Marine and Petroleum Geology 92 (2018) 1010–1027

Contents lists available at ScienceDirect

Marine and Petroleum Geology

journal homepage: www.elsevier.com/locate/marpetgeo

Review article

Early Carboniferous extension in East Avalonia: 350 My record of lithospheric memory

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ARTICLE INFO

Keywords:
Late Paleozoic
Paleogeography
Plate tectonics
Plate kinematics
Avalonia
Variscan
Caledonian
Sedimentary Basins

ABSTRACT

Despite reactivations during Variscan and Alpine orogenies and the opening of the Northern Atlantic, Avalonia is one of the few regions where the initial Mid-Paleozoic basin structure is still recognisable, largely intact, and well studied. Its kinematics and dynamics remain, however, largely unknown, in particular in view of the successive late Paleozoic to recent evolution of the basin. Consequently, the importance of the mid-Palaeozoic tectonic evolution and structural controls are often overlooked and poorly understood in basin studies. In this paper, we reassess the importance of Mid-Palaeozoic tectonics on subsequent sedimentary basin evolution of north-western Europe. To this end, we analyse the dynamics of early Variscan extension in Avalonia based on the integration and re-evaluation of available geophysical and geological data from lithosphere to basin scales. Based on a revised crustal map of the Thor suture zone, we present a new paleo-tectonic reconstruction and tectonic scenario for the Devonian-Carboniferous rifting. These findings are key for a better understanding of long-lived tectonic segmentation and post-rifting deformation phases. Our findings indicate that the structural grain of many crustal fault dominated sedimentary basin structures such as the North Sea Central Graben were created in the early Carboniferous. Consequently, the main basement structuration of northwest Europe was completed before the Variscan orogeny and successive post-Variscan extension and inversion phases reactivated the existing basement structures without creating major new fault groups. Incorporation of the Paleozoic structural grain allows for a consistent tectonic framework for the Mesozoic, contributing to fundamental understanding of basin evolution. From our tectonic framework analysis, Avalonia therefore stands out as a fine example of long lived lithosphere memory, spanning over 350 My of structural control in geodynamic evolution.

1. Introduction

The late Devonian-early Carboniferous (early Variscan) was a period of intense rifting in the Avalonia microplate (Fig. 1) that took place in between the Caledonian and the Hercynian-Alleghanian collision phases (e.g. Dewey, 1982; Leeder, 1988; Ziegler, 1990). Extension started in the late Devonian and was concentrated mainly along Avalonia's margins, followed by early Carboniferous extension of its interior (Fraser and Gawthorpe, 1990). This extension is referred to as late Caledonian (e.g. Coward, 1993) or early Variscan (e.g. Fraser and Gawthorpe, 1990). We choose the latter based on the genetic relation between the extension and closure of the Rheic Ocean (Variscan).

In the Southern North Sea, the Netherlands and northwest Germany, the late Devonian-early Carboniferous rift structure and units are partly obscured by the thick cover of late Carboniferous-to-Recent basin fill and by recurrent fault reactivation. Little is known of the Southern North Sea Basin's (SNSB) pre-Permian basement due to a lack of outcrops and cores. The nature and structure of the East Avalonian crust and lithosphere are even less constrained in the absence of deep seismic (refraction) lines. Various studies (e.g. Ziegler, 1990; Coward, 1993; Worthington and Walsh, 2011) have signalled the importance of the reactivation of the early Carboniferous fault network during each consecutive Mesozoic and Cenozoic tectonic phase, demonstrating the key role of weak zones from the early Carboniferous structural grain in partitioning of structural deformation and vertical basin motions at various scales. Although the older basin history and the basement attract increasing interest, the pre-Permian tectonics of the Southern North Sea Basin remains little studied with most attention focused on the Permian and younger history (e.g. Glennie, 1998; Doornenbal and Stevenson, 2010; Guterch et al., 2010). Although in theory this rifting created the fault network and, therefore, the basis for the 350 My of lithospheric memory and ultimately present-day basin configuration, its kinematics and dynamics remain largely unknown. Proposed mechanisms for early Variscan extension include back-arc rifting (e.g. Leeder,

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https://doi.org/10.1016/j.marpetgeo.2018.01.004
Received 11 July 2017; Received in revised form 21 December 2017; Accepted 4 January 2018
Available online 10 January 2018
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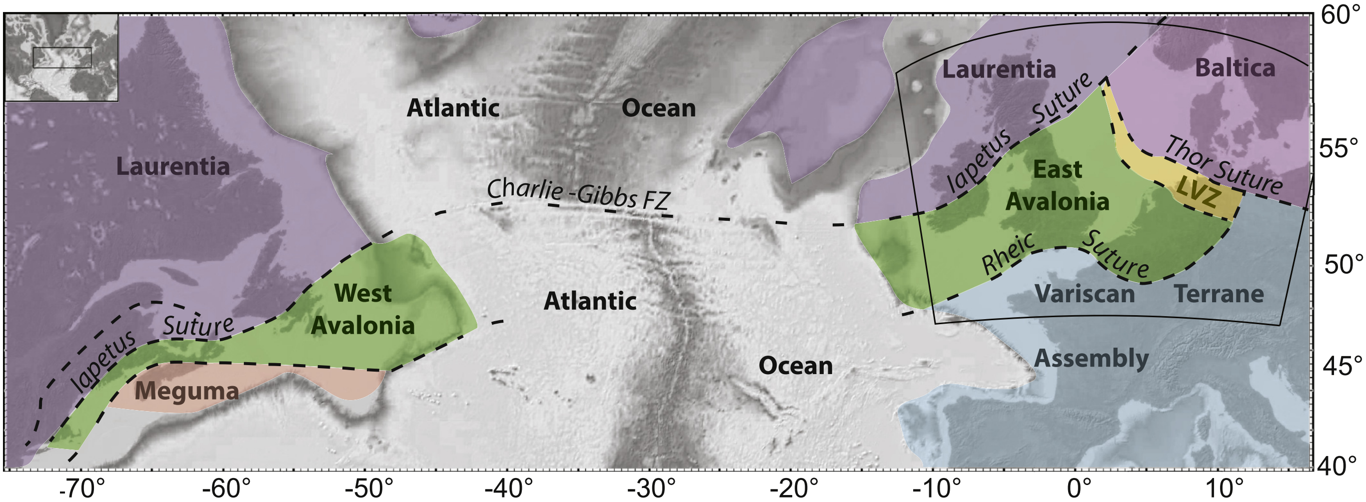

Fig. 1. Extent of Avalonia across the Atlantic Ocean (dashed domains) after Mesozoic opening of the Atlantic Ocean (based on Ziegler, 1990; Sibuet et al., 2007; Welford et al., 2012; Domeier, 2016; Smit et al., 2016). West Avalonia includes parts of the East Coast of the US and Canada (Lynch and Tremblay, 1994; Martel and Gibling, 1996; Gibling et al., 2008; Torsvik et al., 2012). East Avalonia covers the area of NW Europe between the Caledonian Iapetus and Thor and the Variscan Rheic suture. Black box marks the location of Fig. 4b and 9.

1982, Leeder and Hardman, 1990) and continental escape tectonics (Coward, 1993), with an intermediate scenario proposed by Ziegler (1990).

Repeated reactivation and burial during Variscan and Alpine orogenies and the opening of the Northern Atlantic have obscured early Carboniferous extension in some parts of Avalonia. Other parts stand out as some of the oldest regions where the initial Mid-Paleozoic basin structure is still recognisable and largely intact. The early Variscan rifting phase created the typical horst-and-graben structure of much of East Avalonia's crust that is well known from the British Isles and Ireland where the horsts and the graben infill are located at or near the surface (e.g. Leeder, 1982; Fraser and Gawthorpe, 1990; Strogen et al., 1996). Major open questions include the mode and total amount of extension as well as the age and origin of the North Sea fault network and whether it formed in single or multiple tectonic phases. The strong dispersal of existing constraints requires a comprehensive regional analysis based on an extensive literature study and the reinterpretation of publicly available data, linking constraints from the crust and mantle to stratigraphic-sedimentological information. Based on the re-interpretation of the Thor suture zone, Smit et al. (2016) proposed an alternative geometry and a new crustal domain map for the Thor suture zone as well as a scenario for this suture's post-accretion history. Building on this new crustal model and scenario for the Thor suture's post-accretion history, we examine consequences of the nature and extent of the major crustal/lithospheric domains with contrasting structural behaviour and the major boundaries that separate them. Furthermore, we assess the early Variscan extension of Avalonia and propose a new paleo-geographic reconstruction and tectonic scenario for the early Carboniferous extension. Our results shed light on the effects of long-lived differences in crustal fabric that are responsible for spatial heterogeneity in stress and strain magnitudes and zonations of fracturing, burial history and temperature history. Our findings also indicate that the main basement structuration of northwest Europe was completed before the Variscan orogeny and that successive post-Variscan extension and inversion phases reactivated the existing basement structures without creating major new fault groups.

2. General tectonic setting

Avalonia is one of the peri-Gondwana terranes, together with other continental fragments of Gondwana affinity including Armorica, Adria, Iberia and Saxothuringia (e.g. Torsvik and Cocks, 2013). As summarised by several authors (e.g. Ziegler, 1989; Ziegler, 1990; Cocks and Fortey, 2009; Torsvik and Cocks, 2013; Matthews et al., 2016; Franke et al., 2017), its Paleozoic history started as part of the Gondwana passive margin until around the Cambro-Ordovician boundary (ca. 490 Ma) when rifting and opening of the Rheic Ocean caused Avalonia to drift northward toward Baltica and Laurentia (North America, Greenland, North Ireland and Scotland) (Fig. 2a). The Thor Ocean, between Avalonia and Baltica was closed around the Ordovician-Silurian boundary by subduction under the north Avalonian margin (ca. 440 Ma) (Fig. 2b). The absence of indications for real mountain building along the Thor suture has led to the term "soft-docking" for this event (e.g. Torsvik and Rehnström, 2003). Calc-alkaline magmatism of that age from Ireland to the Ardennes (e.g. Flöttmann and Oncken, 1992; Verniers et al., 2002; Linnemann et al., 2012; Woodcock, 2012) are indications for the southward subduction of Iapetus oceanic lithosphere under Avalonia over its full length, which appears to be a plausible scenario. The final closure of the Thor Ocean was accompanied by a flip of oceanic subduction from southward under Avalonia to northward under the Laurentia margin. Baltica-Avalonia together moved towards Laurentia, closing the Iapetus Ocean. Final closure of the Iapetus took place during the late Silurian-early Devonian (ca. 420-400 Ma) (Fig. 2c), not long after Avalonia-Baltica docking. The formation of the Thor and Iapetus sutures are both part of the late Caledonian orogeny and the newly formed continent of Laurentia, Baltica and Avalonia is known as Laurussia (Ziegler, 1989).

Final closure of the Rheic Ocean along the southern margin of Avalonia and amalgamation of Pangea took place during the Variscan orogeny in late Carboniferous times, adding the remaining peri-Gondwana terranes to Laurussia (Zwart and Dornsiepen, 1978; Ziegler, 1989, 1990; Winchester et al., 2002; Ballèvre et al., 2009). It should be noted that the maximum width of the Rheic Ocean and the timing of onset of its final closure are strongly disputed (e.g. Zeh and Gerdes, 2010; Nance et al., 2012; Franke et al., 2017). The Variscan orogeny marked the end of extension in Avalonia and the onset of post-rift thermal subsidence (see Kombrink et al., 2008 for a review). This transition occurred during late Visean/early Namurian (ca. 330 Ma) and caused deepening of the Dinantian basin and the onset of clastic sedimentation along its southern margin (Leeder and Hardman, 1990; Kombrink et al., 2008). Collision finished by the end of the Westphalian (ca. 305 Ma), when the late Variscan Permo-Carboniferous wrenching took over (Arthaud and Matte, 1977; Ziegler, 1990). We use the old west European stratigraphic time scale since it still prevails in practice and literature (see Fig. 3 for comparison with the new classification).

Avalonia was separated in an eastern and western part by the

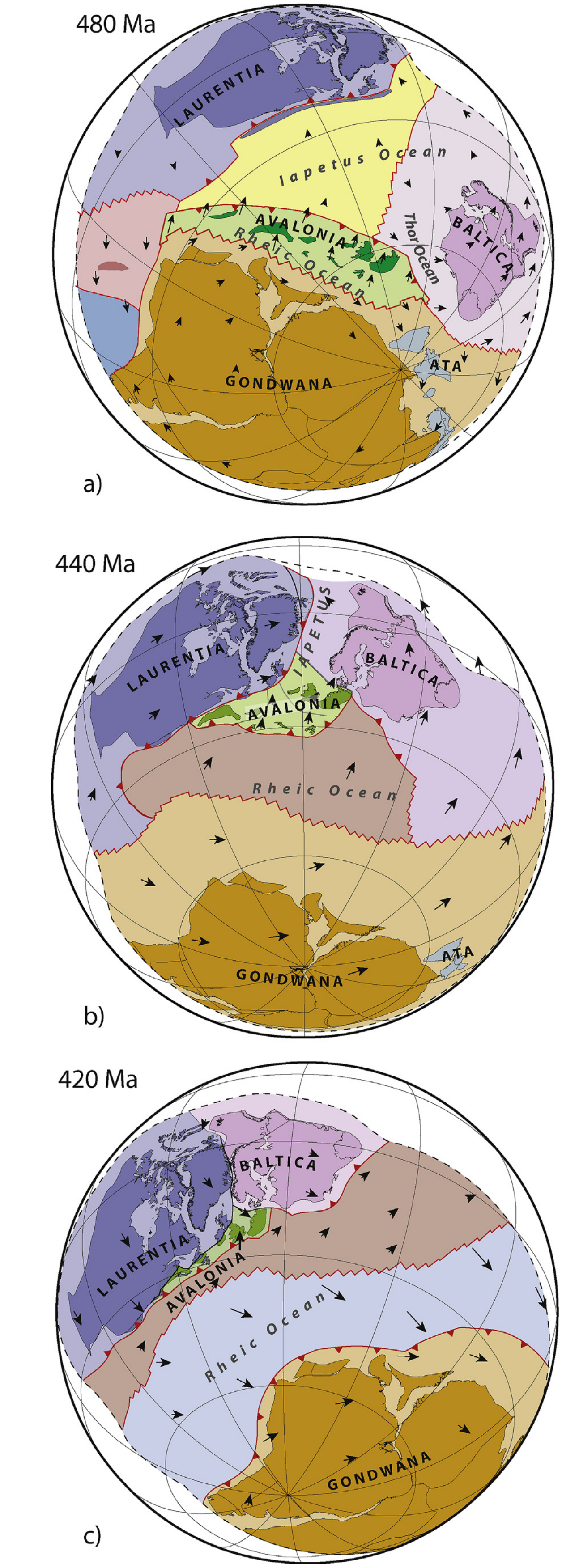

Fig. 2. Early-Mid Paleozoic paleogeography of Avalonia and surrounding terranes for three time-slices of 480 Ma, 440 Ma and 420 Ma, respectively (Modified from Domeier, 2016). a) northward drift of Avalonia from Gondwana towards Baltica in the Ordovician during opening of the Rheic ocean. Southward subduction of Tornquist (Thor) and Iapetus oceans along northern margin of Avalonia, b) Final closure of the Thor Ocean and soft-docking of Avalonia to Baltica. End of southward subduction of Iapetus ocean under Avalonia along the future Iapetus suture (e.g. Torsvik and Rehnström, 2003). c) Oblique collision of Avalonia and Baltica with Laurentia, forming the British-Norwegian Caledonides/Appalachians after final Iapetus ocean subduction under Laurentia (that is, along the British-Irish section of Iapetus suture zone) (Soper et al., 1992; Dewey and Strachan, 2003). White, light blur, hatched and dark blue colours mark exposed terranes, shallow marine, rifted continental margin and oceanic domains, respectively. ATA, Armorican Terrane Assemblage.

opening of the Atlantic Ocean (Ziegler, 1990; Welford et al., 2012) (Fig. 1). West Avalonia includes parts of the east coast of the US and Canada from Massachusetts to the Maritimes basin and Nova Scotia (Lynch and Tremblay, 1994; Martel and Gibling, 1996; Gibling et al., 2008; Torsvik et al., 2012). East Avalonia covers the area of NW Europe between the Iapetus, Thor and Rheic sutures (Ziegler, 1990; Pharaoh, 1999; Cocks and Fortey, 2009) (Figs. 1 and 4).

2.1. Constraints on crustal structure

The age and composition of the crust are obviously important factors for basin analysis of early (Paleozoic) basins (Van Wees et al., 2000) and basins in general (e.g. Cloetingh et al., 2013a; Cloetingh et al., 2013b; Cloetingh and Haq, 2015). Different levels of the Avalonian crust can be studied in north-western Europe at or near the surface thanks to contrasting late Mesozoic and Cenozoic vertical motions and associated erosion. Avalonia has been strongly exhumed along the Atlantic where the pre-Caledonian basement (Murphy et al., 2008) and Devonian-Carboniferous basins (Hamblin and Rust, 1989; Langdon and Hall, 1994; Lynch and Tremblay, 1994; Force and Barr, 2006; Strogen et al., 1990, 1996; Jones and Somerville, 1996) can be studied in outcrop. Much of the late Paleozoic and Mesozoic series from the British Isles and Ireland have been eroded by the ~2 km of Cenozoic uplift and denudation (e.g. Hillis et al., 2008; Holford et al., 2008), bringing the Lower Carboniferous basins to, or close to the surface (Leeder, 1982; Fraser and Gawthorpe, 1990; Fraser et al., 1990; Leeder and Hardman, 1990; Davies et al., 2012). Contemporaneous with this Cenozoic uplift, the Southern North Sea underwent 2 km of additional subsidence and burial, bringing the early Carboniferous series to a depth of 8 km in places (e.g. Kombrink et al., 2008).

The core and oldest part of East Avalonia is formed by the Midlands micro-craton (MMC) that is mostly concealed by a cover of lower Paleozoic strata. Its late Proterozoic basement outcrops in places in South England and Wales (e.g. Pharaoh et al., 1987; Pharaoh, 1999) (Fig. 4). Exposures of Precambrian rocks on basin highs are related to flower structures formed by transcurrent displacements along major faults along and within the micro-craton, such as the Malvern Line, or Lineament (Lee et al., 1990). The MMC is located in between the Rhenohercynian zone (Variscan fold-and-thrust belt) to the south and the Wales basin and London-Brabant massif (Pharaoh, 1999; Winchester et al., 2002; Pharaoh et al., 2010). However, structural relations (Coward and Smallwood, 1984), seismic profiles (Bois et al., 1988) and potential field data (e.g. Banka et al., 2002) indicate that the Midlands micro-craton has a larger geographical extension. To the south and the southeast it probably extends under the Rhenohercynian zone, possibly as far as the Rheic suture (e.g. Oncken et al., 1999; Verniers et al., 2002). The LISPB DELTA refraction profile shows its northern continuation under, and north of the Wales Basin (Maguire et al., 2011) where it forms the Irish Sea Horst. The London-Brabant massif and the Welsh basin border the Midlands micro-craton to the northeast and northwest, respectively (Fig. 4). They are composed of the same early Paleozoic sedimentary sequences (Verniers et al., 2002; Linnemann et al., 2012) and were inverted during the early Devonian

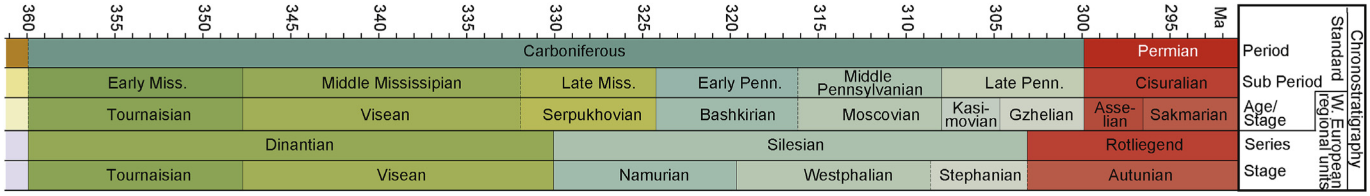

Fig. 3. International stratigraphic time scale with previous, west European time scale for comparison. Comparison after Heckel and Clayton (2006).

Acadian phase, which at least partly overlapped with the Caledonian orogeny (e.g. Debacker et al., 2005; Woodcock et al., 2007). The basement of the northern Rhenish massif represents an extension of the early Paleozoic sequence of the London-Brabant massif, whereas the southern Rhenish massif is made of medium-grade Cadomian gneisses (possibly part of the Midlands micro-craton) (Oncken et al., 1999). The London-Brabant massif, Welsh basin and the Meguma terrane of Nova Scotia (West Avalonia) are remarkably similar, which has led to the conclusion that they are part of the same elongated Cambrian rift system (Linnemann et al., 2012). During late Devonian-early Carboniferous extension, the Welsh Basin–London-Brabant massif forms a stable block together with the Midlands micro-craton. Therefore, we group the Welsh-London-Brabant massif and the Midlands micro-craton on regional maps in what is called the Wales-Brabant massif (e.g. Kent, 1975; Besly, 2009) (e.g. Fig. 4).

In summary, Avalonia seems to have formed a fairly narrow part of Gondwana's margin before the opening of the Rheic ocean. This margin was subjected to at least two rift phases. The Wales and London-Brabant basins were formed more or less contemporaneously during the first, Cambrian, phase. The second, early Ordovician rifting phase led to the separation from Gondwana and drifting towards Baltica. This final rifting took place at the craton side of the Midlands micro-craton. Therefore, Avalonia consists of a part of Gondwana's craton (the Midlands micro-craton), the Wales basin and London-Brabant massif and Gondwana's old margin (the part north of the Wales-Brabant massif).

The northern boundary of the London-Brabant massif is marked by the NW-SE oriented Dowsing-South Hewett Fault Zone (DSHFZ) (Fig. 4) and its south-eastern extension, the Roer Valley fault. It marks a strong and long-lived contrast between the Wales-Brabant massif and Southern North Sea Basin that was repeatedly reactivated since at least the Carboniferous. Strong geophysical contrasts and a possible Moho step inferred from deep seismic data let to the suggestion of a plate boundary between east Avalonia and the southern North Sea of Ordovician age (e.g. Pharaoh, 1999; Pharaoh et al., 2010, and references herein) (Fig. 4a). However, the South Hewett fault bends westward following the northern edge of the London-Brabant massif and the Dowsing fault does not cross the Southern Uplands/Mid North Sea high. Alternatively, the South Hewett fault zone continues W-ward into the Welsh borderland fault system (e.g. Woodcock, 2012) as part of the semi-circular northern border of the Wales-Brabant massif (Fraser et al., 1990). Instead of forming a single basement fault, the Dowsing and South Hewett faults linked up in a post-extensional setting, mainly during the Mesozoic. This implies that the "classical" separation in different terranes between the British Isles and the North Sea-Lüneberg terrane does not exist but that Northern England and its Irish extension continue into the North Sea, instead.

According to most published maps, the Moho depth increases to ca. 36 km to the south of the DSHFZ, whereas north of it the Moho is almost flat and shallow at ca. 28–30 km (e.g. Ziegler and Dézes, 2006; Kelly et al., 2007; Tesauro et al., 2008; Grad et al., 2009a). The Moho depth underneath the Brabant massif was determined at 31 ± 1.9 km based on arrival times of local seismic events (Sichien et al., 2012). Just north of the Brabant massif, these authors found similar Moho depths of 31–32 km. For the Netherlands, a relatively flat Moho with a country-wide average depth of 33 km is predicted by a recent 3-D shear velocity model of the crust, derived from ambient seismic noise recordings (Yudistira et al., 2017).

The metamorphic age of the Midlands micro-cratonic crust is Neoproterozoic, whereas the basement is not exposed further north (Woodcock and Strachan, 2012). The base of the sedimentary cover in Avalonia, except for the Midlands micro-craton is Cambrian in age. As the Dowsing-South Hewett fault zone comes on land within this Neoproterozoic basement, it follows that the crust north and south of the DSHFZ is Neoproterozoic. Comparison with other peri-Gondwanan micro-plates from Central America to eastern Europe has led Keppie et al. (2012) to suggest that the Avalonian basement is characterised by protolith ages of ca. 1.0–1.3 Ga and igneous rocks with depleted mantle model ages (TDM) of 1.35–1.77 Ga.

3. Avalonia's margins, inferences from the sutures

Avalonia's margins are vital for understanding its history and roots of its crustal and underlying lithosphere framework. For the reconstruction of early Variscan extension, we focus on Avalonia's early Carboniferous extent, hence its configuration prior to the Variscan orogeny.

Sutures, including the sutures of Avalonia, are historically defined by the front of the accretionary prism, often determined on the basis of faunal evidence. This "faunal" suture does not coincide with the plate limit at deeper crustal levels, which is located closer to the back of the accretionary wedge(e.g. Chadwick and Holliday, 1991). As Avalonia forms the lower plate along its Iapetus and Rheic sutures, its crust and lithosphere extend beyond these two sutures. To determine the original extent of Avalonia, we review below constraints from deep seismic profiles and potential-field data.

3.1. The Thor suture: Avalonia's north-eastern margin

The Caledonian Thor suture zone (TSZ) separates Baltica from Avalonia (Fig. 1) and formed during the Ordovician-early Silurian closure of the Thor Ocean/Tornquist Sea by southward subduction of Baltica under Avalonia. At present day, the Thor suture is buried from the North Sea to the North German Basin by late Paleozoic - Recent sedimentary thicknesses of up to 15 km (Thybo, 1990, 2001) (Fig. 5b and c). The Thor suture continues as trans-European suture zone towards the Black Sea (e.g. Gee and Stephenson, 2006).

In classic interpretations, Avalonia's northern margin rests on the Baltica margin. At present its location coincides more or less with the northern margin of the north German basin, whereas its crustal base is positioned at the Elbe line (e.g. Eugeno-S Working Group, 1988; Abramovitz and Thybo, 2000; Guterch et al., 2010). Abnormally low seismic P-wave velocities in the lower crust along the suture were interpreted as Caledonides and attributed to Avalonia (e.g. Eugeno-S Working Group, 1988; Thybo, 1990; Aichroth et al., 1992; Abramovitz and Thybo, 1998). Abramovitz and Thybo (2000) explained these rocks as a mixture of meta-sediments and intercalated granitic intrusions that may have originated from the former accretionary wedge of the fore-arc complex. The section of the European GeoTraverse that crosses the Thor suture zone and the North German Basin (Thybo, 1990, 2001; Aichroth et al., 1992) is the only refraction seismic profile that images the full width of the lower crustal low P-wave velocity zone (LVZ). Based on the

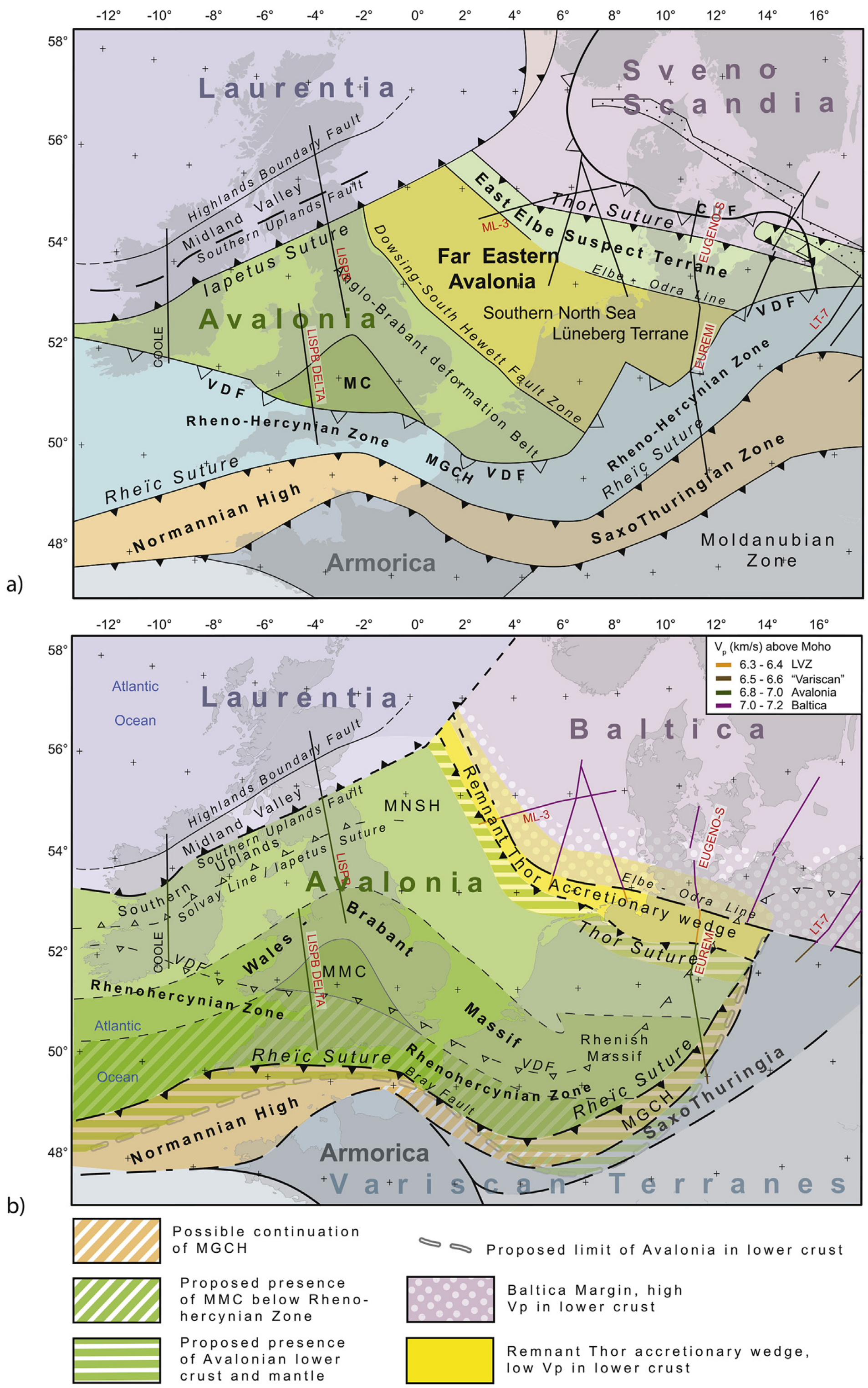

Fig. 4. Present-day tectonic setting of East Avalonia and surroundings. a) Classic map (Pharaoh et al., 2010). b) Revised map of the present-day tectonic setting of East Avalonia, emphasising Avalonia's interior crustal units and extent in the lower crust and upper mantle. (For location see Fig. 1), including the revised geometry of the Thor suture (modified from Smit et al., 2016). LVZ, Low seismic Velocity Zone. The LVZ is the collapsed accretionary complex of the Caledonian Thor suture that separates Avalonia from Baltica. Elbe-Odra is the southern limit of the Baltica Margin. Avalonia is absent eastward of the Rheic suture. The contact between Laurentia and Avalonia more or less coincides with the northern limit of the accretionary wedge (Southern Uplands) and Avalonian crust (and lithosphere). The dashed line trending parallel to this contact marks the Solvay line, i.e. the geological suture and southern limit of the accretionary wedge. In this interpretation, this accretionary wedge is part of Avalonia. The green hatching below the mid-German crystalline high (based on Oncken et al., 2000) and the Normannian High is the interpreted extent of Avalonia's southern margin. The London-Brabant massif and the Welsh basin are shown as a single unit. Different Variscan domains along Avalonia's southern margin are after Ballèvre et al. (2009). MC, Midlands micro-craton; MGCH, Mid-German Crystalline High; MNSH, Mid North Sea High; VDF, Variscan Deformation Front.

reinterpretation of this and other refraction seismic profiles, Smit et al. (2016) proposed an alternative configuration for the Thor suture zone, in which the 50–100 km wide LVZ is newly defined as an individual crustal unit that separates Avalonia and Baltica over the full length of the suture. Consequently, the northern boundary of Avalonia is shifted ca 150 km southward. This crustal unit is characterised by its anomalous seismic velocity structure (Fig. 5b and c) of low P-wave velocities in the lower crust that cannot be easily attributed to Avalonia or Baltica plates abutting the TSZ. Analogy with Low Velocity Zones in the active Cascadia (Ramachandran et al., 2006) and Kuril (Nakanishi et al., 2009) subduction zones supports the interpretation by Abramovitz and Thybo (2000) that the TSZ's lower crustal LVZ is composed of remnants of the collapsed Caledonian accretionary complex (Smit et al., 2016) (Fig. 6).

In the North Sea, Avalonia's north-eastern margin is located west of the Central Graben, with an unknown exact position, as deep seismic lines do not image the Avalonia-LVZ transition (Fig. 6). The profiles located east of the EGT line image Variscan crust south of Baltica's remnant passive margin, which indicates that the LVZ and Avalonia are absent between Variscan terranes and Baltica east of the Rheic suture (e.g. Guterch and Grad, 2006; Smit et al., 2016). Continued subduction of oceanic lithosphere and related accretionary wedge may explain the existence of what is known as the Polish Caledonides. Alternatively, the Polish Caledonides are created by accretion of an elusive continental block that may or may not have been part of Avalonia.

Smit et al. (2016) presented a scenario for the temporal evolution of the TSZ based on its present-day geometries and comparison with the Kuril subduction zone (Nakanishi et al., 2009) and the Rhodope massif (Kydonakis et al., 2015). This scenario explains the present-day geometry as the result of pre-Variscan extension-related eduction (i.e. exhumation of subducted crustal material by extension along the suture (Fig. 7) (Andersen et al., 1991; Duretz et al., 2012). Slab break-off after the end of subduction (Fig. 7a) paves the way for resurfacing of the subducted Baltica margin during later extension (Fig. 7b). According to Van Hunen and Allen (2011), slab break-off occurs between 10 My and 20–25 My after the end of collision for young and old oceanic lithosphere, respectively, slightly earlier than the 30–40 My mentioned in Smit et al. (2016). This extension that is localised along the former suture creates a gap that is being filled by the collapsing accretionary complex possibly including material from the exhumed subduction channel) and by rising asthenosphere from below during the early Variscan extension of Avalonia that took place from the late Devonian to the early Carboniferous. Thermal relaxation, subsidence and burial of TSZ (Fig. 7c) started during Variscan convergence, as marked by the deep late Carboniferous foreland basin of northwest Europe.

3.2. *The Iapetus suture: Avalonia's north-western margin*

In its current configuration, the Iapetus suture runs from Norway across the North Sea, separating England from Scotland and cutting through Ireland into the Atlantic. The Iapetus suture continues along the North American east coast where it separates Laurentia from what is known as west Avalonia (Fig. 1).

Initially, closure of the Iapetus ocean between Avalonia and Laurentia took place by repeated accretion of small terranes and the Midland Valley arc along the southern Laurentian margin and by southward subduction along the Avalonian margin. The end of subduction along the Thor suture further to the east was followed by a subduction flip between Avalonia and Laurentia (Ryan and Dewey, 1991, 2004). Final suturing of Avalonia and Laurentia (e.g. Soper et al.,

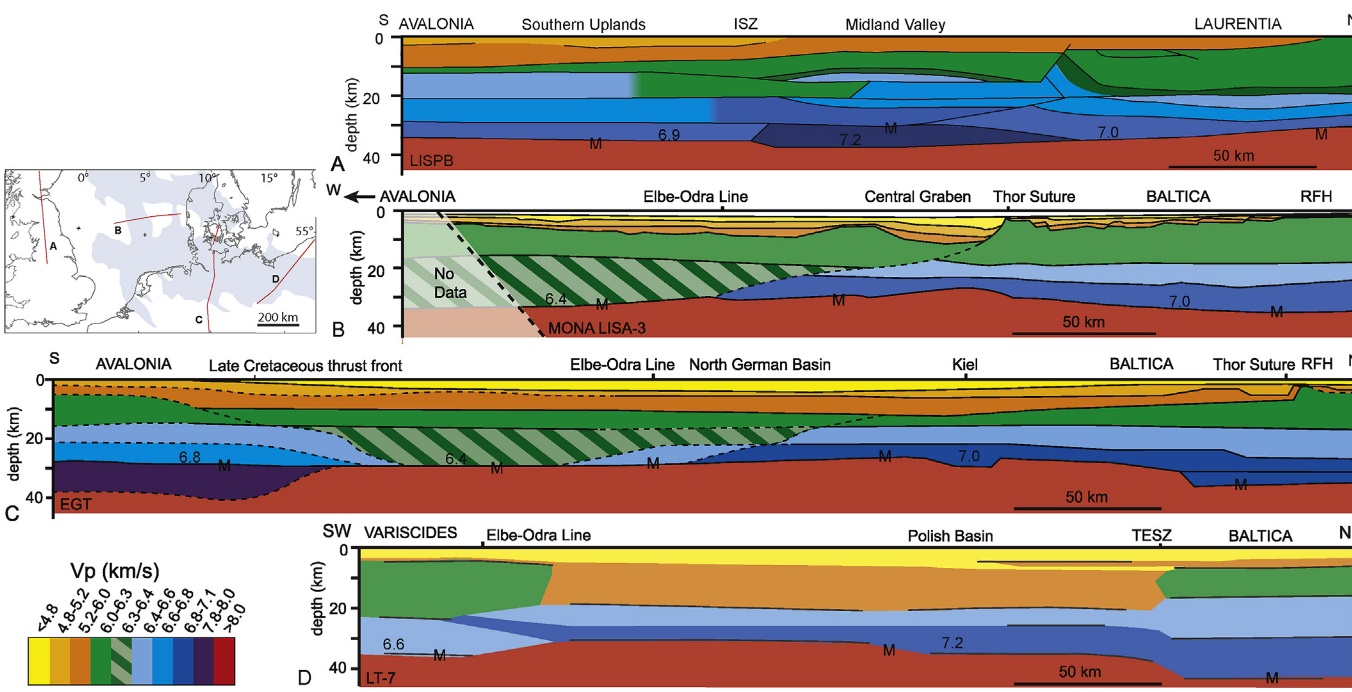

Fig. 5. Seismic refraction profiles across northwest and northeast Avalonian margins and the Iapetus and Thor sutures, respectively. a) LISPB profile across the Iapetus suture zone, Avalonian lower crust (Vp 6.6–6.9 km/s) is in direct contact with Laurentia (modified from Barton, 1992). b) MONA LISA 3 (profile ML-3) across the North Sea Central Graben (based on Lyngsie and Thybo, 2007; from Smit et al., 2016). c) Combined European GeoTraverse sub-profiles EUGEMI and EUGENO-S 1, showing relations between Thor Suture Zone, North German Basin, and northern Avalonian margin (from Smit et al., 2016; based on Aichroth et al., 1992; Thybo, 2001{). d) LT-7 profile across the Baltica margin, east of the Rheic suture, with absence of the low velocity zone (based on Guterch and Grad, 2006; from Smit et al., 2016).

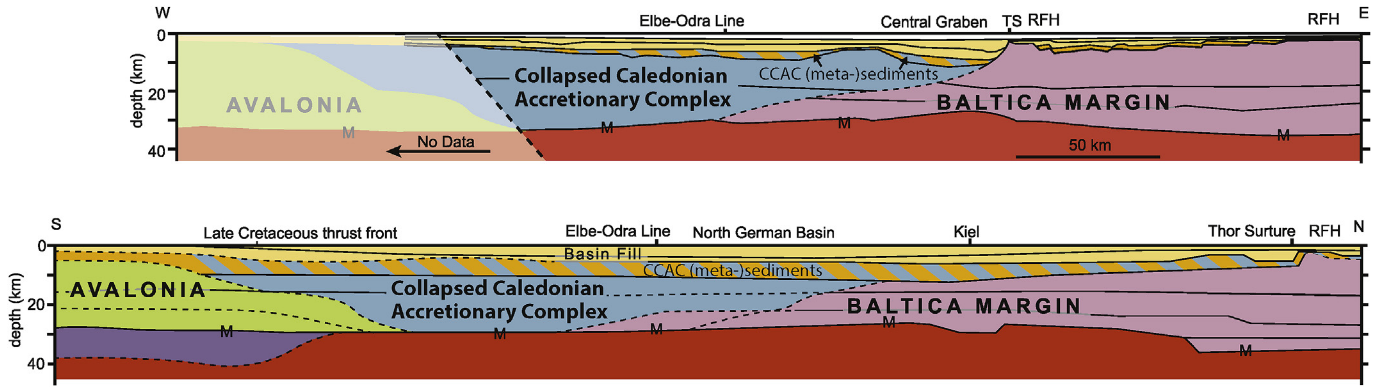

Fig. 6. New interpretation (Smit et al., 2016) for a) North Sea MONA LISA 3 profile across the North Sea Central Graben and b) combined EGT EUGEMI and EUGENO-S profiles across the north German basin in which the Low Velocity Zone (LVZ) forms a separate crustal unit in between Avalonia and Baltica. M, Moho; RFH, Ringkøbing-Fyn High; TS, Thor Suture.

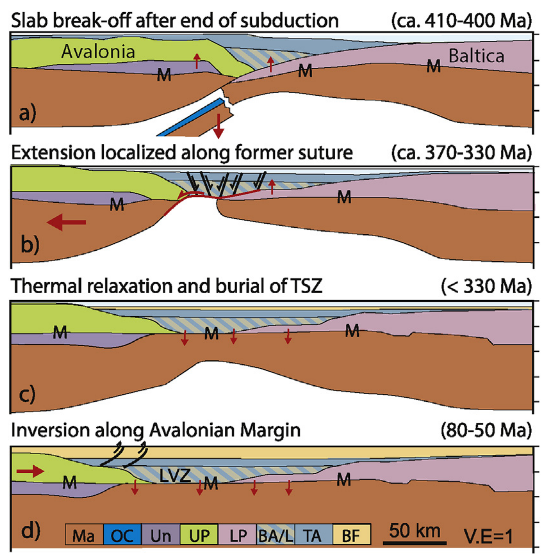

Fig. 7. a-c: Scenario (Smit et al., 2016) for the temporal evolution of the Thor Suture Zone (TSZ) based on its present-day geometries and comparison with the Kuril subduction zone and the Rhodope massif (Kydonakis et al., 2015). a) Slab break-off after end of subduction (Early Devonian ca. 410-400 Ma). b) Extension localized along former suture, with the created gap filled by rising asthenosphere and collapsing accretionary complex (possibly including material from the exhumed subduction channel) (Late Devonian-Early Carboniferous, ca. 370-330 Ma). c) Thermal relaxation, subsidence and burial of TSZ (Since Late Carboniferous, ca. 330 Ma). Continued subsidence and burial of TSZ and plate margins during most of Mesozoic-Cenozoic, aided by repeated reactivation and plume activity. M, Moho, Ma, mantle, OC, oceanic crust, Un, underplated material, UP, upper plate, LP, lower plate, BA/L, base accretionary complex; LVZ, low-velocity zone; TA, top accretionary complex, BF, late Paleozoic–Cenozoic basin fill; V.E., vertical exaggeration.

1992) occurred by northward subduction under Laurentia during late Silurian-early Devonian times (e.g. Cocks and Fortey, 2009). The closure of the Iapetus between Avalonia and Laurentia was highly oblique, causing sinistral transpression during the late Silurian and early Devonian (e.g. Dewey and Strachan, 2003).

Classically, the Solvay line along the southern limit of the Southern Uplands (Fig. 4) is defined as the suture based on biostratigraphy. Deep crustal seismic profiles LISPB (Barton, 1992, see Fig. 5a) and NERC (Soper et al., 1992) indicate that the Avalonian crust and lithosphere continues further north under the Southern Uplands that correspond to the late Ordovician-Silurian accretionary wedge (e.g. Leggett, 1987; Soper et al., 1992; Dewey and Strachan, 2003; Mange et al., 2005). Therefore, we draw the Avalonia-Laurentia boundary along the Southern Uplands fault, which marks the limit of Avalonia between the Southern Uplands and the Midland Valley (e.g. Fig. 4). Eastward, the Southern Uplands, including the Solvay line, continue into the Mid-North Sea High (MNSH) (Fig. 4).

Late Caledonian granites Late or Newer Granites, c. 430-380 Ma (see e.g. Atherton and Ghani, 2002; Brown et al., 2008; Miles et al., 2014, 2016; Lundmark, pers. comm. 2017) (Fig. 9) were emplaced immediately after the cessation of Iapetus subduction. Their emplacement was explained in terms of slab beak-off (Atherton and Ghani, 2002) and delamination of Avalonian mantle lithosphere (Miles et al., 2014). In both cases they would be spatially related to the Iapetus suture. A low velocity lower crust as present along the TSZ is absent along the Iapetus margin (Fig. 5a). This is evidenced from the LISPB profiles (e.g. Barton, 1992; Maguire et al., 2011) that transect Avalonia from the Iapetus suture zone to the Rheic suture. These profiles show that the Avalonian crust has a laterally rather uniform two-layer velocity structure with lower crustal P-wave velocities Vp ~6.6–6.9 km/s, that are considered normal for a Phanerozoic crust (e.g. Barton, 1992; Smit et al., 2016).

3.3. Avalonia's southern margin, the Rheic suture

The Rheic suture juxtaposes East Avalonia with some of the other peri-Gondwanan terranes, Iberia, Armorica and Saxothuringia. It runs from the Thor suture under the North German Basin across Germany, northern France and the Channel into the Atlantic Ocean. The Rheic suture along Avalonia's southern margin closed during the upper Carboniferous Variscan orogeny. Since this paper focuses on the extension preceding this orogeny, the following description focuses on the pre-convergence setting of the Avalonia's Rheic margin, its extent and the subduction direction and those elements of the convergence that are of direct relevance to the reconstruction of extension, amount of shortening direction and amount of basin inversion.

Avalonia's southern margin was a passive margin from its rifting off Gondwana around the Cambrian-Ordovician transition until the end of the Caledonian orogeny during early Devonian times. Devonian back-arc extension as documented in southern England (e.g. Shail and Leveridge, 2009) and Germany (e.g. Oncken et al., 1999) signals the transition from passive to active margin and the onset of closure of the Rheic ocean since late Emsian times (Franke, 2000). The subduction direction during Devonian back-arc extension was supposedly northward, whereas the subduction direction during early Carboniferous extension of Avalonia's interior is less clear.

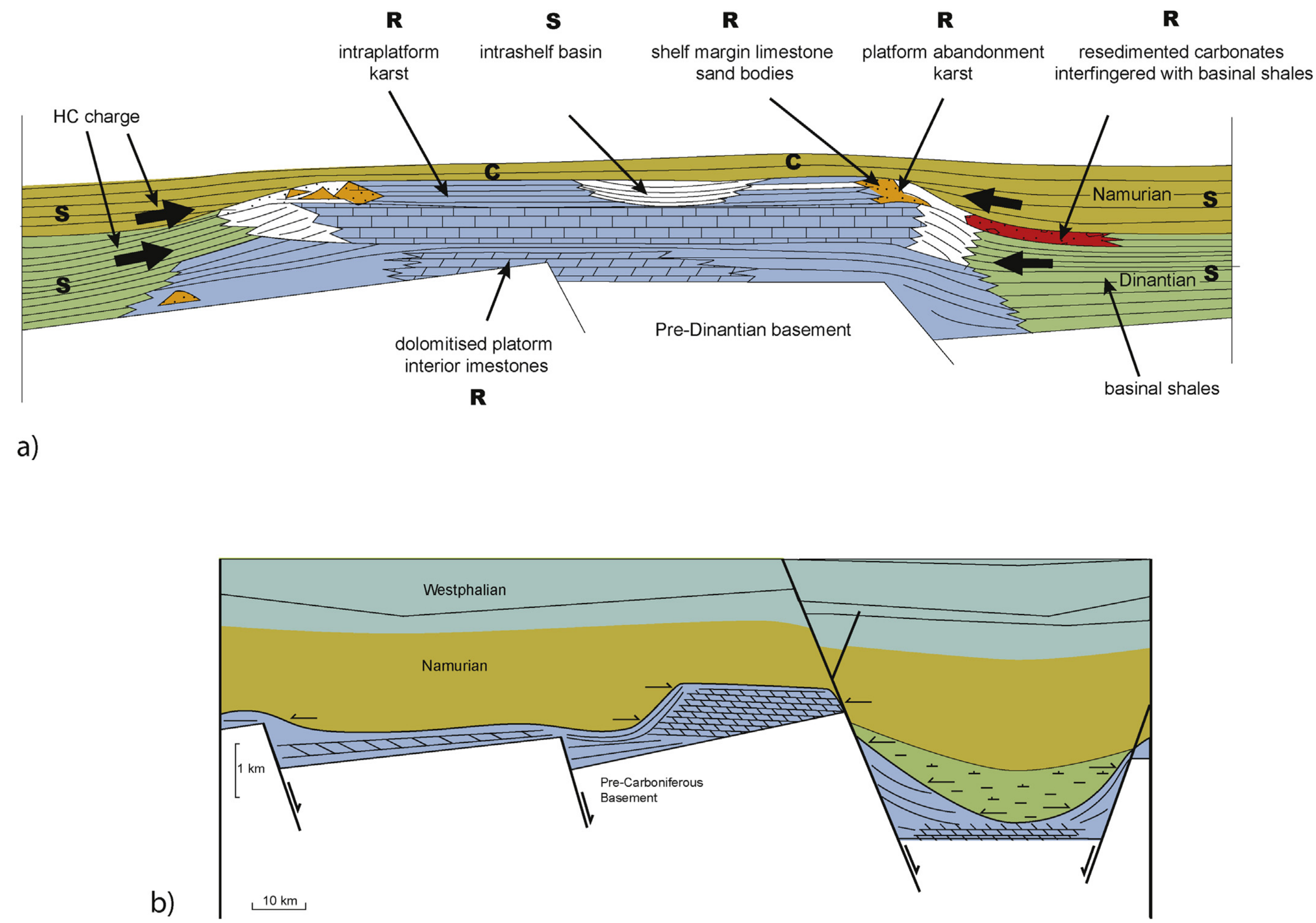

Fig. 8. Schematic cross-sections showing interpretation of the Dinantian structural and stratigraphical setting of the study area. a) from (Total E&P UK, 2007), S, source rock; R, reservoir and C, cap rock. b) From Kombrink et al. (2010).

Seismic profiles show a southward dipping Avalonian margin underneath the Variscan terranes, suggesting southward subduction (Bois et al., 1988; Bois, 1990; DEKORP Research Group, 1991; Oncken, 1997; Oncken et al., 1999, 2000; Plesch and Oncken, 1999; Franke et al., 1990).

The Mid-German Crystalline High (MGCH, Fig. 4) is the volcanic arc that at present is underlain by the NNE-SSW-oriented German section of the Avalonia margin. S-ward subduction of Avalonia oceanic lithosphere and margin under the MGCH is deduced from this geometry (e.g. Ziegler, 1990; Flöttmann and Oncken, 1992; Oncken, 1997; Franke, 2000). The MGCH is believed to link up with the EW-trending Bray fault that runs into the Channel to link up with the NE-SW (parallel to the Iapetus suture) trending Lizard suture (e.g. Zwart and Dornsiepen, 1978; Matte, 1986; Bois, 1990). Here, the Normannian high, including the Léon domain (Fig. 4), along the northern Margin of Armorica may be the westward continuation of the MGCH (e.g. Ballèvre et al., 2009; Faure et al., 2010). Alternatively, the volcanic arc is continuous from the Mid German Crystalline high and/or the Saxothuringian zone to the Normannian high (e.g. Ziegler et al., 2006; Ballèvre et al., 2009; Faure et al., 2010). The Bray fault (Fig. 4) is often regarded as the limit of Avalonia along the NW-SE trending section of the Rheic suture below the Paris basin (e.g. Zwart and Dornsiepen, 1978; Matte, 1986; Ballèvre et al., 2009; Doublier et al., 2012; Tabaud et al., 2014). This is also supported by the ECORS Nord de la France profile (e.g. Cazes et al., 1986). However, the possible identification of crustal units across such large strike-slip faults is not always trivial (Matte and Hirn, 1988), leaving the scenario open that Avalonia extends south of the Bray fault (Bois et al., 1988).

Palinspastic restoration on the basis of fieldwork and deep seismic profile DEKORP 1A-C (Oncken, 1997) has yielded an estimated shortening of the Avalonian margin of approximately 150 km (~50%) to create the Rheohercynian belt of Belgium, Germany and northern France. The same profile shows that Avalonian crust continues beneath the MGCH, indicating that the edge of early Carboniferous Avalonia is located east of the MGCH (Oncken, 1997). Accordingly, we position the limit of Avalonia to the east, instead of to the west of the MGCH (e.g. Figs. 4b and 9).

The regional direction of maximum late Variscan shortening was towards the northwest (e.g. Corfield et al., 1996; Oncken et al., 2000), sub-parallel to the early Carboniferous basins in the North Sea that where mainly reactivated by strike-slip tectonics (e.g. Corfield et al., 1996). The Iapetus-parallel basins of Ireland and the British Isles, as far north as the Midland Valley, however, where strongly inverted.

4. Evidence for Variscan extension of Avalonia

4.1. Two-phase early Variscan extension

Early Variscan extension of Avalonia can be divided in an Upper Devonian and an early Carboniferous phase based on the location of extension. The early extension took off in the Frasnian (late Devonian) along the margins of Avalonia with extension along the Rheic margin (Oncken et al., 2000; Leveridge and Hartley, 2006; Leveridge, 2011), along the Iapetus suture in the Midland Valley (e.g. Monaghan and Parrish, 2006) and in the Central North Sea (e.g. Ziegler, 1990; Lundmark et al., 2012; Milton-Worssell et al., 2010). Extension in

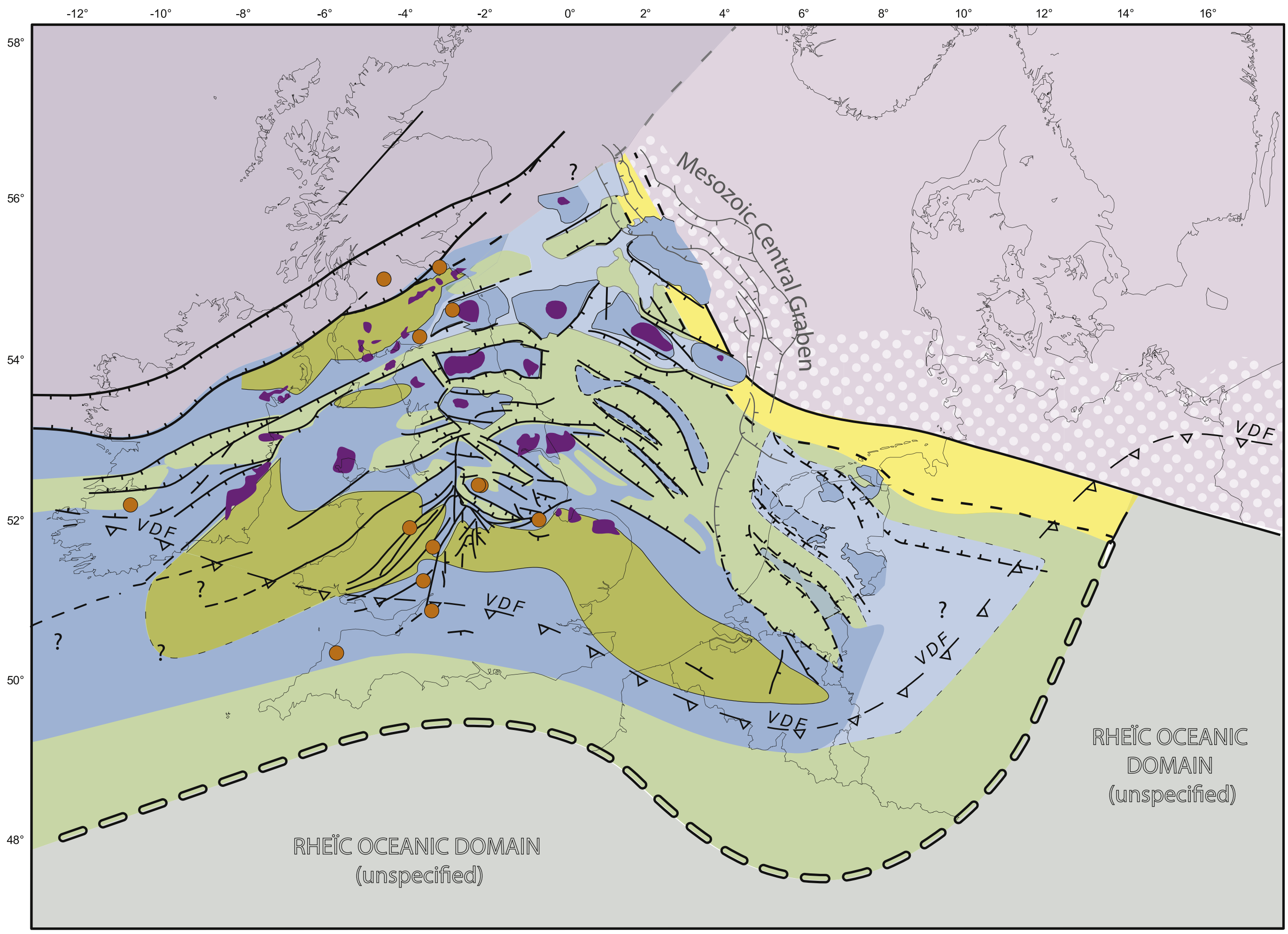

Fig. 9. Paleogeography at end of early Carboniferous rifting including basement structures as far as known (horsts-and-grabens, blue). (Compiled from Fraser and Gawthorpe, 1990; Corfield et al., 1996; Jones and Somerville, 1996; Strogen et al., 1996; Kombrink et al., 2010; Milton-Worssell et al., 2010; Worthington and Walsh, 2011; Harings, 2014; Boxem et al., 2016; Smit et al., 2016). Purple: late Caledonian intrusives, in North Sea area inferred from gravity anomalies (Donato, 1993; Milton-Worssell et al., 2010). Orange dots: Locations of Dinantian (syn-extension) magmatic activity (Timmerman, 2004). Thin black lines, early Carboniferous faults; thin black dashed lines, possible early Carboniferous faults; thin grey lines, post-Carboniferous North Sea Central Graben. Structures south of Variscan Deformation Front (VDF) are not well-constrained).

Avalonia's interior and formation of the early Variscan basins started in early Carboniferous times (e.g. Leeder, 1982; Besly, 2009; Fraser and Gawthorpe, 1990). Extension affected Avalonia from the North American Atlantic Margin (Hamblin and Rust, 1989; Lynch and Tremblay, 1994; Martel and Gibling, 1996; Force and Barr, 2006, 2013; Gibling et al., 2008; Force, 2014) to the North Sea and northwest Germany and from the Mid-North Sea High (MNSH) and the Midland Valley in the north to the London Brabant massif in the south.

4.1.1. Early Carboniferous basin and fault patterns

This extension is best known from the British Isles and Ireland (Figs. 8 and 9) (e.g. Leeder, 1982, 1992; Glennie, 1986; Fraser and Gawthorpe, 1990; Johnston et al., 1996; Worthington and Walsh, 2011) where Cenozoic erosion has removed most of the cover, whereas the basins have largely escaped from later reactivation, notably in northern England. Dinantian extension has been recognised in the North Sea on the MNSH high and further south (Leeder and Hardman, 1990; Kombrink et al., 2010; Van Hulten, 2012) thanks to the presence of Dinantian limestone platforms on top of the horsts, providing sharp seismic contrasts in areas where the early Carboniferous is buried by younger strata. Recently, seismic mapping of the basement structure (Milton-Worssell et al., 2010; Ter Borgh et al., 2017a,b) revealed early Carboniferous horsts and grabens in Avalonia's northern corner in the North Sea, from the Iapetus suture to the MNSH. Basement structures have been recognised to the south of the MNSH but remain badly constrained. East of the North Sea Central Graben, in the Netherlands and northwest Germany, the extent of extension and geometries remain largely unknown although indirect indications suggest a low level of extension, decreasing eastward.

From west to east, the early Variscan basin system can be divided in three domains based on geometry, orientation and post-extension tectonic history (Fig. 10). The transition between western and central domains roughly coincides with the much older Malvern Line/Lineament, the transcurrent fault that cuts the Midlands micro-craton (Lee et al., 1990), and its northern continuation towards the Iapetus suture. The transition between central and eastern domains coincides with the North Sea Central Graben.

4.1.2. Ireland and western England (western domain)

From Ireland to western England, the main early Carboniferous basins are oriented NE-SW, (sub-)parallel to the Caledonian Iapetus suture (Figs. 9 and 10). Based on fault and mineralized vein geometries, Johnston et al. (1996) concluded that most of the observations are in agreement with dextral transtension (oblique extension with a component of clockwise rotation), resulting from northeast-southwest directed extensional reactivation of east to northeast-trending Caledonian basement structures (e.g. Johnston et al., 1996; Woodcock and Strachan, 2012). Lower Carboniferous extension was accompanied by

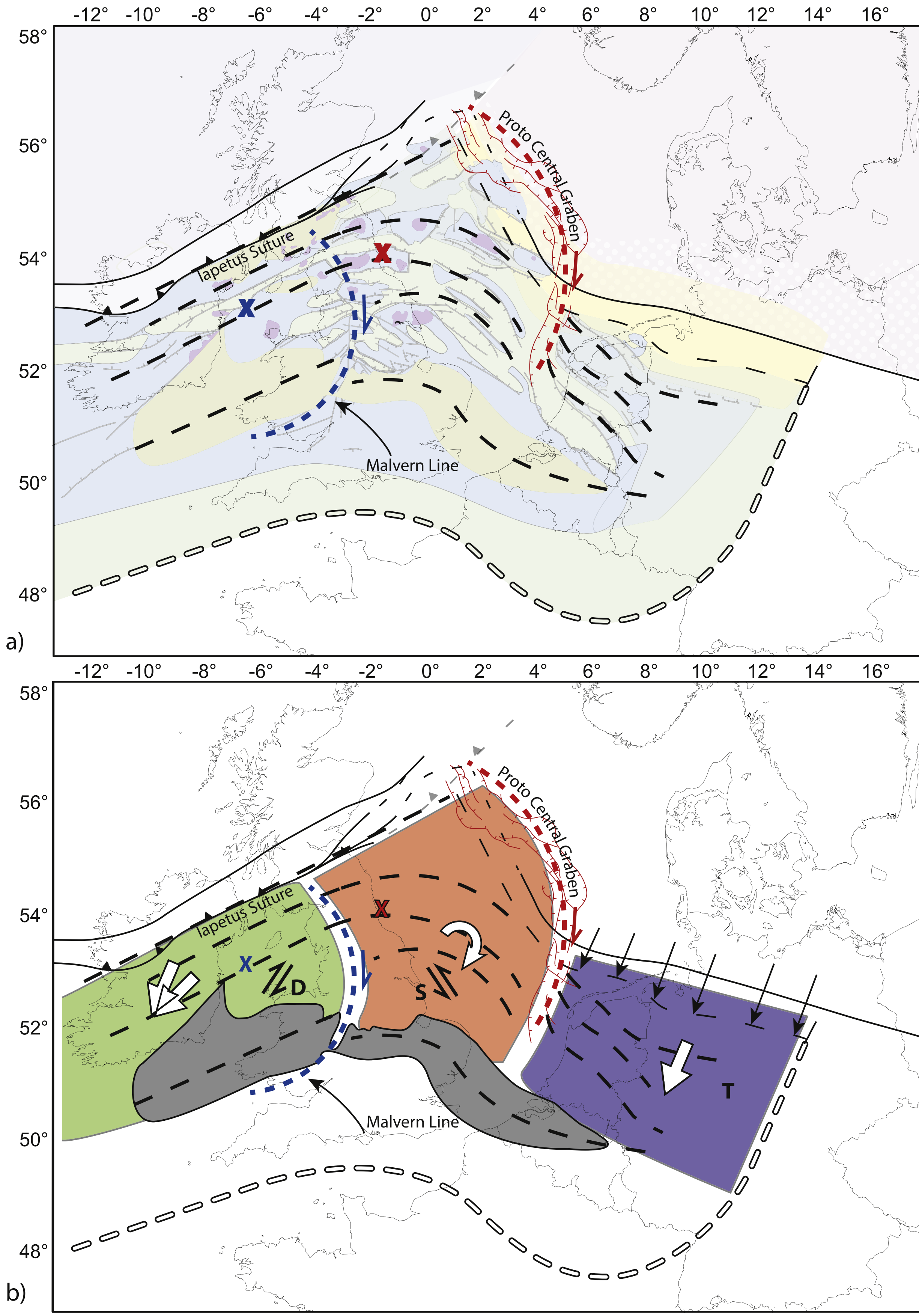

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Fig. 10. Structural zonation of early Carboniferous Avalonia based on basement trend and deformation style. a) In Ireland, western England and Wales, structures trend NE-SW, parallel to the Iapetus suture. East of the circle segment that coincides with the Malvern Line and west of the Central Graben (CG), the structural trends quickly rotate clockwise. East of the CG, the trend rotates anticlockwise from NW-SE to WNW-ESE. Strikingly, circle segments can be drawn along both Malvern Line (blue dashed line) and CG (red dashed line). Blue and black crosses mark corresponding rotation poles, whereas blue and red half arrows mark sense of shear. b) three zones, separated by Malvern Line trend and the proto-Central Graben. West of Malvern Line (green) deformation is marked by an overall NE-SW to NNE-SSW directed dextral transtension. Sinistral transtension with a strong clockwise rotational component occurs between the Malvern Line and proto Central Graben (Red). East of the Central Graben, deformation is mainly accommodated by SW- to SSW-ward translation with a relatively small extensional component. The location of the early Carboniferous uplands of the Wales Brabant massif is added for reference (grey). Small black arrows estimate direction and amount of extension along the Thor Suture east of the CG. Large arrows mark the extension direction based on structural data from Ireland (Johnston et al., 1996). This direction is also parallel to the south-easternmost Avalonian margin after extension. Figure conventions as in Fig. 9.

mildly alkaline basaltic volcanism (Fig. 9) that started in the Tournaisian and peaked during the Visean (e.g. Leeder, 1982, 1988; Timmerman, 2004).

4.1.3. From eastern England to North Sea Central Graben (central domain)

East Avalonia between the Malvern Line and the Central Graben/Netherlands Jurassic Basins was subjected to dextral strike slip motion on NW-SE trending faults during Variscan inversion and some faults and basins (e.g. Cleveland and Sole Pit Basins) were reactivated during the Permian and later tectonic phases (e.g. Van Hoorn, 1987; Ziegler, 1990; Imber et al., 2014). Other than that, the fault network and basin configuration between Malvern Line and Netherlands Jurassic Basins remained intact since the end of Devonian-Carboniferous extension. Hence, this area has preserved its original structure and contains important clues to the reconstruction of early Carboniferous lithospheric configuration and rifting history.

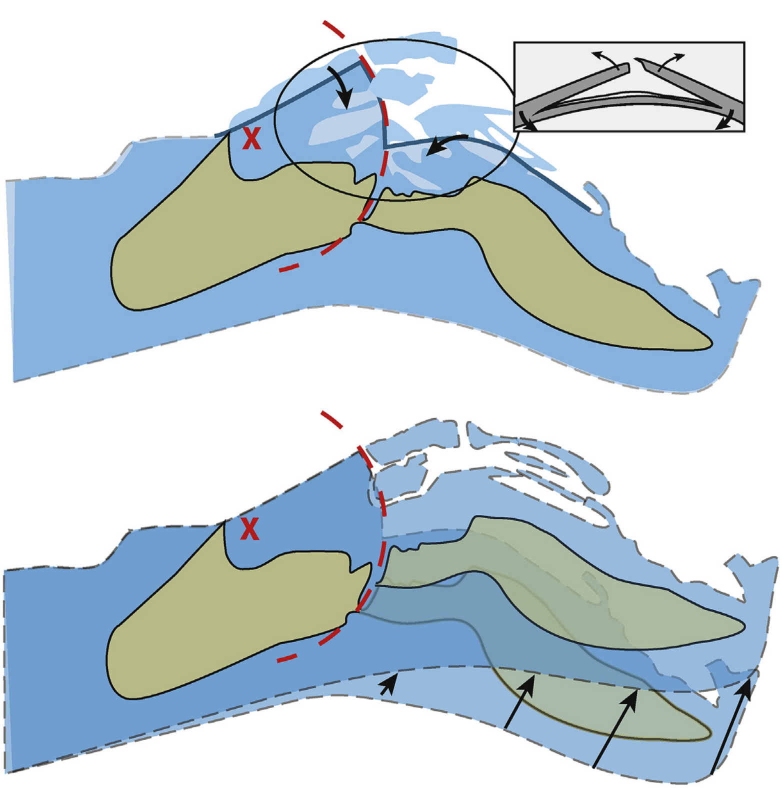
Several gravity anomalies west of the Central Graben in the southern North Sea are attributed to granitic batholiths (Donato, 1993; Milton-Worssell et al., 2010). Like in northern England and Ireland, these intrusions are all located under early Carboniferous basement highs (Fig. 9).

Early Variscan extension in the central domain (Figs. 9 and 11) resulted in the formation of multiple basins in between the Wales-London-Brabant massif and the Caledonian sutures (Fraser and Gawthorpe, 1990; Leeder and Hardman, 1990; Johnston et al., 1996; Maynard and Dunay, 1999; Milton-Worssell et al., 2010; Ter Borgh et al., 2017a,b). Dinantian basins in eastern England and the Southern North Sea open in a scissor-like manor with a superimposed clockwise rotation (Fig. 10). The transition from western, to central domain occurs along a roughly north-south axis across the apex of the Midland Craton (Fig. 10). This axis coincides with the Malvern Line in the Midlands micro-craton that together with its northern continuation roughly forms an arc shape, which to our knowledge has not been noted before.

East of the Malvern Line, fault and basin orientations show a sudden and sharp clockwise rotation (Figs. 9 and 10). In the northern extension of the Malvern Line, it forms the western limit and locus of semi-radial rifting generating both EW and NS trending grabens that surround the horsts on all sides. In Fig. 11a arrows mark simultaneous NS and EW extension directions eastward of the northern extension of the Malvern Line.

4.1.4. East of the North Sea Central Graben (eastern domain)

The part of the eastern domain close to the Rheic suture seems not or little affected by early Variscan extension. The early Variscan basin and fault pattern is less well known towards the Central domain in the Netherlands because early Variscan extension east of the Central Graben concentrated along the former Thor suture by eduction (Smit et al., 2016). Thereby, most of this eastern domain is located onshore and covered by a kilometres thick Upper Carboniferous to recent succession (e.g. Kombrink et al., 2008) that obscures potential other basement highs and their early Carboniferous limestone platforms. Recent seismic profiles and a limited number of wells have provided new data of the Lower Carboniferous in the Netherlands (Van Hulten



a)

b)

Fig. 11. Starting point for restoration of lower Carboniferous deformation, based on the geometry of Midland micro-craton, Wales-Brabant massif and directly surrounding platform. a) Closure of Central England basins (based on Fig. 9). The geometry and location of these basins are reminiscent of a twig fracture (inset) and b) Restoration by rotation along the Malvern Line of the outcrop outline of Wales-Brabant massif with approx. 10–15° anti-clockwise rotation of the Brabant massif around a circle coinciding with Malvern Line and its N-ward continuation (red hatched line). Large black arrows indicate direction and approximate amount of movement of Brabant massif.

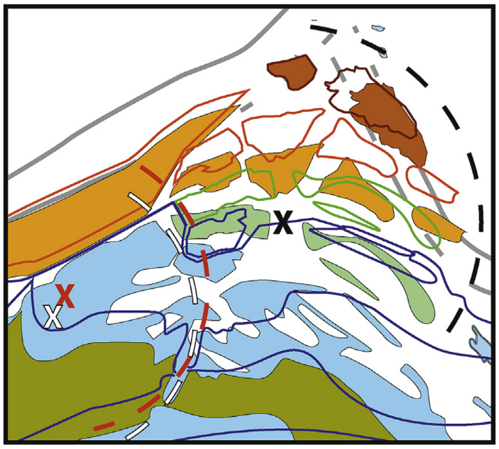


Fig. 12. Restoration of area between Malvern Line and Central Graben based on counter-clockwise rotation of Brabant massif (Fig. 11). Dashed red and white lines mark restored and present-day position of rotation circle segments that roughly coincide with the Malvern Line; dashed black circle segment coincides with proto-Central Graben shear zone ; red, white and black crosses mark their corresponding rotation poles; colour-filled blocks indicate the present-day position of basement highs (based on Fig. 9); outlines of blocks mark their restored position.

and Poty, 2008; Kombrink et al., 2010; Van Hulten, 2012; Harings, 2014). The few platforms that have been mapped have more irregular and rounded outlines and therefore, fault control is less obvious (Fig. 9). The early Variscan upper crustal structural grain of the eastern domain is also strongly overprinted by Permo-Triassic and late Jurassic extension and by late Cretaceous-Paleogene inversion (e.g. Ziegler, 1992).

The strong rotation to a NW-SE trending fault network occurs immediately east of the Malvern Line and is well-documented due to its location close to the surface. Although the extensional structure is less clear in the southern North Sea as it is buried under a thick succession of Upper Carboniferous to present units, at least part of the Dinantian highs are recognised thanks to their limestone cover (e.g. Fraser and Gawthorpe, 1990; Leeder and Hardman, 1990; Total E&P UK, 2007). From the Mid North Sea High northward, north-derived Dinantian clastics (Yoredale facies) are present instead of limestones (e.g. Besly, 2009; Kombrink et al., 2010; Milton-Worssell et al., 2010). The seismic interpretation by Milton-Worssell et al. (2010) provides a clear image of the distribution of Dinantian highs and basins in this part of the North Sea.

In the eastern zone, between Central Graben and Rheic suture, extension is localised along the Caledonian Thor suture (Smit et al., 2016). Here, Dinantian extension inside the Avalonian plate remains a matter of discussion, mainly due to a lack of data due to deep burial of the Dinantian in most places (e.g. Kombrink et al., 2010; Van Hulten, 2012; Boxem et al., 2016). Muchez, and Langenaeker (1993) describe Dinantian extension in the Campine Basin at the north-eastern extremity of the Brabant massif. Other known Dinantian limestone platforms in the Netherlands either seem isolated (e.g. the Groningen platform) or have irregular shapes that suggest that they are not, or not all, fault-controlled. However, Kombrink et al. (2010) present data showing that at least some of these platforms fit the model proposed in the UK of fault blocks onto which these rimmed shelf carbonates developed.

In view of the lack of clear structural indicators east of the North Sea Central Graben, we adopt the recently developed scenario for the development of the Thor suture zone in which extension is localised along the suture and occurred by eduction and collapse of the Thor accretionary system (Smit et al., 2016) (see section 3.1 and Fig. 6). This scenario implies that Avalonia east of the Central Graben has likely moved as a block (Fig. 10b), although deformation by shearing cannot be excluded. Evidently, we do not know how far the Baltica margin subducted under Avalonia during closure of the Thor Ocean. Numerical models predict a slab-break-off from depths of 40 km–400 km (van de Zedde and Wortel, 2001; Duretz et al., 2011). Therefore, the present-day distance between Avalonia and Baltica (i.e. width of the LVZ, 50–100 km) should be considered as the minimum amount of early Variscan extension. Jurassic extension had roughly the same NE-SW direction but was in the order of a few tens of kilometres and largely reversed during late Cretaceous inversion.

5. New kinematic model

A new kinematic model for early Carboniferous extension obviously has to take into account the regional NNE-SSW to NE-SW extension direction as inferred from structural data from Ireland (Johnston et al., 1996) and eastern Canada (Waldron et al., 2015). NE-SW oriented extension is also in agreement with geometries east of the Central Graben as it is perpendicular to the Thor suture zone under the North German Basin and parallel to the east section of the Rheic suture (Smit et al., 2016). Ideally, post-extensional deformation must be accounted and corrected for. The Variscan collision arguably caused the largest horizontal displacements of the later tectonics phases. Variscan shortening of Avalonia's interior was oriented NW-SE to NNW-SSE and, therefore, inversion was concentrated on the early Variscan basins of Ireland and Britain that are parallel to the Iapetus trend (Corfield et al., 1996). The NW-SE-oriented faults of the southern North Sea (Fig. 9) mainly accommodated oblique slip during the late Carboniferous (Corfield et al., 1996). Post-Variscan tectonic activity has mostly been restricted to vertical motions in the western North Sea and on-shore England, thin skinned salt-tectonics excluded. Basement reactivation of the Sole Pit and the Silver Pit basins was limited until the late Cretaceous inversion.

The eastern margin of Avalonia (German section) is oriented NNE-SSW, parallel to the assumed regional NE-SW to NNE-SSW extension, suggesting that it was either a Subduction-Transform Edge Propagator (STEP) type transform margin, with ongoing tearing of oceanic lithosphere (Govers and Wortel, 2005; Wortel et al., 2009) or a transfer fault during early Carboniferous extension. In case of semi-rigid block movements, the eastern section (Netherlands and northwest Germany) moved parallel to this eastern transform margin with the same displacement as the most eastern part of the Brabant massif (Fig. 10). To the west of the Central Graben (Fig. 10), early Variscan scissor-like extension is accommodated by the formation of multiple basins in between the Wales-London-Brabant massif and the Caledonian sutures, accompanied by clock-wise rotation (Fig. 10b).

Figs. 10–13 summarize our model for the formation of the structural framework, rotation and extension in Avalonia. The late Caledonian, pre-extension geometry is reconstructed by rotations along the Malvern Line and Central Graben. The structural framework after early Carboniferous extension is summarised in Fig. 10, highlighting the three different Paleozoic sectors, separated by the Malvern Line and Central Graben. Extension in the westernmost domain is relatively limited and accommodated by several grabens. In the central domain, the southwestern North Sea, the Avalonian plate is highly extended between the Mid North Sea High and the London Brabant massif (Smit et al., 2016). In the eastern domain extension is localised along the former Thor suture and accommodated by eduction.

Our map view restoration of lower Carboniferous deformation starts with the closure of Central England basins (Fig. 11a). The geometry and location of these basins is reminiscent of a twig fracture (Fig. 11a inset). The outcrop outline of Wales-Brabant massif (Figs. 9 and 11) is one of the major controls in this restoration. An approximately 10–15° anticlockwise rotation of the Brabant Massif around a circle coinciding with Malvern Line and its N-ward continuation gives a remarkably good fit (Fig. 11b). The restored Wales -Brabant massif forms a strikingly regular structure, with the remaining central bend possibly inherited from the Caledonian collision. This counter-clockwise rotation of the Brabant massif forms the basis for the restoration in the strongly extended

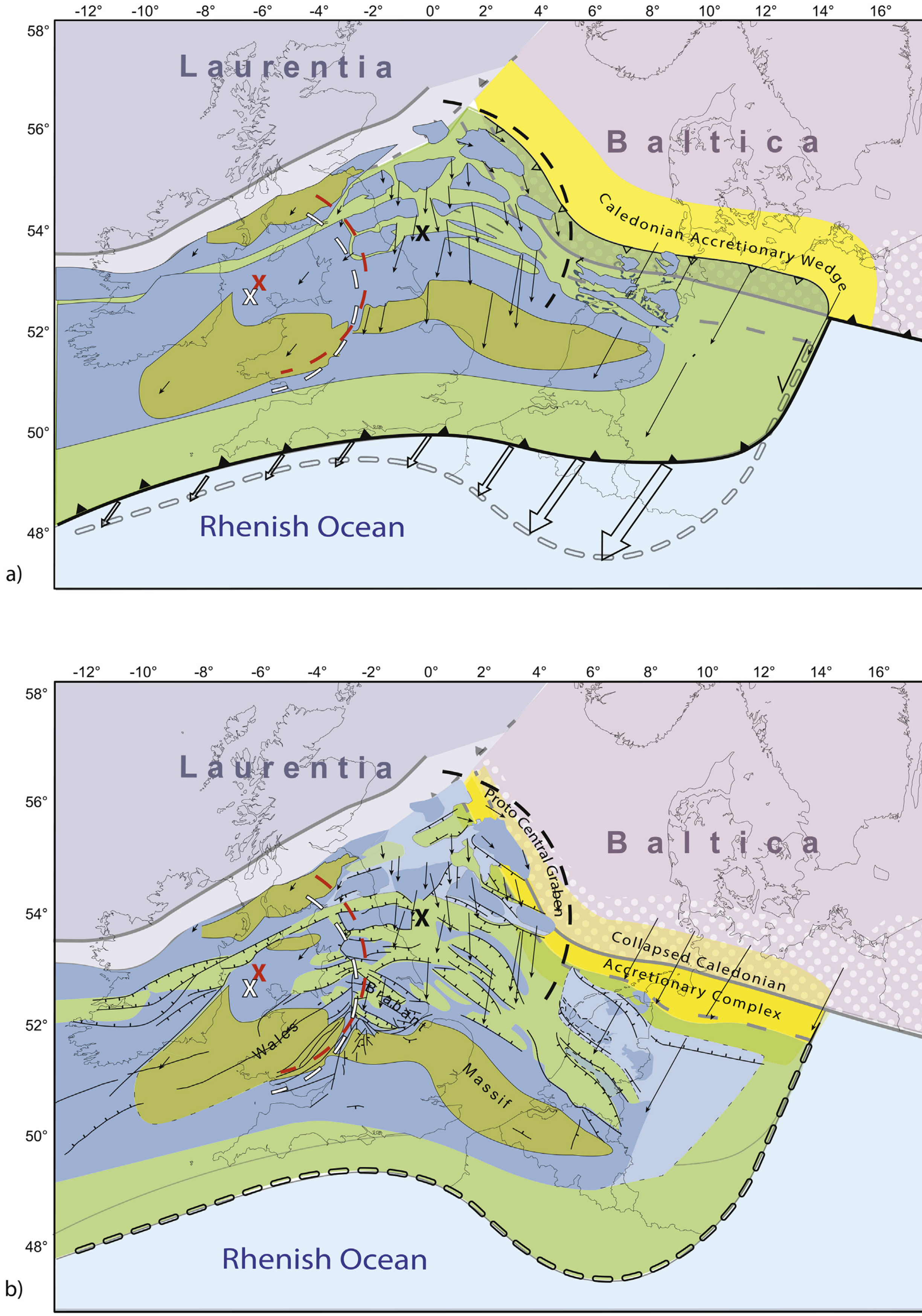


Fig. 13. Map view restoration of early Variscan, Lower Carboniferous extension of Avalonia. a) Initial late Caledonian, pre-extension configuration as deduced from restoration (See Figs. 7, 11 and 12). b) Configuration at end of extension (Variscan blocks S of Avalonia excluded). Deformation by SSW-SW directed dextral transtension west of the Malvern Line, rotational sinistral transtension east of it and eduction along Thor Suture with SSW-SW translation with little internal extension that decreases eastward. Similarities with present day supra-subduction settings (e.g. eastern Mediterranean, SE Asia) suggests extension by slab rollback beneath Avalonia's Rheic margin.

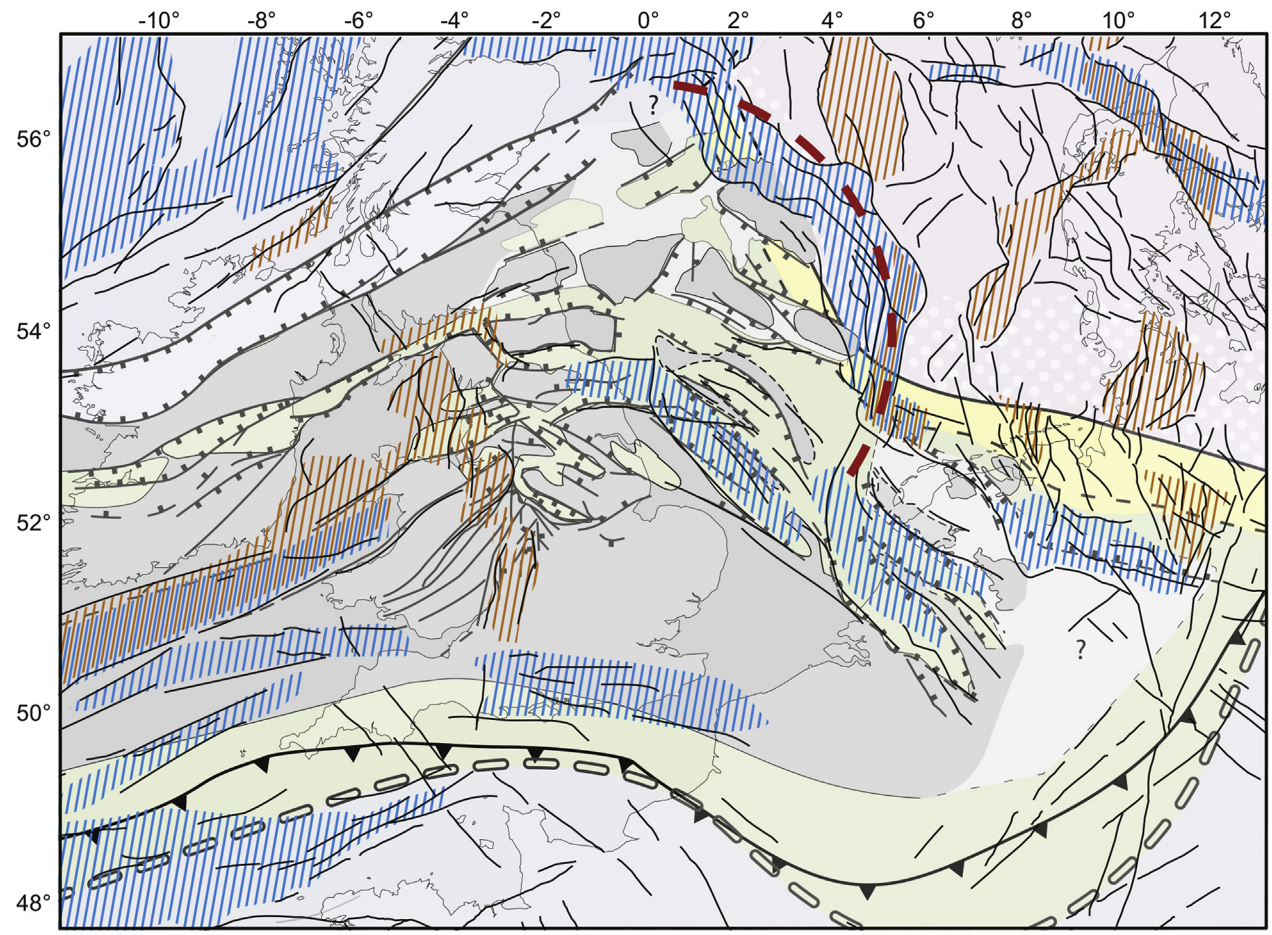


Fig. 14. Comparison between Carboniferous and Mesozoic fault networks and fault-controlled basins, demonstrating the importance of structural inheritance on the spatial distribution of Mesozoic basins in north-western Europe. Mesozoic map is based on Ziegler (1990) and Peacock (2004). Carboniferous map as Fig. 9. Black lines, Mesozoic faults; brown hatching, Permo-Triassic fault-controlled basins; blue hatching, Jurassic fault-controlled basins; thick red hatched line, early Variscan proto-Central Graben shear zone.

central section between Malvern Line and Central Graben as illustrated in Fig. 12.

6. Discussion and conclusions

Our reconstruction of early Carboniferous extension takes into account well-constrained geometries of crustal structural elements and basin architecture. It is also consistent with the various basin orientations, the clockwise rotation of the basin axis east of the Malvern Line and the multiple basins vs. localised extension on either side of the Central Graben. The Malvern Line and its continuation towards the Iapetus suture as well as the proto-North Sea Central Graben were major crustal-scale transcurrent faults that accommodated important rotations during early Carboniferous extension. The current model explains the entire network of basins and major upper crustal faults in the conceptual framework of a single, continuous, early Variscan extension that took place during the early Carboniferous. At least one major fault group was conveniently enough oriented to be reactivated during each of the later deformation phases.

Basins to the west of the Malvern Line are parallel to the Iapetus suture, which has led previous authors (e.g. Leeder, 1982; Fraser and Gawthorpe, 1990; Worthington and Walsh, 2011) to conclude that this involves a reactivation of Caledonian structures. Here in the western section, extension was accompanied by a clockwise rotation of the London-Brabant massif and Midland micro-craton along the Malvern Line. Scissor-like extension in the central section, between Malvern Line and Central Graben, involved a clockwise rotation and multiple-graben formation from the Midland Valley in the north to the edge of the Wales-Brabant massif in the south. Extension east of the Central Graben was largely localised by eduction along the Caledonian Thor suture. This eastern section of Avalonia moved 100–150 km to the southwest, most likely with only limited graben formation. It follows that the eastern, German margin of Avalonia was a transform or a STEP-type margin during early Variscan extension. The limited internal deformation of this block was accommodated by shearing along faults that would later control Mesozoic graben formation and inversion.

Similarities between the map view restoration of early Variscan, lower Carboniferous extension of Avalonia (Fig. 13) and present-day supra-subduction settings (e.g. eastern Mediterranean, SE Asia) suggests that extension occurred by slab rollback of a northward subducting slab under Avalonia's active Rheic margin. This northward subduction under Avalonia is in conflict with the prevailing opinion, based on geometries found in the Variscan terranes, that early Carboniferous subduction of Rheic oceanic lithosphere was southward directed. The Avalonian crust under the mid-German crystalline high, imaged by deep seismics (DEKORP-1), is one indication for southward subduction. In this scenario, the mid-German crystalline high is the magmatic arc above the subducting Avalonian oceanic Lithosphere. Alternatively, the mid-German crystalline high formed the continental magmatic arc of Avalonia separated from each other by a (Devonian) back-arc basin. In this scenario, both Avalonia and mid-German crystalline high would together have formed the upper plate with northward subduction along the south side of the mid-German crystalline high. The mid-German crystalline high could subsequently have thrust over the back-arc basin against the Avalonian margin during Variscan inversion and closure of the back-arc basin, instead of Avalonia subducting under the mid-German crystalline high, Avalonia's arc, under which northward subduction took place.

Fig. 14 shows a comparison of Carboniferous and Mesozoic basin and fault networks. The key role of structural inheritance of early Variscan extension in setting the stage for the spatial distribution of Mesozoic basins in north-western Europe is illustrated by Fig. 14. In Ireland and western Britain, Permian and later extension related to opening of the Atlantic is accommodated along early Variscan structures in both Avalonia's western and eastern sections. The Central section (south-western North Sea and adjacent England) has remained largely unaffected by extension and inversion since the Variscan. Our findings demonstrate that the geomechanical control of large crustal-scale fault structures can provide important geometrical and compositional constraints for local models of stress and strain. Our results hold potential for validating and testing inferred erosion patterns and stress differentiation in the context of exploration and production of (un) conventional hydrocarbons as well as geothermal energy. This fault network remained unchanged since the end of the Dinantian with the notice that the long, suture and Wales-London-Brabant massif parallel faults are most probably inherited from Caledonian or older deformation phases. The Central Graben formed as a transform fault to accommodate differential shear between distributed extension west and suture-localised extension east of it.

Acknowledgements

This research was sponsored by the Dutch TKI Gas foundation, under grant TKIG1018, and the 2F2S Program with financial support from EBN, ENGIE and Wintershall. The authors are grateful for valuable reviews by H. Kombrink and A.M. Lundmark.

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