

# Vendian–Lower Cambrian acritarch biostratigraphy of the central Caledonian fold belt in Scandinavia and the palaeogeography of the Iapetus–Tornquist seaway

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Microfossils are reported from Vendian (?)–Lower Cambrian successions in the central and southern Caledonides in Sweden (Laisvall and Vassbo). The *Heliosphaeridium dissimilare* – *Skiagia ciliosa* (age-equivalent to the *Holmia kjerulfi* Assemblage Zone) and *Asteridium tornatum*–*Comasphaeridium velvetum* Zones (age-equivalent to the *P. antiquissimus* Zone) are recognized and correlated with strata in Baltica, Laurentia, Barentsia, Avalonia and elsewhere. The *Skiagia ornata*–*Fimbriaglomerella membranacea* Zone (age-equivalent to the *Schmidtellus/Rusophycus* faunal zone) is unrecognizable in most of the Caledonides. It is possible that it may comprise condensed low stand units. Trilobites and acritarchs identify strata corresponding to a maximum marine flooding event part of the *Heliosphaeridium dissimilare* – *Skiagia ciliosa* Zone (and coeval faunal zones in Laurentia). Sedimentary phosphates formed on the shelves of Baltica and Laurentia along a longitudinally oriented seaway in which nutrient-rich waters intensified productivity in association with recurrent marine flooding.

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## Introduction

Moderately deformed but virtually unmetamorphosed sedimentary successions are preserved along the present day eastern border of the Scandinavian Caledonides in Norway, Sweden and Finland. The successions were affected by late Caledonian thrusting and occur at various tectonic levels within the Scandes, but most often along a narrow autochthonous belt between the Scandinavian Caledonides and the largely Proterozoic core of Baltica (Fig. 1). The thin, predominantly detrital strata overlying the Proterozoic crystalline basement complexes have been thought to span the late Neoproterozoic to early Cambrian time interval. Early Cambrian units are sparsely fossiliferous (Ahlberg 1984a) and underlying Neoproterozoic units are either devoid of fossils or yield ichnofossils and problematic organisms. Their age assignment and the biochronologic status of presumably Upper Vendian strata in Baltica are thus chiefly based on problematic fossils such as *Kullingia concentrica* and Cambrian-type ichnofossils such as *Treptichnus* (? = *Phycodes pedum*), *Scolicia*, *Palaeophycus*, *Helminthoidichnites* (e.g. at Luopakke; Fig. 1; Jensen & Grant 1992), vendotaenids and phytoplankton (Vidal 1981a; Vidal & Knoll 1983; Moczydłowska 1991).

Acritarchs (largely organic walled phytoplankton representing resting cysts of algal protists and cyanobacteria) are locally abundant (Vidal 1981a), but strata whose age is questionably Vendian and/or at the earliest Cambrian contain mostly undiagnostic taxa (Moczydłowska

1991). Their age attribution is then difficult to resolve on biochronological grounds.

Here we report on acritarchs from the Upper Vendian (?)–Lower Cambrian Laisvall Group at Laisvall (central Scandes; Fig. 1) from the Lower Cambrian Vassbo Formation at Vassbo (southern Scandes; Fig. 1). We also propose a plausible acritarch- and trilobite-based correlation for the Grammajukku and Vassbo Formations with early Cambrian successions elsewhere (Fig. 4, 5). We discuss the possible palaeogeographical significance of coeval biotas and sedimentary phosphorites accumulated on the fragmented shelves of the Iapetus–Tornquist seaway during early Cambrian times.

## Geology

Until recently, the Vendian–Lower Cambrian successions along the northwestern rim of Baltica and the Scandes were collectively referred to as the Dividal Group (Føyn 1967; see Thelander (1982) for a discussion). The successions are generally thin ( $\pm 100$  to ca. 200 m) and may include major tectonic disconformities (Thelander 1982; Fig. 4). They consist of detrital rocks accumulated in a shallow to moderately deep epicontinental marine basin bordering western Baltica. The successions were folded and thrust during the Caledonian Orogeny. At Laisvall mild disharmonic folding is locally observed within shales of the Grammajukku Formation in the neighbour-

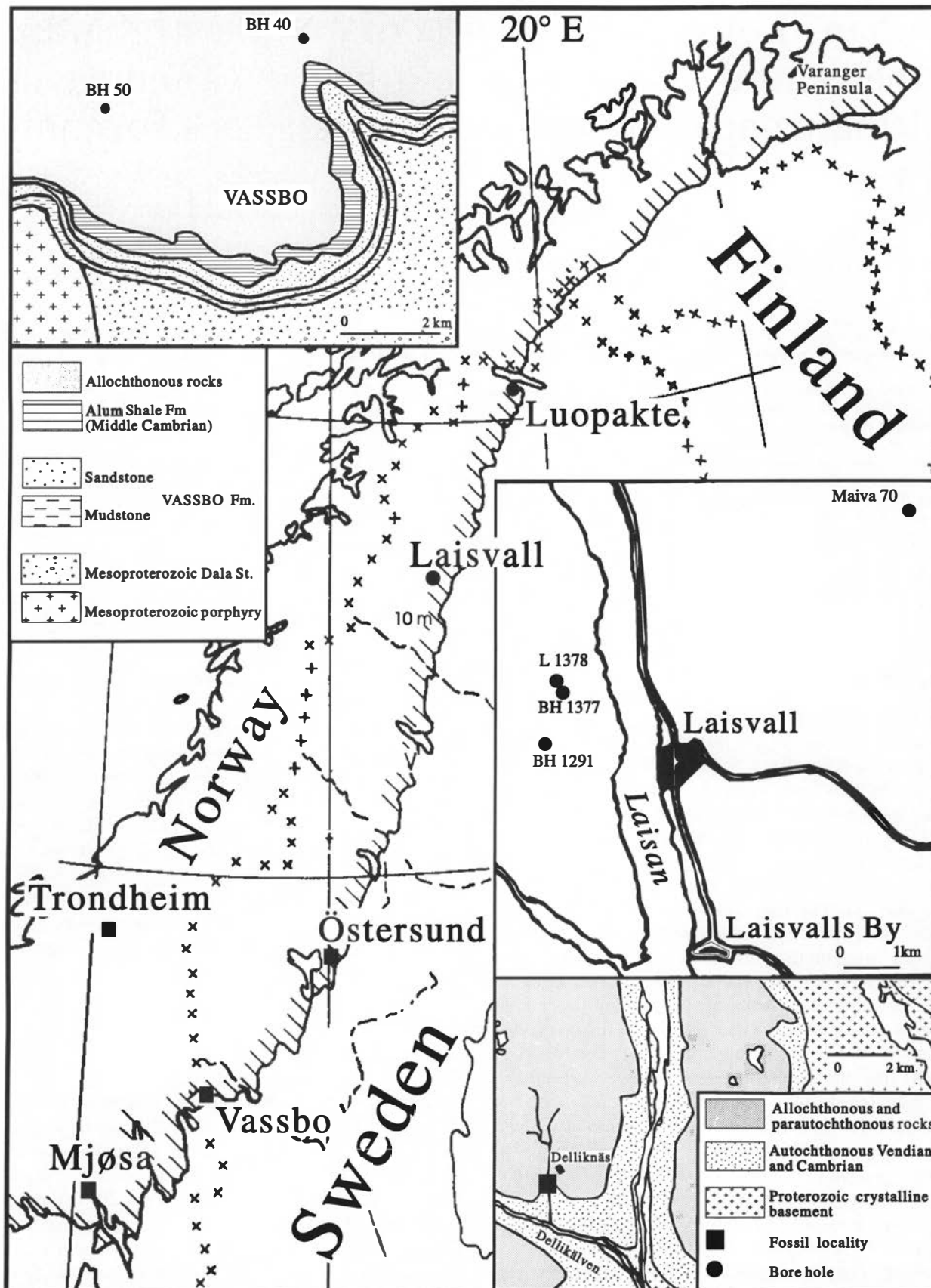


Fig. 1. Sketch-map of the Scandinavian Caledonides showing the extent of the eastern limit of the autochthonous border zone (shaded) in Norway, Sweden and Finland, and simplified geological sections at Luopakte, Laisvall, Vassbo and Lake Mjøsa (Fig. 4). Inset maps show the location of investigated samples from drillcores and surface samples in the Laisvall and Vassbo areas.

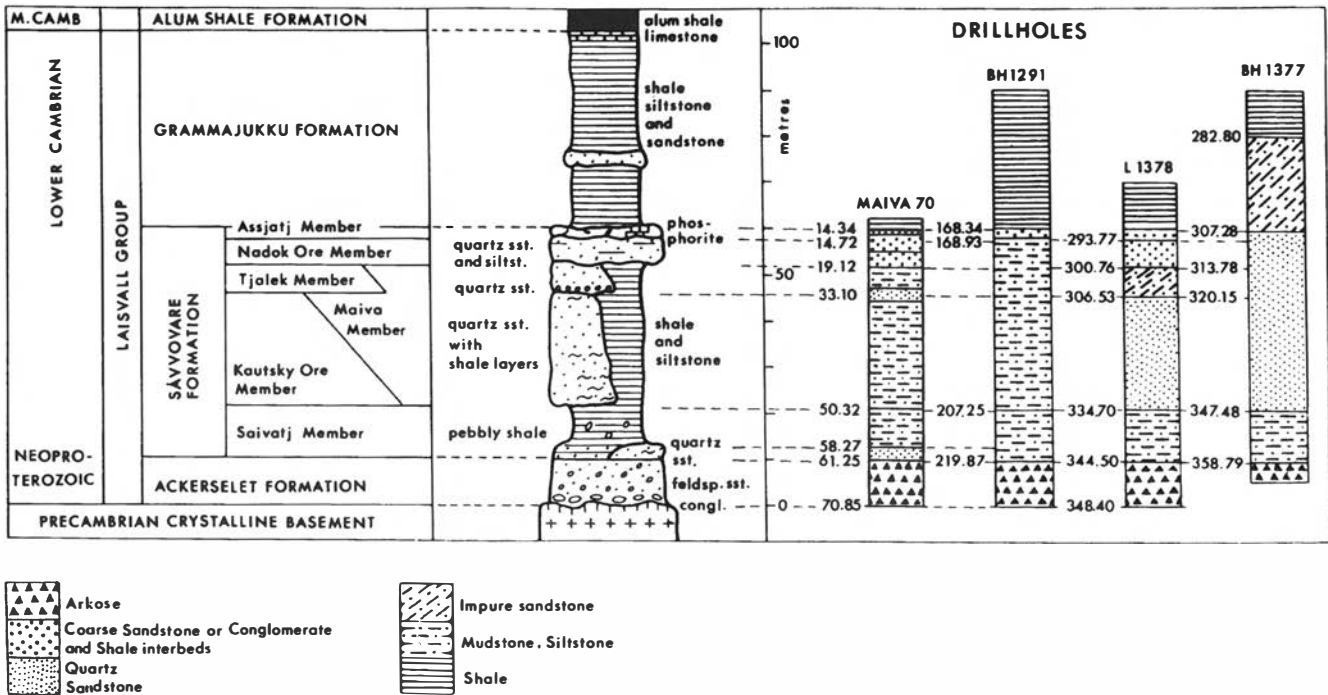


Fig. 2. Idealized section of the Neoproterozoic-Middle Cambrian succession at Laisvall (modified after Willdén 1980) showing the succession penetrated by investigated drillholes. Figures on the left of each drillhole section indicate the depth of boundaries of distinguished stratigraphic units of the Laisvall Group (left).

hood of late Caledonian thrust faults (e.g. at Delliknäs; Fig. 1).

*Laisvall*

The autochthonous sedimentary succession at Laisvall has an estimated total thickness of about 100 m (Willdén 1980; Fig. 2). In ascending stratigraphic order, the Laisvall Group comprises the Ackerselet, Sävovare and Grammajukku Formations (Figs. 2, 4; Willdén 1980). The Laisvall Group is overlain with sharp lithological contact (affected by Caledonian deformation) by the supposedly Middle Cambrian (but unfossiliferous at this site) Alum Shale Formation (Willdén 1980, p. 12). The Laisvall succession is an integral part of the autochthonous sedimentary belt bordering Baltica (Fig. 1). Although probably forming part of a single depositional province (Thelander 1982), the succession displays local facies developments that result in discrete lithosomes (Willdén 1980).

The Ackerselet Formation (7–9 m thick; Fig. 2) consists of feldspathic sandstone with coarse conglomeratic mixtite at base. Its thickness varies laterally as it wedges out towards residual basement promontories. Willdén (1980) distinguished two subunits of mass-transported material within the formation and suggested glaciogenic deposition with glaciofluvial input in a continental environment. This includes a mixtite interpreted as lodgement till overlying the crystalline basement and, uppermost, a flow till and glaciofluvial deposits (Fig. 2).

The Sävovare Formation (40–50 m thick) consists of quartzitic sandstone, siltstone, shale and a phosphatic

conglomerate at the top. It is divided into six formal members reflecting complex facies relationships (Fig. 2; Willdén 1980). The stratigraphically lowest Saivatj Member was interpreted to represent distal glacial-influenced conditions suggesting rhythmic deposition of suspended sediment (Willdén 1980). The succeeding Kautsky Ore Member (lower sandstone member of Lilljequist 1973) is a 25–27 m thick arenaceous body interpreted to represent offshore bar-beach tidal flat deposition flanked by contemporaneous argillitic bay and lagoon deposits. The unit displays complex facies relationships that depend on the palaeorelief of the underlying basement (Willdén 1980, pp. 30–31).

The Maiva Member consists of dark-grey argillitic rocks with a maximum thickness of 30 m. Shaly deposits were recorded in the Maiva area NE of Laisvall (lower inset map in Fig. 1). Immediately SSW of Laisvall, the Maiva Member interfingers with the chiefly arenaceous rocks of the Kautsky Ore Member as widely spread tongues of shale and siltstone (Willdén 1980, pp. 38–40). NNE of Laisvall (Fig. 1) lagoonal depositional conditions were inferred to have taken place surrounded by sand flats, whereas the area SSW of Laisvall was probably an extensive bay bordering sublittoral platforms, and tidal flats. The overlying Tjalek Member (middle sandstone member of Lilljequist 1973) has a variable thickness of 4–10 m that is reduced considerably as a result of local erosion and wedging out in a southwesterly direction. The Tjalek Member consists of white to greyish medium-grained sandstone pigmented by clayey matrix and disseminated organic matter and pyrite representing deposition in a sandy tidal flat environment (Willdén

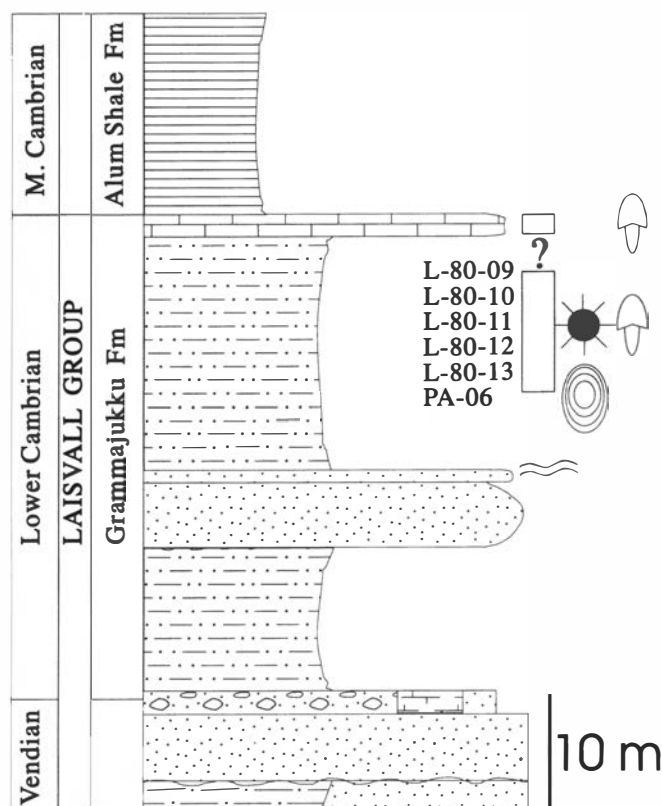


Fig. 3. Sketch geological section of the Neoproterozoic-Middle? Cambrian succession at Delliknäs (Fig. 1) and position of fossiliferous samples and shelly fossils. Modified after Ahlberg (1984).

1980, pp. 83–84). The Nadok Ore Member (upper sandstone member; Lilljequist 1973) has a thickness of 3–8 m and consists of coarse, medium and fine-grained sandstones and siltstone. It has a transitional contact with the Maiva Member, whereas the contact with the Tjalek Member is often sharp. Genetically the Nadok Ore Member was inferred to represent a tidal influenced unit containing channels and shoals.

The Assjatj Member (shale conglomerate member; Lilljequist 1973) has a variable thickness of a few decimeters to about 1 m. It consists of white to grey coarse-grained sandstone and limestone with black pebbles of phosphorite and phosphatic sandstone interpreted to have formed in an extensive exposed shore with sheltered lagoons (Willdén 1980).

The Grammajukku Formation has a rather constant thickness of about 43 m (Fig. 3), but it is often reduced through tectonic disturbance by overriding nappes. It overlies coarse sandstones of the Sävovare Formation with sharp contact. Six unnamed units have been distinguished within the Grammajukku Formation (not shown in Figs. 2, 3; Willdén 1980). Its lower half was interpreted as deposited under the sheltered conditions provided by a sand bar system resulting in the deposition of dominantly argillitic deposits. The uppermost portion is conformably overlain by black, organic-rich shales of the Alum Shale Formation (Willdén 1980).

### Vassbo

The Vassbo Formation is a condensed (28 m thick) detrital succession resting on the Mesoproterozoic Dala Sandstone and porphyry basement complexes ( $1.635 \pm 0.38$  Ga; Welin 1980; Fig. 1). It is entirely early Cambrian in age and is overlain by the Middle Cambrian Alum Shale Formation (Fig. 1). Both units are overridden by Caledonian nappe units (Fig. 1; Wallin 1982). The Lomviken and lower Flötningen Members form the base of the Vassbo Formation and represent a transgressive shift followed by a coarsening upward cycle representing a regressive succession that includes most of the Flötningen Member and the overlying Guttsjö and Grövelöden Members (Wallin 1982, pp. 65–66).

### Palaeontology of the autochthonous (?) Vendian-early Cambrian successions at Laisvall and Vassbo

The Neoproterozoic-Lower Cambrian succession at Laisvall is sparsely fossiliferous. Undescribed trace fossils were reported to occur within portions of the Grammajukku Formation (Ahlberg 1984b). Trace fossils were also observed in rocks of the Sävovare Formation (Sören Jensen, pers. comm. 1994) and an 'Ediacaran-like' medusoid (?) probably deriving from the Assjatj Member of this formation was reported (Kulling 1967; Lilljequist 1973, p. 11). A relatively rich trilobite fauna was first described by Kautsky (1945) from the Grammajukku Formation and later reassessed by Ahlberg & Bergström (1978), Bergström (1973, 1980, 1981), Bergström & Ahlberg (1981) and Ahlberg (1983).

The entirely Cambrian age of the succession at Vassbo (Fig. 1) is indicated by the occurrence of *Torellella* at the base of the succession and by olenellid trilobites diagnostic for the *Holmia kjerulfi* group Zone (Bergström & Gee 1985) from locally drifted boulders originating from an unspecified portion of the Vassbo Formation. Acritarchs were formerly reported from the Grammajukku and Vassbo Formations at Laisvall and Vassbo together with other occurrences in Baltica (but not illustrated) and their stratigraphic significance was preliminarily estimated (Vidal 1981b).

### Palaeontology and biostratigraphy of autochthonous (?) Vendian-early Cambrian successions in western Baltica

The lower arenaceous parts of the Vendian–Lower Cambrian succession in western Baltica lack time-diagnostic fossils, a feature that adds uncertainty to their correlation. This also renders difficult attempts at lithostratigraphically tracing some distinctive lithological units, such as the informal red and green siltstone member of the Torneträsk Formation, into the presently investigated Laisvall area (Thelander 1982; Fig. 4).

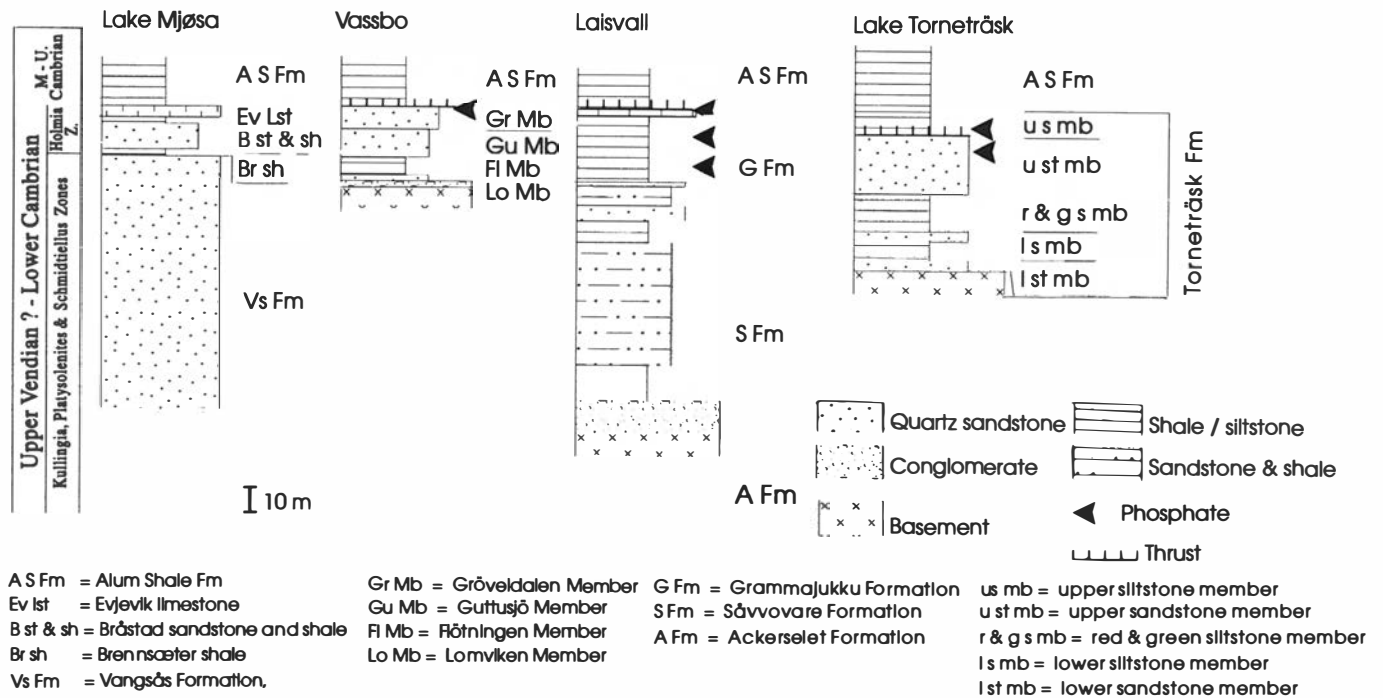


Fig. 4. Sketch sections of Upper Vendian(?)–Upper Cambrian successions on the eastern rim of the Scandinavian Caledonides. From left to right Lake Mjøsa, Vassbo, Laisvall and Lake Torneträsk (Luopakte). Base line marks the junction of the Middle–Upper Cambrian Alum Shale Formation (whose junction with the underlying upper Lower Cambrian units may be conformable or marked by a thrust fault) with underlying units characterized by the appearance of faunas of the *Holmia kjerulfi* Assemblage-Zone and *Proampyx linnarssoni* Zone and acritarchs of the coeval *Heliosphaeridium dissimulare*–*Skiagia ciliosa* and *Volkovia dentifera*–*Liepaina plana* acritarch Zones. Compiled from various sources. Shaded lines indicate major marine flooding and low stand events discussed in text.

**Lake Torneträsk area**

In the Lake Torneträsk area in northern Sweden (Fig. 1), the marine offshore red and green siltstone member (Thelander 1982; Fig. 1, 4) of the Torneträsk Formation is scarcely fossiliferous. It yielded only *Platysolenites antiquissimus* (a possible astrorhizacean foraminifer; Lipps 1992) and fossils identified as *Volborthella tenuis* (Kulling 1964), but regarded by Bergström & Gee (1985; p. 251) as not determinable. The fossiliferous beds are part of the Dividal Group and can be traced over substantial areas of northern Norway and Sweden (Vogt 1967; Føyn 1967). The beds are generally customarily considered part of the *P. antiquissimus* Zone in the East European Platform (EEP) of Baltica (Urbanek & Rozanov 1983).

Ichnofossils from the lower siltstone and lower sandstone informal members of the Torneträsk Formation (Thelander 1982; Fig. 4) include *Kullingia concentrica* and Cambrian-type ichnofossils such as *Treptichnus* (? = *Phycodes pedum*), *Scolicia*, *Palaeophycus*, *Helminthoidichnites* (Jensen & Grant 1992), whereas the Lower siltstone member yielded *Vendotaenia* and undiagnostic phytoplankton (Vidal 1981a; Moczyłowska 1991). The Lower siltstone and sandstone informal members were formerly considered to be Vendian in age, but the above-mentioned ichnofossils could suggest equally plausible late Vendian or early Cambrian ages (Jensen & Grant 1992). Only rare and stratigraphically long-ranging (*Platysolenites* Zone-? Middle Cambrian) acritarchs, such

as *Leiosphaeridia* sp., *Lophosphaeridium tentativum*, *Tasmanites* sp., *Comasphaeridium strigosum* (Vidal, unpublished data in Moczyłowska 1991) were recovered from the Upper sandstone member. The Upper siltstone member yielded the trilobites *Strenuaeva inflata* Ahlberg & Bergström, *Comluella? lapponica* Ahlberg, *Proampyx triangularis* Ahlberg & Bergström of the *Holmia kjerulfi* group Zone (Ahlberg & Bergström 1978; Ahlberg 1979, 1980, 1985; Bergström & Gee 1985).

**Southern Norway (Lake Mjøsa area)**

The Proterozoic–Lower Cambrian succession around Lake Mjøsa (Fig. 1) is also sparsely fossiliferous (Vidal & Nystuen 1990a). The Vangsås Formation consists of the Vardal Sandstone and the Ringsaker Quartzite Members. The former is unfossiliferous and the latter yielded burrows of *Skolithos* and *Diplocraterion* (Skjeseth 1963) and rare acritarchs suggestive of an early Cambrian age (Vidal & Nystuen 1990a). *Platysolenites antiquissimus* Eichwald was reported in the Bråstad sandstone (Skjeseth 1963; Martinsson 1974), but there is substantial uncertainty concerning this occurrence since the beds where *Platysolenites* was recorded were correlated with beds containing *Volborthella* (Vogt 1924) referred by Skjeseth (1963) to the overlying Bråstad sandstone and shale. The Brennsæter shale and the Bråstad sandstone and shale yielded acritarchs of the assemblage defining the *Heliosphaeridium dissimulare*–*Skiagia ciliosa* Zone

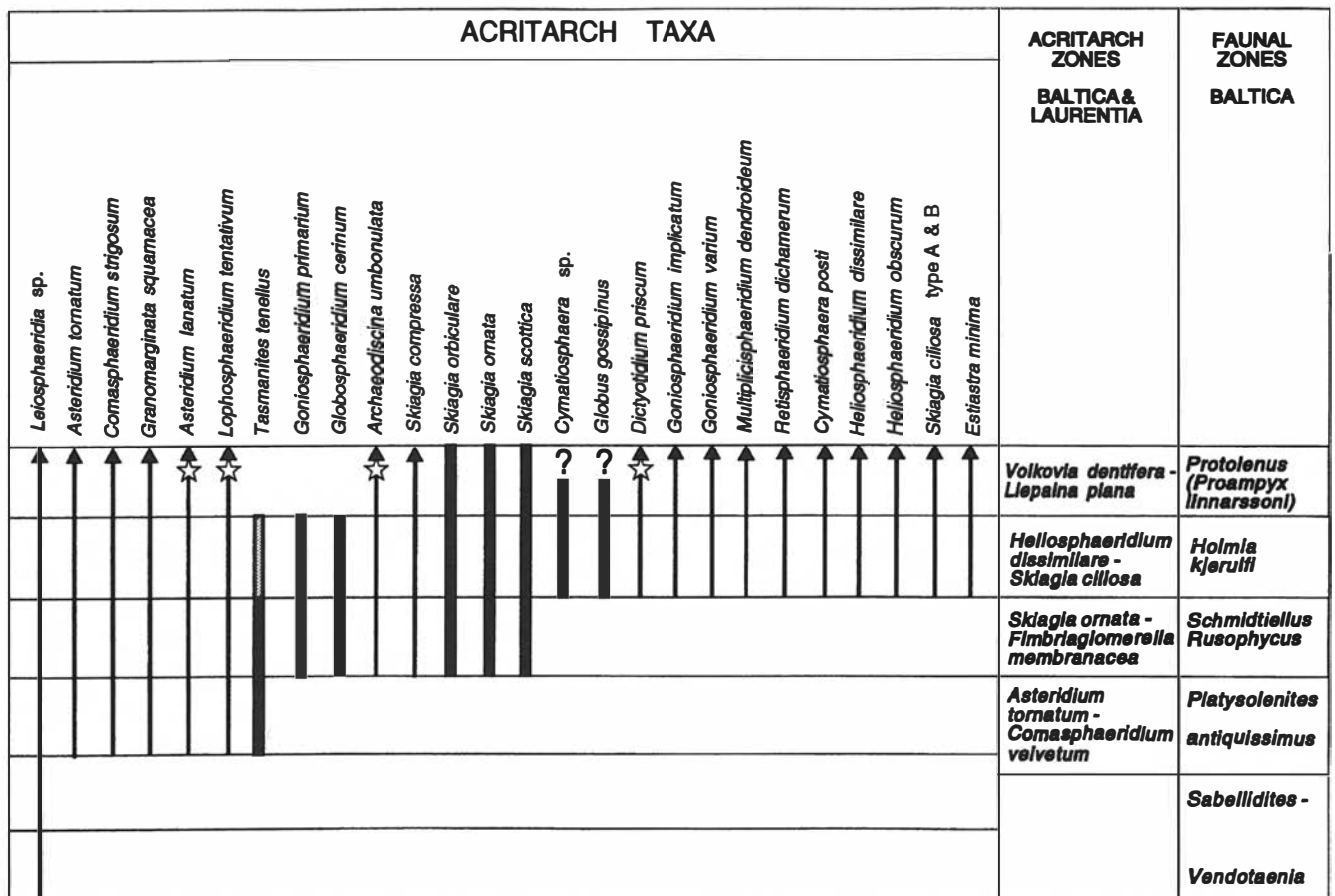


Fig. 5. Stratigraphic ranges of selected acritarchs from the Laisvall and Vassbo successions in the Neoproterozoic-Lower Cambrian of the Western Baltica and the East European Platform (after Moczyłowska 1991). Arrow points indicate stratigraphic ranges extending into the Middle Cambrian. Stars indicate revised ranges in the Baltic Sea (Hagenfeldt 1989a, 1989b). Shaded range bars indicate possible extended ranges as inferred from occurrence in the Buen Formation in northern Greenland (Vidal & Peel 1993). Acritarch and faunal zones according to Moczyłowska (1991).

which corresponds to the *Holmia kjerulfi* Assemblage Zone in the Lublin Slope and to the Vergale horizon in Estonia and Russia (Downie 1982; Vidal & Nystuen 1990a; Moczyłowska 1991). The overlying *Holmia* shale and Evjevik limestone yielded rich trilobite faunas that are part of the *Holmia kjerulfi* Assemblage Zone and the *Proampyx linnarsoni* Zone (Bergström & Gee 1985), respectively. The *Holmia* shale also yielded acritarchs of the *Heliosphaeridium dissimilare*-*Skiagia ciliosa* and *Volkovia dentifera*-*Liepaina plana* acritarch Zones, whereas the Evjevik limestone is micropalaeontologically barren (Vidal & Nystuen 1990a; Moczyłowska 1991).

*The Laisvall area*

The Neoproterozoic-Cambrian succession at Laisvall yielded 26 diagnostic acritarch taxa (Fig. 5; Appendix 1), but no time-diagnostic taxa were recovered from the investigated portion which is supposedly of Neoproterozoic age. The poor assemblage from the Sävovare Formation includes abundant aggregates of the possibly cyanobacterial or bacterial *Sphaerocongregus* that is known to be particularly abundant in late Neoproterozoic (Vendian) deposits (Vidal & Nystuen 1990b).

Rare acritarchs including *Leiosphaeridia* sp., *Granomarginata squamacea* and *Lophosphaeridium tentativum* were recovered from one sample from the lowermost part of the Grammajukku Formation in the Maiva 70 drillcore (Fig. 2) at a depth of 14.34 m. *Leiosphaeridia* sp., *G. squamacea* and *Comasphaeridium strigosum* were also retrieved in limited numbers from the lower part of the formation in drillhole L 1378 at a depth of 288.19 m (Fig. 2). While the stratigraphic range of *G. squamacea* within the Cambrian is comprehensive (Fig. 5), its lowest stratigraphic appearance is generally taken to mark a close proximity to the Neoproterozoic-Cambrian boundary (e.g. in the EEP; Volkova 1968; Volkova et al. 1979; Svalbard; Knoll & Swett 1987; eastern Poland; Moczyłowska 1991 and eastern Newfoundland; Strauss et al. 1992). A previously indicated earlier record in Neoproterozoic rocks is clearly erroneous (Strauss et al. 1992). We consider that *G. squamacea* indicates and is consistent with a Cambrian age, while at the same time not requiring a placement near the base of the Cambrian System for the base of the Grammajukku Formation. If correct, the Grammajukku Formation may encompass the entire Lower Cambrian (Fig. 5) and the assemblage from the lower part of the Grammajukku Formation

could be interpreted to belong to the *Asteridium tornatum*–*Comasphaeridium velvetum* Zone. This would suggest time equivalence of the lower Grammajukku with the red and green siltstone member of the Tornetråsk Formation at Luopakte attributed to the *P. antiquissimus* Zone (Fig. 4).

The upper portion of the Grammajukku Formation yielded a trilobite fauna that includes *Strenuaeva spinosa*, *Strenuaeva? kullingi*, *Kjerulfia? palpebra*, *Holmia? sp.*, *Ellipsocephalus gripi* and *Fallotaspis? ljungeri*. This fauna was first referred to the *Holmia kjerulfi* group Zone (Ahlberg 1984b) and subsequently to the *Holmia kjerulfi* Assemblage Zone (Moczyłowska 1991; Ahlberg & Bergström 1993). Diagnostic acritarchs from mudstones indicate that the upper fossiliferous part of the Grammajukku Formation (Fig. 3) roughly corresponds to the *Heliosphaeridium dissimulare*–*Skiagia ciliosa* acritarch Zone (Moczyłowska 1991). Although time-diagnostic fossils were not recovered from the entire formation, available data indicate that the Grammajukku Formation is within the span of the *Asteridium tornatum*–*Comasphaeridium velvetum* and *Heliosphaeridium dissimulare*–*Skiagia ciliosa* acritarch Zones corresponding to the *Platysolenites antiquissimus* Zone and *Holmia kjerulfi* Assemblage Zone (Moczyłowska 1991; Ahlberg & Bergström 1993).

#### The Vassbo area

Part of the Flötningen Member of the Vassbo Formation yielded a few diagnostic acritarch taxa (Appendix 1), comprising *Skiagia ciliosa*, *Heliosphaeridium obscurum* and *H. dissimulare*, species ranging through the *Heliosphaeridium dissimulare*–*Skiagia ciliosa* and *Volkovia dentifera*–*Liepaina plana* acritarch Zones (Moczyłowska 1991) and extending into the Middle Cambrian *Eccaparadoxides oelandicus* Superzone (age-equivalent to the Kibartai 'stage') in the EEP (Fig. 5). On this limited evidence the Flötningen Member may appear to be time-equivalent to the Grammajukku Formation at Laisvall and the Brennsæter shale, Bråstad sandstone and shale and *Holmia* shale at Lake Mjøsa (Fig. 4).

#### Biostratigraphic remarks

In terms of sequence stratigraphy (Van Wagoner et al. 1988) the Lower Cambrian transgressive succession in southern Norway has been regarded as a major genetic sequence comprising several parasequences and marine-flooding surfaces (Vidal & Nystuen 1990a). Thus, a major flooding surface underlies the Bråstad shale, whereas carbonate bioclastic detrital units (such as the Evjevik limestone) were thought to represent condensed subaqueous transgressive events (Vidal & Nystuen 1990a).

The term genetic sequence (Galloway 1989) defines sequences bounded at top and base by maximum flood-

ing surfaces, whereas depositional sequences were defined by (Van Wagoner et al. 1988) as bounded by erosive unconformities. In the present context the boundaries of units under discussion probably represent conformities followed by facies of palaeobathymetric deepening.

In previously proposed correlations based on litho- and biostratigraphy, the upper siltstone member of the Tornetråsk Formation is possibly time-equivalent to the entire Grammajukku Formation (Thelander 1982; Fig. 4). In accordance with the presently proposed correlation, two flooding events and intervening low-stand are recognized in *Platysolenites* and *Holmia kjerulfi* times, respectively (Fig. 4). They are represented by shale and arenaceous units of the Grammajukku Formation (Laisvall Group) and red and green siltstone and upper siltstone members of the Tornetråsk Formation (Fig. 4). While both are viewed as transgressive cycles (Thelander 1982), the latter represents a maximum high-stand immediately followed by the deposition of a thin, condensed fossiliferous carbonate unit (at Laisvall & Lake Mjøsa; Fig. 4), immediately succeeded by the Middle–Upper Cambrian Alum Shale Formation (Bergström & Gee 1985).

The fossiliferous shale/mudstone units are palaeontologically recognizable and, containing diagnostic trilobites and equally diagnostic acritarchs, may represent the most widespread early Cambrian maximum marine-flooding event in Baltica, Barentsia and Laurentia. Rocks formed during this event yield the *H. kjerulfi* Assemblage Zone trilobite fauna (see above) and/or distinctive acritarchs of the *Heliosphaeridium dissimulare*–*Skiagia ciliosa* Zone (Moczyłowska 1991; Fig. 5). Parallel to the Evjevik Limestone in southern Norway, a condensed sequence may be recognized in the upper Grammajukku Formation in the Laisvall area (Fig. 4) and this may also correspond to the recorded coarsening upward regressive arenaceous succession forming the upper Vassbo Formation at Vassbo (Wallin 1982, pp. 65–66; Fig. 4). Whether this interval of low-deposition rate has to do with the Hawke Bay regressive event detected in the Scandes (Bergström & Gee 1985) remains unclear in the current absence of conclusive biochronological evidence. Palaeontological comparisons across western and eastern Baltica indicate that the Hawke Bay Event did not affect the entire Baltic area equally and that it partly influenced deposition in the western part of the Baltic and Bothnian Sea areas, thus contrasting with a more gradual palaeontological transition in the northern part of the Island of Gotland and the east Baltic area (Hagenfeldt 1989b, p. 236; Fig. 1).

Alternatively, the carbonate facies at Laisvall and Mjøsa (Fig. 4) capping shale units could constitute the culmination of the highstand event in *H. kjerulfi* times as detrital input was superseded by carbonate deposition. This view is in accordance with the widespread distribution of the unit and its distinctive biotic assemblage over Baltica, which according to palinspastic reconstructions was once located 130–150 km northwest of its present



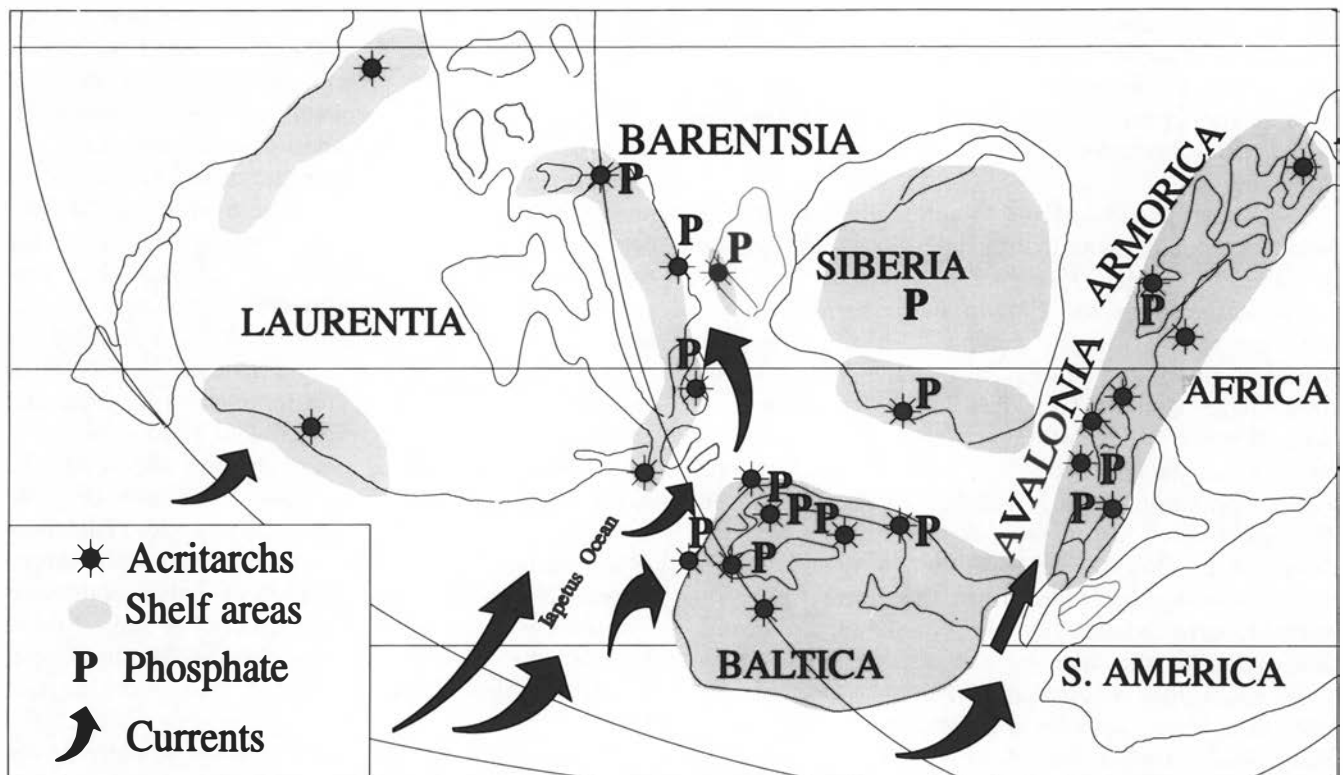


Fig. 6. Sketch palaeogeographic reconstruction during early Cambrian times showing the location of coeval biochronologically dated Lower Cambrian successions in Laurentia, Avalonia, Barentsia, Baltica, Siberia, Avalonia, Armorica and Africa associated with the occurrence of areas of phosphate deposition. Arrows indicate the possible source and direction of nutrient flow onto the shelves bordering the Iapetus-Tornquist, Barentsia and Avalonia-Armorica seaways. Land contours for the early Cambrian modified after Neuman & Max (1989), Scotese & Brasier (1992), Courjault-Radé et al. (1992) and Moczyłowska (1995). The position of Baltica is after Torsvik et al. (1992). Acritarch data are mostly from Moczyłowska (1991). Phosphorite occurrences are largely according to Notholt & Braiser (1986).

allochthonous location within the Osen Nappe (Nystuen 1981). Although the biochronological support is clearly insufficient for detail correlation, the Flötninge, Guttsjö and Grövelöden Members of the Vassbo succession could be interpreted as being part of a continuous depositional 'standby succession' deposited in an area close to the detrital source in a nearby hinterland where the rate of detrital influx superseded the rate of sea-level rise. Hence, most of the Vassbo succession could constitute a genetically prograding unit formed during *H. kjerulfi* times.

### Early Cambrian biogeography

Acritarchs are generally abundant in a variety of marine sedimentary rocks spanning a wide range of depositional environments (Tappan 1980). Although markedly cosmopolitan, assemblages of early Cambrian acritarchs are taxonomically homogeneous (Moczyłowska & Vidal 1992). This allows the definition of acritarch zones (Moczyłowska 1991) that can be widely recognized in Baltica (Downie 1982; Eklund 1990; Hagenfeldt 1989a, 1989b; Jankauskas 1976; Moczyłowska 1991; Moczyłowska & Vidal 1986, 1988, 1992; Volkova et al. 1979), Laurentia (Baudet, Aitken & Vanguetaine 1989; Downie 1982; Knoll & Swett 1987; Moczyłowska & Vidal 1986; Vidal

1979; Vidal & Peel 1993), peri-Gondwana (Palacios & Vidal 1992; Erkmén & Bozdoğan 1981), Avalonia (Potter 1974; Wright et al. 1993), Siberia (Pyatiletov & Rudavskaya 1985; Rudavskaya & Vasilieva 1984; Vidal, Moczyłowska & Rudavskaya 1995) and China (Wang & Chen 1987; Zang 1992). The precision of acritarch biochronology can be estimated through recent advances in the isotopic geochronology of the basal Cambrian (Bowring et al. 1993; Tucker & Pharaoh 1991; Compston et al. 1992, 1995; Cooper et al. 1992; Grotzinger et al. 1995) which indicate a length of about 5 to 6 Ma for the Tommotian and Atdabanian stages. Hence, the *H. dissimulare*-*S. ciliosa* (age-equivalent to the *Holmia kjerulfi* trilobite Zone) and *Skiagia ornata*-*Fimbriaglomerella membranacea* (age-equivalent to the *Schmidtellus/Rusophycus* faunal zone) acritarch zones, probably contemporaneous with lower and middle parts of the Tommotian regional stage in Siberia, may span no longer than 2–4 Ma each (Compston et al. 1995; Knoll 1994).

Trilobites are among the most widespread fossils in Cambrian strata and have come to form the basis of biostratigraphic and palaeofaunistic/palaeogeographic reconstructions. Hence, Early Cambrian faunas display marked variations in taxonomic composition that are probably related to faunal provincialism. However, as a notable exception the Lower Cambrian trilobite *Calodiscus lobatus* occurs in deposits ranging from slope



or shelf-margin to shallow-water and has an area of occurrence comprising three faunal provinces in the North Atlantic region (Ahlberg & Bergström 1993). On the other hand, its recorded stratigraphic range suggests that *C. lobatus* is a long-ranging species (Ahlberg & Bergström 1993).

Organisms with pelagic life habits (even if only at their larval stage) are geographically widespread but are generally believed not to 'see' early Palaeozoic continental boundaries clearly (Fortey & Mellish 1992). This would certainly apply to acritarchs since for the most part they had a planktonic motile life habit (Tappan 1980).

The allochthonous Lower Cambrian succession at Lake Mjøsa (Fig. 1) is thought to have been deposited 140–150 km to the NNW relative to the autochthonous successions at the eroded nappe front, as inferred from palinspastic restorations of the decollement sheet in the Oslo Region (Nystuen 1981; Morley 1986). The Lower Cambrian beds in both tectonostratigraphical positions were deposited within the same epicontinental foreland sea east of the incipient Iapetus Ocean and the Caledonian mobile belt (Kumpulainen & Nystuen 1985). This early Cambrian epicontinental seaway bordered the northwestern rim of Baltoscandia and transgressed the craton in a southeasterly direction. Most palaeogeographic reconstructions of early Cambrian Baltica suggest that an emerged axial elevation extended in a southwesterly direction towards the border zone of Baltoscandia and probably separated areas of epicontinental sea in northwestern Baltoscandia from submerged areas in southeastern Baltoscandia (Thorslund 1960; Skjeseth 1963; Martinsson 1974; Bergström 1980). The two epicontinental seas merged into the Iapetus seaway along the Teisseyre-Tornquist Lineament.

Both autochthonous and allochthonous Lower Cambrian successions in western (Norway and Sweden), eastern (Estonia) and southern Baltica (eastern Poland and the Ukraine) have yielded an array of similar trilobite faunas (Bergström & Gee 1985; Ahlberg & Bergström 1993) and comparable acritarch assemblages (Hagenfeldt 1989a, 1989b; Moczyłowska 1991; Moczyłowska & Vidal 1992). Both benthic and planktonic biotas occupied the productive shelf areas of western and eastern Baltica along the Iapetus-Tornquist seaway (Fig. 6). Discrepancies in the taxonomic composition of trilobite faunas in early Cambrian faunal provinces of the North Atlantic region refer to Avalonia, Baltica and Armorica, as shown in recent palaeogeographic and tectonic reconstructions for parts of the North Atlantic region (e.g. Neuman & Max 1989; McKerrow, Scotese & Brasier 1992; Courjault-Radé, Debrenne & Gandini 1992; Fig. 6). However, faunal differences seem to have been overemphasized since some Lower Cambrian trilobite taxa occur both in Baltica and in Armorica (Liñan et al. 1995; Moczyłowska 1995). As faunal provinces differ, the homologous taxonomic composition of acritarch assemblages recorded from portions of Laurentia, Barentsia, Armorica, Avalonia and Baltica are striking

(see above; Moczyłowska 1995 and unpublished data). While the taxonomic homogeneity of early Cambrian acritarch populations during short intervals of time makes them clearly useful in biostratigraphy (Hagenfeldt 1989a; Moczyłowska 1991; Moczyłowska & Vidal, 1992; Volkova et al. 1979), this same feature needs explanation in terms of proposed palaeogeographic reconstructions. Taxonomic similarity among assemblages from probably coeval Lower Cambrian units can only be interpreted in the light of cyst accumulation in contiguous shelf areas bordering the Iapetus-Tornquist seaway (Moczyłowska 1993, 1995). However, this is also in contrast with the variability and patchy distribution of recent phytoplankton populations in regions where nutrient-rich water is carried to the mixed layer of the oceans (Gower, Denman & Holyer 1980; Pollard & Regier 1990). Plankton populations respond to the motion of water masses of different temperature and salinity as the isolation of surface water results in declining phytoplankton populations due to nutrient consumption, whereas active vertical water motion results in increasing populations through nutrient recovery (Moczyłowska & Vidal 1992). Of course, the implied comparison of uniform acritarch assemblage compositions against the documented plankton heterogeneity in high-productive modern shelves needs qualifying. Hence, instantaneous samples reflect an enhanced taxonomic heterogeneity, whereas time-compression and averaging over the relatively brief time spans represented in recent and sub-recent environments result in comparably homogeneous assemblages.

We suggest that whenever available, the known distribution of early Cambrian faunas and phytoplankton assemblages could be accommodated in a palaeobiogeographic model reflecting distributions along the relatively close shelves of eastern Laurentia, Baltica, Siberia, Avalonia and Armorica (Moczyłowska 1995, Fig. 6).

### Early Cambrian phosphogenic events

Phosphorites have a widespread occurrence in Vendian (?)–Lower Cambrian strata bordering the present North Atlantic region (Notholt & Brasier 1986; Shergold & Brasier 1986). The nature of Lower Cambrian phosphorites in the North Atlantic region is quite variable and comprises both reworked phosphate nodules (Kidder & Swett 1989) and *in-situ* or nearly *in-situ* phosphatized beds (de Marino 1980).

The Lower Cambrian successions in Baltica share a multitude of features (see Martinsson 1974; Bergström & Gee 1985 for reviews). The stratigraphically most complete successions are in northwestern (Varanger Peninsula; Farmer et al. 1992) and southeastern Baltica (Lublin Slope of the East European Platform; Moczyłowska 1991) which display transitional contacts with marine Vendian-age deposits. Several shallow shelf units consisting of quartz sandstones, mudstones and shales make the bulk of the Lower Cambrian succession in both

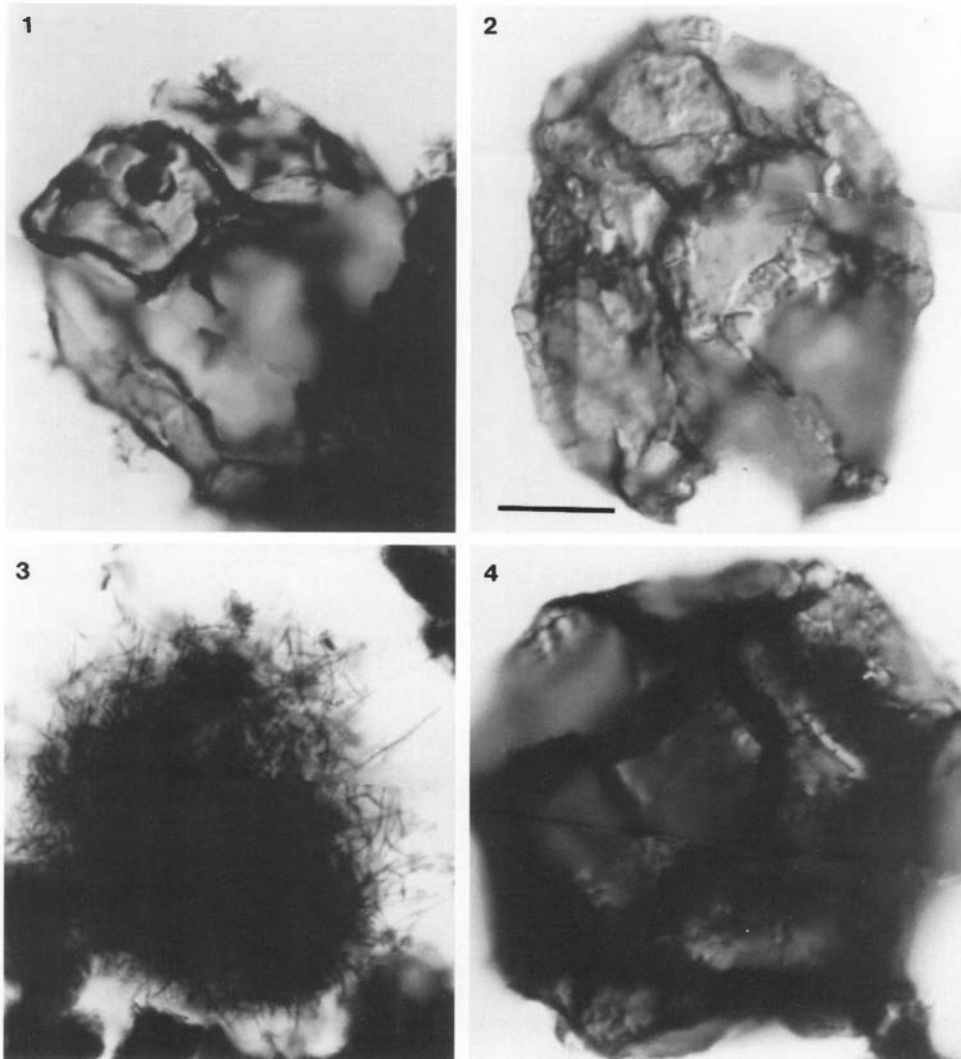


Fig. 7. (1) *Retisphaeridium* sp. (1) PMU-L8-09/80 prep 1. P/31-4. Sävovare Formation; Assjatj Member. (2, 4) *Retisphaeridium* cf. *dichamerum* Staplin, Jansonius and Pocock 1965 (2) PMU-L-80-12 prep. 1. Z/46-3. Grammajukku Formation; Delliknäs section. (4) PMU-L1377-277:07-17 prep. 1. U/36, drillhole Bh 1377, at depth of 277.07 m, Grammajukku Formation. (3) *Globus gossipinus* Vidal 1988; PMU-L-80-13 prep. 1. Z/25-2. Grammajukku Formation; Delliknäs section. Length of bar at 2 is 10  $\mu$ m for 1, 2, 4 and 12.5  $\mu$ m for 3.

areas. Extensively investigated, the latter comprises four successive acritarch biozones that were correlated with Baltoscandian faunal zones (Moczyłowska 1991; Fig. 5). While no phosphatic deposits were recorded in Varanger Peninsula, the succession in the Lublin Slope contains several phosphogenic events represented as nodular phosphorites present throughout the succession (Moczyłowska 1991). As indicated by biochronology based on faunal and/or acritarch assemblages, the Lower Cambrian Baltoscandian successions represent the upper 3 acritarch biozones recognized in the EEP (Moczyłowska 1991; Fig. 11).

Successions in western Baltica (southern Norway and southern and western Sweden; Fig. 4, 6) consist of terrestrial and fluvial sandstones (e.g. the Nexø Sandstone Formation in the Island of Bornholm; Surlyk 1980; Pedersen 1989; and the Vardal Sandstone Member of the Vangsås Formation in the Lake Mjøsa area; Dreyer 1988) in gradual transition with shallow marine quartz sandstones (e.g. Balka Sandstone Formation or Hardeberga Sandstone Formation; Surlyk 1980; Bergström & Gee 1985; Hamberg 1990, 1991 in Bornholm and south-

ern Sweden, and Ringsaker Quartzite Member of Vangsås Formation at Lake Mjøsa; Dreyer 1988; Nystuen 1987). They represent transgressive inner shelf, tidal channels and shoreface facies (Hamberg 1990, 1991) that locally might be gradually succeeded by siltstones and fine-grained sandstones (e.g. the Broens Odde member on Bornholm and in southern Sweden) deposited in shelf and prograding coastline environments, following transgressive and regressive shifts. Phosphorite nodules and strong bioturbation are common, indicating slow sedimentation with periods of non-deposition (Surlyk 1980). Overlying coarse-grained quartzitic and glauconitic sandstones, intercalated with phosphorite layers, include intraformational erosional unconformities (Rispebjerg Sandstone; de Marino 1980).

Parts of the Lower Cambrian successions corresponding to the *Schmidtellus/Rusophycus* (age-equivalent to the *Skiagia ornata-Fimbriaglomerella membranacea* Zone), *Holmia kjerulfi* (age-equivalent to the *Heliosphaeridium dissimulare-Skiagia ciliosa* Zone) and *Protolenus/Proampyx linnarssoni* (age-equivalent to the *Volkovia dentifera-Liepaina plana* Zone) Zones in south-and west-

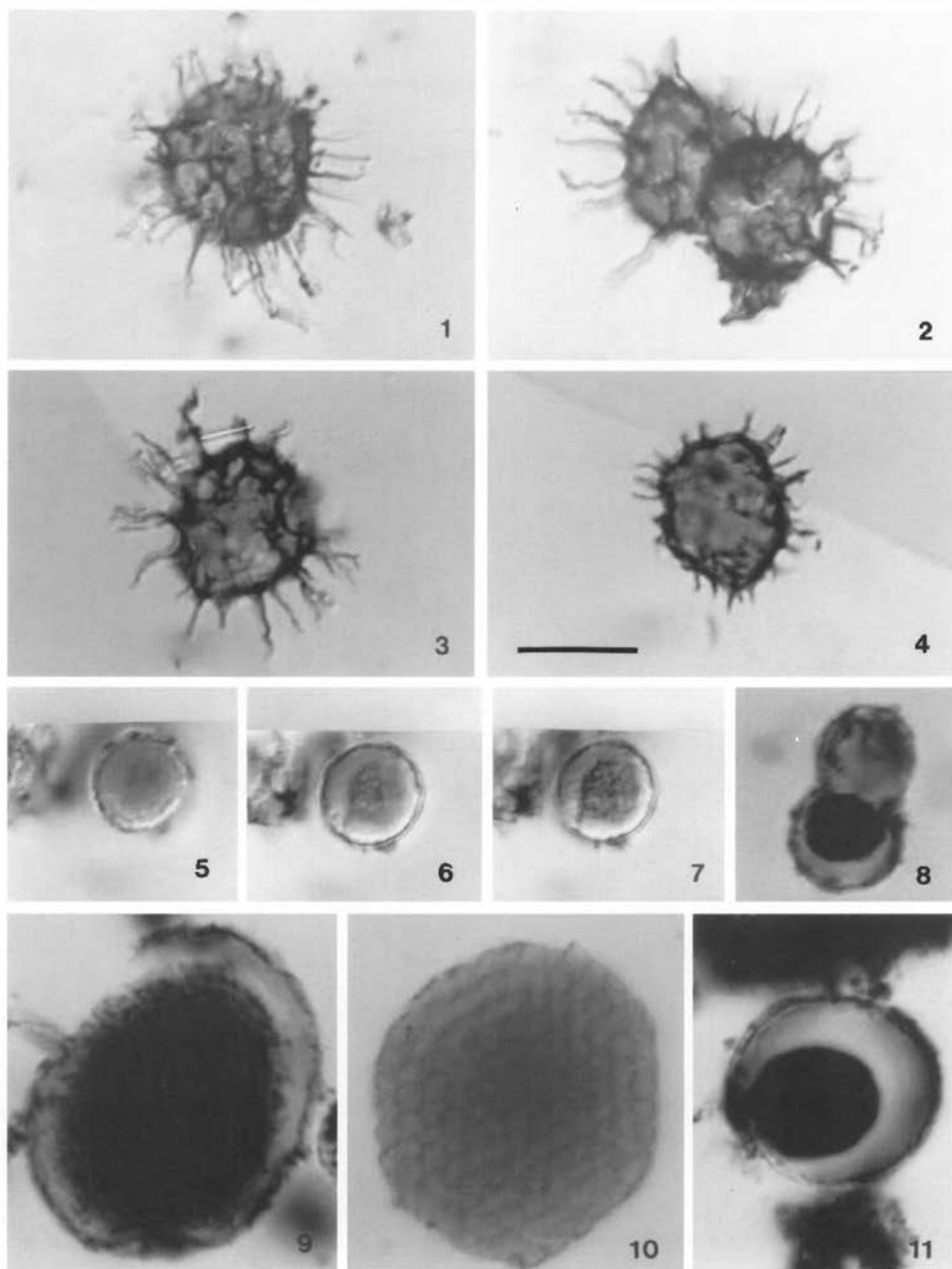


Fig. 8. (1–4) *Heliosphaeridium dissimilare* (Volkova 1969) Moczyłowska 1991. (1) PMU-L-80-13 prep. 1. Q/36. Grammajukku Formation, Delliknäs section. (2) PMU-L-80-12 prep. 2. M/35. Grammajukku Formation, Delliknäs section. (3) PMU-L-80-12 prep. 1. W/37-3. Grammajukku Formation, Delliknäs section. (4) PMU-L-80-11 prep. 1. L/45-2. Grammajukku Formation, Delliknäs section. (5–9, 11) Sphaeroidal cyanobacterial (?) microfossils, (5–7) three focal levels. PMU-M-70-55:49-63 prep. 1. V/36-4, drillhole Maiva 70, at depth of 55.49 m, Sävovare Formation, Saivatj Member. (8) PMU-M-70-22:45-54 prep. 1. O/39-2, drillhole Maiva 70, at depth of 22.45 m, Sävovare Formation Tjalek Member. (11) PMU-L-1377-352:00-07 prep. 1. W/48-2, drillhole Bh 1377, at depth of 352.00 m, Sävovare Formation Saivatj Member. (9–10) *Sphaerocongregus variabilis* Moorman, 1974. (9) PMU-M-70-22:45-54 prep. 1. C/40-2, drillhole Maiva 70, at depth of 22.45 m, Sävovare Formation Tjalek Member. (10) PMU-L-1377-277:07-17 prep. 1. U/37, drillhole Bh 1377, at depth of 277.07 m, Grammajukku Formation. Length of scale bar at 4 is 10  $\mu\text{m}$ .

ern Baltica (Bornholm and southern and western Sweden) reveal low rates of sedimentation and consist of amalgamated shallow marine condensed sequences that hold several hiatus and non-depositional breaks (Surlyk 1980). A similar feature appears to apply to coeval successions in the Scandinavian and east Greenland Caledonides (the latter being part of Laurentia; Fig. 6), Svalbard (Barentsia; Fig. 6) and Great Britain (Notholt & Brasier 1986).

Berry, Wilde & Quinby-Hunt (1989) proposed that early Palaeozoic oceans were anoxic beneath the surface mixed layer and that eustatic sea rise resulted in anoxia and the accumulation of black shale facies and the existence of distinct biofacies. Dysaerobia and sediment accumulation under oxygen deficient conditions were

inferred for parts of Neoproterozoic and Lower Cambrian successions (Vidal & Nystuen 1990b; Moczyłowska & Vidal 1992) in Baltica. Hence, late Neoproterozoic anoxygenic photosynthetic bacteria may have substantially contributed to primary productivity in largely stratified basins in western Baltica (Vidal & Nystuen 1990b). In fact,  $^{34}\text{S}$ -enriched sulfides from the late Neoproterozoic (Vendian)–early Cambrian succession in the Lublin Slope of SE Poland (Fig. 6) were interpreted as resulting from early diagenetic sulphate reduction progressing at a rate exceeding sulphate replenishment and subsequent Rayleigh distillation effects (Bottomley et al. 1992). A cosmopolitan fossil record in the Lublin and adjacent basins in Baltica (Moczyłowska 1991; Bottomley et al. 1992) would appear to make stratifica-

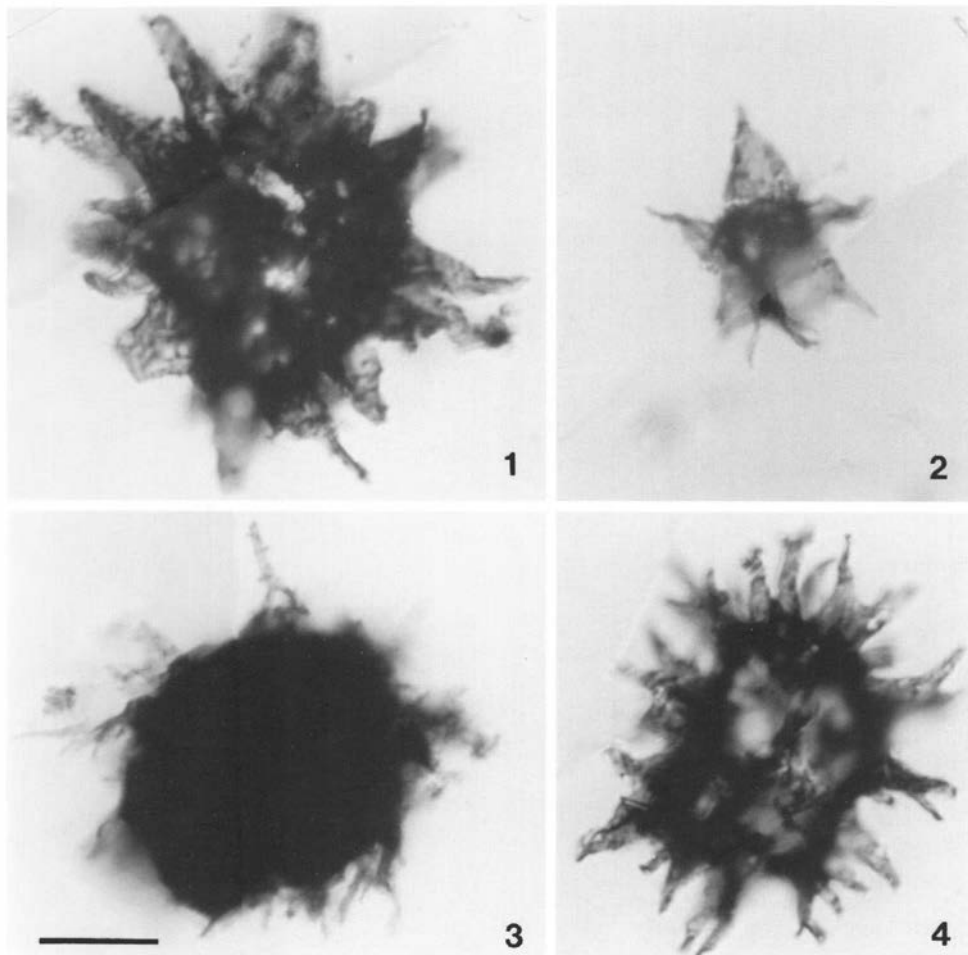


Fig. 9. (1) *Goniosphaeridium varium* (Volkova 1969) Downie 1982. PMU-L-80-13 prep. 1. T/38. (2) *Estiastra minima* Volkova 1969. PMU-L-80-12 prep. 1. F/49. (3) *Goniosphaeridium implicatum* (Fridrichsone 1971) Downie, 1982. PMU-L-80-12 prep. 1, Z/46-1. (4) *Multiplicisphaeridium dendroideum* (Jankauskas 1976) Jankauskas & Kirjanov 1979. PMU-L-80-12 prep. 1, R/26. All from Grammajukku Formation; Delliknäs section. Length of scale bar at 3 is 10  $\mu\text{m}$ .

tion and restricted sea water circulation unlikely. However, as suggested by late Vendian ages for basaltic volcanism in southeastern Baltica and eastern Avalonia (Compston et al. 1995; Vidal & Moczyłowska 1995), at an initial stage of rifting the Iapetus-Tornquist seaway was probably narrow (Fig. 6). In the present late Vendian-early Cambrian palaeogeographic reconstruction the Tornquist Shelf of Baltica is synonymous with the Iapetus Shelf, thus implying that the Tornquist Sea is homologous with the initial stage of the Iapetus 'Ocean' (at this time merely a seaway; Fig. 6). Although allowing the free dispersal of biotas in late Vendian and earliest Cambrian times, the inflow of sea water could have been greatly restricted. The basins might have been stratified and sulphate replenishment effected largely by heliothermal exchange. Basin stratification might have extended well into early Cambrian times, when the roughly longitudinal Iapetus-Tornquist seaway acquired sufficient width to allow extensive sea water exchange, this coinciding with the onset of the late early Cambrian extensive flooding in *H. kjerulfi* Zone times. Hence, a scenario substantially differing from the above governed the early Cambrian transgressive episodes that resulted in the flooding of the margins of peneplaned continents, lock-

ing riverine waters that carried mineral nutrients. Nutrient recovery due to upwelling cold currents could have led to the major accumulation of soluble mineral nutrients and the formation of early Cambrian phosphorites (Wallin 1982; Notholt & Brasier 1986; Kidder & Swett 1989). However, in the light of recent palaeogeographic reconstructions, the existence of upwelling currents along the extensive shallow platform of the continental margin of western Baltica is speculative since the orientation of seaways for phosphogenesis is most significant. Cook & McElhinny (1979) emphasized that 'generally phosphogenic conditions can occur relatively soon after the initiation of sea-floor spreading if the narrow seaway formed in a near-equatorial location and has a longitudinal (i.e. east-west) orientation', whereas 'broad-scale phosphogenesis is likely to occur only in a latitudinally (north-south) oriented seaway, when sea-floor spreading has proceeded to the stage where the ocean is sufficiently broad for stable oceanic gyres to form in low latitude location'.

The biochronologically constrained ages of Neoproterozoic-Lower Cambrian successions forming part of the former shelf rims of the Iapetus-Tornquist seaway (Fig. 6) indicate that phosphogenesis occurred

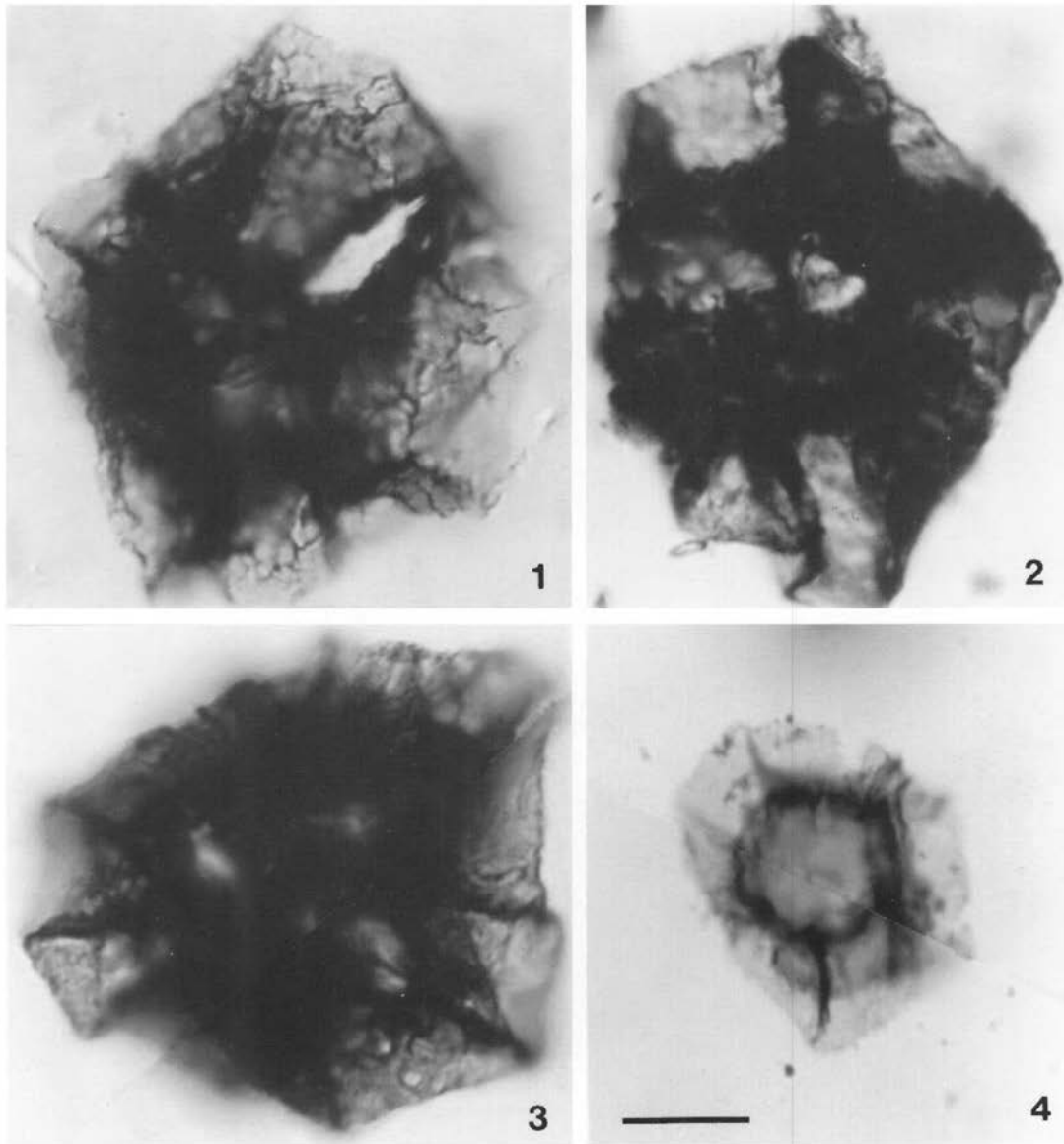


Fig. 10. (1–2) *Cymatiosphaera* sp. (1) PMU-Bh 1291-138:83-92 prep. 1, Z/30, drillhole Bh 1291, at depth of 138.83 m, Grammajukku Formation. (2) PMU-L-80-13 prep. 1, Y/45-4, Grammajukku Formation, Delliknäs section. (3) *Cymatiosphaera postii* (Jankauskas 1976) Jankauskas 1979. PMU-L-80-12 prep. 1, E/48, Grammajukku Formation, Delliknäs section. (4) *Pterospermella* sp. PMU-Bh 40 prep. 1, J/34-3, drillhole Bh 40, Flötningen Member. Length of scale bar at 4 is 10  $\mu\text{m}$  for 1, 2, 3 and 20  $\mu\text{m}$  for 4.

during several flooding episodes in Cambrian times. Recent palaeogeographic reconstructions based on palaeomagnetic data place Baltica 'upside down' (Torsvik et al. 1992) locating the Tornquist Shelf obliquely facing the eastern shelf of Avalonia (Fig. 6). It remains unclear to what an extent the incipient Iapetus-Tornquist seaway (formed during the initial rifting of Baltica, Laurentia and Avalonia) was sufficiently wide to prevent the migration of contemporaneous trilobite faunas (except for that of the widely dispersed trilobite *Calodiscus lobatus*; cf. Ahlberg & Bergström 1993). The co-occurrence of early Cambrian trilobite taxa in Baltica and Iberia (Liñan et al. 1995; Moczyłowska 1995) and the largely homogeneous composition of discrete plankton assemblages along the Iapetus-Tornquist shelves (Fig. 6) appears more consistent with free dispersal along nearly contigu-

ous shelf areas affected by the rifting motion of the Baltic and Laurentian plates. We further suggest that phosphogenic events were probably not related to upwelling currents, since that would have demanded the existence of an ocean basin sufficiently wide to sustain stable oceanic gyres (see above). On the contrary, palaeogeographic reconstructions advocate a longitudinal seaway (e.g. Neuman & Max 1989; McKerrow, Scotese & Brasier 1992) between Baltica and Laurentia (Fig. 6) consistent with faunal associations. Furthermore, phytoplankton dispersal suggests the existence of a narrow seaway along which nutrient rich waters enhanced primary productivity and the accumulation of sedimentary phosphate following recurrent transgressive/regressive shifts. We consider the present model attractive in that it accounts for contemporaneous phosphorite accu-

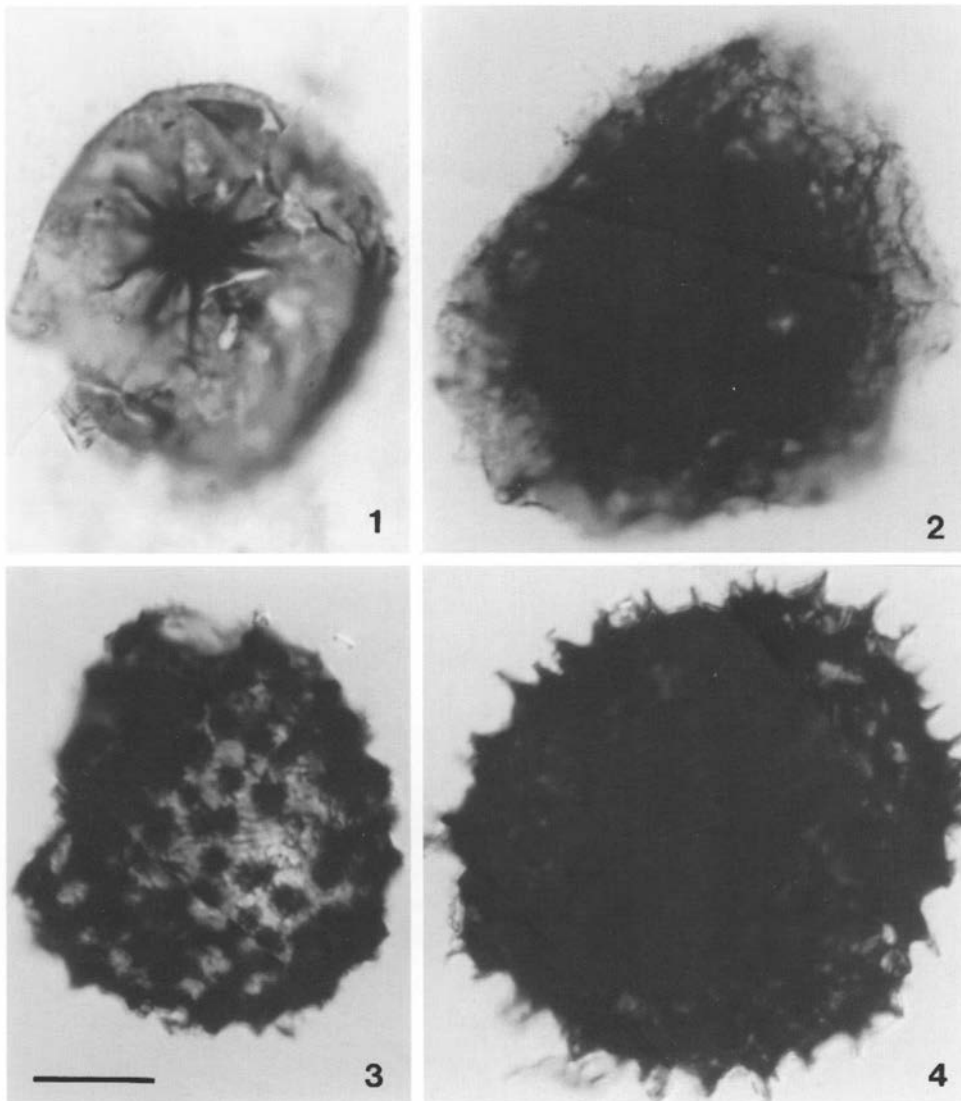


Fig. 11. (1) *Archaeodiscina umbonulata* Volkova 1968. PMU-L-80-10 prep. 1, P/26, Grammajukku Formation, Delliknäs section. (2) *Granomarginata squamacea* Volkova 1968. PMU-M-70-14:34, prep. 1, U/44, drillhole M-70 at depth of 14.34 m, Grammajukku Formation. (3) *Lophosphaeridium?* sp. PMU-L-80-11 prep. 1, Z/25, Grammajukku Formation, Delliknäs section. (4) *Skiagia* cf. *ciliosa* (Volkova 1969) Downie 1982. PMU-L-80-11 prep. 1, Z/24-3, Grammajukku Formation, Delliknäs section. Length of scale bar at 3 is 10  $\mu$ m.

mulation on the western Baltica shelves rimming the emerged Baltoscandian height inferred in various reconstructions (Thorslund 1960; Skjeseth 1963; Martinsson 1974; Bergström 1980).

### Palaeontologic remarks

Acritarchs reported in this study were extracted using standard palynological techniques. As in the case of occurrences in southern Norway (Vidal & Nystuen 1990a) acritarchs from Laisvall and Vassbo display colours ranging from light brown for the small acritarchs (hue 10YR 5/6) to dark-brown (hue 10YR 3/2) for the larger and thicker-walled specimens (Pearson 1984). The colours correspond to TAI 3+ to 4- (AMC 5+ to 6 in Rovnina 1981) and may indicate thermal alterations approximately corresponding to 175–<200°C (Rovnina 1981).

The taxonomic status of Early and early Middle Cambrian acritarchs in the north Atlantic region has been the

subject of recent studies which include geographic and stratigraphic distribution (e.g. Downie 1982; Volkova et al. 1979; Moczyłowska & Vidal 1986, 1992; Knoll & Sweet 1987; Hagenfeldt 1989a, 1989b; Eklund 1990; Vidal & Nystuen 1990a; Moczyłowska 1991). Species here recorded from the Laisvall and Vassbo successions are listed in Appendix 1 and their recorded stratigraphic ranges are shown in Fig. 5.

In the present collection, specimen numbers with the PMU acronym refer to the collections of the Palaeontological Museum, Uppsala University and are followed by England Finder coordinates. Slide labels are always oriented to the left of the microscope stage.

*Archaeodiscina umbonulata* (Volkova 1968) is represented by rare but well-preserved specimens (Fig. 11:1) from the Grammajukku and Vassbo Formation.

The genus *Asteridium* (Moczyłowska 1991) includes here *Asteridium lanatum* and *A. tornatum* (Volkova 1968; Moczyłowska, 1991), both represented by extremely rare occurrences in the Vassbo and Grammajukku Formations (Appendix 1).



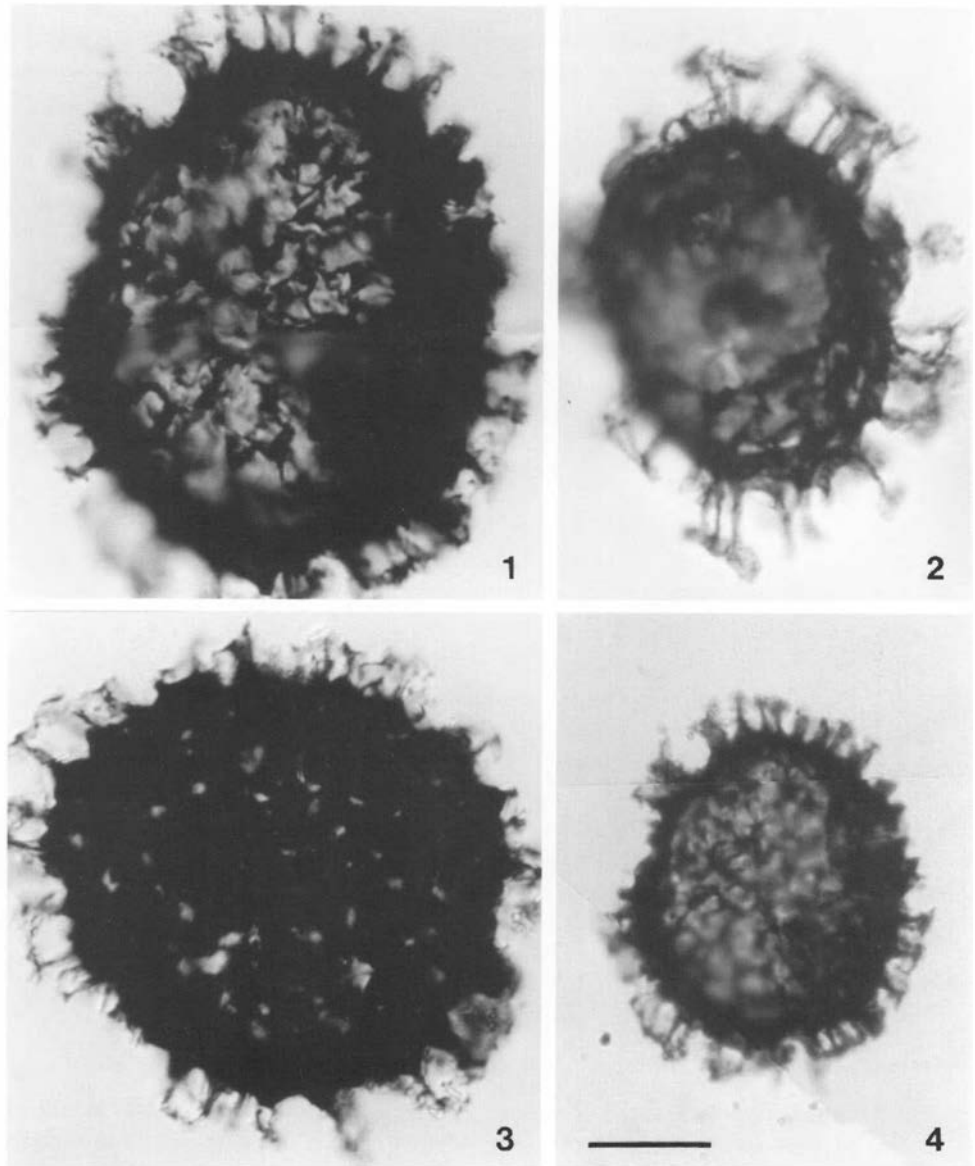


Fig. 12. (1–4) *Skiagia scottica* Downie 1982. (1) PMU-L-80-11 prep. 1, N/38-3. (2) PMU-L-80-12 prep. 1, M/41. (3) PMU-L-80-11 prep. 1, Z/45-2. PMU-L-80-11 prep. 1, N/37-2. All from Grammajukku Formation, Delliknäs section. Length of scale bar at 4 is 10  $\mu\text{m}$  for 1, 2, 3 and 20  $\mu\text{m}$  for 4.

A single specimen of *Comasphaeridium strigosum* was recorded in sample L-80-09 (Appendix 1) from the Grammajukku Formation.

A number of microfossils recovered were identified as prasinophycean green algae. They are attributed to the genera *Cymatiosphaera* O. Wetzel ex (Deflandre 1954) and *Pterospermella* (Eisenack 1972). *Cymatiosphaera* sp. (Fig. 10:1–2) consists of compressed sub-polygonal vesicles with high crests that split the surface into polygonal-shaped fields (campi). *Cymatiosphaera postii* (Jankauskas 1976, Jankauskas 1979 in Volkova et al. 1979; Fig. 10:3) is represented by one uncertainly identified specimen from the Grammajukku Formation (Appendix 1). It has an ovoidal vesicle that possesses high ridges which divide the surface of the central body into polygonal fields. Six to eight ridges are generally observed in the outline of the vesicle. We here attribute to *Pterospermella* sp. (Fig. 10:4) acritarchs with a circular or oval vesicle consisting

of an inner spherical or ovoidal body equatorially surrounded by a thin membrane with a polygonal outline and with irregularly distributed supporting rods.

Microfossils attributed to the prasinophycean Tasmanitaceae belong to the genus *Tasmanites* (Newton 1875). The fossils were identified as *Tasmanites tenellus* (Volkova 1968) and *Tasmanites* sp.

The acritarch genus *Dictyotidium* (Eisenack 1955; emend. Staplin 1961) is represented by single specimen occurrences of poorly preserved acritarchs attributed to *Dictyotidium priscum* (Kirjanov & Volkova 1979 in Volkova et al. 1979) in samples of the Grammajukku Formation (Appendix 1).

*Estiastra minima* (Volkova 1968) (Fig. 9:2) occurs as one single well-preserved specimen from one sample of the Grammajukku Formation (Appendix 1). Previous occurrences of the species are restricted to the East European Platform (Moczyłowska 1991). In western

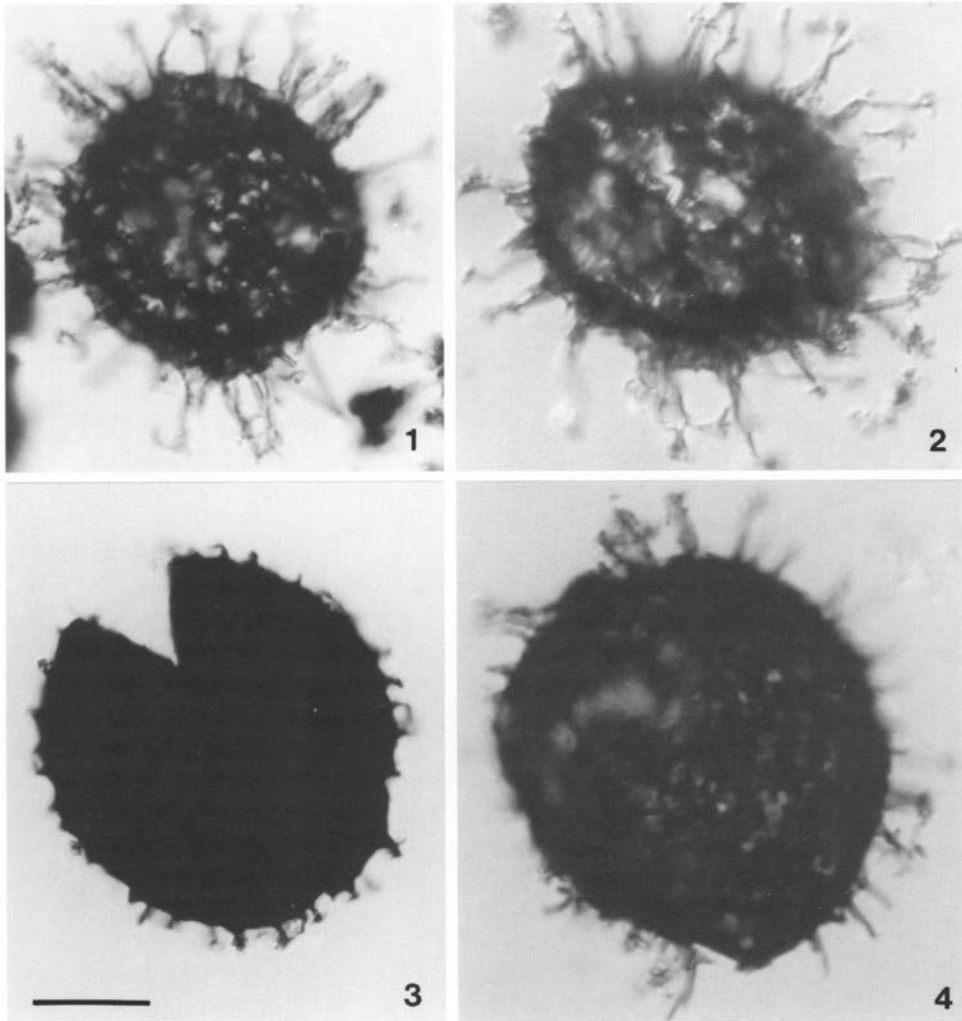


Fig. 13. (1–2) *Skiagia ornata* (Volkova 1969) Downie 1982. (1) PMU-L-80-13 prep. 1, V/23-3. (2) PMU-L-80-13 prep. 1, V/40-1. (3–4) *Skiagia ciliosa* (Volkova 1969) Downie 1982. (3) PMU-L-80-11 prep. 1, M/24 (4) PMU-L1377-277:07-17 prep. 1, W/47-3. Specimens at 1, 2, 3 are from Grammajukku Formation, Delliknäs section. Specimen at 4 from Grammajukku Formation, drillhole L1377 at depth of 277.07 m. Length of scale bar at 3 is 10  $\mu\text{m}$  for 1, 2, 4 and 15.5  $\mu\text{m}$  for 3.

Baltica the species was reported from the Lower Cambrian Mickwitzia and Lingulid Sandstone Members of the File Haidar Formation and lower Middle Cambrian Glauconite Sandstone and 'Oelandicus' mudstone in Östergötland (southern Sweden; Eklund 1990; Fig. 6). Knoll & Swett (1987) reported *E. minima* from the Lower Cambrian Tokamane Formation in East Spitsbergen, Svalbard.

The Genus *Globosphaeridium* was introduced by Moczydlowska (1990), whose type species (*Globosphaeridium cerinum* (Volkova 1968; Moczydlowska 1990) = *Baltisphaeridium cerinum* (Volkova 1968) is here represented only in the Flötningen Member of the Vassbo Formation.

*Globus gossipinus* (Vidal 1988 in Moczydlowska & Vidal 1988; Fig. 7:3) consists of spherical clusters of sub-micron wide filaments irregularly protruding along the periphery in several samples of the Grammajukku Formation. Although its biological affinity is obscure (Moczydlowska & Vidal 1988), its present known distribution in the *H. kjerulfi* shales in southern Norway (Vidal & Nystuen 1990a) and in the Bastion and Ella Ø Formations (North American *Olenellus* Zone) may be

stratigraphically significant. The Bastion and Ella Ø Formations are considered time equivalent to the *Holmia kjerulfi* Assemblage Zone (Moczydlowska & Vidal 1986).

*Goniosphaeridium primum* (Jankauskas) (Downie 1982) and *Goniosphaeridium varium* (Volkova 1969; Downie 1982 (Fig. 9:1) are rare taxa in few samples from the Grammajukku Formation. The extended stratigraphic range of *Goniosphaeridium primum* (Jankauskas) (Downie 1982), as suggested by its reported occurrence in the Buen Formation in North Greenland (Vidal & Peel 1993), appears confirmed by the present finds in the Grammajukku Formation (Fig. 5).

*Goniosphaeridium implicatum* (Fridrichsone 1971; Downie 1982; Fig. 9:3) is here represented by a single occurrence in the Grammajukku Formation. As with *E. minima* (see above), *G. implicatum* is well represented in the Baltic Sea area (Hagenfeldt 1989a, 1989b) and in the Lublin Slope of the East European Platform (Moczydlowska 1990). Downie (1982) erroneously reported the species from the Lower Cambrian Fucoid Beds in Scotland (Moczydlowska, unpublished data). West of the Baltic Sea area the only previous occurrence was in the Lower Cambrian Mickwitzia and Lingulid Sandstone

Members of the File Haidar Formation and the lower Middle Cambrian Glauconite Sandstone and 'Oelandicus' mudstone in Östergötland (southern Sweden; Eklund 1990; Fig. 6), the Lingulid Sandstone Member of the File Haidar Formation in Västergötland (Moczyłowska & Vidal 1986) and the Lower Cambrian Tokamane Formation in Svalbard, East Spitsbergen (Knoll & Swett 1987).

*G. squamacea* Volkova 1968 (Fig. 11:2) occurs in several samples of the Vassbo and Grammajukku Formations.

The genus *Heliosphaeridium* (Moczyłowska 1991) is variably represented in the Vassbo and Grammajukku Formations by small numbers of acritarchs attributed to *Heliosphaeridium dissimulare* (Volkova 1969; Moczyłowska 1991; Fig. 8:1–4), *Heliosphaeridium coniferum* (Downie 1982; Moczyłowska 1991) and *Heliosphaeridium obscurum* (Volkova 1969; Moczyłowska, 1991).

Acritarchs attributed to *Leiosphaeridia* sp. are solitary, corroded and folded smooth vesicles that occur abundantly in the investigated samples.

*Lophosphaeridium* (Timofeev 1959; ex Downie 1963; emend. Lister 1970) is represented as acritarchs attributed to *Lophosphaeridium?* sp. (Fig. 11:3) from the Grammajukku Formation and *Lophosphaeridium tentativum* (Volkova 1968), recorded in the Grammajukku and Vassbo Formations.

*Multiplicisphaeridium dendroideum* (Jankauskas 1976; Jankauskas & Kirjanov 1979 in Volkova et al. 1979; Fig. 9:4) was recorded in one single instance in the Grammajukku Formation.

*Retisphaeridium* sp. (Fig. 7:1) was recovered from the Sävovare Formation; Assjatj Member, whereas *Retisphaeridium* cf. *dichamerum* (Staplin, Jansonius & Pocock 1965; Fig. 7:2–4) occurs in the Grammajukku Formation only in small numbers.

Acritarchs attributed to the Genus *Skiagia* (Downie 1982) represent *Skiagia* cf. *ciliosa* (Volkova 1969; Downie 1982; Fig. 11:4), a form in which the processes appear to be only partially preserved, and *S. ciliosa* (Fig. 13:3–4). The latter represents two morphotypes also recorded in the *Holmia* shale in Lake Mjøsa (Vidal & Nystuen 1990a). Both occur in the Grammajukku Formation, whereas only the latter occurs in the Vassbo Formation.

*Skiagia compressa* (Volkova 1968; Downie 1982) is abundant but poorly preserved in the samples of the Vassbo and Grammajukku Formation.

*Skiagia orbiculare* (Volkova 1968; Downie 1982) refers to extremely rare acritarchs in the Grammajukku Formation with ovoidal to spheroidal vesicles and numerous medium-length processes that are slender tapering along their length from the proximal part and distally where they terminate funnel-shaped.

*Skiagia ornata* (Volkova 1968; Downie 1982; Fig. 13:1–2) is distinctively represented in small numbers in the Grammajukku formation. Only forms with a spheroidal vesicle carrying numerous, long cylindrical processes that are widened proximally and distally (fun-

nel-shaped) are here represented. This corresponds to morphotype 2 in Moczyłowska & Vidal (1986), whereas *Skiagia ornata* type 1 (Moczyłowska & Vidal 1986; later described as *Elektoriscos flexuosus* sp. nov., misspelt *Elektoriscos*, by Eklund 1990) is not represented.

*Skiagia scottica* (Downie 1982; Fig. 12:1–4) is very rare in the Grammajukku Formation and totally absent in the Vassbo Formation.

*Sphaerocongregus variabilis* (Moorman 1974; Fig. 8:9–10) refers to colonial aggregates of spheroidal cells 1–2 µm in diameter with an average diameter of 20 µm that are possibly related to chroococcalean or pleurocapsalean cyanobacteria (Vidal & Nystuen 1990b). The species was recorded preferently in samples of the Sävovare Formation, but also more rarely in the Grammajukku Formation; Fig. 2). Other spheroidal, possibly bacterial microfossils (Fig. 8:5, 8, 11) occur also abundantly in the Sävovare Formation; Fig. 2).

*Trachysphaeridium timofeevi* (Vidal 1976) consists of ovoidal thick-walled vesicles with an scabrate sculpture recorded only in one sample of the Grammajukku Formation.

## Conclusions

Acritarchs from Vendian (?)–Lower Cambrian successions at Laisvall and Vassbo in the central and southern Scandinavian Caledonides allow the identification of biozones established within coeval strata elsewhere in Baltoscandia, the East European Platform (EEP) and North America. The upper Grammajukku Formation (Laisvall) and the Vassbo Formation (Vassbo) are inferred to have been formed as a result of maximum marine flooding in late early Cambrian *Holmia kjerulfi* Zone times. On account of acritarch assemblages, maximum flooding events can be traced into the Laurentian and Barentsian realms of the Iapetus shelf in Greenland and Svalbard. A preceding flooding event occurred in earliest Cambrian *Platysolenites antiquissimus* Zone times in northwestern Baltica (Laisvall, Luopakke and Varanger Peninsula) and the EEP. At present, it is impossible to identify the intervening *Schmidtellus-Rusophycus* Zone recognized in southern and northernmost Baltoscandia (Sweden and Norway) and the EEP. This biozone may be undetected within low stand sand-dominated and unfossiliferous strata representing amalgamated hiatus and periods of non-deposition.

Acritarch assemblages attributed to the *Heliosphaeridium dissimulare*–*Skiagia ciliosa* Zone (age-equivalent to the *Holmia kjerulfi* Assemblage Zone) are both homogeneous and composed largely of cosmopolitan taxa. This feature contrasts with the provincialism of trilobite faunas that are the foundation of Cambrian biochronology. This refers particularly to assemblages from several segments of the present North Atlantic region that in early Cambrian times formed contiguous margins of the Iapetus-Tornquist seaway.

The homogeneous composition of discrete plankton assemblages depended on free dispersal along shelves bordering the Baltic and Laurentian plates. Contemporaneous phosphogenesis in *H. kjerulfi* Zone times is unlikely to have resulted from upwellings, since such a mechanism would have demanded deposition facing a wide ocean basin sustaining stable oceanic gyres. On account of recent palaeogeographic reconstructions and faunal and phytoplankton evidence we advocate the formation in early Cambrian times of a longitudinal seaway between Baltica and Laurentia along which nutrient rich waters would have enhanced primary productivity that resulted in the accumulation of sedimentary phosphate in association with recurrent transgressions and regressions.

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