 \times 10^{-11}$ year^{-1} (Söderlund et al., 2004) and CHUR values of $^{176}Hf/^{177}Hf = 0.282785$ and $^{176}Lu/^{177}Hf = 0.0336$ (Bouvier et al., 2008). Main orogenic phases are indicated in blue. (a) Data from Chernicoff et al. (2010), Reimann et al. (2010), Bahlburg et al. (2011, 2016), Hauser et al. (2011), Dahlquist et al. (2013, 2016), Pankhurst et al. (2014, 2016), Augustsson et al. (2016), Ortiz et al. (2017), Otamendi et al. (2017), Casquet et al. (2018), Rapela et al. (2018), Tazzo-Rangel et al. (2019) and van der Lelij et al. (2019). (b) Data from Gerdes and Zeh (2006), Bahlburg et al. (2010), Avigad et al. (2012, 2018), Zlatkin et al. (2013), Linnemann et al. (2014), Abbo et al. (2015), Albert et al. (2015), Díez Fernández et al. (2015), Orejana et al. (2015), Antić et al. (2016), Beyarslan et al. (2016), Honarmand et al. (2016), Moghadam et al. (2016, 2017, 2019), Sagawe et al. (2016), Villaseca et al. (2016), Chelle-Michou et al. (2017), Montero et al. (2017), Abati et al. (2018), Ballouard et al. (2018), Naidoo et al. (2018), Siegesmund et al. (2018), Zieger et al. (2018) and Couzinié et al. (2019).

2013; Bahlburg et al., 2016; Otamendi et al., 2017; Rapela et al., 2018; Tazzo-Rangel et al., 2019; van der Lelij et al., 2019). Finally, the Silurian record is restricted to the Mérida Andes and Santander Massif, showing a slightly shift towards more radiogenic compositions revealed by ε_{Hf} values from ca. −5 to +8.

On the other hand, the occurrence of early Ediacaran magmatism is rare in Cadomian domains (e.g., Fernández-Suárez et al., 1998; Abati et al., 2018), and most zircons yielding U–Pb ages >580 Ma comprise inherited xenocrysts in younger units (e.g., Villaseca et al., 2016; Montero et al., 2017). Nevertheless, coeval detrital zircons are widespread and record a large spread in ε_{Hf} values from ca. −15 to +10 (Fig. 6b). Such values are typical for Pan-African magmatism of the Arabian–Nubian Shield and northern Africa (Oriolo et al., 2017, and references therein), which supports sediment provenance from denudation of Pan-African mainland sources located therein (Avigad et al., 2005; Squire et al., 2006; Meinhold et al., 2013; Veevers, 2017; Stephan et al., 2019a, 2019b).

Isotopic data show a well-defined cluster at ca. 580–520 Ma, dominantly characterized by ε_{Hf} values between ca. −8 and +8, which corresponds to the timing of the Cadomian arc. This trend of subchrondritic to suprachrondritic values is recorded in several areas, including the Bohemian, Iberian, French Central and Serbo-Macedonian Massifs, and basement blocks of Iran and Turkey (Zlatkin et al., 2013; Linnemann et al., 2014; Abbo et al., 2015; Antić et al., 2016; Beyarslan et al., 2016; Moghadam et al., 2016, 2017, 2019; Chelle-Michou et al., 2017; Abati et al., 2018; Zieger et al., 2018). Values are homogeneously distributed for most regions, whereas those from the Ossa-Morena Zone (Iberian Massif) and Iranian blocks define a nearly bimodal distribution of ε_{Hf} with subchondritic and suprachondritic groups, a trend that is also observed by detrital zircons yielding U–Pb ages up to ca. 500 Ma (Fig. 6b). Magmatic zircons with U–Pb ages of ca. 520–500 Ma are scattered between the latter groups, recording ε_{Hf} from ca. −4 to +8. Finally, late Cambrian to Ordovician magmatism (ca. 500–450 Ma) records a shift towards more radiogenic compositions dominated by suprachondritic ε_{Hf} values, which vary between −5 and +12. This trend is well-recorded in the Iberian, Armorican and Serbo-Macedonian Massifs (Díez Fernández et al., 2015; Antić et al., 2016; Villaseca et al., 2016; Montero et al., 2017; Ballouard et al., 2018), whereas the Saxo-Thuringian Domain of the Bohemian Massif is dominated by nearly chondritic to slightly subchrondritic ε_{Hf} values (Sagawe et al., 2016).

5. Discussion

5.1. Late Ediacaran to Ordovician paleogeography and tectonic evolution

The paleoreconstruction of continental landmass position in ancient times greatly relies on paleomagnetic data (e.g., Cocks and Torsvik, 2002; Scotese, 2017). However, the apparent polar wander path for Gondwana in the Ediacaran to Early Paleozoic is poorly defined, particularly between ca. 470 Ma and 410 Ma, since paleomagnetic poles are scarce and partially imprecised due to undetected rotations or uncertain age of the timing of magnetization (e.g., Van der Voo, 1993; Torsvik and Van der Voo, 2002). Though these limitations preclude describing the precise extent and details of Gondwana movement during this time span, it is clear that the supercontinent moved over the pole between ca. 470 Ma and 410 Ma (McElhinny et al., 2003; Amenna et al., 2014), which roughly implies a northward movement of northern Western Gondwana (Van der Voo, 1993). The precise nature and extent of the movement is, however, strongly dependent on the selection of paleomagnetic poles, and its definition is also hampered by the paleolongitude uncertainty of the paleomagnetic method. Therefore, many different paleoreconstructions are permissible with the available data. Among them, paleoreconstructions of Scotese (2016) were considered, since they include not only paleomagnetic but also further paleogeographic data. Paleogeographic reconstructions were thus integrated with geological, petrological, geochronological, isotopic, structural and geochemical data (Sections 2–4). In the case of most peri-Gondwanan domains, however, paleomagnetic data are scarce, mostly due to the fact that Ediacaran to Ordovician basement rocks are affected by polyphase metamorphism and deformation.

Geological, geochronological and petrological evidence supports a relatively common evolution recorded all along the proto-Andean margin of South America, from the Northern Andes to Patagonia (Ramos, 2018, and references therein), which is further supported by similarities in the Late Ediacaran–Ordovician isotopic record (Fig. 6a). The early stages are attributed to the onset of the Pampean arc magmatism (Fig. 1), succeeded by a trenchward migration and instalment of the Famatinian arc during the Late Cambrian–Ordovician (Fig. 7). Both Pampean and Famatinian peaks of magmatism were attributed to major flare-up events (Ducea et al., 2015; Casquet et al., 2018; Rapela et al., 2018).

The tectonic setting of the Pampean Orogeny still remains controversial and has led to several contrasting proposals, including the collision of large continental blocks or accretion of an active ridge (e.g., Rapela et al., 1998a, 1998b; Gromet and Simpson, 2000; Piñán-Llamas and Simpson, 2006; Schwartz et al., 2008; Ramos et al., 2010, 2014; Siegesmund et al., 2010; Escayola et al., 2011; Steenken et al., 2011; Casquet et al., 2018; Weinberg et al., 2018; Perón Orrillo et al., 2019). Strengths and limitations of all these models, which are out of the scope of this contribution, were revised by Ramos et al. (2014). On the other hand, the Famatinian Orogeny has been commonly attributed to the collision of Laurentia-derived terranes (i.e., Precordillera/Cuyania Terrane) with the southwestern Gondwana margin (Fig. 7; Astini et al., 1995; Ramos et al., 1998; Rapela et al., 1998a; Astini and Dávila, 2004; González et al., 2004; Ramos, 2004; Mulcahy et al., 2011; Cristofolini et al., 2014; Rapela et al., 2018; Otamendi et al., 2020).

Though the Pampean and Famatinian orogenies represent compressional/transpressional events, the proto-Pacific margin was dominated by subduction, mostly related to the evolution of a retreating accretionary orogen. Crustal extension, associated anatexis and back-arc basins are recorded over ca. 50 Myr, starting at ca. 505–500 Ma (Fig. 7; Cristofolini et al., 2012; Rapela et al., 2018; Weinberg et al., 2018, 2019; Wolfram et al., 2019; Otamendi et al., 2020). This is further supported by the dominance of high-temperature/low-pressure metamorphism in the arc and back-arc regions and associated high geothermal gradients (Fig. 4; Büttner et al., 2005; Larrovere et al., 2011). Though uncertain, a similar setting could be suggested for the Late Ediacaran–Cambrian, based on similarities in metamorphic conditions and isotopic record (Figs. 4 and 6a). In this context, a retreating accretionary orogen characterized the Late Ediacaran to Ordovician evolution of the South American proto-Pacific margin, which underwent two distinct orogenic events.

In a similar way, the Late Ediacaran to Cambrian Cadomian arc in northwestern Gondwana has been interpreted as a retreating accretionary orogen, associated with a magmatic flare-up event and widespread intra-arc/back-arc extension (Fig. 7; Linnemann et al., 2007, 2014; Schulz et al., 2008; Abbo et al., 2015; Garfunkel, 2015; Moghadam et al., 2017, 2019). The Cadomian pulse of transpressional/compressional deformation, in turn, has been mostly interpreted as the development of an advancing mode orogen due to changes in subduction parameters (e.g., Linnemann et al., 2007; Díez Fernández et al., 2019). In contrast, the tectonic setting of the widespread Late Cambrian–Ordovician tectonomagmatic activity in Cadomian domains still remains controversial, and has been alternatively interpreted as the result of subduction or rifting processes, which are related to the early evolution of the Rheic Ocean (e.g., Nance et al., 2010, 2012; von Raumer et al., 2013; Zurbriggen, 2017; Stephan et al., 2019a). One of the most critical aspects is the presence of calc-alkaline, mostly S-type, magmatism (Section 3), which may record continental arc magmatism. In the case of models supporting a rifting setting, this geochemical fingerprint has been interpreted as the result of inheritance from older arc-related rocks, due to remelting and assimilation (Stephan et al., 2019a, and references therein).

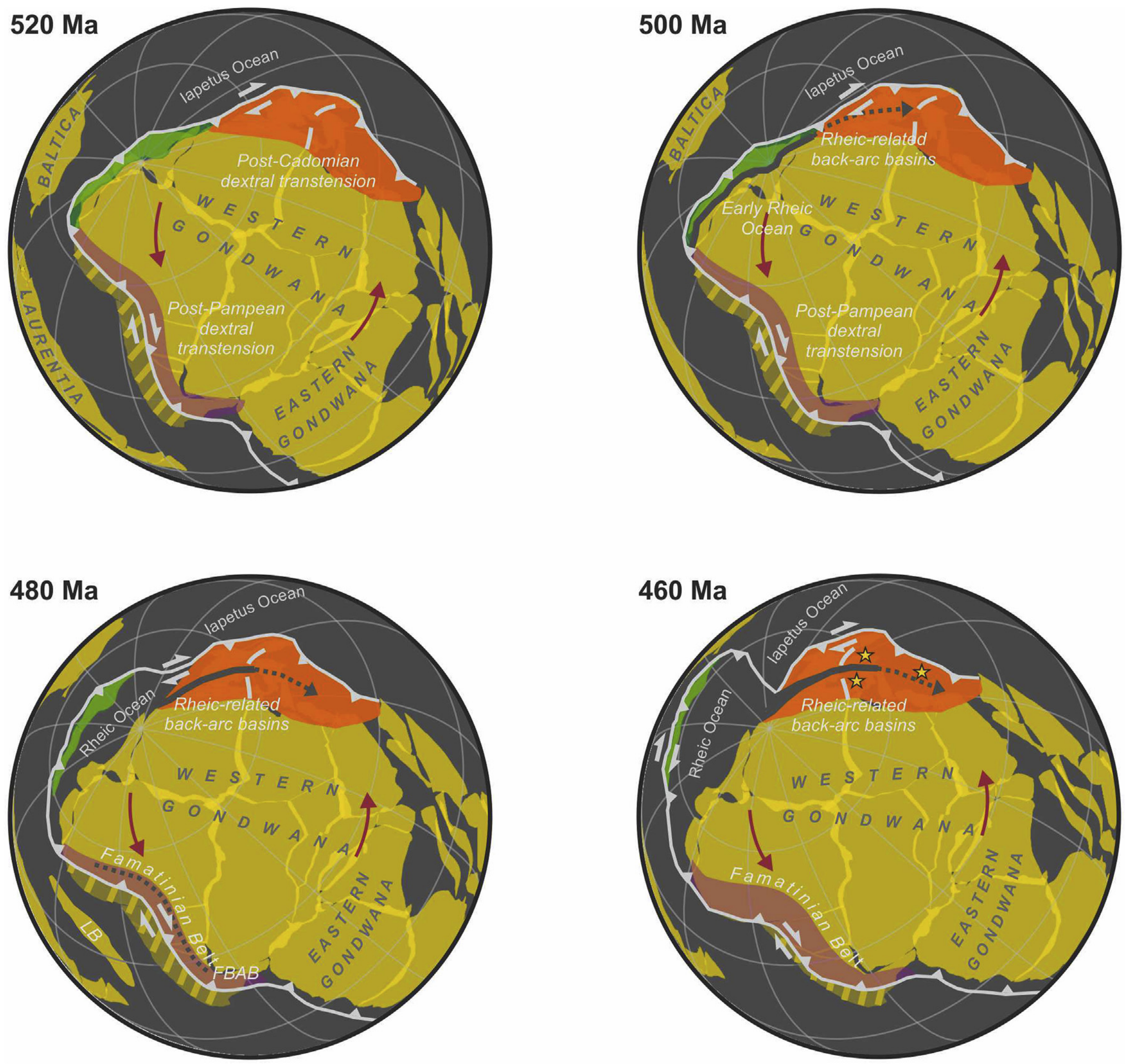

Fig. 7. Cambrian–Ordovician paleogeographic evolution of Western Gondwana (see Fig. 1 for references). Red arrows represent anticlockwise rotations, probably starting at ca. 520 Ma, coupled with generalized dextral transtension. Full and dotted grey lines represent evolved and embryonic back-arc basins, respectively. The evolution between ca. 500 Ma and 460 Ma depicts the eastward decrease in the rate of crustal extension and propagation of rifting along the northwestern margin, favouring the opening of the Rheic Ocean in the back-arc region of Avalonia-Carolonia-Ganderia and the development of extended/hyperextended margins in Cadomian domains. Stars illustrate regions recording the Sardic-Cenerian Orogeny, probably between ca. 480 Ma and 460 Ma. The position of Laurentia-derived blocks (LB) colliding with the southwestern margin, triggering the closure of Famatinian back-arc basins (FBAB), is schematic. See Section 5 for further details.

The opening of the Rheic Ocean triggered the separation of peri-Gondwanan domains, such as Avalonia, Carolinia and Ganderia, from the Gondwana mainland, and their subsequent drift and collision with Laurentia and Baltica (Fig. 7; e.g., van Staal et al., 1998; Murphy et al., 2006; Pollock et al., 2012). In contrast, Cadomian domains remained attached to the Gondwana margin during the Rheic opening (Murphy et al., 2006; Žák and Sláma, 2018; Romer and Kroner, 2019; Stephan et al., 2019a), which is however registered by their Late Cambrian tectonomagmatic record (Section 3). These differences can be explained by a combination of both eastward decrease in the rate of crustal extension and propagation of rifting along the margin (Fig. 7; von Raumer et al., 2015; Cambeses et al., 2017; Stephan et al., 2019a). For this reason, Cadomian domains recorded Late Cambrian to Ordovician alkaline and tholeiitic magmatism (Giacomini et al., 2005; Díez Fernández et al., 2015; Villaseca et al., 2015; von Raumer et al., 2015; Antić et al., 2016) and hyperextension (Žák and Sláma, 2018), but never drifted far away from Gondwana.

If coeval subduction took place during Rheic opening (Zurbriggen, 2017, and references therein), a retreating accretionary orogen could satisfactorily explain most characteristics of Cadomian realms (Fig. 7). In the first place, it would account for the nearly uninterrupted magmatic record between Cadomian and subsequent Late Cambrian to Ordovician tectonic processes (e.g., Linnemann et al., 2007), which in some cases yield a very similar geochemical fingerprint (Mandl et al., 2018). Intra-/back-arc extension coeval with subduction would thus explain both S-type calc-alkaline and alkaline/tholeiitic magmatism (e.g., Zurbriggen, 2017; García-Arias et al., 2018, and references therein), and also the existence of high-grade (Klötzli-Chowanetz et al., 1997; Abati et al., 1999, 2007; Fernández-Suárez et al., 2002b) and high-pressure metamorphism (Schaltegger, 1993; Schaltegger et al., 2003; Franz and Romer, 2007; Balen et al., 2015). In this context, the Cenerian and Sardic phases could be interpreted as the result of either distinct transtensional deformation events, which may even cause folding (e.g., Fossen et al., 2013), or transpressional/compressional phases resulting from a change to an advancing mode, possibly due to changes in subduction dynamics favouring higher interplate coupling (e.g., ridge subduction, higher convergence rates).

In sum, the Western Gondwana margin might have been dominated by retreating accretionary orogens during the Late Ediacaran–Early Paleozoic. Discrete compressional/transpressional orogenic events resulted from an advancing-mode phase of orogens, mostly related to changes in subduction parameters that favoured increasing interplate coupling. However, the accretion of continental microplates might also have triggered some of these events, as in the case of the Famatinian Orogeny, attributed to the collision of the Precordillera/Cuyania Terrane. The role of retreating orogens and subduction dynamics was thus crucial for the opening of oceanic basins such as the Rheic Ocean. In this sense, the Rheic Ocean opening resulted either from slab pull along the northern Iapetus margin (Murphy et al., 2006; Nance et al., 2010) or Iapetus slab roll back along the Cadomian arc margin (von Raumer et al., 2003; Martínez-Catalán et al., 2009; Díez Fernández et al., 2012). However, considering a Late Cambrian–Ordovician active Cadomian margin, the latter seems to be more likely, implying that the Rheic Ocean was therefore born as a back-arc basin (Martínez-Catalán et al., 2009; van Staal et al., 2012). Slab roll back might also have played a major role during the early Cadomian active margin, also favouring the development of a supra-subduction zone complex (Arenas et al., 2018).

Oblique subduction characterized Peri-Gondwanan oceanic crust subduction (von Raumer et al., 2003), thus accounting for the presence of non-coaxial transtensional deformation in retreating orogens and alternating transpressional pulses. Interestingly, the South American margin records a clear dextral component of deformation during the Pampean to Famatinian evolution in both transpressional and transtensional pulses (Martino, 2003; Simpson et al., 2003; Whitmeyer and Simpson, 2004; Piñán-Llamas and Simpson, 2006; Martino et al., 2010; von Gosen and Prozzi, 2010; von Gosen et al., 2014; Tibaldi et al., 2019). Though the reconstruction of the structural history of Cadomian domains is largely overprinted by Late Paleozoic to Cenozoic tectonics, Cambrian dextral transtension was also indicated for the Bohemian Massif (Zulauf et al., 1999; Dörr et al., 2002; Linnemann et al., 2007), succeeding sinistral transpression during peak Cadomian orogenic activity at ca. 560–540 Ma recorded in both the Armorican and Bohemian massifs (Brun et al., 2001; Chantraine et al., 2001; Dörr et al., 2002). Cambrian to Ordovician dextral transtension along the northwestern margin is, however, further supported by paleomagnetic data indicating a large anticlockwise rotation of Western Gondwana mainland (Figs. 7 and 8), in line with coeval dextral deformation documented along the Avalonian–Ganderian margin (van Staal et al., 2012; see also Section 5.2). These similarities suggest that, at least since the Late Cambrian, a large segment of the Western Gondwana margin was dominated by synchronous oblique subduction triggering a dextral component of deformation, which suggests global-scale geodynamic controls in the evolution of the peri-Gondwanan subduction zones.

5.2. Crustal growth and geodynamic implications

Accretionary orogens are the dominant locus of juvenile crust addition deriving from subcontinental mantle magmas or accretion of island arc systems along the margin, though the net crustal growth results from the balance with crustal loss processes such as subduction erosion, chemical weathering and surface erosion (e.g., Clift et al., 2009; Scholl and von Huene, 2009; Stern, 2011). Lu–Hf isotopes in zircon are key monitors of these processes (e.g., Kemp et al., 2006; Belousova et al., 2010; Hawkesworth et al., 2019), since more radiogenic compositions imply addition of juvenile crust, as in the case of accretionary orogens (Collins et al., 2011). However, zircons formed in advancing orogens typically yield less radiogenic compositions than those of retreating orogens, mostly as the result of crustal thickening/thinning, respectively (Kemp et al., 2009; Phillips et al., 2011; Roberts, 2012).

The nearly continuous subduction along the southwestern Gondwana margin records a relatively homogenous fingerprint characterized by slightly suprachondritic to subchondritic ε_{Hf} values (Fig. 6a; Section 4). This signature might result from mixing of both recycled crustal sources and mantle-derived magmas, as evidenced by modelling of Lu–Hf zircon data of Otamendi et al. (2017) for Famatinian magmatism. Several authors, however, pointed out the existence of a metasomatized subcontinental lithospheric mantle for this magmatic event (e.g., Alasino et al., 2016; Rapela et al., 2018). The composition of this mantellic source could thus be tentatively estimated by considering the most radiogenic Lu–Hf compositions obtained for the Famatinian magmatism (Fig. 6a), which implies a metasomatized mantle source with a present-day composition of $^{176}Hf/^{177}Hf = 0.282777$ and $^{176}Lu/^{177}Hf = 0.00095$, resulting in an ε_{Hf} of ca. 10.3 at ca. 488 Ma (Rapela et al., 2018). On the other hand, the crustal component of the Famatinian magmatism is well-constrained, and essentially represents metasedimentary rocks derived from the older Pampean accretionary prism, which occupied an arc/back-arc position in the Late Cambrian–Ordovician, and might undergo subsequent assimilation and/or anatexis (Casquet et al., 2012b; Cristofolini et al., 2012; Otamendi et al., 2017; Sola et al., 2017; Rapela et al., 2018; Wolfram et al., 2019). In this sense, the homogeneous isotopic signature resulting from this mixing process does not seem to be restricted to the Famatinian arc in southern South America (Rapela et al., 2018) but may be also extended all along the proto-Pacific margin during the Ordovician, being even valid for previous Pampean tectonomagmatic stages. The larger dispersion observed in ε_{Hf} during the Famatinian flare-up could be explained by mixing of different proportions of mantellic/supracrustal materials, or compositional differences of the latter (Otamendi et al., 2017).

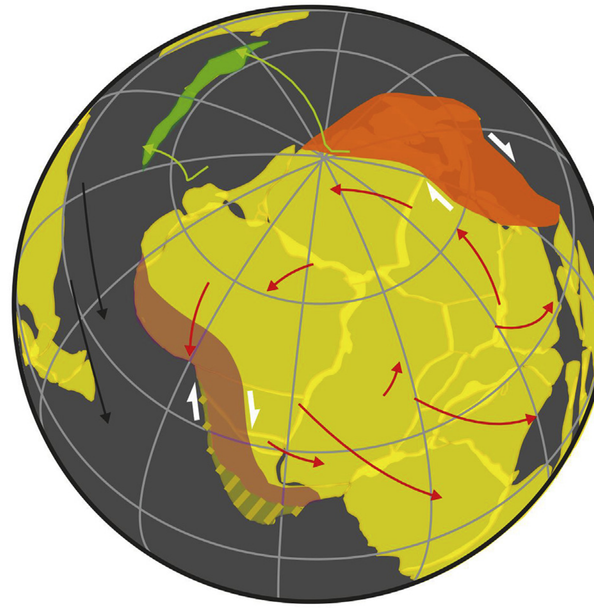

Fig. 8. Late Cambrian–Early Ordovician displacement vectors calculated on the basis of absolute paleoreconstructions proposed by Scotese (2016), showing the anticlockwise rotation of Gondwana (red) which, combined with the northward displacement of Laurentia (black), causes relative dextral movement along Gondwanan marginal orogens.

In a similar way to the Famatinian arc, Cadomian magmatism records variable subchrondritic to suprachrondritic values, which resulted from mixing of juvenile mantle and metasedimentary crustal sources in a dominantly retreating accretionary orogen (Zlatkin et al., 2013; Chelle-Michou et al., 2017; Abati et al., 2018; Zieger et al., 2018). The presence of scarce Early Paleozoic, mostly Ordovician, zircons yielding Depleted Mantle-like Lu–Hf compositions may suggest a juvenile depleted mantle source (Díez Fernández et al., 2015; Antić et al., 2016; Ballouard et al., 2018). However, the relatively homogeneous isotopic composition of Cadomian zircons with suprachondritic ε_{Hf} values documented in the Ossa-Morena Zone (Iberian Massif) and Iranian blocks (see Section 4) may suggest a possibly metasomatized mantle source underlying the Cadomian arc, a hypothesis that should be evaluated in future contributions. The Ordovician shift towards more radiogenic compositions dominated by suprachondritic ε_{Hf} values may be associated with an extended/hyperextended margin due to the evolution of a retreating accretionary orogen and the consequent opening of the Rheic Ocean due to Iapetus slab roll back, which facilitated the ascent of mantle-derived magmas to upper crustal levels.

The Lu–Hf isotopic array of Cadomian domains is very similar to that of Ganderia, with variable subchrondritic to suprachondritic compositions during the Late Ediacaran–Cambrian and a shift towards more radiogenic values in the Ordovician (Henderson et al., 2018). These similarities might result from a similar tectonic evolution, with Ediacaran–Ordovician arc development along the peri-Gondwanan margin and Ordovician back-arc extension that triggered the drift of Ganderia and the opening of the Rheic Ocean (Pollock et al., 2012; van Staal et al., 2012; Henderson et al., 2018). According to van Staal et al. (2012), rapid roll back of the Iapetus slab beneath the Ganderian arc was a key factor in the opening and subsequent expansion of the Rheic Ocean, further supporting similarities with Cadomian domains. On the other hand, the Ediacaran Lu–Hf fingerprint is also comparable to that of Avalonia (Willner et al., 2013; Pollock et al., 2015; Henderson et al., 2016), suggesting a common peri-Gondwanan origin (Fig. 7). However, there is a Cambrian–Ordovician magmatic lull in Avalonia, interpreted as the development of a passive margin dominated by a dextral strike-slip regime, which favoured the displacement of Avalonia towards a back-arc position behind Ganderia (e.g., Pollock et al., 2012; van Staal et al., 2012; Murphy et al., 2019). Avalonia, Carolinia and Ganderia fill the spatial gap between Pampean–Famatinian and Cadomian domains, and thus support a common evolution for the entire Western Gondwana margin.

As a whole, Late Ediacaran to Ordovician peri-Gondwanan accretionary orogens show a similar history of crustal growth, with nearly continuous addition of mantle-derived magmas in the arc/back-arc region that favoured net crustal addition, and mixing with (meta)sedimentary and minor intercalated igneous sources due to anatexis and/or assimilation. This implies that, in most cases, isotopic model ages of rocks of these regions do not provide direct evidence of the underlying basement age but, instead, a mixing between (possibly metasomatized) mantellic and crustal sources, though local cratonic roots might contribute as well.

After a certain orogenic phase, the locus of magmatism migrated trenchwards, giving rise to assimilation and anatexis of previous forearc sedimentary sources in the context of arc/back-arc magmatism, as indicated by the short time span (i.e., less than ca. 30–20 Myr) between sedimentation, burial, metamorphism and magmatism (e.g., Casquet et al., 2012b; Cristofolini et al., 2012; Fiannacca et al., 2013; Chelle-Michou et al., 2017; Zurbriggen, 2017; Otamendi et al., 2020). This process was intimately related to the evolution of accretionary orogens in retreating mode, playing slab roll back a major role for trenchward migration of the arc system, in a similar way to modern active continental margins (e.g., Cochrane et al., 2014). In addition, the presence of retreating-mode accretionary orogens contributed to the development of extended/hyperextended margins (e.g., Žák and Sláma, 2018), which further allowed the widespread intrusion of mantle-derived magmatism and their mixing with slightly older, dominantly (meta)sedimentary sources in a relatively thin continental crust (Ducea et al., 2015).

Though uncertain, geodynamic controls of peri-Gondwanan accretionary orogens can be tentatively evaluated. Murphy et al. (2011) postulated the emergence of a superplume during the Ordovician, triggered by slab avalanche events within the Iapetus and Paleopacific. Such events might be intimately associated with generalized slab roll back which, in turn, might result from relatively low convergence rates and slow plate velocities, possibly attributed to instabilities derived from the Ediacaran assembly of Gondwana (Bercovici and Long, 2014). Slab roll back, associated with oblique subduction and a consequent dextral component of crustal deformation (Section 5.1), might trigger toroidal mantle flow and, therefore, widespread back-arc transtension (Figs. 7 and 9; Schellart and Moresi, 2013). These processes might also result in the Early Paleozoic anticlockwise rotation of Gondwana mainland (Figs. 8 and 9). This rotation arises from the paleoreconstruction of Scotese (2016), which broadly follows the approach of Dalziel et al. (1994) and Dalziel (1997) of a Paleozoic clockwise path for Laurentia around the proto-Andean margin of South America in route to its well-defined position within Pangea. The relative movement of northern Western Gondwana relative to the southern Iapetus plate thus reveals an anticlockwise rotation, which is accommodated by dextral shearing in high-strain peripheral orogens (Fig. 8). In this sense, the evolution of Early Paleozoic accretionary orogens in retreating mode was the result of top-down tectonics succeeding the amalgamation of Gondwana.

6. Final remarks

Early Paleozoic retreating orogens were dominated by high-temperature/low-pressure metamorphism and relatively high geothermal gradients, resulting from the development of extended/hyperextended margins dominated by transtension, which favoured mantle-derived magmatism and mixing with relatively young (meta) sedimentary sources in a thin continental crust. Crustal reworking of previous forearc sequences thus took place through assimilation and anatexis in the arc/back-arc regions. Marginal retreating subduction zones were thus the locus of Early Paleozoic crustal growth in Western Gondwana during nearly continuous subduction and resulting flare-up events, such as those related to the Cadomian and Famatian arcs.

These orogens were characterized by trenchward migration of the locus of arc magmatism, which was controlled by slab roll back, probably resulting from decreasing convergence rates and plate velocities after Gondwana assembly. Slab roll back coupled with oblique subduction and crustal-scale dextral deformation might trigger toroidal mantle flow and, therefore, widespread back-arc extension/transtension and a large-scale anticlockwise rotation of Gondwana mainland.

Bulk dextral transtensional strain at the orogen-scale was probably partitioned into different domains, with areas dominated by strike-slip or pure-shear extension. Paleomagnetic evidence suggests that a large component of dextral strike-slip deformation was accommodated along the trench (Fig. 8), favouring anticlockwise rotations of Gondwana mainland, whereas extension was most likely localized in the arc/back-arc regions. However, the latter domains also record locally dextral components of deformation (Sections 2 and 3), indicating a more complex strain distribution. Since structural and kinematic data are still scarce, future works should evaluate deformation of different structural domains (i.e., forearc, arc and back-arc), in order to reconstruct the orogenic architecture, strain partitioning processes and bulk strain in different areas along the margin.

Similarities in the Early Paleozoic tectonomagmatic record, implying back-arc basin development and extensional/transtensional deformation, may also suggest a comparable evolution for several segments of the Eastern Gondwana margin (e.g., Foster et al., 2005; Cawood et al., 2007; Rocchi et al., 2011; Johnson et al., 2016; Gao et al., 2019). The presence

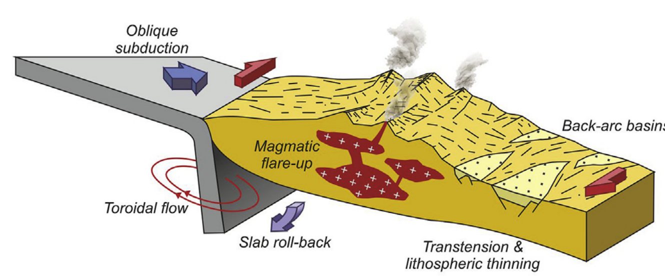

Fig. 9. Sketch showing coupling between slab roll back, toroidal mantle flow, back-arc extension and oblique subduction (modified after Schellart and Moresi, 2013).

of Early Paleozoic retreating accretionary orogens may thus have a larger extension, along most regions of the Gondwana margin, a hypothesis that has to be evaluated.

Finally, it is also likely that Early Paleozoic tectonic processes might have influenced Variscan orogen-parallel dextral deformation associated with oblique subduction and subsequent collision (e.g., Leblanc et al., 1996; Gleizes et al., 1998; Kroner et al., 2007; Michard et al., 2010; Kroner and Romer, 2013; Carreras and Druguet, 2014; Martínez Catalán et al., 2015). In the first place, Variscan geodynamic controls favoring regional dextral deformation were possibly active already by the Early Paleozoic. On the other hand, structural inheritance of Early Paleozoic structures might have played a significant role during Variscan tectonics.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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