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Stratigraphie / Stratigraphy

Reworked acritarchs as provenance indicators in the Lower Palaeozoic of Denmark

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Abstract – Profuse and well-preserved acritarchs were recovered from subsurface Lower Palaeozoic successions cored by the boreholes Slagelse-1 and Pernille-1 (Danish–North German Basin). Together with Llandovery in situ microphytoplankton, reworked Cambrian and Ordovician species occur. The reworked Ordovician acritarchs show a clear Perigondwanan palaeobiogeographic affinity and indicate clastic sedimentary input from a Perigondwanan-related terrane located south of the East European Platform. Microfloral similarity enables identification of the detrital source area with the Avalonia Terrane. The present data also suggest that development of a foreland basin marginal to the Caledonian Deformation Front in the Danish–North German Basin started in Early Silurian times. © 2001 Académie des sciences / Éditions scientifiques et médicales Elsevier SAS

Acritarchs / Danish–North German Basin / foreland basin / Lower Silurian / Ordovician

Résumé – Acritarches remaniés comme indicateurs de provenance dans le Paléozoïque inférieur du Danemark. Des acritarches nombreux et bien conservés ont été trouvés dans deux sondages du Paléozoïque inférieur, Slagelse-1 et Pernille-1 (bassin Danemark–Allemagne du Nord). Des acritarches cambriens et ordoviciens remaniés, d'affinités périgondwaniennes, accompagnent un microphytoplancton d'âge Llandovery in situ. Les palynomorphes remaniés indiquent un apport de sédiments provenant de l'érosion d'un microcontinent périgondwanien situé au sud de la Plateforme est-européenne. Les affinités du microplancton permettent de localiser la région source dans Avalonia. Les données actuellement disponibles indiquent que la formation d'un bassin d'avant-pays bordant la front de déformation calédonien dans le bassin Danemark–Allemagne du Nord a commencé au Silurien inférieur. © 2001 Académie des sciences / Éditions scientifiques et médicales Elsevier SAS

acritarches / bassin Danemark–Allemagne du Nord / bassin d'avant-pays / Silurien inférieur / Ordovicien

Version abrégée

1. Introduction

Des recherches palynologiques détaillées sur le Paléozoïque inférieur de la région située dans le secteur est du Bassin norvégo-danois ainsi que dans la partie sud de la mer Baltique (région de l'île de Bornholm) ont récemment été entreprises dans le cadre du Programme PACE (*Palaeozoic Amalgamation of Central Europe*), dont les objectifs sont (1) d'élaborer une subdivision plus détaillée des successions sédimentaires allant du Cambrien au Silu-

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rien, (2) de faciliter les reconstitutions paléogéographiques et (3) d'acquérir une meilleure connaissance de l'évolution géodynamique paléozoïque de la partie septentrionale de la Zone de suture trans-européenne.

Le premier résultat nous permet de décrire des acritarches siluriens bien préservés et des assemblages de prasinophytes provenant des sondages Slagelse-1 et de Pernille-1 situés à la bordure sud-ouest de la Plate-forme est-européenne. Ces assemblages sont caractérisés par la présence d'acritarches remaniés d'âges Cambrien supérieur et Ordovicien inférieur, d'affinités gondwaniennes. Nous suggérons que ces acritarches proviennent d'une région soumise à l'érosion pendant l'Ashgill, au début de la collision Avalonia–Baltica.

2. Conditions géologiques et stratigraphiques

Les sondages Slagelse-1 (lat. 55°22′2″ N, long. 11°22′42″ E) et Pernille-1 (lat. 55°00′53″ N, long. 14°18′43″ E) pénètrent les successions sédimentaires principalement siliciclastiques du Paléozoïque inférieur, dans une région que l'on rapporte à la zone de suture trans-européenne (*Trans European Suture Zone*) (*figure 1*). Le sondage Slagelse-1 a atteint des couches du Cambrien inférieur [5], après avoir recoupé une épaisse série de quelques 400 m allant du Cambrien jusqu'au Silurien inférieur. Poulsen [5] distinguait quatre intervalles dans le Paléozoïque inférieur du sondage Slagelse-1, avec, de bas en haut : 2 972–2 944 m, Cambrien inférieur ; 2 944–2 917 m, *Alum Shale*, Cambrien supérieur– ?Ordovicien inférieur ; 2 917–2 637 m « grey shale and siltstone series », Silurien. À cause de la présence de graptolites typiques de la zone de *Monograptus crispus*, Poulsen [5] attribuait l'intervalle 2 811–2 637 m au Llandovery inférieur.

Dans le sondage Pernille-1, le Paléozoïque inférieur est seulement représenté par 47 m de schistes siluriens, entre 3 624 et 3 217 m (zone de *Cyrtograptus ellesae*, fin du Wenlock inférieur) ; à ce niveau, la succession silurienne est tronquée par une surface d'érosion correspondant à la base de dépôts permiens.

Dans l'ensemble, la stratigraphie du Paléozoïque inférieur des sondages étudiés est conforme à la succession de l'île de Bornholm et à celle du sondage G-14 au sud-ouest. La succession du Paléozoïque inférieur augmente en épaisseur vers l'est, c'est-à-dire de Slagelse-1 vers le sondage G-14 (*figure 2*). Du point de vue paléogéographique, les sondages Slagelse-1, Pernille-1 et G-14 se situent à la bordure sud-ouest de la plate-forme balte ; le sondage G-14 atteint des roches cristallines datées à 1 450 Ma, ce qui indique le caractère autochtone des successions sédimentaires [12].

3. Palynologie

Trois échantillons renfermaient des assemblages bien conservés, comportant des espèces d'acritarches en grand nombre ainsi que quelques rares prasinophytes. Pour la liste complète des acritarches et des prasinophytes, voir le texte en anglais (les formes remaniées sont signalées par un astérisque).

On peut diviser les palynomorphes en deux grandes catégories. L'une se caractérise par un assemblage homogène, appartenant au début du Silurien, et l'autre par des formes remaniées, qui se distinguent par leur état de conservation et leur couleur et dont l'âge, dans un même échantillon, va du Cambrien supérieur–Tremadoc inférieur jusqu'à l'Ordovicien supérieur.

Les assemblages de palynomorphes non remaniés sont très comparables dans les deux sondages et indiquent un âge Llandovery–Wenlock, ce qui est conforme aux données des graptolites [5, 15]. Parmi les espèces les plus importantes du point de vue chronostratigraphique, *Ammonidium microcladum* et *Visbysphaera brevifurcata* sont des composants typiques des assemblages d'acritarches siluriens, décrits en Suède [3], en Angleterre [2] et en Belgique [10].

Les formes remaniées comprennent des espèces typiques de différents intervalles stratigraphiques (*Cristallinium cambriense*) et d'autres formes, comme *Acanthodiacrodium* cf. *ubui*, sont connues dans des dépôts du Cambrien supérieur–Ordovicien inférieur, dans le monde entier [13]. La majorité des palynomorphes remaniés appartient à des espèces d'âge Ordovicien moyen (Arenig–Llanvirn), comme *Arkonia virgata*, des espèces de *Frankea*, *Stelliferidium striatulum* et *Striatotheca quieta*. Ce sont des composants caractéristiques du microplancton de la province péri-gondwanienne, clairement distincte à l'Ordovicien moyen de la province balte [11]. *Villosacapsula setosapellicula* est une espèce typique de l'Ordovicien supérieur, que l'on trouve dans les dépôts de l'Ashgill de l'Amérique du Nord, d'Europe centrale, d'Afrique du Nord et du Moyen-Orient [13].

4. Discussion

La formation des Calédonides du Danemark–Nord de l'Allemagne–Pologne est associée généralement à la collision du microcontinent Avalonia avec Baltica. À la bordure de la *Thor Suture* (front de déformation calédonien) se formait un bas-fond ; les successions du Silurien supérieur très épaisses au bord sud-ouest de la plate-forme balte (y compris la partie nord du Danemark, Scania et la région du Cattégat) sont considérées comme le remplissage principal de ce bassin à subsidence rapide [7].

Dans les couches du Silurien du bassin du Danemark–Nord de l'Allemagne, on trouve des acritarches remaniés, d'âge Ordovicien moyen et d'affinité paléogéographique péri-gondwannienne. Si l'on accepte le scénario esquissé plus haut, cela signifierait que le type de sédimentation d'avant-pays s'est manifesté activement dès le Silurien inférieur. Les données actuelles montrent qu'au Llandovery, la plate-forme balte fut couverte de sédiments clastiques très fins, produits par l'érosion d'une région plissée lors de la collision entre Baltica et un « terrane » péri-gondwanien (*figure 3*). Les similitudes entre les acri-

tarches remaniés et ceux de l'Ordovicien moyen en Allemagne, en Belgique, en Angleterre et au Pays de Galles sont en faveur d'une identification de ce « terrane » périgondwanien avec le microcontinent Avalonia. Plus précisément, la source de ces acritarches remaniés pourrait être, par exemple, l'Ordovicien de Rügen ou celui de Poméranie, régions généralement considérées comme les parties est d'Avalonia [8]. On peut noter que des assemblages d'acritarches remaniés d'affinité gondwanienne et semblables à ceux décrits dans la présente étude ont aussi été trouvés dans le sondage G-14, dans des sédiments de l'Ashgill inférieur [7]. Ces résultats confortent l'idée que la collision entre Avalonia et Baltica et la formation d'un bassin de type avant-pays se sont produites au plus tard, dans le Silurien inférieur et probablement, dès l'Ashgill moyen, mais certainement après le Caradoc moyen [14].

5. Conclusions

1. Des acritarches et des prasinophytes ont été récoltés en grande quantité dans les sondages Slagelse-1 et Pernille-1 (bassin du Danemark et Allemagne du Nord), ce qui a permis d'attribuer ces carottes de sondage au Llandovery et Wenlock inférieur.
2. Des acritarches ordoviciens remaniés, d'affinité paléobiogéographique péri-gondwanienne, accompagnent le microphytoplancton trouvé in situ dans les échantillons étudiés.
3. Les palynomorphes remaniés témoignent en faveur d'une sédimentation fine d'origine péri-gondwanienne (Avalonia est) pendant le Silurien inférieur. Ceci implique que le développement d'un bassin d'avant-pays avait déjà commencé au bord sud de la plate-forme européenne orientale au cours du Silurien inférieur.

1. Introduction

The present paper summarizes a preliminary palynological investigation of parts of the Lower Palaeozoic successions penetrated by exploratory wells in the subsurface of Denmark. Although the Lower Palaeozoic stratigraphy of the area has been the subject of relatively numerous studies in the past [4, 5, 15], detailed chronostratigraphy and accurate correlation among the various subsurface sections are still to be achieved. Results from unpublished palynological analysis of the Ordovician–Silurian successions of Terne-1 borehole were briefly mentioned by Michelsen and Nielsen [4]; palynological analyses of further boreholes (e.g., Pernille-1) have been carried out by commercial service companies, but the results are often in the form of unpublished and sketchy reports.

A comprehensive palynological investigation of the Lower Palaeozoic rocks of the area comprising the eastern sector of the Norwegian-Danish Basin and the southern Baltic Sea (area of Bornholm Island) is currently being carried out in the framework of the EU-funded PACE (Palaeozoic Amalgamation of Central Europe) research network, with the aims of: (1) establishing a refined biostratigraphic subdivision of the Cambrian through Silurian subsurface sedimentary successions, (2) facilitating palaeogeographic reconstruction, and (3) increasing the knowledge of the Palaeozoic geodynamic evolution of the northern section of the Trans-European Suture Zone.

The present first results permit to describe very well preserved Early Silurian acritarch and prasinophyte assemblages from the Slagelse-1 and Pernille-1 sections. These assemblages are characterized by the presence of reworked acritarchs of Late Cambrian and Ordovician ages, which give clear indications of sediment provenance from a Perigondwanan detrital source. We suggest here that these reworked acritarchs were transported onto the south-western margin of the East European Platform (EEP) from a corrugated and eroding area, formed during the start of the Avalonia–Baltica collision in Middle Ashgill times.

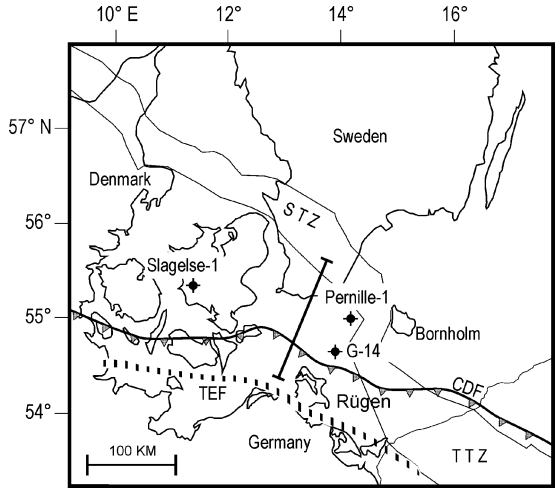

Figure 1. Geographic setting and location of wells Slagelse-1, Pernille-1 and G-14. **CDF**: Caledonian Deformation Front. **TEF**: Trans-European Fault. **TTZ**: Teisseyre–Tornquist Zone. **STZ**: Sorgenfrei–Tornquist Zone.

Figure 1. Situation géographique et localisation des sondages Slagelse-1, Pernille-1 et G-14. **CDF** : Caledonian Deformation Front. **TEF** : Trans-European Fault. **TTZ** : Teisseyre–Tornquist Zone. **STZ** : Sorgenfrei–Tornquist Zone.

2. Geological setting and stratigraphy

The boreholes Slagelse-1 (western Sealand; lat. 55°22′2″ N, long. 11°22′42″ E) and Pernille-1 (off-

shore of Bornholm Island; Lat. 55°00′53″ N, Long. 14°18′43″ E) penetrate Lower Palaeozoic, mainly siliciclastic sedimentary successions in the area known as the Norwegian-Danish Basin [4], or as the 'Danish Embayment' [5]. This area is part of the so-called Trans-European Suture Zone, representing the transition from the Proterozoic Baltic Shield to the younger lithospheric domains of Central Europe affected by the Cadomian and Variscan orogenies (*figure 1*). The Slagelse-1 borehole reached the Lower Cambrian in its deepest part [5], cutting a ca 400 m thick, almost continuous Cambrian through Lower Silurian section. Poulsen [5] distinguished four different intervals in the Lower Palaeozoic succession of the Slagelse-1 borehole (from bottom to top): 2 972–2 944 m, Lower Cambrian; 2 944–2 917 m 'Alum Shale', Upper Cambrian–?Lower Ordovician; 2 917–2 637 m 'grey shale and siltstone series', Silurian. On the basis of the presence of graptolites typical of the *Monograptus crispus* Zone, the interval 2 811–2 637 m was attributed to the Upper Llandovery [5]. The interval 2 917–2 811, devoid of macrofossils, was tentatively referred to the Lower Llandovery [5].

In the Pernille-1 borehole, the Lower Palaeozoic is represented only by 47 m of Silurian shales, between 3 624 m (bottom depth) and 3 217 m; at this level, the Silurian succession is truncated by an erosional surface basal to Permian deposits. The Silurian shales have been attributed to the *Cyrtograptus ellesae* graptolite Zone, of Late–Early Wenlock age [15].

On the whole, the Lower Palaeozoic stratigraphy of the present boreholes can be directly correlated to the succession of the G-14 borehole section, offshore Bornholm Island, and to the classical Lower Palaeozoic successions exposed on Bornholm (*figure 2*). The Cambrian is represented by shallow marine clastic successions followed by thinner shallow marine black shale deposits (Upper Cambrian–Arenig; Alum Shales); the Ordovician consists of a few tens of meters of fine clastic, carbonate-rich sediments, followed by relatively thick (up to ca 300 m) organic-rich shales of Silurian age. The Lower Palaeozoic succession increases in overall thickness towards the east, i.e., from the Slagelse-1 to the G-14 borehole (*figure 2*). Palaeogeographically, the Slagelse-1, Pernille-1, and G-14 sections are located at the south-western margin of the Baltic platform; the G-14 borehole reached the crystalline rocks, dated to ca 1450 Ma, thus showing that the sedimentary successions are autochthonous with respect to the Baltic Shield [12].

3. Material and methods

Four core samples from the Slagelse-1 borehole between 2 640.00 and 2 815.15 m, and four core samples from the Pernille-1 borehole between 3 615.0 and 3 264.5 m were processed by means of a standard palynological procedure, involving maceration of the rock samples in HCl and HF, and successive removal of fine (< 10 μm) residual debris by filtering. No oxidation or density separation were performed on the resulting organic-rich residue. The residue was characterized by abundant framboidal pyrite crystals, which in some cases were formed inside the vesicle of palynomorphs. Only one sample from the Slagelse-1 well (sample Slag-1/2814) and two samples from the Pernille-1 borehole (Pe-1/3623 and Pe-1/3620), proved palyniferous. Abundant and well-preserved acritarchs and prasinophytes were particularly represented in sample Slag-1/2814.

4. Palynology

The three fossiliferous samples yielded well-preserved palynomorph assemblages comprising numerous acritarch species and rare prasinophytes. The palynomorphs can be separated in two main groups, one characterized by an homogeneous assemblage of Early Silurian age, and the other by reworked forms of Late Cambrian to Late Ordovician age. The occurrence of identified species in each one of the palyniferous samples is discussed below; reworked palynomorphs are indicated with an asterisk.

5. Sample slag-1/2814

This sample contains the richest and most diverse microphytoplankton assemblage, in good state of preservation. The following species were recognised:

Class Prasinophyceae Christensen, 1962
Cymatiosphaera sp. aff. *C. cornifera* Deunff, 1955; *Pterospermopsis* sp. cf. *P. martinii* Cramer, 1967; *Leiosphaeridia* spp.

Group Acritarcha Evitt, 1963
Acanthodiacrodium sp. cf. *A. ubui* Martin, 1969*; *Ammonidium microcladum* (Downie) Lister, 1970; *Arkonia virgata* Burmann, 1970*; *Cristallinium cambriense* (Slaviková) Vanguestaine, 1978*; *Comasphaeridium* sp. cf. *C. hirtum* Le Hérissé, 1989; *Domasia limaciforme* (Stockmans & Willière) Cramer, 1970; *Dictyotidium dictyotum* (Eisenack) Eisenack, 1955; *Estiastra* sp.; *Evittia remota* (Deunff) Lister, 1970; *Evittia robustispinosa* (Downie) Lister, 1970; *Evittia sanpetrensis* (Cramer) Lister, 1970; *Eupoikilofusa striatifera typica* Cramer & Diez, 1272; *Frankea sartbernardensis* (Martin) Colbath, 1986*; *Frankea breviuscula* Burmann, 1970*; *Frankea hamata* Burmann, 1970*; *Helosphaeridium* sp. 1; *Multiplicisphaeridium cladum* (Downie) Eisenack, 1969; *Multiplicisphaeridium paraguaferum* (Cramer) Eisenack,

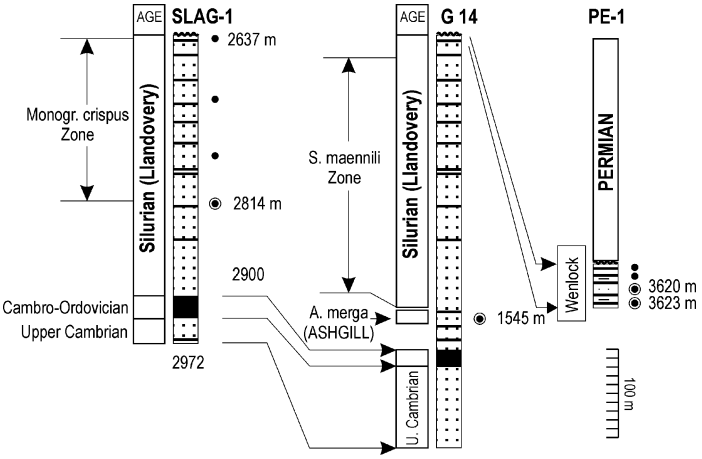

Figure 2. The Slagelse-1, Pernille-1, and G-14 wells: lithologic logs with location of the study samples, biostratigraphy, biostratigraphic correlation and age. The well G-14 is shown for comparison; biostratigraphic dating of this borehole by Samuelsson et al. [10]. ◉ = samples containing reworked acritarchs.

Figure 2. Les sondages Slagelse-1, Pernille-1, and G-14 : colonne lithologique avec la position des échantillons étudiés, la biostratigraphie, la corrélation biostratigraphique et l'âge. Le sondage G-14 est reproduit pour les besoins de la comparaison ; datation biostratigraphique par Samuelsson et al. [10]. ◉ = échantillons contenant des acritarches redéposés.

Cramer & Diez, 1973; *Oppilatala* sp. cf. *O. ramusculosa* (Cramer & Diez) Le Hérissé, 1989; *Polygonium* spp.; *Stelliferidium striatulum* (Vavrdová) Deunff, Górka & Rauscher, 1974*; *Striatotheca quieta* (Martin) Rauscher, 1974*.

Tunisphaeridium sp. cf. *T. parvum* Deunff & Evitt, 1968; *Tylotopalla caelamenicutis* Loeblich, 1970; *Veryhachium* spp.; *Villosacapsula setosapellicula* (Loeblich) Loeblich & Tappan, 1976*; *Visbysphaera brevifurcata* (Eisenack) Le Hérissé, 1989.

6. Samples Pe-1/3623 and Pe-1/3620

These two samples yielded virtually identical acritarch assemblages in which the following species have been recognized (asterisk indicates reworked forms):

Ammonidium microcladum (Downie) Lister, 1970; *Arkonia virgata* Burmann, 1970*; *Domasia* sp. cf. *D. limaciforme* (Stockmans & Willière) Cramer, 1970; *Evittia remota* (Deunff) Lister, 1970; *Evittia robustispinosa* (Downie) Lister, 1970; *Frankea sartbernardensis* (Martin) Colbath, 1986*; *Frankea breviuscula* Burmann, 1970*; *Multiplicisphaeridium cladum* (Downie) Eisenack, 1969; *Multiplicisphaeridium paraguaferum* (Cramer) Eisenack, Cramer & Diez, 1973; *Oppilatala* sp. cf. *O. ramusculosa* (Cramer & Diez) Le Hérissé, 1989; *Stelliferidium striatulum* (Vavrdová) Deunff, Górka & Rauscher, 1974*; *Striatotheca quieta* (Martin) Rauscher, 1974*; *Tylotopalla* sp.; *Visbysphaera brevifurcata* (Eisenack) Le Hérissé, 1989.

Although of different ages (Llandovery in the Slagelse section and Wenlock in the Pernille section), the above assemblages are closely comparable palynologically. All the *in situ* acritarch species are well compatible with a Llandovery–Wenlock age. The presence of *Domasia limaciforme* in sample Slag-1/2814 is more indicative of a Llandovery age for this sample (in accordance with graptolite data). Forms similar to *D. limaciforme* occur also in samples Pe-1/3623 and Pe-1/3620, suggesting an Early Wenlock age for the associated sediments.

Together with in situ palynomorphs of Early Silurian age, reworked acritarch species characteristic of older ages, ranging from Late Cambrian–Early Tremadocian, through Late Ordovician, occur. These reworked forms can generally be distinguished from the *in situ* ones, for their comparatively poorer preservational state; that is, corrosion of the vesicle, broken appendices, and either much darker or much lighter colour. In some cases, however, the preservation of the reworked forms is remarkably good, and fine details of vesicle sculpturing are still visible (e.g., very small bacula on the vesicle of specimens of *Villosacapsula setosapellicula*; striations and rugulae on the vesicle of some specimens of *Striatotheca* and *Arkonia* spp.). The *in situ* species are all always very well preserved, light to dark brown in colour, rarely black (due to vesicle wall thickness; i.e., *Visbysphaera brevifurcata*).

Among the most important species from a chronostratigraphic point of view, *Ammonidium microcladum*, *Domasia limaciforme*, *Evittia robustispinosa*, *Multiplicisphaeridium cladum*, *Tylotopalla caelamenicutis*, and *Visbysphaera brevifurcata* are typical components of Lower Silurian (Llandovery–Wenlock) acritarch assemblages described from Sweden [3], England [2], and Belgium [10]. The palynological dating is also in good agreement with the chronostratigraphic evidence from the graptolites of the Slagelse-1 and Pernille-1 boreholes [5, 15].

The prasinophyte species, only found in sample Slag-1/2814, are less significant from a chronostratigraphic point of view. The species *Cymatiosphaera cornifera* Deunff, 1955, is typically present in Devonian sediments. Our specimens (attributed to *C.* sp. aff. *C. cornifera*), are morphologically similar to the latter, but probably represent a different species, hence our using the open nomenclature. *Pterospermopsis* sp. cf. *P. martini* Cramer, 1967, and *Leiospha-*

eridia spp. give no useful biostratigraphic information.

The reworked forms include species characteristic of different chronostratigraphic intervals. *Cristallinium cambriense* and other forms such as *Acanthodiacrodium* cf. *ubui* are known from Upper Cambrian–Lower Ordovician deposits of various worldwide localities [13]. The most abundant reworked palynomorphs are species of Middle Ordovician age (Arenig–Llanvirn) such as *Arkonia virgata*, species of *Frankea*, *Stelliferidium striatulum*, and *Striatotheca quieta*. These are also characteristic components of the peri-Gondwanan microphytoplankton province, as opposed to the Baltic province, clearly distinguishable in Middle Ordovician times [11]. *Villosacapsula setosapellicula* is a typical Upper Ordovician acritarch species occurring in Ashgill deposits of North America, central Europe, North Africa, and the Middle East [13].

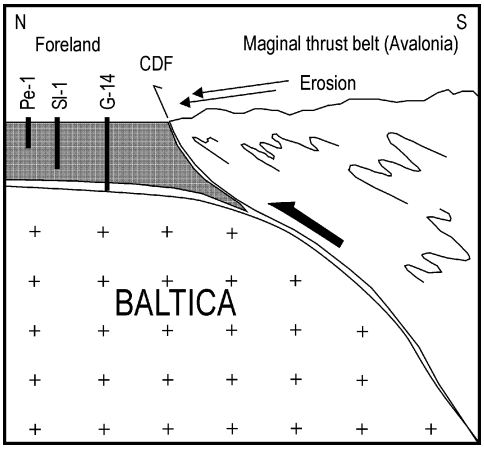

Figure 3. Geodynamic interpretation: hypothetical simplified cross section across the CDF with projected position of study boreholes. Modified after Dallmeyer et al. [1].

Figure 3. Interprétation géodynamique : coupe transversale à travers la CDF, avec position des forages étudiés. Modifié d'après Dallmeyer et al. [1].

7. Discussion

The formation of the Danish–North German–Polish Caledonides is generally interpreted to be associated with the collision between Baltica and the microcontinent Avalonia, which originated in Late Cambrian to Early Ordovician times from the fragmentation of the northern margin of Gondwana. Marginally to the Thor Suture (formerly known as the Caledonian Deformation Front), a foreland basin developed; the thick Upper Silurian successions present at the southwestern margin of the Baltic Platform (including North Denmark, Scania, and the Kattegat area) are thought to represent the main filling of this rapidly subsiding basin [7].

In this geodynamic scenario, the presence of Middle Ordovician reworked acritarchs of clear Perigondwanan palaeobiogeographical affinity in Llandovery–Wenlock strata of the Danish–North German basin suggests that in this region, foreland-type sedimentation was active at least since the Early Silurian. The present data show that in Llandovery times the Baltic Platform was receiving fine-clastic sediments originated by the erosion of a corrugated area formed consequently to the collision between Baltica and a Gondwana-derived terrane (*figure 3*). The similarity between the reworked acritarchs discussed here and the acritarch flora described from Middle Ordovician deposits of Germany, Belgium, England and Wales favours the identification of this Gondwana-derived terrane with the Avalonia microcontinent. The intensely tectonized Ordovician clastic successions present, e.g., in the subsurface of the island of Rügen, NE Germany, have been interpreted as an accretionary prism thrusted onto the southwestern border of the Baltic Platform during the Avalonia–Baltica collision [7, and references therein]. Palaeogeographically, the Ordovician of Rügen can be attributed to the easternmost extension of Avalonia [8, 9, 14]. Accordingly, it is reasonable to think that the source area of the reworked acritarchs corresponds to the Ordovician of Rügen, where Lower to Middle Ordovician acritarchs closely comparable to the reworked microflora of the Slagelse-1 and Pernille-1 boreholes occur [8], or another area, such as Pomerania (North Poland) which also formed part of the 'Danish–North German–Polish Caledonides'.

Reworked acritarch assemblages of Perigondwanan affinity, similar to those described in the present study, were found also in the G-14 borehole in sediments as old as Middle Ashgill [7]. The latter borehole (*figures 1* and *2*) penetrates a complete Cambrian through Early Silurian (Llandovery) clastic succession, deposited at the southwestern border of the EEP, thus directly correlatable to the sections Slag-1 and Pernille-1. In the G-14 section, Late Ordovician (Middle Ashgill) sediments containing reworked acritarchs have been precisely dated by means of chitinozans [7].

The present results thus corroborate the idea that the Avalonia–Baltica collision occurred not later than the Early Silurian, and that foreland-basin formation started in Middle Ashgill times, certainly not earlier than Middle Caradoc [14].

The presence of reworked acritarchs typical of Upper Cambrian and Upper Ordovician sediments are less indicative in terms of sediment provenance. During Late Cambrian times Baltica was located at high southern palaeolatitudes, close to the northern border of Gondwana, and the two palaeocon-

tinents shared essentially similar microphytoplankton communities. The Late Ordovician species *Villosacapsula setosapellicula* is particularly interesting, being recorded frequently in numerous localities worldwide, such as North America (Laurentia), Great Britain (Avalonia), the North Sahara Platform and the Arabian peninsula (North Gondwana). This species is also commonly found as a reworked element in younger sediments in central Europe (Bohemia) and North Africa. In this latter case, the reworking of Ashgill sediments into younger deposits can be explained with an uplift and erosion of the southern circum-polar regions caused by isostatic rebound linked to the Late Ordovician deglaciation process. This possibility however, can be excluded as an explanation for the presence of reworked specimens of *Villosacapsula setosapellicula* in the Silurian sediments of the Avalonia–Baltica borderland, because of the southern subtropical palaeogeographic position of this region during Late Ordovician times. The common occurrence of *V. setosapellicula* in North American and central European localities, however, does support the existence of microphytoplankton exchanges between the Tornquist and Iapetus palaeoceans, thus suggesting palaeogeographical proximity between Laurentia, Avalonia and Baltica during the Late Ordovician. Recovered chitinozoan assemblages in the G-14 borehole and from the Brabant Massif, Belgium, corroborate this conclusion [6, 7].

8. Conclusions

1. Abundant and well preserved acritarch and prasinophyte floras were recovered from the Slagelse-1 and Pernille-1 boreholes (Danish-North German Basin), enabling datings of the cored successions to the Llandovery and Early Wenlock.
2. Reworked acritarchs of Late Cambrian through Late Ordovician age and Perigondwanan palaeobiogeographic affinity occur together with in situ microphytoplankton.
3. The reworked palynomorphs testify to fine sediment input from an uplifted Perigondwanan source-area (eastern Avalonia) in the Lower Silurian clastic successions of the study area, thus suggesting that foreland basin development at the southern margin of the East European Platform was already active during Early Silurian times.

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References

[1] Dallmeyer R.D., Giese U., Glasmacher U., Pickel W., First $^{40}Ar/^{39}Ar$ age constraints for the Caledonian evolution of the Trans-European Suture Zone in NE Germany, J. Geol. Soc. London 156 (1999) 279–290.

[2] Hill P.J., Stratigraphic palynology of acritarchs from the type area of the Llandovery of the Welsh borderland, Rev. Palaeobot. Palynol. 18 (1974) 11–23.

[3] Le Hérissé A., Acritarches et kystes d'algues Prasinopycées du Silurien de Gotland, Suède, Palaeontographia Italica 76 (1989) 57–302.

[4] Michelsen O., Nielsen L.H., Well records on the Phanerozoic stratigraphy in the Fennoscandian Border Zone, Denmark, Danmarks geol. Unders., ser. A 29 (1991) 1–37.

[5] Poulsen C., Further contributions to the knowledge of the Palaeozoic of Slagelse No. 1, Western Sealand, Danmarks geol. Unders., II Ser. 101 (1974) 1–72.

[6] Samuelsson J., Verniers J., Ordovician chitinozoan biozonation of the Brabant Massif, Belgium, Rev. Palaeobot. Palynol. 113 (2000) 105–129.

[7] Samuelsson J., Vecoli M., Beier H., Ordovician–Silurian palynostratigraphy (Chitinozoa and acritarchs) of the G 14-1/86 borehole, southern Baltic Sea, N. Jb. Geol. Paläont. Mh. (in press).

[8] Servais T., The Ordovician acritarchs from Rügen (NE-Germany): palaeobiogeographical evidence for the attribution to Eastern Avalonia, N. Jb. Geol. Paläont. Mh. 9 (1994) 566–580.

[9] Servais T., Fatka O., Recognition of the Trans-European Suture Zone (TESZ) by the palaeobiogeographical distribution pattern of Early to Middle Ordovician acritarchs, Geol. Mag. 134 (1997) 617–625.

[10] Stockmans F., Willière Y., Les Hystrichosphères ou mieux les Acritarches du Silurien belge, Sondage de la brasserie Lust à Courtrai, Kortrijk, 1963.

[11] Tongiorgi M., Di Milia A., Appearance and spread of the Baltic acritarch microflora (Arenig-Llanvirn), in: Tongiorgi M., Playford G. (Eds.), Studies in Palaeozoic palynology. Selected papers from the CIMP Symposium at Pisa, 1998, Boll. Soc. paleont. ital. 38 (1999) 297–312.

[12] Tschernoster R., Giese U., Kramm U., Glodny J., The evolution of the Baltica–Gondwana suture along the TESZ during Lower Paleozoic times. Implications from detritus analysis and isotope studies, Terra Nostra 97/11 (1997) 148–152.

[13] Vecoli M., Cambro-Ordovician palynostratigraphy (acritarchs and prasinophytes) of the Hassi-R'Mel area and northern Rhadames Basin, North Africa, Palaeontographia Italica 86 (1999) 1–112.

[14] Vecoli M., Samuelsson J., Quantitative evaluation of microplankton palaeobiogeography in the Ordovician–Early Silurian of the northern TESZ (Trans European Suture Zone): implications for the timing of the Avalonia–Baltica collision, Rev. Palaeobot. Palynol. (in press).

[15] Vejbaek O.V., Stouge S., Poulsen K.D., Palaeozoic tectonic and sedimentary evolution and hydrocarbon prospectivity in the Bornholm area, Danmarks Geol. Unders. Ser. A 34 (1994) 1–23.