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Tectonics

Early Palaeozoic orogenic events north of the Rheic suture (Brabant, Ardenne): A review

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Abstract

The Lower Palaeozoic rocks exposed in the Brabant-Ardenne region (Belgium, France) recorded the Early Palaeozoic history on the southern margin of the perigondwanan microcontinent of Avalonia, north of the Rheic suture. These rocks crop out in the Brabant basement and in the Ardenne basement inliers within the Variscan Ardenne allochthon. The two main unconformities are classically associated with distinct orogenic episodes, the Late Ordovician ''Ardennian'' event and the Early Devonian ''Brabantian'' event. A review of the current state-of-knowledge with respect to the reconstruction of Early Palaeozoic geodynamics in the Brabant-Ardenne region is presented. It is demonstrated that an unconformity does not necessarily represent an orogenic event, and that the hiatus related to an unconformity does not necessarily coincide with tectonic activity, especially when tectonism is diachronous in nature. The former applies to the Ardennian unconformity, while the latter applies to the Brabantian unconformity. Finally, the well-constrained Brabantian orogeny, as well as the Ardenne-Eifel basin development, is tentatively framed within the Early Palaeozoic geodynamic context of the northern margin of the Rheic realm. By doing so, it is shown that the Brabant-Ardenne region links, both in space and time, the Rheic and Rhenohercynian ocean. ***To cite this article: M. Sintubin et al., C. R. Geoscience 341 (2009).***

Résumé

Épisodes orogéniques du Paléozoïque inférieur au nord de la suture du Rhéique (Brabant, Ardenne) : l'état de l'art. Les roches du Paléozoïque inférieur qui affleurent au Brabant et en Haute Ardenne (Belgique, France) ont enregistré l'histoire éovarisque de la marge méridionale du microcontinent périgondwanien d'Avalonia, au nord de la suture du Rhéique. Ces roches affleurent dans le socle brabançon et dans les boutonnières ardennaises de l'allochtone ardennais. Deux discordances majeures sont classiquement considérées comme le résultat d'épisodes orogéniques distincts, l'événement « ardennais » à l'Ordovicien supérieur et l'événement « brabançon » au Dévonien inférieur. L'état actuel des connaissances concernant la reconstruction de l'évolution géodynamique au Paléozoïque inférieur dans la région Brabant-Ardenne est présenté. Il est démontré qu'une discordance ne représente pas nécessairement un événement orogénique et que le hiatus associé à la discordance ne coïncide pas avec la durée de l'épisode orogénique. Le premier cas s'applique à la discordance ardennaise. Le second cas s'applique à la discordance brabançonne. Finalement, l'orogénèse brabançonne bien définie, ainsi que le développement du bassin de l'Ardenne-Eifel, sont

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placés dans le contexte géodynamique de la marge septentrionale du domaine Rhéique. De ce fait, il est montré que la région Brabant-Ardenne relie, et dans le temps et dans l'espace, les océans Rhéique et Rhéno-hercynien. ***Pour citer cet article : M. Sintubin et al., C. R. Geoscience 341 (2009).***

Keywords: Early Palaeozoic; Rheic ocean; Rhenohercynian ocean; Brabantian; Ardennian; Eovariscan; Unconformity

Mots clés : Paléozoique inférieur ; Océan Rhéique ; Océan Rhéno-hercynien ; Brabançon ; Ardennais ; Eovarisque ; Discordance

1. Introduction

The Brabant-Ardenne region may play a key role in answering some outstanding questions with respect to the Early Palaeozoic geodynamics in the European Variscides. Its substratum is formed by the perigondwanan microcontinent of Avalonia (Fig. 1), north of the Rheic suture. Situated in the southern part of the microcontinent, the Brabant-Ardenne region has a high potential for having recorded events to the south in the Rheic realm. The region is also situated far enough from the northern sutures between Avalonia, Baltica (Tornquist suture) and Laurentia (Iapetus suture) (Fig. 1), to have been protected from any major imprint of events occurring on the northern side of the microcontinent. The Brabant-Ardenne region is, moreover, closely linked to what occurred in the Rhenohercynian realm, being part of the northern passive margin of the Rhenohercynian ocean [38,68]. Thus, the Brabant-Ardenne region has the potential to link the Rheic and Rhenohercynian history.

Historically, the scientific debate on Early Palaeozoic orogenic events in the Brabant-Ardenne region is based on the recognition of two major angular unconformities: the Ardennian and Brabantian unconformities. These unconformities are commonly considered to reflect episodes of deformation, followed by erosion and transgression. The time gap related to the unconformity is interpreted to be the maximum time span within which the orogenic event takes place. Two major orogenic events are consequently considered to have affected the Early Palaeozoic rocks exposed below the two unconformities in the Brabant-Ardenne region. The vestiges of these events are classically categorised as being part of the ''Belgian Caledonides'' [36,66].

This paper presents a review of current understanding of the Early Palaeozoic geodynamics in the Brabant-Ardenne region. It focuses on the Ordovician to Middle Devonian period, starting with the rifting of Avalonia from the Gondwanan margin and ending with the establishment of a carbonate platform on the passive margin of the ''Old Red Continent'', marking the end of

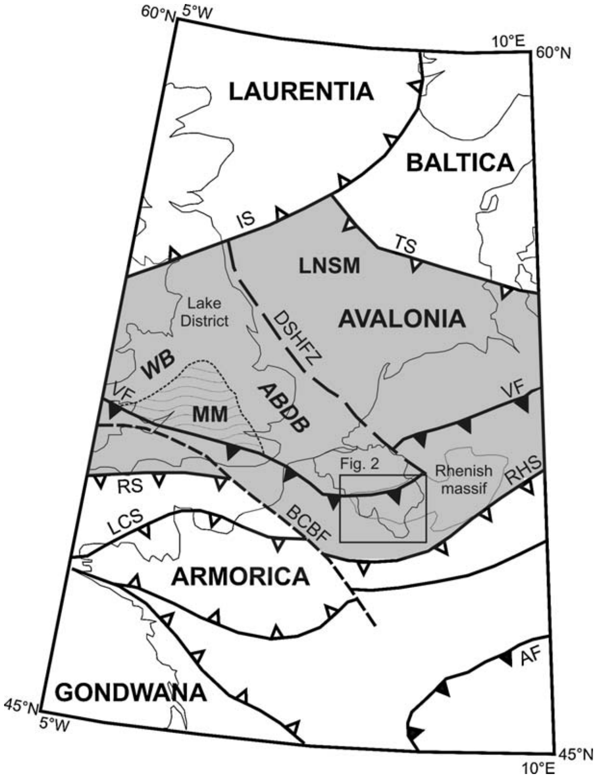

Fig. 1. Terrane map of northwestern Europe (after [97]), centred around Avalonia (gray), with indication of the other Early Palaeozoic continental entities (Gondwana, Armorica, Laurentia, Baltica). VF: Variscan front; AF: Alpine front; RS: Rheic suture; RHS: Rhenohercynian suture; LCS: Le Conquet suture; IS: Iapetus suture; TS: Tornquist suture; BCBF: Bristol Channel-Bray fault; DSHFZ: Downsing-South Hewett fault zone; MM: Midlands microcraton; LNSM: Lüneburg-North Sea microcraton (*i.e*. Far Eastern Avalonia); ABDB: Anglo-Brabant deformation belt; WB: Welsh basin.

Fig. 1. Carte des principaux éléments géodynamiques dans l'Europe du Nord-Ouest (d'après [97]) avec indication des différents paléocontinents au Paléozoïque inférieur : Avalonia (en gris), Gondwana, Armorica, Laurentia, Baltica. VF : front varisque ; AF : front alpin ; RS : suture du Rhéique ; RHS : suture du Rhéno-hercynien ; LCS : suture du Conquet ; IS : suture du Iapetus ; TS : suture du Tornquist ; BCFB : faille Bristol Channel-Bray ; DSHFZ : zone de failles Downsing-South Hewett ; MM : microcraton des Midlands ; LNSM: microcraton de Lüneburg-Mer du Nord ; ABDB : chaîne de déformation Anglo-Brabant ; WB : bassin du Pays de Galles.

the Early Palaeozoic geodynamic history in the Brabant-Ardenne region. The significance of the unconformities with respect to the nature of tectonism and the timing of the tectonic events are discussed. It is demonstrated that the Early Palaeozoic events, recorded in the Brabant-Ardenne region, are part of the ''eovariscan'' geodynamics of the northern margin of the Rheic ocean. The Early Palaeozoic history in the Brabant-Ardenne region is thus tentatively framed within the broader perspective of the Early Palaeozoic geodynamic evolution in the Rheic realm [51,59,98].

2. The unconformities

2.1. The Ardennian unconformity

The **Ardennian unconformity** is exposed in the culmination zone of the High-Ardenne slate belt, part of the Ardenne allochthon (Figs. 2 and 3). It outlines a number of Lower Palaeozoic basement inliers (*i.e.* Rocroi, Serpont, Givonne, Stavelot-Venn inliers). The Ardenne allochthon forms the northernmost thrust nappe of the Rhenohercynian foreland fold-and-thrust belt [1,55,63,68,69] (Fig. 3). The High-Ardenne slate belt is characterised by a pervasive slaty cleavage formed *c*. 325 Ma, *i.e*. during the ''Sudetic'' episode of the Late Palaeozoic Variscan orogeny [34]. The Lower Palaeozoic basement inliers are interpreted as footwall shortcut thrust nappes cut from crustal ramps of the ancient Early Devonian Ardenne-Eifel rift basin [68,69]. They are segmented by Variscan thrust faults (Fig. 7), interpreted as being inverted basin-bounding normal faults [63,65,69]. The overall structure of the inliers is that of north-verging antiforms (Figs. 3 and 7). The internal structure of the inliers exhibits an overall east-west trending structural grain and strongly north-verging fold trains. A south-dipping pervasive slaty cleavage is axial planar with respect to the main folds. The basement inliers expose predominantly fine-grained, siliciclastic rocks of Cambrian to Middle Ordovician age [95,96]. In the Rocroi, Serpont, and Givonne inliers only Cambrian metasediments are found. In the Stavelot-Venn inlier the sedimentary sequence is continuous up to the Middle Ordovician (Darriwillian, *c.* 465 Ma).

Due to Variscan deformation, two types of Ardennian unconformity can be distinguished (Fig. 4). These two types do not only differ in their structural setting but also with respect to the time hiatus represented. The first sediments covering the basement show systematic younging to the north, reflecting the northwards

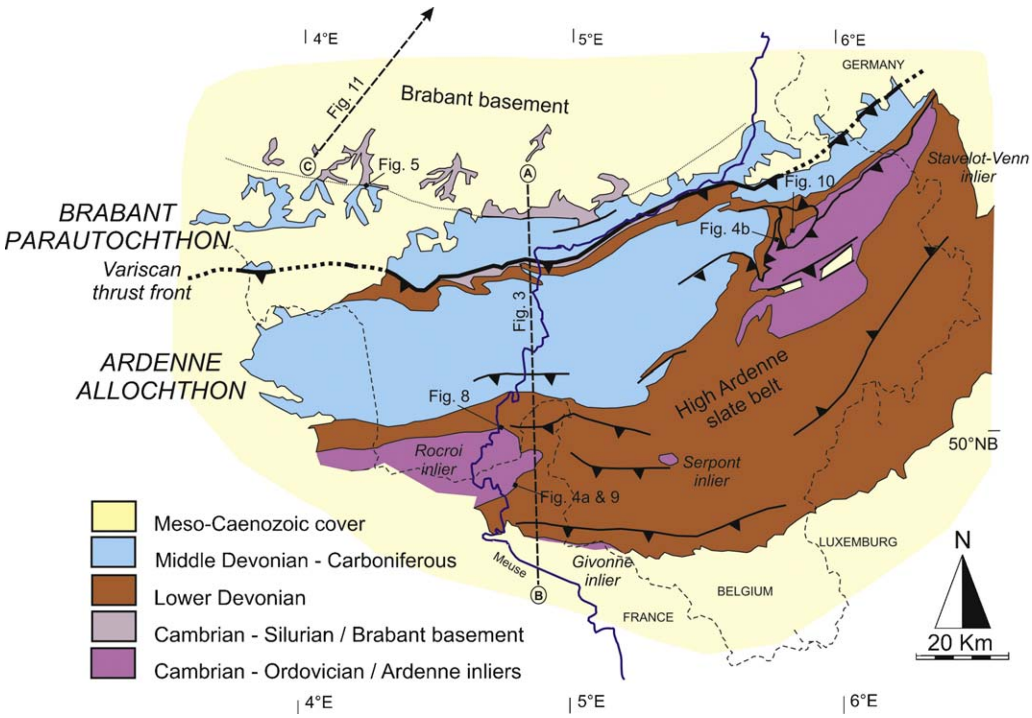

Fig. 2. Simplified geological map of the Brabant-Ardenne region with indication of the main tectonostratigraphical entities.

Fig. 2. Carte géologique simplifiée de la région Brabant-Ardenne avec indications des unités tectonométamorphiques majeures.

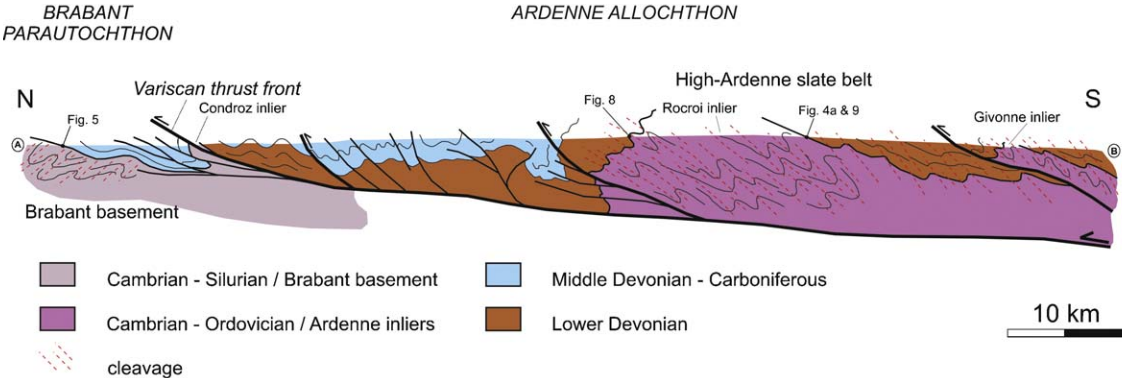

Fig. 3. Simplified cross-section of Variscan foreland fold-and-thrust belt in the Ardenne with indication of the Variscan cleavage in the Ardenne allochthon and the Brabantian cleavage in the Brabant basement (see Fig. 2 for location).

Fig. 3. Coupe géologique simplifiée de la chaîne d'avant-pays varisque en Ardenne, avec indications du clivage varisque dans l'allochtone ardennais et le clivage brabançon dans le socle brabançon (voir Fig. 2 pour localisation).

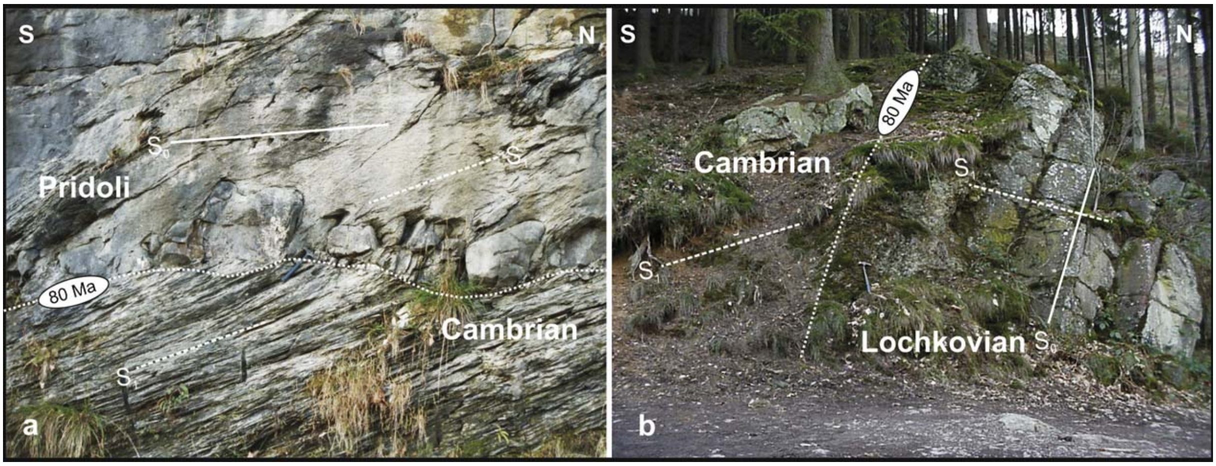

Fig. 4. The Ardennian unconformity. a: the south-type unconformity at the southern margin of the Rocroi inlier at Naux (France) (see Figs. 3 and 7 for location). b: the north-type unconformity at the northern margin of the Stavelot-Venn inlier at Remouchamps (Belgium) (see Fig. 2 for location). S_0: bedding; S_1: cleavage. The time gap at the unconformity is indicated.

Fig. 4. La discordance ardennaise. a : la discordance du type méridional à la bordure sud de la boutonnière de Rocroi à Naux (France) (voir Fig. 3 et 7 pour localisation). b : la discordance du type septentrional à la bordure nord de la boutonnière de Stavelot-Venn à Remouchamps (Belgique) (voir Fig. 2 pour localisation). S_0 : stratification ; S_1 : clivage. Le hiatus représenté par la discordance est indiqué.

transgression of the Rhenohercynian ocean. The south-type unconformity is well-exposed on the southern limb of the Givonne [6] and Rocroi inliers (Figs. 4a, 7 and 9) [7,8,27,28,47]. The basement-cover interface is sub-horizontal to gently south-dipping. The youngest basement rocks directly below the unconformity are of Late Cambrian age (*c.* 500 Ma), while the oldest cover rocks are of Latest Silurian age (Pridoli, *c.* 419 Ma) [9,42,43], leaving a time hiatus of *c.* 80 Ma. The basement-cover interface is cross-cut at a small angle by a single pervasive slaty cleavage [47,55,88]. The north-type unconformity is best exposed on the northern limb of the Rocroi (Figs. 7 and 8) [52,62,64] and Stavelot-Venn inliers (Fig. 4b and 10) [35,37,46,54,78]). In the case of the Rocroi inlier (Fig. 8) the youngest basement rocks directly below the unconformity are also of Cambrian age, while the oldest cover rocks are of Lockovian age (*c.* 415 Ma) [56,61]. In the case of the Stavelot-Venn inlier (Fig. 4b and 10) the youngest basement rocks directly below the unconformity are mostly Darriwillian in age (*c.* 465 Ma), while the oldest cover rocks are of Late Lochkovian age (*c.* 411 Ma), leaving a time hiatus of only *c.* 50 Ma. Structurally, this type of unconformity is

Fig. 5. The Brabantian unconformity at the southern margin of the Brabant basement at Ronquières (Belgium) (see Fig. 2 for location). S_0: bedding; S_1: cleavage. The time gap at the unconformity is indicated.

Fig. 5. La discordance brabançonne à la bordure nord du socle brabançon à Ronquières (Belgique) (voir Fig. 2 pour localisation). S_0 : stratification ; S_1 : clivage. Le hiatus représenté par la discordance est indiqué.

commonly steeply dipping (Fig. 10), subvertical to overturned (Fig. 4b), being part of a step-fold sequence (Fig. 10). Cleavage cross-cuts the basement-cover interface. Cleavage attitude is gently south-dipping, to subhorizontal, to locally even gently north-dipping, hence cross-cutting the unconformity at high angles.

2.2. *The Brabantian unconformity*

The **Brabantian unconformity** is exposed both in the direct footwall of the Variscan thrust front and in the Variscan foreland, north of the Variscan deformation front. In the former case the unconformity outlines the Condroz inlier (Fig. 2), a very elongated inlier of highly deformed, Lower Palaeozoic rocks in thrust sheets in the direct footwall of the Variscan thrust front (*i.e.* Midi overthrust) (Fig. 3). In the latter case, the unconformity outlines the Brabant basement (Fig. 2). The basement-cover interface in the outcrop area of the Brabant basement (*e.g.* Ronquières section, [19]) is gently south-dipping (Fig. 5). The youngest deformed basement rocks in outcrop are of Ludlow age (*c.* 420 Ma), while the oldest cover rocks are Givetian deposits (*c.* 390 Ma), leaving a time hiatus of *c.* 30 Ma. The unconformity truncates both folds and associated slaty cleavage [19]. To the west boreholes show even younger basement rocks, from Pridolian (*c.* 419 Ma) in the west of Flanders (Belgium) to Lochkovian (*c.* 417 Ma) in northern France, unconformably overlain by Middle Devonian deposits [89,94]. The youngest basement rocks below the Brabantian unconformity are thus of the same age as the oldest cover rocks above the Ardennian unconformity.

3. The Belgian "Caledonides"

Already at the beginning of the 20th century the temporal difference between both unconformities has been recognized and related to two distinct orogenic events. Due to a coincidence in time, these events were considered as being part of the Caledonian orogeny (Fig. 6).

The orogenic event, causing the Ardennian unconformity, is commonly considered to have occurred in Latest Caradoc – Earliest Ashgill times (*c.* 455 Ma). The classically advanced evidence of this age is a thin conglomerate horizon (Cocriamont conglomerate), supposedly covering a hiatus of part of the Upper Ordovician [58,66], exposed in the Condroz inlier. This orogenic event is called the **eocaledonian** [36] or **Ardennian** event [66] (Fig. 6b).

The Brabantian unconformity is classically considered to be the result of a **neocaledonian** [36] or **Brabantian** event [66] (Fig. 6d) that occurred during the Early Devonian (*c.* 400 Ma).

Fourmarier [36] framed these events in a sequence of orogenic pulses affecting the entire European continent. Michot [66] understood the confined nature of the events, both affecting only the Lower Palaeozoic rocks in the Ardenne-Brabant region. The latter author placed both events in the cyclic history of basin development ("geosyncline") and mountain building ("geoanticline"), in the tradition of the 19th century geosyncline paradigm (Fig. 6). Although this geodynamic interpretation reflects the predominant ideas predating the general acknowledgement of the plate tectonic paradigm in the late 1960s, it is remarkable that this model still appears in guides and textbooks on Belgian geology.

4. The "Ardennian" event?

Both the nature and the significance of the "Ardennian" event have been a matter of controversy since long. Even the existence of this orogenic event is highly disputed and to date these questions still remain largely unresolved. The main obstacle to identify an "Ardennian" event is that the Variscan tectonometamorphic event during the Carboniferous obscures any possible earlier, pre-Variscan structures. The Lower Palaeozoic metasediments are found in a

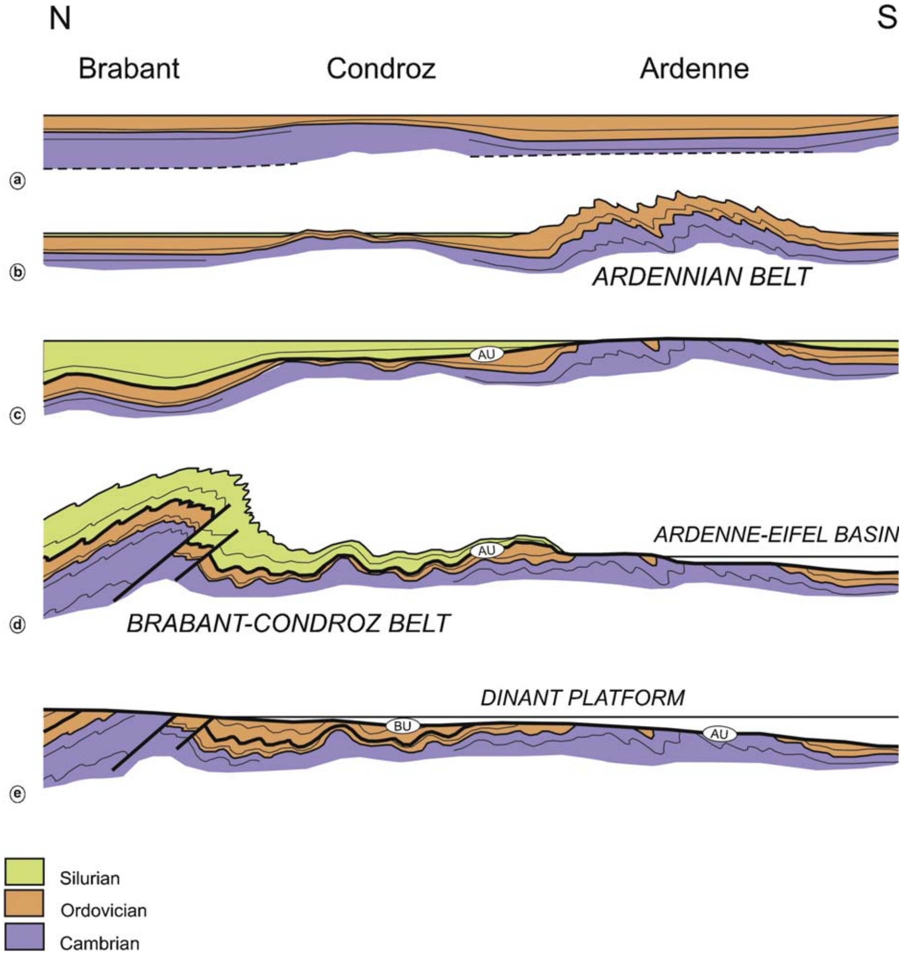

Fig. 6. Simplified geodynamic reconstruction of the ''Belgian Caledonides'' by Michot [66] with indication of the Ardennian and Brabantian orogenic events. a: Arenig. b: Middle Caradoc. c: Late Ludlow. d: Lochkovian. e: Late Emsian. AU: Ardennian unconformity; BU: Brabantian unconformity.

Fig. 6. Reconstruction géodynamique simplifiée des « Calédonides » belges par Michot [66], avec indication des phases orogéniques ardennaise et brabançonne. a : Arenig. b : Caradoc moyen. c : Ludlow supérieur. d : Lockovien. e : Emsien supérieur. AU : discordance ardennaise ; BU : discordance brabançonne.

basement-involved antiformal stacking of thrust duplexes [55] in the culmination zone of the High-Ardenne slate belt, affected by a pervasive slaty cleavage development (Figs. 3 and 7). The basement inliers are cross-cut by major Variscan thrusts, juxtaposing tectonostratigraphic domains that originated from different crustal levels [55,65]. They acted as ''low-strain'' bodies, enclosed by ''high-strain'' shear zones, extending on both sides of the basement-cover interface [10,33,55], *i.e*. the ''Rocroi shear zone'' in the Rocroi inlier (Fig. 7) [55,88] and the ''Monshau shear zone'' in the Stavelot-Venn inlier [33,74]. The rocks on both sides of the southern basement-cover interface are affected by a high temperature – low pressure metamorphism, reaching 400–450 °C and 100–300 MPa in the southern Stavelot-Venn inlier and up to 500 °C and 200–300 MPa in the Rocroi-Serpont inlier [34]. This metamorphism is believed to have a burial to early synkinematic origin, affecting the rocks during Early Carboniferous times. At the northern unconformity metamorphism only reached anchizonal conditions (up to 230 °C) [34].

4.1. *Classical views on the ''Ardennian'' event*

Two opposing views can be found in literature, emphasizing different structural evidence. One group of authors [5,27,28,49,50] considers the angular unconformity as the primary evidence in favour of an important tectonometamorphic event. Moreover, the complexity of folding observed within the inliers, but absent in the

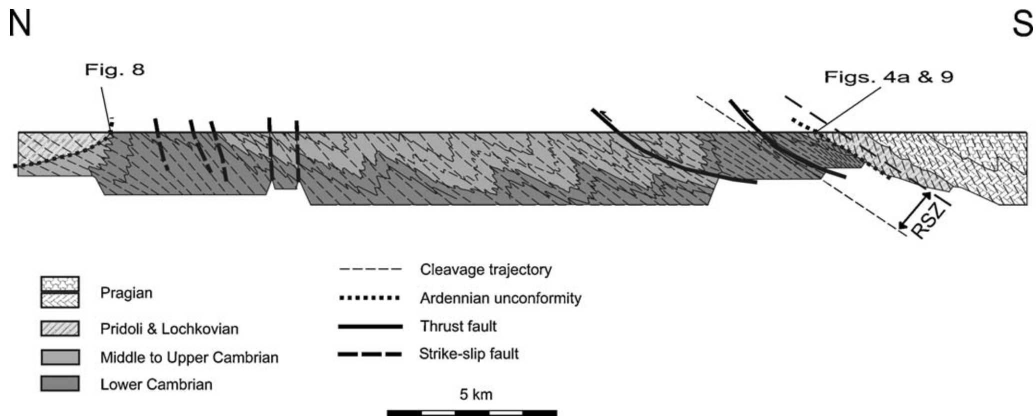

Fig. 7. Structural cross-section of the Rocroi inlier (after [47,55,88]) with indication of the trajectory of the main cleavage in basement and cover. RSZ: "Rocroi shear zone" [55].

Fig. 7. Coupe géologique de la boutonnière de Rocroi (d'après [47,55,88]), avec indication du trajectoire du clivage principal dans le socle et la couverture. RSZ : « zone de cisaillement de Rocroi » [55].

cover sequence, is considered to be largely the result of a polyphase deformation history [28]. A first phase resulted in NW-SE-trending, south-east-plunging, north-east-verging recumbent folds (P1) with highly curved fold hinge lines and an associated axial-planar pervasive cleavage. Superposed on these folds, north-south to NW-SE trending, upright cylindrical folds (P2) developed without an associated axial-planar cleavage. Subsequent Variscan deformation is considered to have occurred highly partitioned, only locally affecting the previously structured slaty basement and causing minor folding (P3) and occasional multiple crenulation of the main cleavage [5,27,28]. Variscan reactivation of a pre-existing, thus "Ardennian", slaty cleavage is hence seen as the reason why the basement rocks are apparently affected by only a single pervasive cleavage and that the unconformity is apparently cross-cut by a single cleavage (Figs. 4a and 8). Determination of the age of the "Ardennian" orogenic event is made by reference to the Late Ordovician Cocriamont conglomerate exposed in the Condroz inlier (see above) [58,66]. The other group of authors stresses the singularity of the pervasive cleavage on both sides of the basement-cover interface and within the inliers [47,48,52,55,63,65] and uses this as the primary argument to minimize the significance of an "Ardennian" deformation of the basement rocks. These authors postulate that the rocks were only affected by the main, Early Carboniferous, Variscan tectonometamorphic event.

4.2. Reassessment based on recent studies

Based on a number of recent studies some new insights regarding this controversy are presented here successively dealing with the different arguments used in favour or against the Late Ordovician "Ardennian" orogenic event.

Detailed surveys in the Condroz inlier have shown that the Cocriamont conglomerate is not the so-called basal conglomerate indicative of the "Ardennian" orogeny [92,96]. Chitinozoan biostratigraphy reveals that these conglomeratic horizons have a Llandovery age (*c*. 438 Ma) [90–92]. They also contain lower to Middle Ashgill limestone boulders indicative of a nearby carbonate platform [87]. Detailed biostratigraphy furthermore identified two disconformities in the Ordovician-Silurian transition period [90,91]. Although eustatic sea level changes (*e.g*. Solvang Lowstand) may have caused the oldest disconformity, tectonic influences cannot be excluded [90,91]. With the Late Ashgillian deposits the third megasequence in the Early Palaeozoic Brabant-Condroz basin starts [96] (Fig. 12). This megasequence records shelf deposits that evolve into a thick foreland basin deposit from the Llandovery onwards (see below) [96]. This third megasequence is part of the continuous sedimentary record in the Brabant-Condroz basin and largely coincides with the hiatus represented by the Ardennian unconformity (Fig. 12). The sedimentary record in the Brabant-Condroz basin seems, however, not to contain any direct indication of an orogenic event in its direct proximity at the end of the Ordovician.

With respect to the metamorphism, an extensive fluid-inclusion and mineralogical study of quartz veins in and around the Stavelot-Venn inlier [32] has revealed the existence of a pre-Variscan metamorphism affecting the Lower Palaeozoic basement rocks. In the southern domain the pressure-temperature conditions

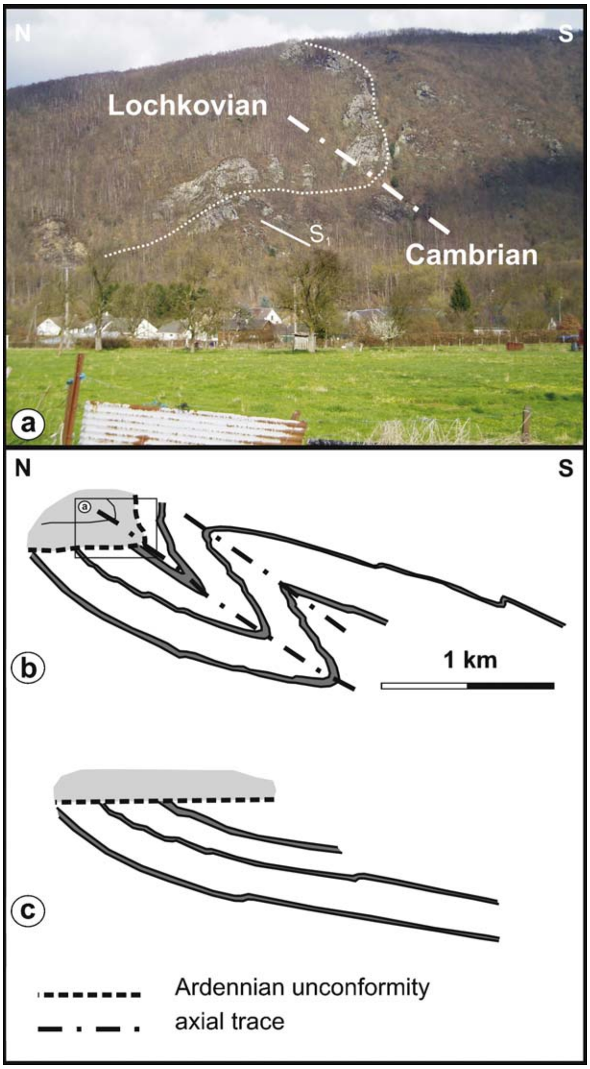

Fig. 8. The Ardennian unconformity at Rocher à Fépin (France), northern margin of Rocroi inlier (see Figs. 2, 3 and 7 for location). a: Rocher à Fépin. b: regional reconstruction of folded basement and unconformity (after [52]). c: unfolding of unconformity (after [52]). S_1: cleavage.

Fig. 8. La discordance ardennaise au Rocher à Fépin (France), bordure nord de la boutonnière de Rocroi (voir Fig. 2, 3 et 7 pour localisation). a : Rocher à Fépin. b : reconstruction régionale de la structure du socle et de la discordance (d'après [52]). c : géométrie anté-raccourcissement varisque (d'après [52]). S_1 : clivage.

(200–300 °C; 205–295 MPa at a temperature gradient of 30 °C/km) are lower than the Variscan metamorphic conditions (385–435 °C; 175–275 MPa), whereas in the northern domain the pre-Variscan conditions (180–270 °C; 80–130 MPa at a gradient of 50 °C/km) are comparable with the anchizonal Variscan conditions (*c*. 240 °C). The cause of metamorphism remains enigmatic.

The nature of the Ardennian unconformity has been reassessed based on two studies in the Rocroi inlier [52,88] (Figs. 8 and 9) and some new observations in the Stavelot-Venn inlier (Fig. 10). The unfolding of the folded Ardennian unconformity shows that the angular unconformity is primarily related to a tilt of the basement strata (Figs. 8–10). In other cases, the basement-cover interface shows only evidence of a disconformity. There is no strong evidence of hard-rock tectonic fold hinges truncated by the unconformity. In most cases, this is only an assumption based on a classical view of an unconformity representing a contractional orogenic event. In cases where the truncation of fold hinges can be observed, it concerns small-scale, highly curvilinear folds, which may be interpreted as synsedimentary slump folds [52,64] caused by basin instabilities in the Middle Cambrian [53]. With respect to the significance of the unconformity, it should also be mentioned that in the case of the Stavelot-Venn inlier the geological map shows that the youngest basement rocks (Middle Ordovician Bihain formation) are nearly always to be found directly underneath the unconformity [39,40], rather suggesting a regional disconformable contact between basement and cover. The unfolding of the Ardennian unconformity [52,88] also reveals that folding in the basement (at different scales) can be directly related to the folding of the unconformity (Figs. 8 and 9). These particular folds (P1) and their associated axial-planar cleavage, commonly interpreted as reflecting the main Ardennian deformation [28]), can hence be attributed to the Variscan shearing. Van Baelen and Sintubin [88] demonstrate that the presence of a tilted basement causes a deformation that is decoupled between basement and cover, leading to complex folding in the basement that is absent in the cover (Fig. 9c). This infers that possible pre-Variscan structures cannot be determined solely based on type and orientation of the structures. A correlation with the deformation of the basement-cover interface is imperative to establish the nature of basement structures. To date, the only structures that can be conclusively considered pre-Variscan are folds evidencing a Middle Cambrian slumping event [53]. Also, no conclusive answer can be given concerning the age of the single pervasive cleavage in the basement. This cleavage is systematically axial-planar to the first-order basement folds (P1). This cleavage cross-cuts the basement-cover interface without a significant refraction, suggesting no major rheological contrast between the basement and cover rocks at the time of cleavage development [88] (Figs. 4a and 7). Also the localised presence of multiple

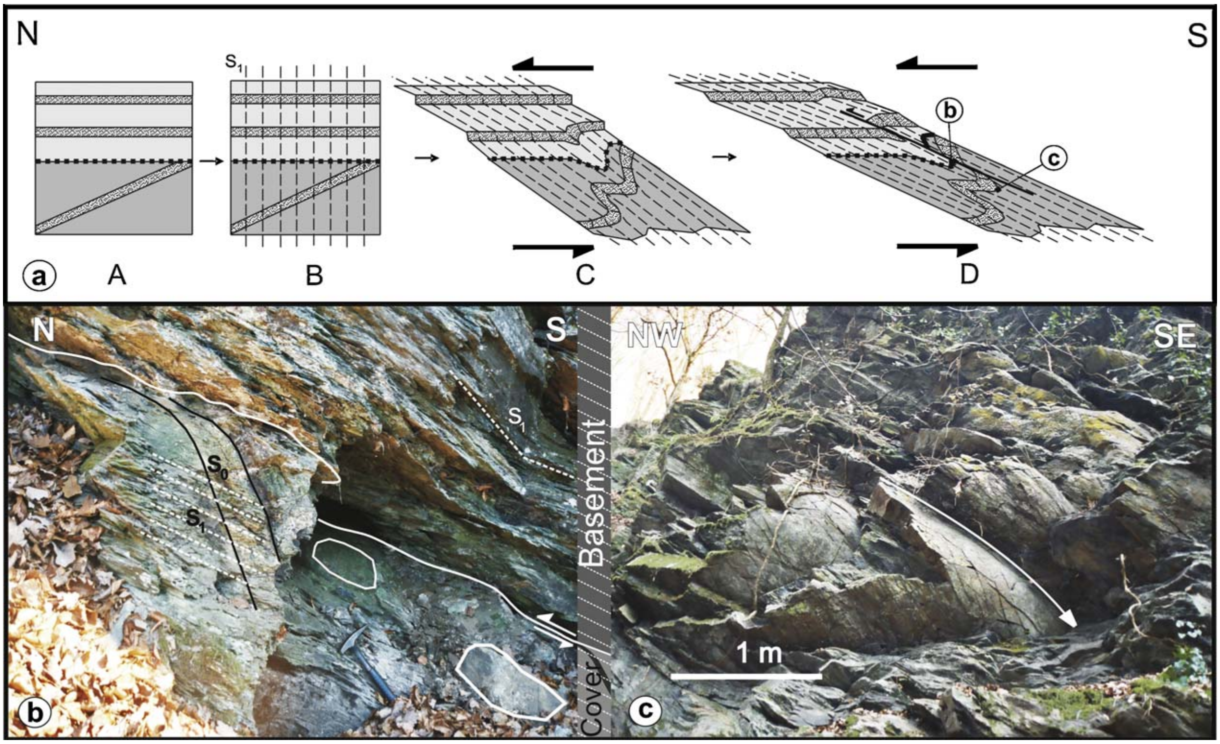

Fig. 9. The Ardennian unconformity at Naux (France), southern margin of Rocroi inlier (see Figs. 2, 3 and 7 for location). a: four-stage evolutionary model for the Variscan cleavage development and shearing of the basement-cover sequence characterised by an angular unconformity [88]. b: overturned and sheared unconformity. c: curved fold hinge lines in quartzite layers in the Cambrian basement (so-called P1 folds), formed by Variscan shearing. S_0: bedding; S_1: cleavage.

Fig. 9. La discordance ardennaise à Naux (France), bordure sud de la boutonnière de Rocroi (voir Figs. 2, 3 et 7 pour localisation). a : modèle de l'évolution du développement du clivage varisque et du cisaillement de l'interface entre socle et couverture, caractérisée par une discordance angulaire [88]. b : renversement et cisaillement de la discordance. c : Pli à charnière courbe dans les couches quartzitiques du socle cambrien. S_0 : stratification ; S_1 : clivage.

crenulation cleavages cannot be applied as evidence in favour of an earlier, pre-Variscan orogenic event. Multiple crenulation cleavages are also found in Devonian rocks in the High-Ardenne slate belt, hence being Variscan. A multiple crenulation cleavage development can also be explained by applying a progressive, non-coaxial shear deformation, as exemplified in the southern domain of the Stavelot-Venn inlier [70].

4.3. The nature of the Ardennian unconformity

Based on these studies it can be concluded that the Lower Palaeozoic basement rocks exposed in the Ardenne inliers, below the Ardennian unconformity, are definitively affected by a pervasive Variscan deformation. Furthermore, there is evidence for:

- a Middle Cambrian synsedimentary folding event that is related to basin instabilities;
- a pre-Variscan metamorphism;
- a pre-Variscan tilting of the basement strata prior to erosion and deposition of the cover sediments.

No data support a Late Ordovician age for these tectonometamorphic event. Moreover, the tilting of the basement strata and the subsequent angular unconformity does not necessarily infer a contractional orogenic event. They can very well be related to an extensional event resulting in a sequence of half grabens structures that may reflect Early Devonian basin dynamics. All other evidence currently available (multiple cleavage, complex folding, angular unconformity) is not conclusive in refuting or proving an "Ardennian" orogenic event. No indication of such an orogenic event can be inferred, from neither the sedimentary record of the Brabant-Condroz basin, nor the regional geodynamic setting of the Avalonia microcontinent (see below) [96,97]. The existence of a Late Ordovician, "Ardennian", orogenic event in the Ardenne realm, responsible for the Ardennian unconformity, is thus strongly questioned.

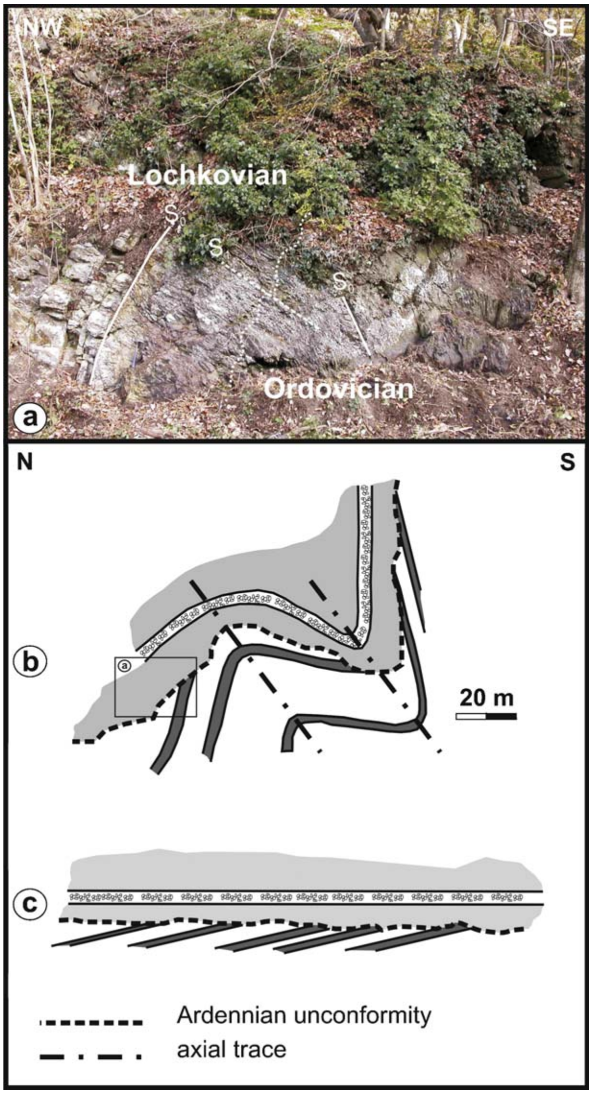

Fig. 10. The Ardennian unconformity at Spa Marteau (Belgium), northern margin of Stavelot-Venn inlier (see Fig. 2 for location). a: the angular unconformity. b: reconstruction of folded basement and unconformity. c: unfolding of unconformity. S_0: bedding; S_1: cleavage.

Fig. 10. La discordance ardennaise à Spa-Marteau (Belgique), bordure nord de la boutonnière de Stavelot-Venn (voir Fig. 2 pour localisation). a : la discordance angulaire. b : reconstruction de la structure du socle et de la discordance. c : géométrie anté-raccourcissement varisque. S_0 : stratification ; S_1 : clivage.

5. The Brabantian event

The Brabantian unconformity truncates a folded and cleaved Lower Palaeozoic basement (Fig. 5) and is located north of the Variscan deformation front, *i.e.* as the basement of the Brabant parautochthon (Figs. 2 and 3). Although the existence of a Brabantian orogenic event has long been generally acknowledged [36], its nature, timing and geodynamic significance have only been established recently. The synthesis of the existing structural data [75,77], new structural studies [4,13, 14,16–23,25,26,80,81] and an analysis of the potential field data [31,57,76,79] allows better understanding of the structure produced by the Brabantian event.

5.1. The structure of the Brabantian orogen

Although only the southern part of the Brabantian orogen is exposed, an overall symmetrical structure is inferred (Fig. 11) [79]. It is interpreted as a NW-SE trending compressional wedge consisting of a central steep belt composed of predominantly Cambrian metasediments, bordered on both sides by deformed Ordovician and Silurian metasediments. The deformation seemingly dies out away from the central steep belt, towards a cratonic area [15,24,77]. The southern cratonic area may potentially represent the southeastern continuation of the Midlands microcraton, overthrust by the Variscan Ardenne allochthon [79]. Consequently, the Lower Palaeozoic rocks of the Ardenne basement inliers (see above) may belong to the undeformed cover sequence of a craton (*cf*. cratonic wegde on the ECORS – Nord de la France seismic section [11]). Moreover, in reconstructing the Early Palaeozoic configuration of the tectonometamorphic entities in the Brabant-Ardenne region we have to take into account that their current disposition is the result of Variscan thrusting, causing a northward displacement of the Ardennian basement of several hundreds of kilometres [55,69,73]. Along the southern extremity of the Brabantian orogen the symmetrical disposition of the NW-SE trending compressional wedge is distorted, leading to an arcuate structure of the southern Ordovician-Silurian belt, curving from NW-SE in the west to ENE-WSW in the east [79]. To the northwest the overall Brabantian structural grain can be followed in the subsurface of Anglia, defining the Anglo-Brabant deformation belt (Fig. 1), bordering the Midlands microcraton to the northeast [30,96]. The Brabantian orogen is currently considered to have resulted from the tectonic inversion of a Cambrian rift basin [79] caused by the convergence of cratonic blocks (*i.e*. Midlands microcraton, Lüneburg-North Sea microcraton; Fig. 1) belonging to the Avalonia terrane assemblage [15,96].

5.2. A long-lived orogeny

Detailed field studies have shown evidence for only one single progressive deformation, which primarily

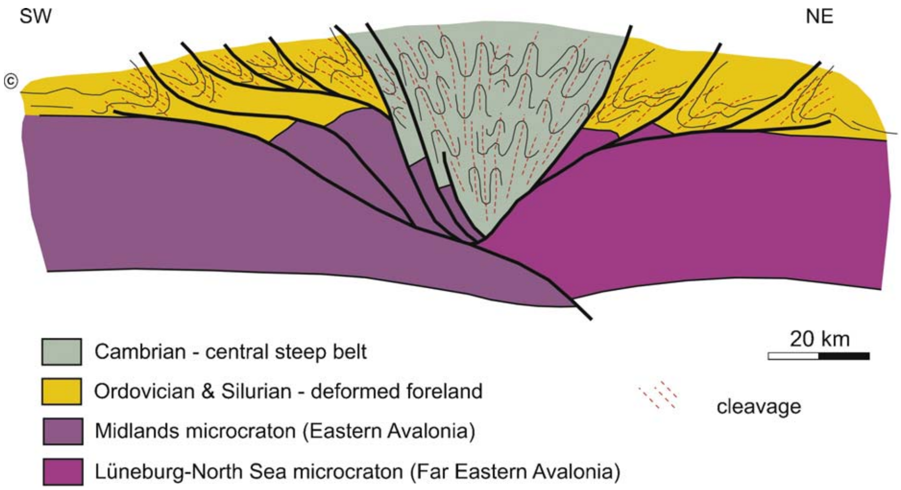

Fig. 11. Conceptual cross-section of the Brabantian belt with indication of the Brabantian cleavage (see Fig. 2 for location) [79].

Fig. 11. Coupe géologique conceptuelle de la chaîne brabançonne (voir Fig. 2 pour localisation), avec indication du clivage brabançon [79].

resulted in the development of folds and an associated cleavage [13–16,19,23,26,77,80]. Evidence for large-scale thrusting [67] is absent [41]. Only locally low-angle reverse shear zones developed [14,71]. The Lower Palaeozoic rocks in the Brabant basement are affected by low-grade metamorphism, ranging from epizone in the Cambrian core to anchizone and diagenesis in the Silurian periphery [89]. This metamorphism has been considered to result primarily from burial [41] continuing during the early stages of deformation [34,41]. A reassessment of the illite crystallinity data reveals a spatial and stratigraphical range of metamorphism that is not concordant with a simple burial origin [15,24]. The illite crystallinity of thick Silurian turbidite deposits in the southern, southeastern and northern peripheral domains is commonly similar to or even higher than the illite crystallinity in the Cambrian and Ordovician rocks in the more central domain. This pattern of metamorphism infers an additional sedimentary load on the peripheral domain from the Silurian onwards relative to the Cambrian and Ordovician strata in the more central domain. This extra sedimentary input is interpreted to be associated with the increased subsidence in the peripheral foreland basins (Fig. 12) and a relative uplift of the Cambrian core [24]. Several lines of evidence show that the timing of the Brabantian orogeny is not exactly confined to the hiatus represented by the Brabantian unconformity. The sudden increase in subsidence and sediment accumulation at the end of the Llandovery (*c*. 430 Ma) (Fig. 12) [24,89,96], with the installation of the Silurian distal turbidite regime, marks the onset of foreland-basin development in the peripheral domain. Corroborated by the metamorphic data, the tectonic loading responsible for the foreland basin development may be due to inversion tectonics in the central core of the orogen. This suggests that around 430 Ma the Brabantian deformation was already affecting the Cambrian rocks in the central domain, more than 10 Ma before the youngest sediments present in outcrop underneath the Brabantian unconformity (Fig. 5) were deposited in the developing foreland basins. Well-preserved and thermally unaltered Silurian and Early Lochkovian reworked arcritarchs in the Lower Devonian deposits in the Dinant basin, situated south of the developing orogen, are thought to have been derived form the unroofing of the central part of the Brabantian orogen [86]. The central core of the Brabant orogen hence seemingly emerged from the Late Lochkovian onwards (*c*. 415 Ma). The extensive Late Emsian to Early Eifelian Burnot conglomerates (Fig. 12), showing a southwards progradational sequence on the Dinant platform [12,44] are considered to result from the emergence and denudation of the Brabantian orogen [24,89,94,96]. Because no more evidence is found for tectonic activity in the Middle-Devonian prior to the deposition of the Givetian sediments on the Lower Palaeozoic basement rocks, the end of the Brabantian orogeny seems to coincide with the development of the Burnot conglomerate (*c*. 400 to *c*. 395 Ma) [24,96]. The integration of stratigraphic, metamorphic, sedimentological, geophysical and structural data demonstrates that the Brabantian orogeny is both diachronous and long-lived, lasting for at least *c*. 30 Ma, from at least the Late Llandovery to the Emsian, possibly even continuing into the Eifelian [24] (Fig. 12). The Cambrian core of the orogen was already deforming during the Late Llandovery (*c*. 430 Ma), after

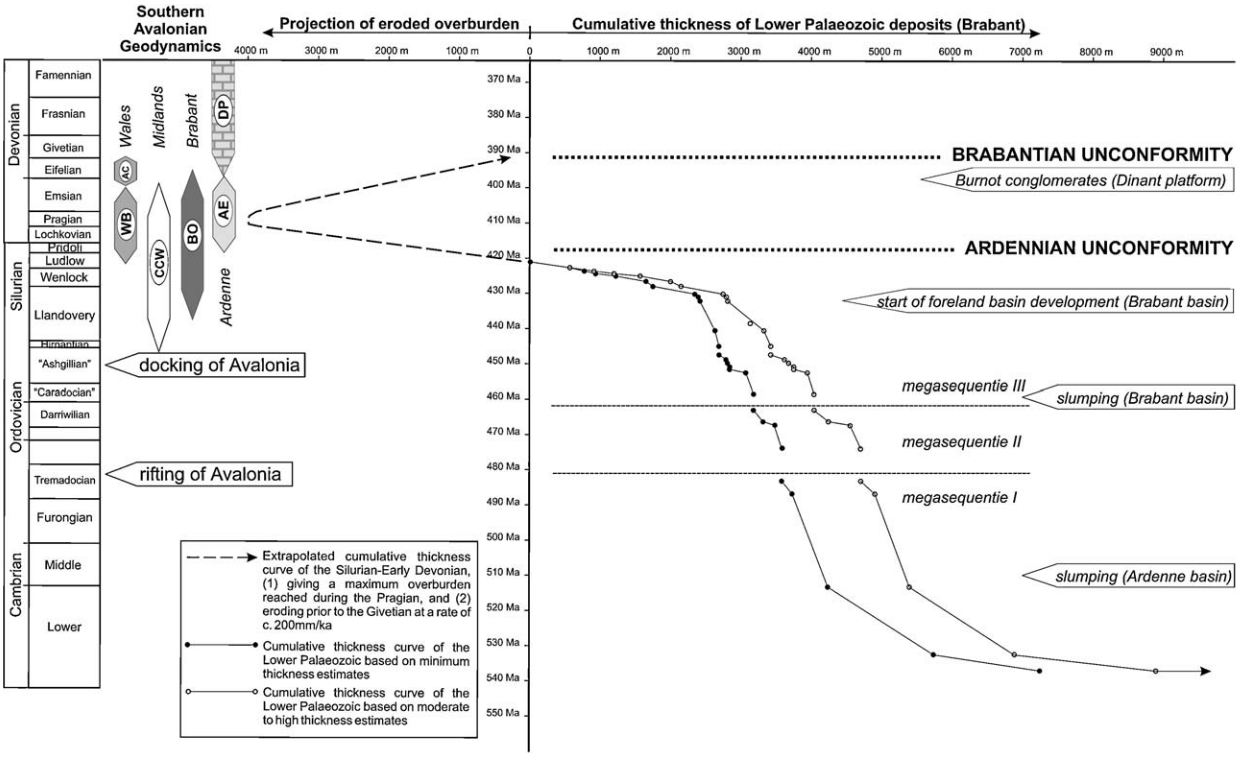

Fig. 12. Cumulative thickness curve of the Lower Palaeozoic sediments in the Brabant basement (after [24] and references therein). Absolute time scale according to Gradstein et al. [45]. Indication of the three megasequences in the Brabant basin evolution [96], and the main reference events in the Brabant-Ardenne region (see text) [20,53,89,96]. Temporal correlation in the Avalonian context: BO: Brabantian orogeny; AE: Ardenne-Eifel basin development; DP: Dinant carbonate platform development (starting with the Givetian deposits on top of the Brabantian unconformity); CCW: counter-clockwise rotation (55°) of the Midlands microcraton with respect to the Lake District [72] (see also Fig. 13); WB: Welsh basin development in a transtensional setting [98]; AC: "Acadian" orogeny in Wales [98] (see also Fig. 13).

Fig. 12. Évolution de l'épaisseur cumulative des sédiments du Paléozoïque inférieur dans le socle brabançon (d'après [24]). Échelle de temps absolu de Gradstein et al. [45]. Indication des trois mégaséquences du bassin brabançon [96] et des événements principaux dans la région Brabant-Ardenne (voir texte) [20,53,89,96]. Corrélation dans le contexte Avalonien : BO : orogénèse brabançonne ; AE : développement du bassin Ardenne-Eifel; DP: développement de la plate-forme carbonatée de Dinant (commençant avec les dépôts du Givétien sur la discordance brabançonne) ; CCW : rotation (55°) dans le sens contraire des aiguilles d'une montre du microcraton des Midlands [72] (voir Fig. 13); WB: développement du bassin du Pays de Galles dans un contexte de transtension [98] ; AC : orogénèse acadienne au Pays de Galles [98] (voir Fig. 13).

which the deformation front spread outwards, gradually deforming both northern and southern foreland-basin deposits. Complete incorporation of the foreland basins in the orogen most probably did not occur prior to the Late Pragian (*c.* 410 Ma). Notwithstanding the singularity of the cleavage and associated structures, there should be a significant age difference between structures in the Cambrian rocks in the central core and structures in the Silurian rocks in the periphery. This implies that absolute dates (ranging from ~450 Ma to ~370 Ma) currently available [2,3] are only local benchmarks in a long, diachronous tectonic history [24]. In particular, recent $^{40}Ar/^{39}Ar$ dating that suggests episodic tectonically-controlled metamorphic fluid circulation in the orogen during a period of at least 25 Ma (~425 tot ~400 Ma) corroborates the long-lived nature of the Brabantian orogeny [29].

5.3. What causes the Brabantian orogeny?

Palaeomagnetic evidence shows that the Midlands microcraton has undergone a 55° counter-clockwise rotation from Caradoc (*c.* 455 Ma) to Emsian (*c.* 400 Ma) [72] with respect to the Lake District (Fig. 13). This time span coincides remarkably well with the timing of the Brabantian orogeny, between at least *c.* 430 Ma and *c.* 400 Ma, hence suggesting a geodynamic link between both events (Fig. 12). Moreover, Sintubin and Everaerts [79] argue that the Midlands microcraton can be extended to the southeast in the subsurface of

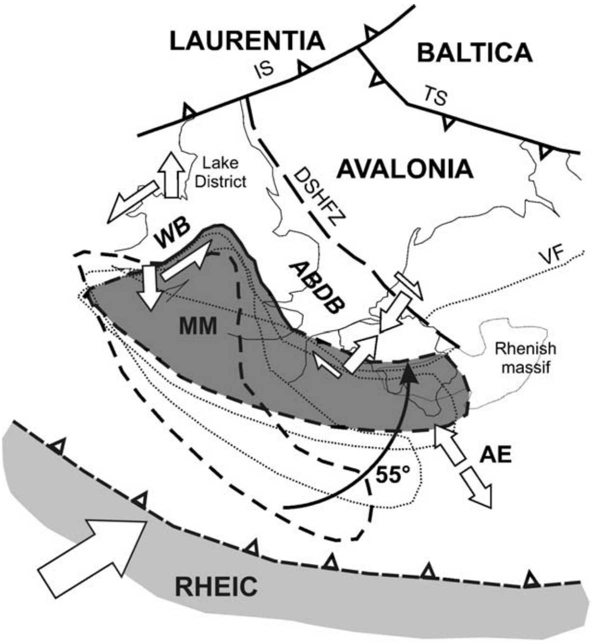

Fig. 13. Conceptual model for a ''Rheic cause'' for the Early Palaeozoic geodynamics in the Brabant-Ardenne region and adjoining regions (after [51,79,96,98]). VF: Variscan front; IS: Iapetus suture; TS: Tornquist suture; DSHFZ: Downsing-South Hewett fault zone; MM: Midlands microcraton; ABDB: Anglo-Brabant deformation belt; AE: Ardenne-Eifel basin; WB: Welsh basin.

Fig. 13. Modèle conceptuel de la « cause rhéique » de la géodynamique du Paléozoïque inférieur dans la partie méridionale d'Avalonia (d'après [51,79,96,98]). VF : front varisque ; IS : suture du Iapetus ; TS : suture du Tornquist ; DSHFZ : zone de failles Downsing-South Hewett ; MM : microcraton des Midlands ; ABDB : chaîne de déformation Anglo-Brabant ; AE: bassin de l'Ardenne-Eifel ; WB : bassin du Pays de Galles.

northern France and southern Belgium. This rotation drives a scissor-like convergence between different cratonic blocks (*i.e.* the Midlands microcration and the Lüneburg-North Sea microcraton; Fig. 1) causing the long-lived shortening across the Anglo-Brabant deformation belt, gradually decreasing from the southeast (*i.e.* the Brabant basement) to the northwest (*i.e.* Anglia Basin) (Fig. 13).

6. Early Palaeozoic geodynamics north of the Rheic ocean

The Rheic ocean originated when the peri-Gondwanan microcontinent Avalonia rifted off Gondwana. The opening of the Rheic ocean between Avalonia, Gondwana and other peri-Gondwanan microcontinents (*e.g.* Armorica) occurred during Cambrian-Ordovician times. In the Brabant basin, this rifting event is most probably reflected in the Early Ordovician hiatus, between Late Tremadoc (*c*. 485 Ma) and Early Arenig (*c*. 475 Ma), in the sedimentary record and the sudden change to a shallow shelf sedimentation (Fig. 12) [96]. This shelf environment persisted throughout the Ordovician and is characterised by a strongly reduced sedimentary sequence (*i.e.* megasequence II according to Verniers et al. [96]), suggesting a limited source area on the isolated Avalonia microcontinent (Fig. 12). Avalonia is commonly assumed to dock with Baltica by the end of the Ordovician (Ashgill, *c*. 450 Ma), closing the Tornquist Sea [93,96] (Fig. 12). By *c*. 420 Ma the Iapetus ocean starts to close when Baltica and Laurentia collide, causing the true ''Caledonian'' [60] Scandian orogeny. By the Late Emsian (*c*. 390 Ma) the closure of the Iapetus ocean will be completed to the south when Avalonia and Laurentia merge. By that time the ''Old Red Continent'', bordering the Rheic ocean to the north, has been assembled.

In this particular time span, between Late Tremadoc and Late Emsian, a number of events that are related to the geodynamic history of Avalonia, are recorded in the Brabant-Ardenne realm. In this sequence of events, the highly disputed, Late Ordovician ''Ardennian'' event can be excluded, as no direct geodynamic cause can be identified in the outlined Avalonian history. In Mid-Caradoc times (*c*. 460 Ma) the sudden appearance of turbidites [95] and large-scale slumping [20] in the Brabant basin suggest tectonic instability. This is followed by a short-lived, subduction-related, magmatic event during Latest Ordovician – Earliest Silurian time (*c*. 450 Ma), and the onset of a foreland basin development from the Late Llandovery (*c*. 430 Ma) onwards [96]. The foreland basin development shows that the Brabantian orogeny has already started. This long-lived event will dominate the geodynamic history in the Brabant-Ardenne realm for more than 30 Ma until Late Emsian times. During the Brabantian orogeny continental rifting occurred in the southwestern foreland of the developing orogen (*i.e.* Ardenne-Eifel area). This continental rifting started in the Late Silurian (*c*. 420 Ma) and terminated by the end of the Emsian (*c*. 395 Ma), when a rift-to-drift transition occurred more basinwards, opening the Rhenohercynian ocean [68] (Fig. 12). In the Brabant-Ardenne region the subsequent Middle Devonian post-rift carbonate platform sedimentation on the northern passive margin of the Rhenohercynian basin, marks the end of the Early Palaeozoic history, as documented by the Brabantian unconformity (Fig. 12).

The Avalonia-Baltica docking may have initiated geodynamic activity within the Avalonian microcontinent. Indirectly, this docking may have triggered the sequence of events happening in the southern extremity of the Avalonian microcontinent (Fig. 12). The area of interest is, however, situated at the southern margin of the microcontinent, facing the Rheic ocean, at a distance of more than 500 km from the Tornquist suture zone (Figs. 1 and 13), now exposed in the Heligoland-Pomerania deformation belt [96,97], also known as the North German-Polish "Caledonides". The counter-clockwise rotation of the Midlands microcratonic block is considered the direct driving mechanism of the Brabantian orogeny (Fig. 13). This rotation may very well be driven from the Rheic ocean to the south, in accordance with the postulated Rheic cause for the Middle Devonian, "Acadian" deformation in Wales and England by Woodcock et al. [98] (Fig. 12). The counter-clockwise rotation of the triangular-shaped microcratonic block may also explain the coincidence during the Early Devonian of the Brabantian orogeny on the northeastern side of the rotating microcraton, in a contractional/transpressional setting, and the development of the Welsh basin on the northwestern side of the rotating microcraton, in an extensional/transtensional setting [83], and even the transpression in Northwest England (Lake District), situated at the apex of the triangular microcraton [82,84] (Figs. 12 and 13).

The cause of this "push from the south" remains highly speculative. Different models are proposed:

- the impingement of Armorica [84,85] or of the Armorican promontory of Gondwana [51];
- the accretion of an island arc to the Laurentian margin of the Rheic ocean [59];
- the flat-slab subduction of the Rheic oceanic lithosphere underneath the Laurussian-Avalonian margin [98].

In the model of Woodcock et al. [98] the flat-slab subduction is driving the Middle Devonian "Acadian" shortening in Wales and England. In our model, however, the episode of flat-slab subduction would occur earlier, in the Early Devonian, driving the rotation of the Midlands microcraton and hence the Brabantian orogeny and the transtension in Welsh basin (and the Rhenohercynian extension, see below) (Figs. 12 and 13). The "Acadian" shortening in Wales and England should have another driving mechanism, possibly related to the activation of the Bristol Channel dextral fault zone, heralding the final closure of the Rheic ocean during the Late Devonian [98].

The Brabant-Ardenne region also holds a key to resolution of the Rheic-Rhenohercynian controversy. The Early Devonian Ardenne-Eifel rift basin indeed develops coevally with the Brabantian orogeny (Fig. 12). Rifting started in Late Silurian times (*c.* 420 Ma), possibly documented by the Ardennian unconformity [88], reached its peak during the Pragian and ended in Late Emsian times (*c.* 395 Ma) when a rift-to-drift transition basinwards created the Rhenohercynian ocean [68] and transformed the Ardenne-Eifel region into a passive margin platform (*i.e.* Dinant platform). Exactly at that time the Burnot conglomerates, the final erosional product of the Brabant orogen, were deposited on this Rhenohercynian passive margin (Fig. 12). This provenancial linking of the Brabant orogen and the Ardenne-Eifel basin precludes any large translational movements along the southern margin of Avalonia and pin-points the spatial relationship between the Rheic and Rhenohercynian oceans in the area under consideration. Both Kroner et al. [51] and Woodcock et al. [98] indeed suggest a supra-subduction zone setting for the Rhenohercynian ocean in the upper plate of the subducting Armorican promontory [51] or Rheic oceanic lithosphere [98]. Moreover, the rotating Midlands microcraton may again be the driving mechanism of the opening of the Rhenohercynian ocean. The Ardenne-Eifel area – in its original Early Palaeozoic position – may very well be situated in the "hinterland" on the southern/southwestern side of the rotating microcratonic block, hence in an extensional setting (Fig. 13). The latter also applies to Southwest England in its Early Palaeozoic configuration, *i.e.* in line with the Ardenne-Eifel region [98].

7. Conclusions

Based on recent research results of the Early Palaeozoic geodynamics in the Brabant-Ardenne region the following conclusions can be made:

- the so-called Late Ordovician "Ardennian" event remains enigmatic, although more and more evidence indicates that a major orogenic event is most unlikely; the time constraints commonly used in literature are, moreover, no longer valid;
- the Ardennian unconformity seemingly only represents a tilting of basement strata; this unconformity may very well be the result of a Late Silurian extensional event related to the Ardenne-Eifel rift basin development;
- the "Brabantian" orogeny is a long-lived, highly diachronous, Early Devonian event, resulting from the tectonic inversion of a Cambrian rift basin due to the convergence of cratonic blocks composing the Avalonian microcontinental assemblage;

- the "Brabantian" orogeny coincides with the Ardenne-Eifel rift basin development; a provenancial link (i.e. the Burnot conglomerate) precludes any large translational movements between both tectonic domains.

These spatial and temporal constrains can furthermore be placed within the geodynamic framework of southern Avalonia. It is inferred that the rotation of the Midlands microcraton is the driving mechanism of the Brabantian orogeny. This rotation may explain the coincidence between shortening in Brabant and Anglia (Anglo-Brabant deformation belt), transtension in England and Wales, and extension/transtension in the Ardenne-Eifel and SW England (Rhenohercynian ocean). A Rheic cause is postulated. Tectonic activity along the Laurentian-Avalonian active margin, as proposed in different models (*e.g.* [51,59,98]), induces a complex tectonic scenario in the upper plate, generating both the Brabantian orogeny and the Ardenne-Eifel basin development. Eventually, the Early Palaeozoic geodynamics in the Brabant-Ardenne region links, both in space and time, the Rheic and Rhenohercynian ocean.

Finally, the Early Palaeozoic events north of the Rheic suture, exposed in the Brabant-Ardenne region, should no longer be considered as part of the Caledonian orogeny [60], but as the first episodes of the Variscan orogeny, as also suggested by Woodcock et al. [98].

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