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Mississippian olistostromes of Iberia revisited: tectonic drivers of synorogenic carbonate platform/reef destruction

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Abstract: This paper reviews the synorogenic basins formed on the Gondwana side of the Variscan Orogen of Iberia, highlighting the widespread occurrence of calciturbiditic formations and olistostromes containing reef limestone olistoliths in Iberia's Variscan basins. Using key examples from the Variscan Orogen for comparison (the Azrou–Khenifra and Rhenohercynian basins), the significance of these olistostromes and flyschoid deposits is discussed. Our tectonic models of the Variscan belt in Iberia propose possible drivers of synorogenic carbonate platform/reef destruction responsible for the origin of calciturbidites and olistostromes. One model proposes the formation of an orogenic plateau via the lateral flow of partially molten orogenic roots in the context of Laurussia–Gondwana convergence following the destruction of the Rheic Ocean and slab retreat of the Gondwana (lower) plate. An alternative model invokes subduction of Palaeotethys oceanic lithosphere beneath the Gondwana (upper) plate. Both emphasize the Mississippian occurrence of a significant thermal anomaly beneath Gondwana that favoured strong lithosphere thinning, creating ideal conditions for synorogenic carbonate platform/reef destruction and the formation of calciturbidite deposits and olistostromes in Iberia. The Variscan palaeotopography would look similar in both situations. Distinguishing between these models is therefore not straightforward, with differences in the kinematics of regional tectonic transport in the superstructure of Mississippian gneiss domes.

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Large-scale submarine landslides and slope failures are common features of synorogenic basins (Festa *et al.* 2016). These processes create turbidity flows, mass transport deposits and mass transport complexes that are also known as olistostromes (Ogata *et al.* 2020 and references cited therein). The turbiditic deposits are sometimes made of calcareous material and are known as calciturbidites, a kind of sedimentary unit not yet completely understood worldwide (Payros and Pujalte 2008; Rubert *et al.* 2012; Reijmer *et al.* 2015). Basin-wide olistostromes are recognized in the geophysical profiles of present day continental slopes, such as the modern Oregon accretionary margin (McAdoo and Watts 2004). These gravity-driven deposits are mapped as block-in-matrix formations (BIMFs) and/or large blocks embedded in layered flysch sequences in the sedimentary record of ancient collisional belts (Festa *et al.* 2016). As the formation of these sedimentary basins is coeval with propagation of the orogeny towards the passive margin, they provide key constraints on the last evolutionary stages of supercontinent assembly, such as Pangaea.

Remarkable occurrences of such sedimentary units formed by gravitational sliding are common throughout Earth history. This paper focuses on the description of BIMFs of Paleozoic age from Iberia that can be compared with the Paleogene olistostromes in the Carpathian mountains (central Europe; Cieszkowski *et al.* 2012 and references cited therein) and the Early Cretaceous olistostromes in the Crimean mountains (eastern Europe; Nikishin *et al.* 2015; Sheremet *et al.* 2017 and references cited therein). These olistostromes of different ages include reef limestone olistoliths, the occurrence and origin of which have intrigued generations of researchers studying synorogenic basins, such as the synorogenic sequences of the Azrou–Khenifra Basin (NW Africa; Cózar *et al.* 2023 and references cited therein) and the Rhenohercynian Zone (western Europe; Leveridge and Hartley 2006; Salamon and Königshof 2010 and references cited therein), interpreted to be related to the Variscan Orogeny (Franke 2000; Hoepffner *et al.* 2006).

This paper aims to revisit the calciturbidites and olistostromes bearing reef limestone olistoliths of the Variscan synorogenic basins in the Gondwanan terranes of the Iberian Variscan Massif and examines the multiple occurrences of Middle Devonian to Mississippian reef limestone olistoliths and calciturbidites. Estimates of the depositional ages of Iberian olistostromes are updated based on new detrital zircon U–Pb geochronology and newly available palaeontological data. Newly proposed tectonic models for explaining the evolution of Variscan synorogenic basins of Iberia are discussed. This information will be used to improve our knowledge of the orogenic processes that may have acted as drivers for the foundation and destruction of synorogenic carbonate platforms, reefs and calcareous slopes in convergent settings.

Regional framework of the Variscan synorogenic basins of Iberia

There is a consensus that the progressive closure of the Rheic Ocean and the epicontinental seas on the Laurussia and Gondwana margins (now in present day Iberia) *c.* 370 Myr ago culminated in continental collision and the development of a Variscan suture zone (the Beja-Acebuches Ophiolitic Complex; Quesada and Dallmeyer

1994). It is suggested that Laurussia and Gondwana acted as the upper and lower plates, respectively, during the Early Devonian when the Rheic oceanic lithosphere was being subducted (Martínez Catalán *et al.* 2009; Pereira *et al.* 2017). However, there is no consensus on this tectonic model because there is still disagreement regarding the polarity of Devonian subduction and the number of oceanic basins that evolved on this convergent boundary (Simancas *et al.* 2009; Ribeiro *et al.* 2010; Arenas *et al.* 2014; Díez Fernández and Pereira 2016; Pereira *et al.* 2017).

The pre-Mesozoic basement rocks of Iberia are divided into several tectonic units representing (Figs 1, 2): (1) the Gondwana side (i.e. the Cantabrian Zone, the West Asturian Leonese Zone (WALZ), the Central Iberian Zone (CIZ) and the Ossa-Morena Zone (OMZ)); (2) the Laurussia side, represented by the peri-Gondwanan Avalonia or Meguma basement that previously collided with the Laurentian margin (i.e. the Pulo do Lobo Zone and the South Portuguese Zone) (Braid *et al.* 2012; Pereira *et al.* 2014); and (3) a rootless section of the Variscan accretionary wedge forming a tectonic stack composed of allochthonous and parautochthonous units from the Galicia-Trás-os-Montes Zone (GTMZ) (Farias *et al.* 1987; Ribeiro *et al.* 1990). The Parautochthon and Lower Allochthonous units represent the Gondwana margin that was tectonically overlain by Cambro-Ordovician (Rheic Ocean) and Early Devonian ophiolitic rocks (Arenas and Sánchez-Martínez 2015), which are themselves overlain by Upper Allochthon units that are likely to be associated with the Laurussia side (Gómez Barreiro *et al.* 2007; Díez Fernández *et al.* 2011; Mateus *et al.* 2016; Dias da Silva *et al.* 2021; Martínez Catalán *et al.* 2021).

The older rocks of Iberia include the development of Ediacaran–Cambrian synorogenic basins (i.e. the Cadomian Orogeny; Quesada 1990; Eguíluz *et al.* 2000; Pérez-Estaún *et al.* 2004; Linnemann *et al.* 2008; Fuenlabrada *et al.* 2020; Sarrionandia *et al.* 2020; Pereira *et al.* 2023). They are recognized in the CIZ, OMZ, WALZ and part of the GTMZ. The Ediacaran meta-sedimentary and meta-igneous rocks of Iberia are unconformably overlain by Cambrian to Early Devonian sedimentary and volcanic rocks recording the evolution of the Gondwana margin during the opening and drifting of the Rheic Ocean (i.e. pre-orogenic strata; Liñan *et al.* 1993; Aramburu *et al.* 2004; Gutiérrez-Marco and Robardet 2004; Marcos 2004; Gutiérrez-Alonso *et al.* 2008; Sánchez-García *et al.* 2008, 2014; Pastor-Galán *et al.* 2013; Dias da Silva *et al.* 2014; González Clavijo *et al.* 2017; Gutiérrez-Marco *et al.* 2019).

The pre-orogenic strata of the Gondwana side of Iberia are overlain unconformably by Mid- to Late Devonian to Mississippian sedimentary and calc-alkaline, alkaline and tholeiitic volcanic rocks that have accumulated in Variscan synorogenic basins (Oliveira *et al.* 2019) (Figs 2–4). In the Cantabrian Zone, the pre-orogenic strata are overlain by a sequence of Mid- to Late Devonian to Mississippian carbonate rocks, including reef limestones (Aramburu *et al.* 2004; Fernández *et al.* 2004; Fernández-Martínez *et al.* 2006). By contrast, there is a pronounced stratigraphic gap of Mid-Devonian age in the other Iberian tectonic units (Gutiérrez-Marco *et al.* 2019) and Mid- to Late Devonian limestones commonly occur as olistoliths surrounded by flysch in the Mississippian synorogenic basins of the GTMZ (NW Iberia Lower Parautochthon), southern CIZ (La Codosera–São Mamede, Almadén and Pedroches basins), the CIZ–OMZ boundary (Guadiato-Kilva basin) and the OMZ (Cabrela and Terena basins). Mississippian carbonate rocks overlying Late Devonian and/or pre-orogenic strata are only described in the CIZ (Gutiérrez-Marco *et al.* 2019) and OMZ (Quesada *et al.* 2019). They also occur as reef limestone olistoliths in BIMFs of the Mississippian synorogenic basins of the southern CIZ (Armendáriz *et al.* 2008*a*), the CIZ–OMZ boundary (Cózar *et al.* 2006; Matas *et al.* 2014) and the OMZ (Oliveira *et al.* 1991; Robardet and Gutiérrez-Marco 2004; Pereira *et al.* 2006).

Variscan olistostromes of Iberia

This description focuses on Mississippian Iberian olistostromes that incorporate reef limestone olistoliths of Mid- to Late Devonian and/or Mississippian age and includes eight synorogenic basins distributed from NW to SW Iberia (Figs 2, 3), the stratigraphic age of which (based on the fossil content) and/or the maximum depositional ages (based on detrital and igneous zircon geochronology) of BIMFs are known (Fig. 3).

Mississippian olistostromes of the GTMZ

The NW Iberia Lower Parautochthon (GTMZ) (Figs 2b, 4b) is composed of a set of piggy-back imbricated tectonic slices of Mississippian flysch and BIMF sequences. This complex structure is interpreted to represent a tectonic carpet along which the Upper Parautochthon and the allochthonous units of the GTMZ moved in the Mississippian (Dallmeyer *et al.* 1997; Martínez Catalán *et al.* 2009) towards and into the external orogenic zones represented by the CIZ (Dias da Silva *et al.* 2021).

The Lower Parautochthon contains a Variscan foreland basin formed between the accretionary wedge and the peripheral bulge of the Gondwana continental margin. In the Alcañices syncline,

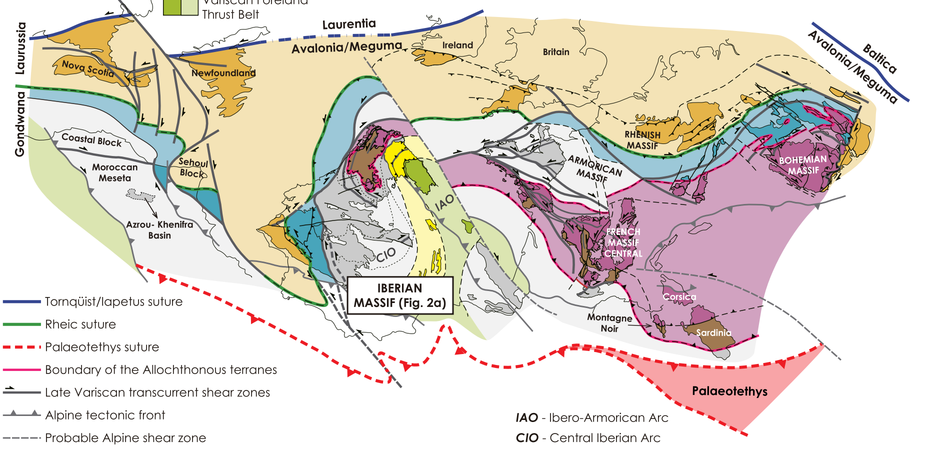


Fig. 1. Simplified geological map of the Variscan Belt at the end of the Carboniferous period. Source: modified from Martínez Catalán *et al.* (2019), Accotto *et al.* (2022) and Dias da Silva *et al.* (2023).

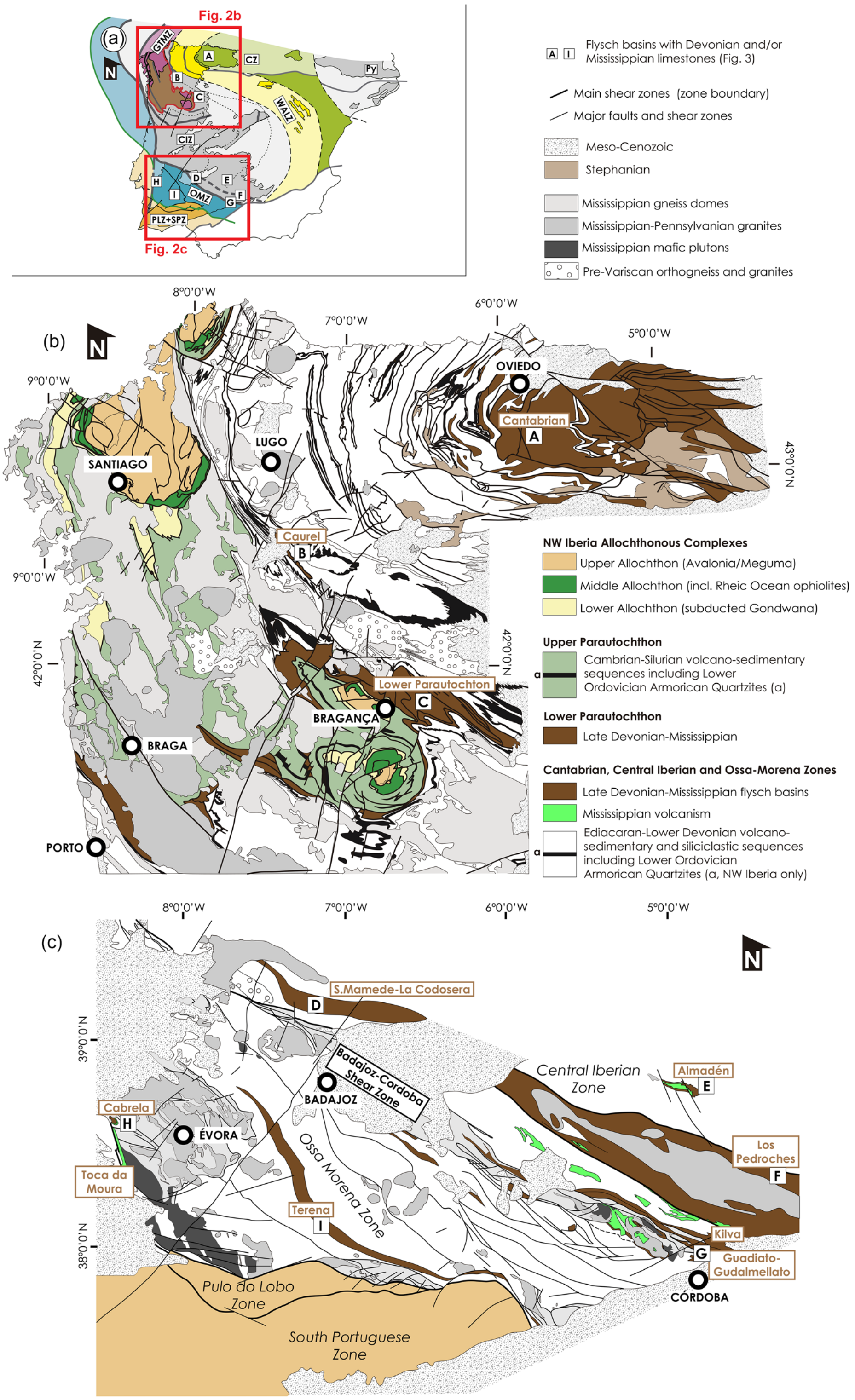
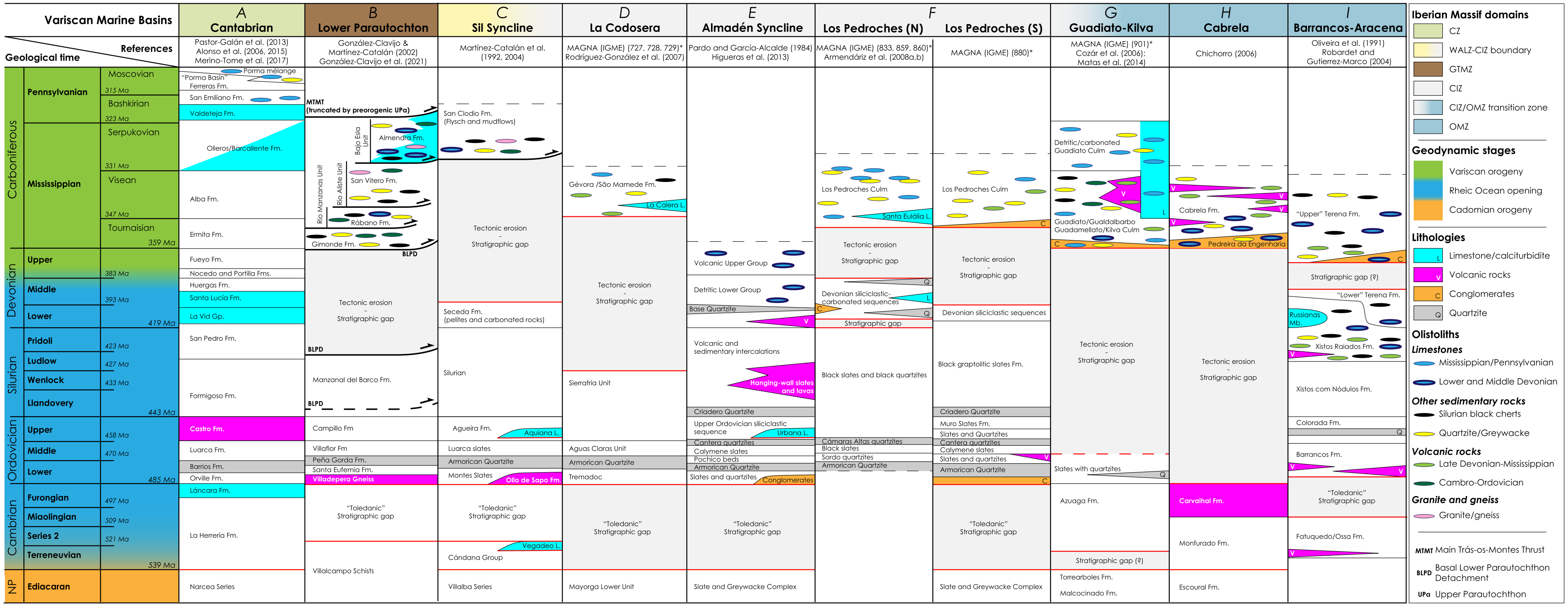


Fig. 2. (**a**) Sketch map of the Iberian Massif (taken from Fig. 1) showing the location of the areas of interest in this work. (**b**) Simplified geological maps of NW and (**c**) SW Iberia, highlighting the known Mississippian synorogenic marine basins, with letter indexation corresponding to the stratigraphic columns in Figure 3. Source: part (b) based on the published works of González Clavijo *et al.* (2021) and Alonso *et al.* (2015).; part (c) produced using published maps from the LNEG and IGME (Portuguese and Spanish geological surveys) and Dias da Silva *et al.* (2023). GTMZ, Galicia–Trás-os-Montes Zone; CZ, Cantabrian Zone; WALZ, West Asturo-Leonese Zone; CIZ, Central Iberian Zone; OMZ, Ossa Morena Zone; PLZ, Pulo do Lobo Zone; SPZ, South Portuguese Zone; Py, Pyrenees.

located at the east of the Bragança Complex, four tectonic slices of Mississippian synorogenic sediments are exposed, the older ones occupying higher structural positions in the piggy-back sequence (González Clavijo 2006). The tectonic slice at the top of the piggy-back sequence exposes the Gimonde Formation. This flysch-olistostrome unit marks the boundary with the overriding, pre-orogenic Upper Parautochthon by the Main Trás-os-Montes Thrust (Ribeiro *et al.* 1990; Dias da Silva *et al.* 2015).

The tectonic slice below the Gimonde Formation contains the Rábano Formation and includes BIMFs composed of olistoliths of volcanic and meta-sedimentary rocks, greywacke and limestone, mostly derived from pre-orogenic sources corresponding to the stratigraphy of the CIZ and the Upper Parautochthon (González Clavijo *et al.* 2002, 2016, 2021). Reef limestone olistoliths containing Early to Mid-Devonian tentaculites and conodonts, and also fragments of crinoids and brachiopods of unknown age, have been recognized in the Rábano Formation (González Clavijo 2006 and references cited therein). The most probable source of these reef carbonate olistoliths is the Devonian shallow carbonate platform of the Cantabrian Zone, which is characterized by several episodes of reef production (Figs 2b, 3A). The younger detrital zircon grains obtained in the Rábano Formation imply early Visean maximum depositional ages for this flysch deposit (González Clavijo *et al.* 2016, 2021; Martínez Catalán *et al.* 2016).



* Using IGME (Geological and Mining Survey of Spain) 1:50.000 scale geologic maps (MAGNA series, maps 727, 728, 729, 833, 859, 860, 880 and 901): Santos García, J.A. and Casas Ruiz, J. (1982); López-Díaz et al. (2007, 2008); Rodriguez Pevida et al. (1990); Fernández et al. (2013); Insúa Márquez et al. (2008); Apalategui et al. (1985b); Apalategui et al. (1985a)

Fig. 3. Synthesis of the stratigraphic columns represented by upper case letters in Figure 2. See text for a more detailed description. Thin red lines indicate stratigraphic unconformities between units. NP, Neoproterozoic; CZ, Cantabrian Zone; WALZ, West Asturian–Leonese Zone; CIZ, Central Iberian Zone; GTMZ, Galicia–Trás-os-Montes Zone; OMZ, Ossa Morena Zone. Red lines indicate the position of the stratigraphic unconformities.

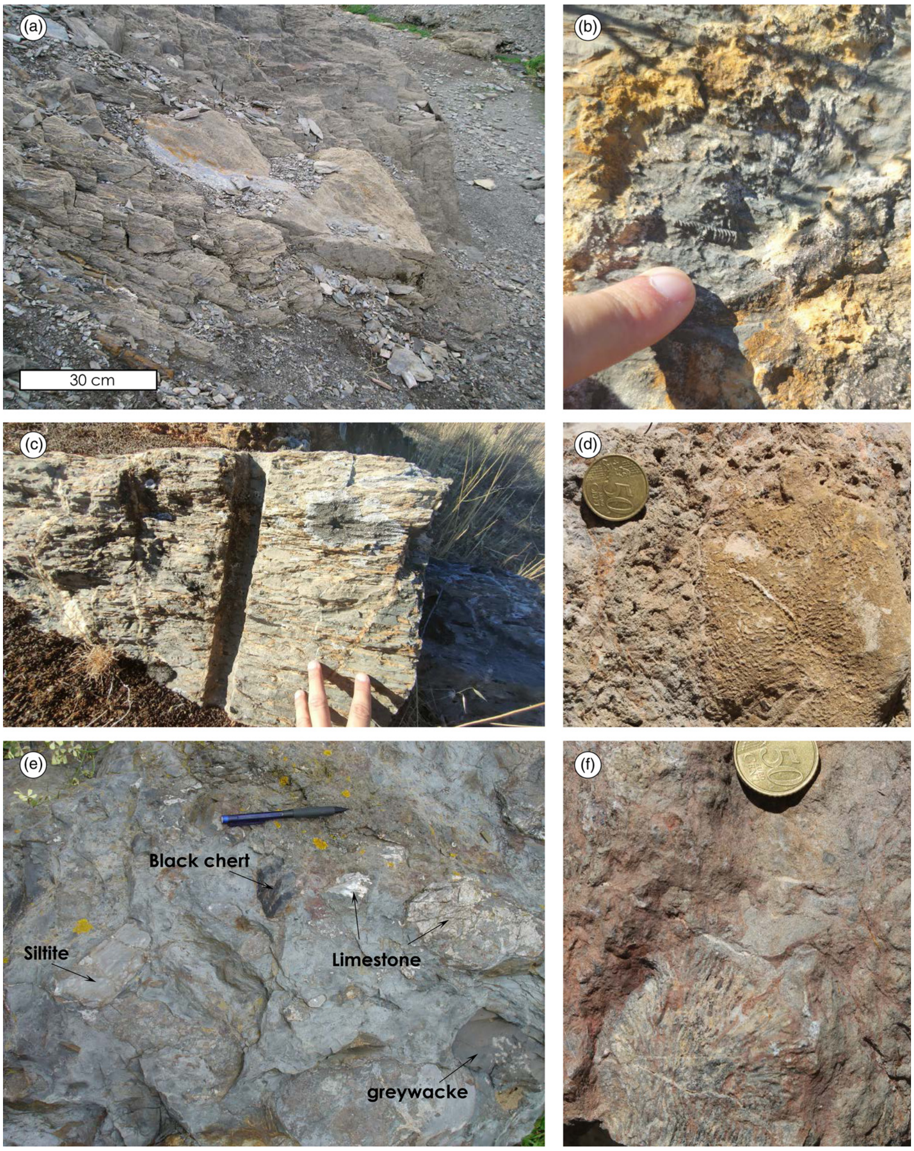


Fig. 4. (**a**) Devonian limestone olistolith in the siltitic–pelitic flysch. (**b**) Tentaculites fossil in a limestone olistolith. (**c**) Calci-turbidite. (**d**, **f**) Coral fragments in Devonian limestones within Mississippian siliciclastic flysch. (**e**) Olistostrome with olistoliths of Silurian black cherts, Devonian limestones and Carboniferous siltites. Parts (a–c) from the Almendra Formation and parts (d–f) from the Cabrela Basin.

The Almendra Formation, which occurs in the lowest and youngest tectonic slice of the piggy-back sequence, is composed of calciturbidites and reef limestone olistoliths (Fig. 4a–c) within an at least 200 m thick flysch sequence (González Clavijo 2006; Martínez Catalán *et al.* 2016). The Almendra Formation includes BIMFs containing Mid-Devonian conodonts and tentaculites (Sarmiento *et al.* 1997) (Fig. 4b), upper Emsian tentaculites (Truyols-Massoni and Quiroga 1981) and many fragments of brachiopods and crinoid stems of unknown age. The maximum deposition age of the Almendra Formation is Serpukhovian based on the young population of detrital zircon grains (Martínez Catalán *et al.* 2016). To date, Mississippian volcanism has not been recognized in the Lower Parautochthon stratigraphic units, but, locally, they are affected by Visean to Bashkirian HT–LP metamorphism associated with the development of gneiss domes (Dias da Silva *et al.* 2015, 2021).

Mississippian olistostromes of the WALZ–CIZ boundary and the CIZ

Located along the WALZ– CIZ boundary, the Sil syncline (Fig. 3C) includes a Variscan flysch (the San Clodio Formation) sequence comparable with similar sequences in the Lower Parautochthon (Martínez Catalán *et al.* 2016). The San Clodio Formation is mostly composed of flysch deposits locally disturbed by slumps, mudflows and conglomerates containing differently sized olistoliths with possible sources in the nearby CIZ and GTMZ, including granites, gneisses, granodiorites, quartzites, slates and limestones with Pragian tentaculites (Barrios Lorenzo *et al.* 2022). The estimated maximum depositional age of the San Clodio Formation, based on detrital zircon geochronology, is Serpukhovian–early Bashkirian (Martínez Catalán *et al.* 2004).

In the southern CIZ, the La Codosera–São Mamede Basin (Figs 2c, 3D) consists of an up to 1200 m thick Visean flysch sequence with interbedded calc-alkaline felsic flows and tuffs intruded by tholeiitic diabases derived from metasomatized mantle (the Gévora and São Mamede formations) (López Díaz *et al.* 2007; López-Moro *et al.* 2007). The Gévora Formation includes a member consisting of limestones, shales and calcareous breccias (i.e. La Calera Limestone; Rodríguez-González *et al.* 2007) that contain crinoids and brachiopods of Early to Mid-Devonian age (Gourvennec *et al.* 2010; Schemm-Gregory and Piçarra 2013). In the upper part of these flysch sequences, there are matrix-supported conglomerates and olistoliths of sandstones and quartzites enclosed in sandstones. The palynological and conodont content of the flysch and the carbonate olistoliths indicate a Mississippian depositional age for both lithologies (Rodríguez-González *et al.* 2007; Lopes *et al.* 2020).

Further east, in the Almadén syncline (Fig. 3E), there is a flysch sequence associated with Lower Devonian to early Mississippian mafic volcanic and volcanoclastic rocks (Pardo and García-Alcalde 1984; Higueras *et al.* 2005, 2013). The Detritic Lower Group and the Volcanic Upper Group, overlying the Middle Devonian 'Basal Quartzite', include limestone bed packages and discontinuous metre-scale lenticular bodies containing Lockovian–Frasnian brachiopods, bryozoans, corals, bivalves, crinoids and tentaculites (Pardo and García-Alcalde 1984). In the nearby Guadalmez Syncline, the stratigraphic sequence includes reef limestones with abundant Tournaisian–Visean fossils (Pardo and García-Alcalde 1984).

In the southern CIZ, the Pedroches Basin along the CIZ–OMZ boundary (Fig. 3F) forms the geographical transition to the Guadiato and Guadalmellato–Kilva basins (Armendáriz *et al.* 2008*a*). The Pedroches Basin includes a Mississippian flysch sequence with a >4000 m thick sequence of shales, greywackes and lens-shaped calcarenite beds with corals, ostracods and conodonts of Visean age and a few conglomerate strata containing pebbles of volcanic rocks probably derived from the pre-orogenic basement located to the south (Rodríguez Pevida *et al.* 1990). These flysch deposits rest on reef limestones that contains corals and conodonts of early Visean age (Rodríguez Pevida *et al.* 1990).

Mississippian olistostromes of the CIZ–OMZ boundary and the OMZ

In the Guadiato Basin (Fig. 3G), located along the CIZ–OMZ boundary (Armendáriz 2006; Cózar *et al.* 2006), two sedimentary units have been distinguished: a lower unit composed of *in situ* reef limestone beds (Cózar *et al.* 2006) with sponges and large brachiopods of Visean age (Armendáriz *et al.* 2008*b*); and an upper unit of flysch deposits, including up to hectometre-sized reef limestone olistoliths (Armendáriz 2006), resembling a BIMF. The overlying Guadalmellato–Kilva Basin stratigraphy (Fig. 3G), defined in the Loma de Kilva syncline, records the evolution of a piggy-back basin younger than the Guadiato Basin (Martínez Poyatos *et al.* 1998). The Guadalmellato–Kilva Basin consists of Tournaisian–Visean flysch deposits at the base, overlain by Visean–Serpukhovian carbonate marine platform deposits followed by continental deltaic facies (Matas *et al.* 2014). The Guadalmellato–Kilva Basin includes a BIMF with mega-olistoliths in which most of the pre-orogenic strata are represented (Gutiérrez-Marco *et al.* 2014). In addition, reef limestone olistoliths with Mississippian corals have been found (Matas *et al.* 2014).

In the westernmost domains of the OMZ, the Cabrela Basin (Fig. 3H) is dominated by flysch deposits. This sequence of shales and greywackes, with a few conglomerates, is interbedded with calc-alkaline bimodal volcanic rocks (the Cabrela Formation) (Santos *et al.* 1987; Chichorro 2006). The Cabrela Formation includes a BIMF composed of calciturbidites and reef limestone olistoliths (Fig. 4d–e) (the Pedreira da Engenharia Member). Mid- to Late Devonian conodonts (Boogaard 1972, 1983; Machado *et al.* 2020) were found in these carbonate rocks enclosed by siliciclastic turbidites (Fig. 4e) containing palynomorphs of Tournaisian–Visean age (Pereira *et al.* 2006 and references cited therein). Their stratigraphic age based on fossil content is compatible with the Mississippian maximum depositional age obtained from the youngest detrital zircon population found in the flysch deposits (Pereira *et al.* 2012) and with igneous zircons from interbedded calc-alkaline felsic volcanic rocks (Pereira *et al.* 2020).

Further east, in the Barrancos–Aracena alignment (Figs 2c, 3I), synorogenic deposits are exposed in the core of narrow synclines and in imbricated thrusts (Perdigão *et al.* 1977; Apalategui *et al.* 1984, 1990; Ruiz López *et al.* 1985; Guindos *et al.* 1990; Fernández-Ruiz *et al* 1994) and are composed of flysch sequences with a few conglomerates that contain olistoliths of different lithologies. The Xistos Raiados Formation is regarded as the oldest of these synorogenic units and has been assigned an uppermost Silurian–Famennian depositional age in accordance with the fossil content of reef limestones and black cherts (Perdigão *et al.* 1977; Robardet and Gutiérrez-Marco 2004), which may represent olistoliths. The younger deposits of the Xistos Raiados Formation (the Russianas Member; Oliveira *et al.* 1991) are composed of calciturbidites, reef limestone olistoliths and polygenic conglomerates. Emsian–Famennian conodonts, brachiopods and corals found in the reef limestone olistoliths have been used to interpret the depositional age of the Russianas Member (Robardet and Gutiérrez-Marco 2004).

The Terena Formation is considered both as partial lateral equivalent and as stratigraphically overlying the Xistos Raiados Formation (Fig. 3I) (Oliveira *et al.* 1991; Piçarra 2000). The Terena Formation (or Basin) is a flysch deposit composed of two members, as described near Aracena in two parallel narrow synforms (Boogaard and Guzmán 1981; Apalategui *et al.* 1984, 1990; Robardet and Gutiérrez-Marco 2004). The lower member includes limestone olistoliths containing Mid- to Upper Devonian fossils and at the base includes kilometre-long conglomerate–sandstone units and interbedded calc-arenites and conglomerates with volcanic and metamorphic pebbles. The upper member of the Terena Formation is a flysch sequence associated with conglomerates and lens-shaped carbonate-rich BIMFs that are increasingly abundant towards the top. These synorogenic deposits contain Mid- to Late Devonian brachiopods, crinoids and tentaculites, and late Tournaisian–early Visean conodonts (Boogaard and Guzmán 1981; Robardet and Gutiérrez-Marco 2004). Further west, in Barrancos, the Terena syncline is mainly composed of greywackes and shales with early Devonian graptolite and palynomorph associations (Piçarra *et al.* 1998; Pereira *et al.* 1999).

Discussion: Variscan orogenesis and the destruction of carbonate/reef platforms

The Variscan synorogenic basins of Iberia include BIMFs containing reef limestone olistoliths of Devonian and/or Mississippian age, the distribution, representativeness and geological significance of which are discussed in the following sections.

Variscan belt correlatives of the Mississippian olistostromes of Iberia

Key examples of Variscan olistostromes provide a framework for the discussion of carbonate platform/reef destruction and the formation of BIMFs in the Variscan synorogenic basins of Iberia. Variscan olistostromes represent the accumulation of reef limestone olistoliths in flysch deposits related to the evolution of different types of synorogenic basins. The Variscan olistostromes of the Azrou–Khenifra Basin were probably formed in a foreland basin (Hoepffner *et al.* 2006). In such Variscan synorogenic basins, the reef limestone olistoliths included in olistostromes likely represent fragments of slightly older carbonate platforms/reefs that were destroyed as accretionary processes progressed and were later transported by gravity-driven processes to the continental slope or rise (e.g. Colmenero *et al.* 2002; Alonso *et al.* 2015). Furthermore, in the European Variscan belt, other calci-turbidite sequences and limestone olistoliths have been recognized in synorogenic foreland basins located to the north of the Lizard Complex (Cornwall, SW England; Holder and Leveridge 1986; Strachan *et al.* 2014) and in the Rhenish Massif, as part of the Rhenohercinian Zone (RHZ) (Walliser and Alberti 1983; Floyd *et al.* 1990; Franke 2000).

A key example of a synorogenic marine basin composed of deep troughs and shallow carbonate platforms is the Azrou–Khenifra Basin of the Moroccan Meseta, developed during the Late

Devonian–Mississippian. This synorogenic basin is located in the Variscan–Appalachian belt (Fig. 1) that extends from North Africa (the Moroccan Meseta), through Western and Central Europe (the Iberian, Armorican and Bohemian massifs) and North America (the Appalachians) (Matte 2001) as a result of closure of the Rheic Ocean and Gondwana–Laurussia collision. In the Azrou–Khenifra Basin, located in the western Atlas Mountains, sedimentation is recorded by turbiditic sequences, olistostromes and gravity-driven nappes sliding in a Mississippian synorogenic basin (Beauchamp and Izart 1987; El Houicha 1994; Bouabdelli and Piqué 1996). The Azrou–Khenifra Basin is variously considered to represent either a foreland basin (Piqué *et al.* 1993; Bouabdelli and Piqué 1996; Hoepffner *et al.* 2006), a retro-arc foreland (Roddaz *et al.* 2002) or a forearc setting (Michard *et al.* 2008), depending on the inferred polarity of subduction. Synsedimentary nappes (e.g. the Azrou–Khenifra and Ziar–Mirt nappes; Bouabdelli 1989; El Houicha 1994) are directly emplaced on the Mississippian flysch deposits and their tectonic origin has been the subject of debate (Allary *et al.* 1972; Piqué *et al.* 1993). The BIMFs probably derived from sources composed of Devonian–Mississippian platform rocks, including reef limestones, deposited on the Cambro-Ordovician basement of the eastern domains of the Moroccan Meseta (Beauchamp and Izart 1987; Huvelin and Mamet 1997). Reef limestone olistoliths found in the Mississippian BIMFs, as described in the Ait Mazel region, are of Devonian and Mississippian ages (Said *et al.* 2013; Cózar *et al.* 2023). This suggests that Mississippian BIMFs were synchronous with tectonic instability, the destruction of carbonate platforms/reefs, and gravity-driven transportation and deposition (El Houicha 1994; Huvelin and Mamet 1997).

In SW England, other examples of Variscan olistostromes are found in deformed foreland basins, equivalent to those of other regions of the RHZ, which include several kilometre-thick synorogenic tectonostratigraphic units (the Veryan and Carrick nappes) tectonically overlain by the Lizard ophiolitic complex (Shail and Leveridge 2009 and references cited therein). They are composed of Late Paleozoic BIMFs bearing limestone olistoliths and calciturbidites (Leveridge and Hartley 2006). In Cornwall, the Upper Devonian Roseland Breccia Formation (Holder and Leveridge 1986) includes olistoliths of Ordovician quartzite and Silurian and Early to Mid-Devonian limestone; sandstone, breccia, metamorphic and mafic/ultramafic igneous rocks of unknown age have been identified in a slate matrix showing slumps probably resulting from mass flow (Lambert 1965; Leveridge 1974; Barnes 1983). These olistostromes were deposited on a deep water slope at the tectonic front and most probably derived from sources located in the Normannian terrane of Gondwana affinity (Shail and Leveridge 2009), as indicated by detrital zircon studies (Strachan *et al.* 2014). In addition, the Pendower Formation included in the Veryan nappe (Leveridge and Shail 2011) is composed of calciturbidites with crinoids and shell fragments, and conodonts probably derived from a hemipelagic platform of Eifelian age (Leveridge and Shail 2011).

It has been proposed that this limestone platform was developed on the Laurussia passive margin peripheral bulge and was later imbricated by the advance of the Variscan orogenic front (Holder and Leveridge 1986). However, there seems to be a discrepancy between the interpretation that these BIMFs record the final stage of inversion of the synorogenic basin (Holder and Leveridge 1986) based on their Late Devonian faunal content and the Late Devonian–Mississippian maximum depositional ages proposed for the closure of the Rhenohercynian basin (Martínez Catalán *et al.* 2021 and references cited therein).

The RHZ extends from Iberia and Cornwall to the Harz mountains of Germany in the east, including the Rhenish Massif (Martínez Catalán *et al.* 2021). In this eastern part of the RHZ, the Laurussian pre-Devonian autochthonous basement is overlain by a thick siliciclastic sequence of Lower Devonian age with Laurussia provenance (Franke and Dulce 2017). Devonian to Early Carboniferous bimodal volcanism recognized in the Rhenish Massif is interpreted to represent the opening and closure of oceanic basins, with the influence of subduction of the Palaeotethys active rift under the Variscan Orogen (Franke 2000, 2014). The progressive closure of the oceanic basins under the influence of Palaeotethys subduction during the Late Paleozoic has been associated with the deposition of Frasnian to Visean flysch sequences (Franke 2000; Zeh and Gerdes 2010), including calciturbidites (Walliser and Alberti 1983). The RHZ allochthonous tectonic units are composed of Early Devonian oceanic crust and sedimentary mélanges (e.g. the Giessen Nappe in the Rhenish Massif). These BIMFs contain olistoliths of Ordovician–Lower Devonian sedimentary rocks most likely derived from the Saxo-Thuringian Zone (Franke 2000). Some olistoliths are Silurian and Lower–Middle Devonian limestones (Floyd *et al.* 1990). Eifelian–Givetian platform limestones have been tentatively proposed as being the source of the Variscan calciturbidites (Franke 2000 and references cited therein; Salamon and Königshof 2010).

The key examples of olistostromes mentioned here have the common characteristic that they formed in synorogenic basins where the tectonic instability was sufficiently intense to dismantle the carbonate platforms/reefs spanned by the convergent setting. In this tectonic context, what were the likely tectonic drivers of synorogenic carbonate platform/reef destruction?

Tectonic models for the synorogenic carbonate platform/reef destruction and origin of the Variscan olistostromes of Iberia

It is widely accepted that the continental collision following the Devonian subduction of the Rheic Ocean under Laurussia was not contemporaneous along and across the Variscan Orogen (Franke 2000; Matte 2001; Martínez Catalán *et al.* 2021) as a result of the uneven closing of the opposing margins and the influence of promontories, as proposed for the North Gondwana passive margin (e.g. Quesada 1991; Murphy *et al.* 2016; Casas *et al.* 2022) or the diachronic closure of the ocean that also favoured the formation of large-scale transcurrent shear zones (e.g. Martínez Catalán *et al.* 2021). In Iberia, Laurussia–Gondwana docking is evidenced by tectonic slices of the unrooted Variscan accretionary wedge (allochthonous units) that were emplaced on top of the Gondwana margin (Martínez Catalán *et al.* 2019 and references cited therein). The subduction of the Rheic oceanic lithosphere beneath the Laurussia margin involving the collision of Gondwana ribbon continents (Meguma, Avalonia) was active during the late Silurian to Mid-Devonian (Arenas *et al.* 2014). Later, in the Late Devonian, the obduction of mid- to high-pressure rocks and orogenic folding took place in response to the regional uplift and formation of topographic highs in the peripheral bulge of the lower plate (Dias da Silva *et al.* 2015, 2021; González Clavijo *et al.* 2016). These tectonic constraints probably caused the partial erosion or even inhibition of Early to Mid-Devonian sedimentation and the subsequent deposition of Mid- to Late Devonian reefs, thus contributing to the regional stratigraphic gap characteristic of the Devonian stratigraphy in the Gondwana margin.

In terms of the palaeographic reconstruction of the Mid- to Late Devonian, Iberia was part of a large marine platform that occupied part of the southern hemisphere tropical zone (Robardet and Gutiérrez Marco 1990) surrounding the Gondwana and Laurussia margins. This marine platform included epicontinental seas that were sourced from the nearest emerged zones of the Laurussia and Gondwana convergent boundary. Under these circumstances, it is likely that continued peripheral bulge migration probably triggered the heterogeneous uplift and erosion of Devonian–early Carboniferous platform/reefs and their gradual incorporation into olistostromes, as olistoliths and calciturbidites, in the surrounding Mississippian marine basins.

The different tectonic models discussed in this section show evidence that the evolution of synorogenic basins during the Mississippian was dependent on far-field orogenic stresses involving the entire lithosphere. A likely tectonic model for Iberia was based on the model idealized for the lithospheric evolution of the French Massif Central (Fig. 5a) (Vanderhaeghe *et al.* 2020). This tectonic model suggests that, in this region of the Variscan Orogen, the ideal conditions for lithospheric thinning were provided by the development of a plateau due to the rise of a high-temperature front reaching shallow depths, slab rollback and lithospheric delamination of the underlying Gondwana plate (Vanderhaeghe *et al.* 2020). This huge thermal anomaly in Gondwana caused the partial melting of previously thickened lithosphere and of the previously metasomatized asthenosphere, producing bimodal magmatism derived from different grades of partial melting and fractioning of alkaline to tholeiitic magmas mixed with calc-alkaline crustal melts because it favoured the formation of flat-lying detachments that mimic the HT–LP metamorphic isograds of Variscan gneiss domes (Dias da Silva *et al.* 2018; Pereira *et al.* 2023). At this stage of the evolution of the Variscan Orogeny, extensional tectonics was responsible for enhancing lithospheric thinning and apparently controlled the opening of epicontinental seas in Gondwana during the Mississippian (Figs 5a, b and 6a, b). In the Mississippian synorogenic basins of Iberia, flysch deposition and BIMF formation probably resulted from the prominent tectonic instability of this convergent setting.

The Mississippian stratigraphy of Iberia indicates that sedimentary environments locally changed from more continental to deeper platform and lower talus conditions (Fig. 3). This bathymetry triggered large olistostromes due to the recycling of flysch sequences and the gravity-driven transference of olistoliths of pre- and synorogenic rocks, including Devonian and Mississippian limestones and volcanic rocks, from the shifting topographic highs.

In this tectonic model the Mississippian synorogenic basins of Iberia do not match any classical classification of forearc, back-arc or foreland basins related to accretionary orogens because they formed when subduction of the Rheic oceanic lithosphere had already been concluded (Fig. 6a). Furthermore, the Mississippian synorogenic sequences of Iberia are not typical of collisional orogens because they are associated with a significant volume of

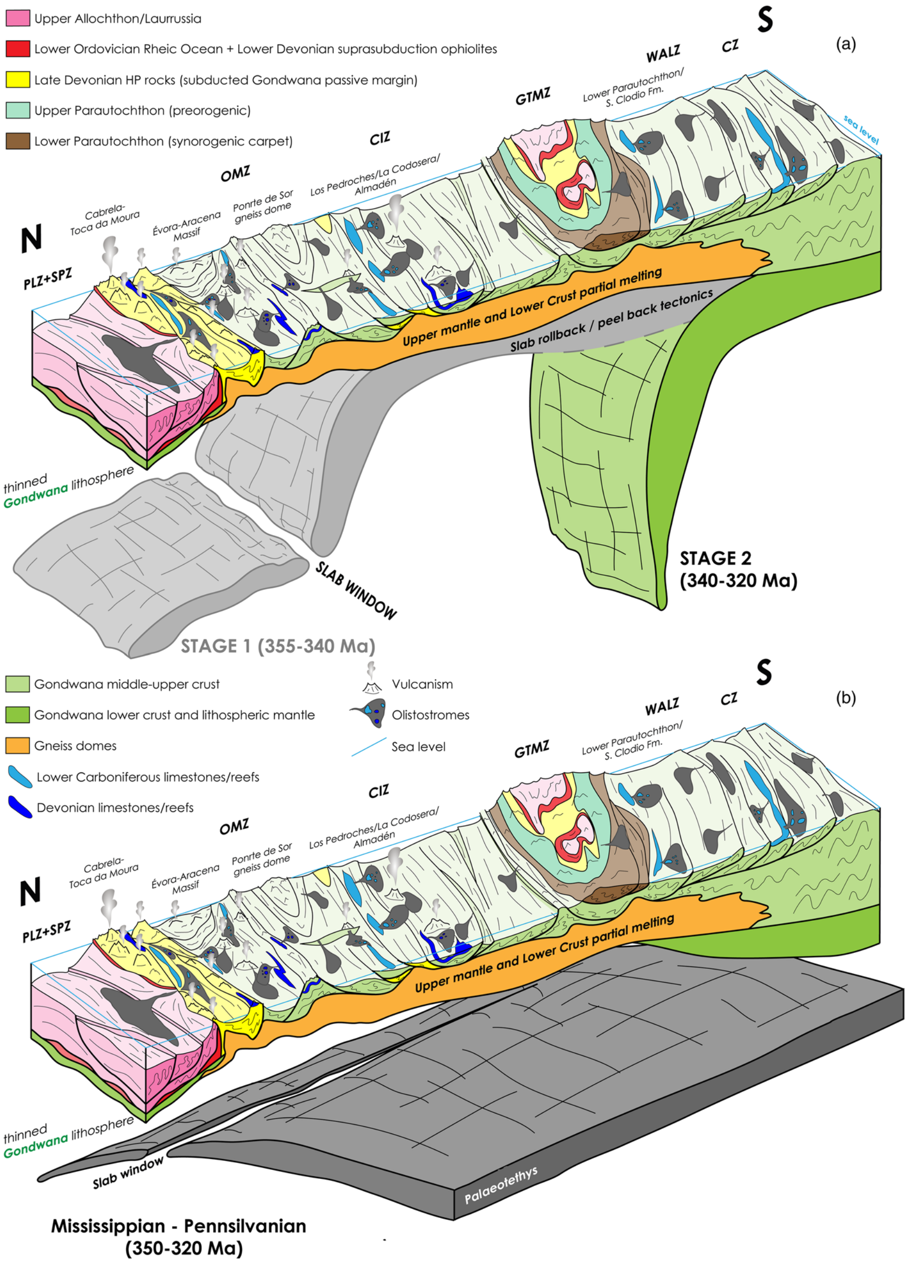


Fig. 5. Block diagrams showing the relationship between far-field geological events and surface phenomena in the NW and SW Iberia transect. (**a**) Model evoking the formation of slab roll-back and peel-back of the north Gondwana subducted margin, evolving into the mainland and forming the decoupling of the lithospheric mantle and lower crust that enhanced the thermal flux in the Gondwana margin. (**b**) Model assuming the formation of an accretionary orogen following continental collision, with the Palaeotethys Ocean as the subducting plate, producing a back-arc setting on the overriding plate formed of Gondwana and Laurrussia (i.e. the Variscan collisional orogen). Source: part (a) based on Vanderhaeghe *et al.* (2020), Colmenero *et al.* (2002) and Dias da Silva *et al.* (2021); part (b) based on Pereira *et al.* (2022). GTMZ, Galicia–Trás-os-Montes Zone; CZ, Cantabrian Zone ; WALZ, West Asturo–Leonese Zone; CIZ, Central Iberian Zone; OMZ, Ossa Morena Zone; PLZ, Pulo do Lobo Zone; SPZ, South Portuguese Zone.

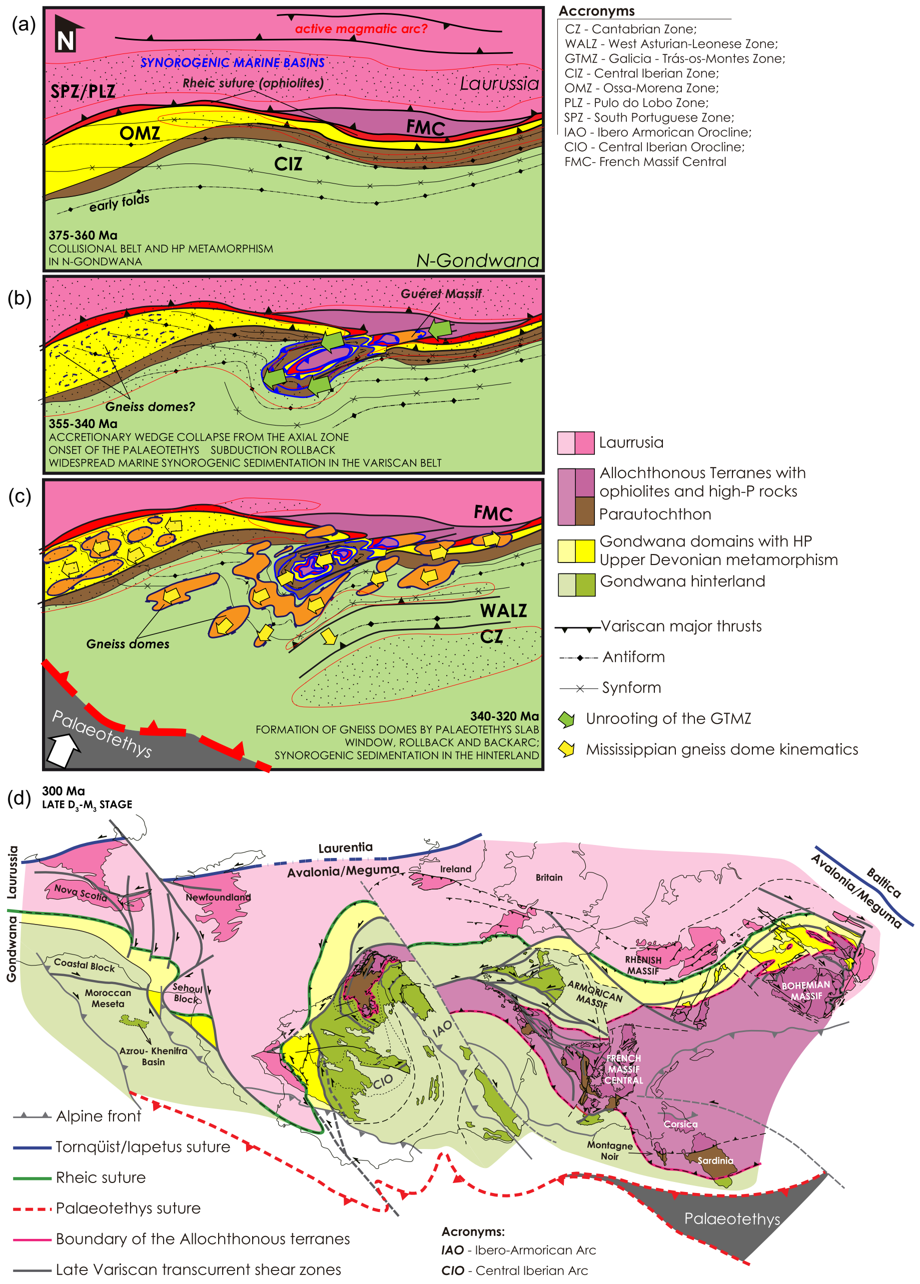


Fig. 6. Sequence of geodynamic events from the Late Devonian to the end of the Carboniferous showing the evolution and distribution of synorogenic epicontinental basins on top of the Variscan Orogen. Sources: parts (a–c) adapted from Dias da Silva *et al.* (2023) and part (d) adapted from Figure 1 using the same colour scheme as in Figures 5 and 6a–c.

volcanism that was coeval with the ductile deformation of the basement, HT–LP metamorphism and plutonism (Figs 5 and 6b, c). Thus the tectonic evolution of Iberia seems to have developed the characteristics of an accretionary orogen after Laurussia–Gondwana collision.

This presents something of a paradox. Let us therefore consider another tectonic model that reconciles the coexistence of different types of synorogenic basins. This alternative model requires that the Variscan Orogen evolved at the same time as a collisional orogenic event in NW Iberia and the occurrence of an accretionary orogenic event in SW Iberia (Figs 5b and 6c, d) (Pereira *et al.* 2020, 2022, 2023). In NW Iberia, where orogenic collapse was marked by the unrooting of the accretionary prism in the form of a thin-skinned lateral extrusion wedge (Dias da Silva *et al.* 2021), all the Mississippian synorogenic basins of Iberia have been interpreted as being of the foreland type. Variscan olistostromes have been interpreted as being the result of deposition in flexural basins in front of an allochthonous orogenic wedge, formed during the collision between Laurussia and Gondwana, later being incorporated into thrust sheets as a parautochthon (Martínez Catalán *et al.* 2008, 2021; González Clavijo *et al.* 2016). Sources of the NW Iberia synorogenic flysch and BIMFs have been assigned to the tectonic exhumation of the Variscan accretionary prism (Fig. 6b) and the growing peripheral bulge in the Gondwana margin (Dias da Silva *et al.* 2015). It is evident that the gravitational collapse of the newly formed collisional orogen occurred during the Mississippian in this segment of the Variscan belt (Fig. 6b, c).

This tectonic model assumes that the gravity-driven collapse of the thickened crust described in NW Iberia may have been contemporaneous with the ongoing subduction of the Palaeotethys oceanic lithosphere in SW Iberia (Figs 5b and 6c, d) (Pereira *et al.* 2020). The proposed evolution of an accretionary orogenic event in SW Iberia, occurring after the continental collision resulting from the closure of the Rheic Ocean, provides a reasonable explanation for the onset of a magmatic arc in this region of the Gondwana margin (Rodríguez *et al.* 2022). Consequently, Gondwana became the upper plate and the Palaeotethys oceanic lithosphere acted as the lower plate (Pereira *et al.* 2022). Variscan olistostromes of SW Iberia have been explained as being related to gravity-driven deposition in Serpukhovian foreland basins associated with the inversion of former Tournaisian–Visean extensional basins (Rodríguez-González *et al.* 2007; Armendáriz *et al.* 2008*a*; Matas *et al.* 2014) or as occurring in a Tournaisian–Visean arc setting (Pereira *et al.* 2020).

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