Sequence stratigraphy, palynology and biostratigraphy across the Ordovician-Silurian boundary in the Röstånga-1 core, southern Sweden

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Dissertations in Geology at Lund University,
Master's thesis, no 315
(45 hp/ECTS credits)

Department of Geology
Lund University
2012

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Cover Picture: The GSSP of the base of the Upper Ordovician Series, Sularp Brook, Fågelsång, Scania. The level of the base is marked by the FAD of the graptolite *Nemagraptus gracilis* below a phosphorite marker bed.

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Badawy, A.S., 2012: Sequence stratigraphy, palynology and biostratigraphy across the Ordovician-Silurian boundary in the Röstånga-1 core, southern Sweden. *Dissertations in Geology at Lund University*, No. 315, 55 pp. 45 hp (45 ECTS credits) .

Abstract: A multiproxy study on sedimentary rocks spanning the Ordovician-Silurian boundary has been performed on material from the Röstånga-1 core, with the aims to improve the biostratigraphical and sedimentological framework and to interpret the depositional environment during this interval in Earth's history.

The sedimentary succession in the Röstånga-1 core is developed in the Scanian Lithofacies Belt and is considered an excellent upper Middle Ordovician-Lower Silurian reference section for southernmost Sweden. The studied succession includes the Sularp Shale, the Skagen Limestone (early middle Katian), the Mossen-Fjäcka formations, the Lindegård Mudstone and the Kallholn Formation. The results from this study, which includes sedimentological, palynological and stratigraphical investigations, add to the knowledge on the climatic changes across the Ordovician-Silurian boundary.

During the time interval covered in the drill core, an intense Ordovician volcanism was climaxed by a short-lived glacial pulse which in turn led to a eustatic regression. The intense volcanism is evidenced by several K-bentonite beds in the Röstånga-1 core. This event left its signature as a development of a sequence boundary and solution structures at the top of the Skagen Limestone. The regressive phase was rapidly succeeded by a return to deeper-water conditions evident within the Mossen-Fjäcka succession, implying that the rate of glacio-eustatic regression was greater than the subsidence rate at that time in Scania. During the deglaciation phase, anoxic black shale coincides with a flooding surface at the base of the Fjäcka Shale. This possibly signifies a high palaeo-productivity and preservation. Following the Fjäcka Shale, the Lindegård Mudstone marks a sea-level highstand and a stable environment.

Based on the palynological results, the succession was subdivided into three informal local palynozones. Palynozone I is of late Katian (pre-Hirnantian Ashgill) age and is characterized by the occurrence of the following acritach taxa: *Baltisphaeridium*, *Buedingiisphaeridium balticum* and *Orthosphaeridium inflatum*. The occurrence of cryptospores within this palynozone provides the oldest evidence of early land plants in Baltica. Through the upper part of this palynozone, the occurrence of diagnostic Early-Middle Ordovician reworked acritarchs such as *Striatotheca*, *Coryphidium* and *Acanthodiacrodium* spp. indicates a detrital Avalonian sedimentary input in front of the Caledonian Deformation and provides an evidence for foreland-type sedimentation.

Palynozone II ranges from early Hirnantian-latest Hirnantian and is characterized by the occurrence of long-ranging and tolerant acritarch taxa such as *Veryhachium* and *Micrhystridium* and a major micro-phytoplankton turnover recognized by the appearance of several taxa with a Silurian affinity, including *Ammonidium* spp., *Diexallophasis denticulate* and the first Baltic record of *Tylotopalla caelamenicutis*. The cryptospore assemblage, through Palynozone II, comprises taxa that have been reported in coeval assemblages globally, possibly indicating homogeneous land plant assemblages. The palynofacies results reveal a relatively high abundance and diversity of scolecodonts coupled with a decrease in the relative abundance of chitinozoans at the base of this palynozone, reflecting a regional similarity with previous results.

Palynozone III ranges from latest Hirnantian-early Llandovery (Rhuddanian) and is characterized by high abundance of graptolites and the occurrence of sphaeromorph acritarchs. The Kallholn Formation, comprising this palynozone, rests on a maximum flooding surface and coincides with a eustatic sea level rise related to the Hirnantian deglaciation, marking new anoxic black shale and a high palaeo-productivity and preservation. Through this palynozone, the acritarchs show the relatively lowest abundance, corresponding to the general feature of the acritarch assemblages through the start of the Silurian, implying that anoxic conditions might be related to this early Silurian "crisis".

The acritarchs from the Lindegård Mudstone are brownish black, indicating a Thermal Alteration Index (TAI) of 4 which is considered to be post-mature with regard to oil generation. There are many controls such as the sedimentary burial and magmatic heating that might have had an effect on the thermal maturity of the organic matter in this basin.

Keywords: Stratigraphy, depositional environments, sea level changes, palynology, Thermal Alteration Index (TAI), Ordovician, Silurian, Röstånga, Scania, Sweden.

Subject: Bedrock Geology

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Sekvensstratigrafi, palynologi och biostratigrafi genom Ordovicium-Silurgränsen i borrkärnan Röstånga-1, södra Sverige

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Badawy, A.S., 2012: Sekvensstratigrafi, palynologi och biostratigrafi genom Ordovicium-Silurgränsen i borrkärnan Röstånga-1, södra Sverige. *Examensarbeten i geologi vid Lunds universitet*, Nr. 315, 55 sid. 45 hp (45 ECTS credits) .

Sammanfattning: En multiproxy-analys har utförts genom ordovicium-silurgränsen i borrkärnan Röstånga-1 från västcentrala Skåne. Målet med studien är att förbättra det biostratigrafiska och sedimentologiska ramverket, samt att tolka avsättningsmiljön under detta tidsintervall. Lagerföljden i Röstånga-1-kärnan tillhör det skånska litofaciesbältet och omfattar Sularpsskiffern, Skagenkalkstenen (tidig–mellersta Katian), Mossenskiffern, Fjäckaskiffern, Lindegårdsslamstenen och Kallholnformationen. Denna studie omfattar sedimentologiska, palynologiska och stratigrafiska undersökningar och resultaten bidrar särskilt till kunskapen om klimatförändringar i slutet av ordovicium och början av silur.

Tidsintervallet som täcks i borrkärnan representerar en period av intensiv ordovicisk vulkanism och en kortlivad köldperiod som i sin tur ledde till en eustatisk havsnivåsänkning. Sistnämnda händelse avspeglas genom en sekvensgräns och upplösningsstrukturer i toppen av Skagenkalkstenen. Den regressiva fasen följdes av en återgång till djupare marina förhållanden med avsättning av Mossen- och Fjäckaskiffern. Basen av Fjäckaskiffern är en översvämningsyta och enheten som helhet domineras av svarta skiffrar som avsattes under syrefattiga förhållanden med hög produktivitet av organiskt material. Lindegårdsslamstenen avsattes under en period med relativt höga havsnivåer och reflekterar stabila sedimentationsförhållanden i bassängen.

Baserat på de palynologiska resultaten, kan lagerföljden delas in i tre informella, lokala palynozoner (I–III). Palynozon I är av sen Katian (pre-Hirnantian Ashgill) ålder och kännetecknas av följande akritarktaxa: *Baltisphaeridium*, *Buedingiisphaeridium balticum* och *Orthosphaeridium inflatum*. Förekomsten av kryptosporer inom denna palynozon utgör de äldsta bevisen för tidiga landväxter på paleokontinenten Baltica. I den övre delen av denna palynozon förekommer omlagrade akritarker av tidig–mellanordovicisk ålder: *Striatotheca*, *Coryphidium* och *Acanthodiacrodium* spp. Dessa indikerar en sedimenttillförsel från Avalonia i samband med den kaledoniska orogenesen samt avsättning i en förlandsbassäng.

Palynozon II sträcker sig från undre Hirnantian till översta Hirnantian och kännetecknas av förekomsten av akritarktaxa med lång stratigrafisk utbredning, såsom *Veryhachium* och *Micrhystridium* samt en omvälvning i planktonassociationerna med första uppträdandet av flera tidigsiluriska taxa, inklusive *Ammonidium* spp., *Diexallophasis denticulate* och den första förekomsten av *Tylotopalla caelamenicutis* i Baltica. Kryptosporerna i Palynozon II innefattar släkten som har identifierats i likåldriga sediment globalt, vilket möjligen indikerar en homogen global vegetation. Palynofaciesresultaten visar en relativt sett högre förekomst och mångfald av scolecodonter i kombination med en minskning av den relativa förekomsten av chitinozoer vid basen av Palynozon II, vilket är samstämmigt med tidigare resultat.

Palynozon III omfattar översta Hirnantian till understa Llandovery (Rhuddanian) och kännetecknas av en hög förekomst av graptoliter och förekomsten av sphaeromorpha akritarker. Palynozon III är representerad i Kallholnformationen som vilar på en sk. maximal översvämningsyta och sammanfaller med en eustatisk havsnivånhöjning relaterad till isavsmältningen under sen hirnant-tid hirnantian. I palynozon III förekommer akritarker i färre antal vilket avspeglar den generella, tidigsiluriska globala signalen och innebär att anoxiska betingelser kan vara relaterade till denna tidiga silurisk "kris". Akritarkerna i Lindegårdsslamstenen är brunsvarta, vilket indikerar ett termalt index (TAI) på 4 och därmed övermognad med avseende på petroleumbildning. Det finns många faktorer som har påverkat den termala mognaden av det organiska materialet i bassängen, främst begravningsdjup och magmatisk påverkan.

Nyckelord: Stratigrafi, avsättningsmiljöer, havsnivåförändringar, palynologi, Thermal Alteration Index (TAI), Ordovicium, Silur, Röstånga, Skåne, Sverige.

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1 Background and introduction

The Ordovician Period (488.3-443.7 Ma) is one of the most interesting geological time intervals with many global and/or regional geological events (climatic, sedimentological, palaeogeographical, palaeontological and stratigraphical). Much work has, historically and recently, been directed to this geological time among workers within many different geological disciplines. For example, many early workers have studied the Ordovician−Lower Silurian succession in the Röstånga area, Scania, southern Sweden which is stratigraphically more complete than in any other areas of southernmost Sweden (e.g. Tullberg 1883; Olin 1906; Moberg 1910; Hadding 1913; and more recently, e.g. Bergström et al. 1999; Pålsson 2002).

A major climatic cooling and extensive glaciers on Gondwana caused large eustatic regressions (dramatic 40-100 m sea level fall), and diamictites of probable glaciogenic origin have been identified in e.g. Egypt (Beall & Squyres 1980), Algerian Sahara (Paris et al. 2000; and references therein), Morocco (Le Heron et al. 2008), and more recently, in the uppermost Ordovician (Hirnantian) of Iran (Ghavidel-Syooki et al. 2011). Many hypotheses have been suggested for the causes of the Hirnantian glaciation which is consistent with one of the largest and globally-recorded $\delta^{13}C$ isotope excursions (the so-called Hirnantian isotope excursion, HICE) which is still a matter of discussion. According to Brenchley (1994, 1995), there was a large increase in marine productivity and organic carbon burial caused a drawdown of atmospheric pCO_2, and consequently the Ordovician cooling. Kump et al. (1999) suggested that an increase in the weathering of silicate rocks due to the Taconic Orogeny and a long-term drop in atmospheric pCO_2 led in turn to the Hirnantian glaciation. Thus, a consequence of an increase in carbonate weathering after exposing the carbonate platforms (major eustatic sea level fall) caused the HICE. Recently, Lenton et al. (2012) suggested that the evolution of the earliest land plant, in part and indirectly, caused the Late Ordovician global changes, climaxing by a glacial episode and a marine mass extinction at the end of Ordovician, through their effect on silicate weathering and CO_2 drawdown.

Palaeontologically, the second largest mass extinction in the Phanerozoic, the so-called end-Ordovician extinction, occurred during the Hirnantian when c. 85% of marine species disappeared (Sepkoski 1996; Sheehan 2001). Noteworthy is that the Great Ordovician Biodiversification Event (GOBE) occurred during the Middle Ordovician with the most important increase of marine diversity in the geological history of the Earth (e.g. Servais et al. 2009). The recovery after the end-Ordovician mass extinction took several million years (Sheehan 2001). Palaeoecologically, the ecosystem structure seems to be unaffected by this extinction, even though, major shifts in community composition and type were implied (e.g. Droser et al. 1997; Sheehan 2001). The glaciation is then widely considered as the major mechanism behind the mass extinction (e.g. Sheehan 2001; Brenchley et al. 2003; Armstrong 2007). Furthermore, Lenton et al. (2012) have recently considered that the evolution of the first plants indirectly contributed to the extinctions during the Late Ordovician in the marine realm. There were two pulses of extinction that are coeval with environmental changes in a sequence of biotic and environmental events (Sheehan 2001; Brenchley et al. 2003). According to Brenchley et al. (2003), the main phase of graptolite extinction in Nevada (i.e. Laurentia) is synchronous with the chitinozoan (planktonic) extinction in Baltica. Brenchley et al. (2003), further states that the main phase of the extinction of the benthic organisms in Baltica correlates with the onset of the HICE, all through the first phase of the extinction during a narrow interval. Later, the second phase affected conodonts (nektonic), benthos and others (except graptolites), and its relation to $\delta^{13}C$ is less clear (Brenchley et al. 2003).

Palynology in part plays a very important role in the study of the Ordovician for palaeontological (evolutionary) and stratigraphical reasons. For example, the globally-recorded cryptospores have given evidence for the presence of the oldest land plants (bryophyte-like) with rarely-recorded plant megafossils because of the lack of potential tissues for fossilization (e.g. Gray 1985; Richardson 1996; Steemans 2000; Strother 2000; Steemans et al. 2009). Consequently, the cryptospores have a great importance in the fossil record. The term "cryptospores" has originally been proposed because of the unusual spore morphology such as tetrads and dyads. Cryptospore such as *Tetrahedraletes grayi*, of Ashgill age/Late Ordovician, is probably of liverwort affinity (Retallack 2000). Early Middle Ordovician (Dapingian) cryptospores from Argentina are the oldest record and evidence for the earliest land plants (Rubinstein et al. 2009). Recently, the first Baltic diverse cryptospore assemblages of Hirnantian age were recorded in Estonia (Vecoli et al. 2011). Steemans (2001) presents an Ashgillian cryptospore-dominated assemblage through a small stratigraphical interval, from graptolitic dark shale deposited far from continents (>100 km from craton), during a volcanic activity, through the Caledonian Brabant Massif, by an emergence of volcanic island (very short time span) which in turn may have favoured the early land plants to locally colonise. Generally, the mass occurrence of cryptospores seems to be linked to the depositional environment and the eustatic sea-level change. While Lakova & Sachanski (2004) had linked this occurrence in distal oceanic sediments, of latest Hirnantion age, to the post-glacial sea level rise, Vecoli et al. (2011) have linked this mass occurrence in proximal and shallow deposits to the glacial sea level fall. On the other hand, trilete spores produced by vascular plants are very rare and only occur locally in the Upper Ordovician (Ashgill of Turkey; Steemans et al. 1996). Trilete spores are also recorded from Saudi Arabia in earliest Ashgill up to the Ordovician-Silurian boundary (Steemans et al. 2009).

Palaeogeographically and regionally, Poprawa et al. (1999) have implied regional tectonic setting by subsidence analysis of Baltic Basin as will be mentioned below. The late Middle Cambrian to Middle Ordovician tectonic setting is characterized by post-rift thermal subsidence of the newly-formed passive continent margin of Baltica along the southwestern edge of the basin. Noteworthy is that an extensional tectonic setting, from the Late Vendian to the Middle Cambrian, has been interpreted by the latest stages of break-up of the Precambrian supercontinent Rodinia into Baltica and Amazonia, and the formation of the Tornquist Sea. According to the same authors, a convergent tectonic regime, from the Caradoc (i.e. Late Ordovician) has been related to the collision of Avalonia with Baltica. As has been palaeomagnetically (Torsvik et al. 1996) and biostratigraphically (Vecoli & Samuelsson 2001b) inferred, a significant separation of Baltica and eastern Avalonia was during the Early and Middle Ordovician until the early Caradoc when the palaeogeographical affinity of Avalonian microfossils started to lessen as compared to the Baltic assemblages. Accordingly, Vecoli & Samuelsson (2001b) have demonstrated that the closure of the Tornquist Ocean and the Avalonia-Baltica collision must have occurred between the middle Caradoc and the early middle Ashgill. That agrees well with the subsidence analysis of Poprawa et al. (1999) since their subsidence curves take on the character of a foreland basin during the Ashgill. According to McCann (1998), a significant degree of closure of the Tornquist Sea was during the Ordovician, even though, the complete closure was not complete until latest Silurian as has been implied from the major tectonic changes in the eastern Avalonia-Baltica area. Thus, this closure led to the Baltoscandian phase of the Caledonian Orogeny. Furthermore, Wilde (1991) has reconstructed the palaeogeography during the Late Ordovician. While the northern and western Gondwana were in the cold-water zones, all other landmasses (i.e. Baltica, Laurentia, Siberia, Australia, and south China) were between 30ºN and 30ºS in the warm-water zone. According to Wilde (1991), the opening of the Rheic Ocean and the related bathymetric ridge-rise blocked major exchanges of water masses between these Late Ordovician zones.

Regional and global stratigraphical correlations, especially through the latest Ordovician and the Ordovician-Silurian (O/S) boundary, are very important, and consequently, geologists around the world have used many various methods (e.g. sequence stratigraphy, stable-isotope stratigraphy, biostratigraphy, etc.) for this purpose. Notwithstanding, not all methods can always or confidently be applied, depending on many geological factors (e.g. geological setting or tectonic controls, depositional environment and conditions, the lack of diagnostic fossils, etc.) which control the potential for using these methods. That has provided some challenges for precise correlations along sedimentary facies belonging to certain belts. For example, Delabroye et al. (2011) have recently showed that some species of acritarchs (microphytoplankton) have a potential for biostratigraphical correlation across the Katian-Hirnantian boundary through low- to mid-latitude carbonate platforms in eastern Laurentia and Baltica. Notwithstanding, an acritarch-based formal palynozonation is still difficult or waiting because of the higher morphological diversity and disparity of acritarchs than other microfossils (e.g. Delabroye & Vecoli 2010; Delabroye et al. 2011). The term “acritarchs” was firstly proposed and defined as small organic-walled microfossils group of unknown and probably various biological affinities by Evitt (1963; p. 300) who also stated that they lack the diagnostic features of dinoflagellates. They appear in Palaeoproterozoic strata and are still present in the oceans today, and are generally similar to dinoflagellates. They are highly dependent on many environmental factors such as oxygenation, salinity, light, depth, nutrient availability, turbidity, pH, sea level changes, and temperature (e.g. Molyneux et al. 1996; Wanhong 1997; Servais et al. 2004; Kui et al. 2005; Delabroye et al. 2011). Notwithstanding, their potential for geological dating and palaeoenvironmental analysis of Paleozoic marine rocks, and for regional and global correlations, is widely recognized and accepted among workers. They have significance because they are considered the primary producers of the Proterozoic and Paleozoic oceans, being the base of the marine food chain. Consequently, they have an influence on the atmospheric CO_2 during photosynthesis, and on the primary productivity and the carbon burial (e.g. Tappan 1986; Simon et al. 2009). As has also been considered, animals such as graptolites or brachiopods are primary consumers, feeding on algae to which acritarchs probably belong (e.g. Wanhong 1997). For all previous reasons, acritarchs have intensely been studied, especially, in a relation to the major palaeoenvironmental perturbations (e.g. Hirnantian (i.e. glaciation): Paris et al. 2000; Vecoli & Le Hérissé 2004; Vecoli 2008; Delabroye et al. 2011, Ludfordian (i.e. Lau event): Stricanne et al. 2006; etc.). Furthermore, acritarchs provincialism or palaeogeographical differentiation during the Early and Middle Ordovician is widely recognized among workers, making a potential for the reworked species of these acritarchs for provenance assignments particularly in active tectonic basin setting (Ribecai & Tongiorgi 1995; Servais 1997; Servais & Fatka 1997; Vecoli & Samuelsson 2001a; 2001b; Servais et al. 2003; Raevskaya et al. 2004; Servais et al. 2008).

Stratigraphically (litho-, sequence, bio-, chemo-), Ordovician has intensely been studied by stratigraphers around the world, as has just been referred above. The International Commission on Stratigraphy has already ratified formal Global Boundary Stratotype Section and Points (GSSPs) for all Ordovician Stages as well as their names (Bergström et al. 2009). On the other hand, global perturbations in the carbon cycle and global climatic changes, through the Katian and Hirnantian Stages (i.e. Upper Ordovician), have been implied since there are up to six positive $\delta^{13}C$ excursions which have been recorded globally through mostly coeval intervals of carbonate sediments on several continents (e.g. Bergström 2007; Bergström et al. 2009; 2010; 2012). Consequently, that has strongly been employed for chronostratigraphical correlations, regionally and globally, because these excursions can be considered as proxies for palaeoenvironmental changes, and as stratigraphical markers which support or integrate sequence stratigraphy- or biostratigraphy-based studies (e.g. Ainsaar et al. 2004; Brenchley et al. 2003; Kaljo et al. 2007; ; Bergström et al. 2010; Calner et al. 2010b; Buggisch et al. 2010; Delabroye et al. 2011; Lenton et al. 2012). Notwithstanding, stable-isotope stratigraphy can sometimes be challenged in some basin settings, being just like sequence stratigraphy- and biostratigraphy-based methods (see below). For example, diagenetic alterations and influences (e.g.; burial, thermal, weathering, etc.) affect the values and can lead to a depletion (e.g. Wigforss-Lange 1999; Calner et al. 2010b; Bergström et al. 2011). Likewise, sequence stratigraphy can also be challenged in some geological settings. Sequence stratigraphy, as has been defined by sequence stratigraphers (e.g. Embry 2009), is simply the stratigraphical discipline which concerns the changes in depositional trends based on property changes of strata which in turn allow the sequence stratigraphic surfaces to be defined (i.e. no change = no sequence stratigraphy). For example, foreland-type sedimentation (i.e. active tectonic settings, rapidly subsiding basin, increased flexural loading, no lithological change or gap) exhibits challenges to the sequence approach (e.g. Jordan & Flemings 1991; Posamentier & Allen 1993). The challenges to biostratigraphy in a relation to various reasons seem to be also very clear. For example, the Laurentian and Baltic correlations, through the Late Ordovician, have challenges because of the absence of the diagnostic *N. extraordinaris* (i.e. the base of the Hirnantian Stage) and *N. persculptus* zones, co-occurring with palynomorphs (e.g. Delabroye & Vecoli 2010; see detailed discussion). Consequently, the base of the Hirnantian Stage is usually traced, using stable-isotope stratigraphical analysis through carbonate successions, as has just been referred above. On the other hand, conodont biostratigraphy is widely recognized in Laurentia and Baltica. Notwithstanding, the latest Ordovician conodonts are only recorded and published from carbonate successions, with some biostratigraphical problems (see Delabroye & Vecoli 2010). Furthermore, one generally needs 500-1000 grams of limestone to yield a representative fauna (10-100 conodonts/kg; Green 2001; and references therein). On the other hand, chitinozoan biostratigraphy is a common tool through the Ordovician on a global scale. While Delabroye & Vecoli (2010) have reviewed the problems of chitinozoan biostratigraphy on a global scale, other biostratigraphical problems might regionally evolve. Grahn & Nõlvak (2007) noted the low diversity of chitinozoan in graptolitic facies compared to the case in carbonate facies of the Central Baltoscandian Confacies Belt, on which the Baltoscandian chitinozoan zones have originally been based, even though, it is not difficult to correlate between the two facies. According to Nõlvak & Grahn (1993), the Baltoscandian chitinozoan zone *Spinachitina taugourdeaui* would regionally correspond to the late Pirgu-earliest Porkuni Stages (i.e. the Katian-Hirnantian boundary). Notwithstanding, *Spinachitina taugourdeaui* is more common in the East Baltic than in Scandinavia, as has also been noted by Nõlvak & Grahn (1993). Accordingly, Grahn & Nõlvak (2010) proposed an “interzone”, in Sweden, to replace the upper Katian and lower Hirnantian *Conochitina rugata*, *Belonechitina gamachiana*, and *Spinachitina taugourdeaui* zones.

Thus, there are consequent challenges for global or regional correlations through interesting stratigraphical intervals along certain geological settings. The Röstånga-1 core (i.e. the Scanian Lithofacies Belt *sensu* Jaanusson 1995), across the latest Ordovician (i.e. Katian-Hirnantian boundary) but not the O/S boundary, is a good example for all the above mentioned challenges. The present study is a continuation of multidisciplinary work initiated in this core by Bergström et al. (1999), and aims (1) to sedimentologically investigate the Röstånga-1 core, and then to establish sequence stratigraphy as far as possible through the basin, providing data for sedimentary basin analysis or modeling. For convenience, a zero line will be taken at a level corresponding to the top of the Skagen Limestone in the core for many reasons: (a) this unit is the only significant carbonate unit in the core, and is a widely-recorded unit not only in Scania but also throughout Sweden; (b) this unit was interpreted in the core and elsewhere by Bergström et al. (1997; 1999) by shallowing caused by a eustatic sea-level fall; and (c) the top of the Skagen Limestone in Sweden, or the base of the Mossen Formation in the Livonian Basin (Ainsaar et al. 2004; Calner et al. 2010a; all present in the core) marks a sequence boundary recently interpreted by Calner et al. (2010b) as a result of middle Katian glaciation in Baltoscandia, based on the amalgamation of this sequence boundary and a widespread palaeokarst by which the Kullsberg Limestone (Siljan district) is topped. The latter unit is stratigraphically equivalent to the Skagen Limestone.

(2) to palynologically investigate the core, through the latest Ordovician and the O/S boundary for acritarchs, to assess the Thermal Alteration Index (TAI), to show the palynofacies pattern through this interval, and then to assess the potential of acritarchs for biostratigraphic correlations globally or regionally. Likewise, linking of the sedimentological, palynological, and biostratigraphical results are needed to get a plausible analysis.

2 Previous work

Since the need had evolved for a reference section to which the small outcrops or undescribed intervals through the O/S successions in Scania could be correlated, a core drilling in the Röstånga area (i.e. Röstånga-1 core) was performed (Figs. 1-4). The core represents a ca. 96 m thick succession from Lower Silurian to upper Middle Ordovician marine strata. The drilling was abandoned at a zone of crushed rocks, probably a fault zone at a depth of 132 m (Bergström et al. 1999). The previous work which was mainly based on Röstånga-1 core can briefly be summarized as follows:

Bergström et al. (1999) first recognized in their preliminary assessment the following units in ascending stratigraphic order: the Sularp Formation, the Skagen Formation (Limestone), the Mossen Formation, the Fjäcka Shale, the Lindegård Mudstone, and the lowermost Kallholn Formation. The same authors referred to the diverse and well-preserved graptolites in the Kallholn Formation, and studied only the uppermost part of the Ordovician in details (34.4-52.7 m). They recognized the base of the *acuminatus* Zone *s.l.* (i.e. the base of the Silurian) at a depth of 52.7 m. There was also little evidence of a history of deep burial or low-grade metamorphism in the Röstånga-1 ash beds.

Pålsson (2002) described the graptolites from the Mossen Formation (very rare), the Fjäcka Shale (fairly diverse) and the Lindegård Mudstone, whereas, there have been no graptolites recovered from the Sularp and Skagen formations. According to this study, the Fjäcka Shale graptolites are indicative of the *Pleurograptus linearis* zone (i.e. the base of the Harju Series or the base of Ka2 Ordovician Stage Slice; Bergström et al. 2009) which is succeeded by the *Dicellograptus complanatus* zone (i.e. the Pirgu Stage of the Harju Series or the base of Ka4 Ordovician Stage Slice; Bergström et al. 2009) in the lower part of the

Lindegård Mudstone just above the graptolites indicative of the *P. linearis* zone.

Koren et al. (2003) showed that the lower boundary of the Silurian in Baltoscandia should be placed at the First Appearance Datum (FAD) of *ascensus s.l.*, and at the base of the *ascensus* Zone, as recognized at the Dob's Linn GSSP in Scotland. That was based on the occurrence of the post-*persculptus* and pre-*ascensus* fauna (*avitus s.s.* fauna, 55.9 - 52.7 m), in the Röstånga-1 drill core, which has been suggested to be older than the lower *ascensus* zone (i.e. assigned to the Late Ordovician *persculptus* Zone). According to these authors, the same graptolite succession has also been recognized across the O/S boundary in other cores in Scania and southern Bornholm. See Fig. 6.

Grahn & Nõlvak (2007) examined scattered samples through the Lindegård Mudstone and the Fjäcka Shale of the Röstånga-1 drill core for chitinozoans. The chitinozoan biostratigraphy in the core was hindered by insufficient sampling, even though, they noted that *Lagenochitina baltica* is present in the Fjäcka Shale and that the presence of *Conochitina scabra* n. sp. in the lowermost part of Kallholn Formation indicates the presence of the *C. scabra* Zone (i.e. late Porkuni Stage, late Hirnantian Stage). *Lagenochitina baltica*, disappears in the upper part of the Fjäcka shale just below the boundary with the Lindegård Mudstone. According to Nõlvak & Grahn (1993), the *Fungochitina fungiformis* Zone (i.e. the Rakvere and lower Vormsi Stages, latest Caradoc- early Ashgill Series) occurs at the base of *Lagenochitina baltica* which disappears at the top of the *Tanuchitina bergstroemi* Zone (i.e. zone of upper Vormsi and lower Pirgu Stages). Regarding the latter zone, the holotype is originally from the upper Vormsi Stages/early Ashgill Series through the Fjäcka Shale, Sweden. Furthermore, *Lagenochitina baltica* already occurs in the uppermost Oandu, but is common from the Rakvere Stage (Grahn & Nõlvak 2010). Thus, this suggests the presence *Fungochitina fungiformis* - *Tanuchitina bergstroemi* zones for the Fjäcka Shale in the core.

3 Geological setting

Scania belongs to the palaeocontinent Baltica that was located at mid-latitudes during the early Late Ordovician (Fig. 4; Scotese & McKerrow 1990; Wilde 1991), with O/S succession stratigraphically more complete than in any other areas of Sweden.

The Röstånga-1 core (Figs. 1-3; site NGC. 621002-134378) is located in W-central Scania, and is considered the stratigraphically most complete section known in this area and was proposed as an excellent Lower Silurian-upper Middle Ordovician reference standard for southernmost Sweden (Bergström et al. 1999). Palaeogeographically, the Röstånga-1 core is located only about 100 km north of the edge of the Baltic Plate within the Tornquist Zone at the SW margin of the Baltic Shield where the Scanian Lithofacies Belt of a graptolitic facies is developed and occupies much of the SW margin of the East European Platform (EEP) (*sensu* Jaanusson 1995). The closure of the Tornquist Sea was not complete until latest Silurian, however, a significant degree of closure occurred during Ordovician (McCann 1998). This resulted in the Baltoscandian phase of the Caledonian Orogeny and the recurring tectonically caused deepening of the depositional environments because of the increased flexure loading along the active margin of the plate, starting in the Ordovician. Consequently, deep marine dark shales and mudstones, with significant sediment thicknesses prevailed to the west and the south in the Oslo Belt and the Scanian Lithofacies Belt respectively (*sensu* Jaanusson 1995). This is in contrast to the starved-sediment character and the mainly shallower epicontinental carbonates with subordinate fine-grained silicaclastic rocks of the intracratonic part of the basin in southern Sweden and the East Baltic region (e.g. Bergström et al. 2002; Calner et al. 2010b). Thus, it is plausible that the Upper Ordovician succession in Scania were deposited on a marginal portion in a foreland basin environment which formed efficient sediment traps and caused the sediment-starved character of the cratonic interior.

This foreland character, during the Ashgill, throughout the Baltic Basin was implied from the subsidence curves that show an increase of tectonic subsidence rates in the western part of the basin, and minor uplifts in the eastern part of the basin (Poprawa et al. 1999). It was also stressed that a convergent tectonic regime began to dominate basin development from the Caradoc (Late Ordovician; Poprawa et al. 1999). Furthermore, Middleton et al. (1996) proposed that a ca. 300 km-wide foreland basin, with a 150 km-wide proximal foredeep, developed in front of the Scandinavian Caledonides because of the Caledonian Orogeny.

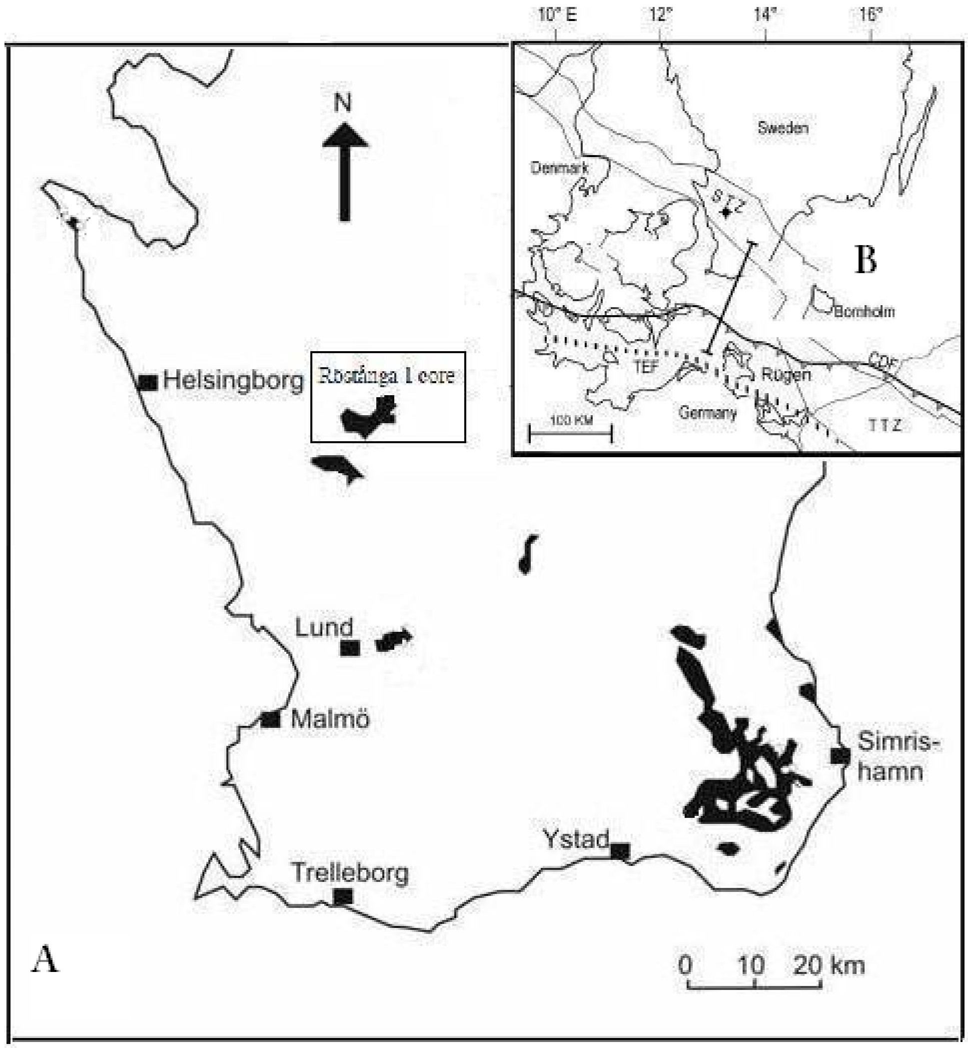

Fig. 1. A) Map showing Ordovician outcrop areas in Scania (black) (modified from Grahn & Nõlvak 2007) and the location of the Röstånga-1 drilling. B) The location of the Röstånga area (cross) within the Sorgenfrei-Tornquist zone (STZ) (modified from Vecoli & Samuelsson 2001a).

By and large, orogenic phases through the Late Ordovician and Late Silurian have been implied from dating by Ar/Ar in low-grade metamorphic rocks (e.g. Liboriussen et al. 1987; Wigforss-Lange 1999; and references therein). It is also worth noting that the subsidence analysis throughout the Baltic Basin shows that the basin development is strongly related to the tectonic evolution of the SW margin of Baltica and that there are two stages of basin development in the Ordovician (Poprawa et al. 1999): (a) the late Middle Cambrian-Middle Ordovician which is controlled by post-rift thermal subsidence of passive continental margin of Baltica along the SW part of the Baltic Basin, and (b) the Late Ordovician which is controlled by the beginning of a convergent tectonic regime with an increase of tectonic subsidence rates in the western part of the basin, and a foreland character coeval with Avalonia/Baltica collision.

4 Material and methods

All the earlier work on the Röstånga-1 core has been reviewed above. The core was obtained in 1997 by Borrbolaget, Västra Frölunda, and the core depth is given in meters. The succession in the core dips 35°. Field excursion to the classical region of Fågelsång, Scania, southern Sweden, was performed. In this study, the Röstånga-1 core was sedimentologically investigated. The study focusses on the core interval 108.8-49 m which comprises the Skagen Formation (Limestone), the Mossen Formation, the Fjäcka Shale, the Lindegård Mudstone, and the lowermost part of Kallholn Formation. The fine-grained siliclastic lithofacies range from black organic-rich shale to light gray mudstone with occasional thin interbeds of limestone. Furthermore, the widely-distributed Skagen carbonate unit is present in the core.

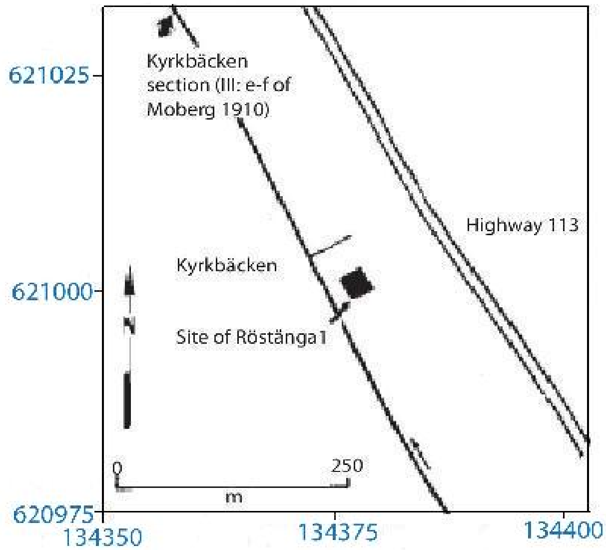

Fig. 2. Map showing the drilling site of the Röstånga-1 core and outcrops along the Kyrkbäcken rivulet (modified from Bergström et al. 1999).

The terminology of Pettijohn (1975) is followed herein. The primary lamination or fissility distinguishes shale from the blocky or massive mudstone. The described colors denote dry samples in order to get the best contrast. A few samples through the Skagen Limestone were collected using a micro-drill for stable isotope chemostratigraphical analysis. They were highly affected diagenetically, and will not be discussed here further. Furthermore, the top of the Skagen Limestone was studied by means of polished slabs. The sedimentological log was then redrawn by SedLog-2.1.4 to which new symbols have been imported, using Inkscape-0.48.2 (Zervas et al. 2009). Likewise, the program was reassigned and customized. The chronostratigraphical classification of the Ordovician follows Bergström et al. (2009). For the palynological analysis and acritarch palynology, a total of 21 samples were collected through the latest Ordovician and the O/S boundary in the Röstånga-1 core, weighted for counting the absolute abundance of palynomorphs/gm., and prepared for palynological investigation according to standard techniques. Thus, standard HCl-HF-HCl acid treatments were carried out during the palynological processing for removing carbonates, silicates, and fluorosilicates after spiking with a known number of *Lycopodium* marker spores (1 tablet) to facilitate the counting of absolute abundance of palynomorphs, and to provide a proxy for the quantity of organic matter or palynomorphs (e.g. Williams et al. 1998; Stricanne et al. 2004; 2006).

For each sample, the slides were prepared after successive removal of fine fractions (< 10 µm) which are mostly lacking palynomorphs. A maximum of 500 palynomorphs were proposed for counting each sample. For the palynological (absolute/relative) counting and the palynofacies pattern, graptolites, acritarchs, chitinozoans, scolecodonts, and cryptospores were used. The reference for color measurements for assessing the Thermal Alteration Index (TAI) is the color standards of Philips Petroleum Company (Pearson 1990). The slides were examined using light on Olympus BX 51 Microscope with digital camera by which photomicrographs with scale were made on a PC. The code RÖ1-X is employed herein, referring to the core name/locality (Röstånga; RÖ), the core number (1; Bergström et al. 1999), and the depth (X m). The core has a diameter of 71 mm (down to a depth of 40.13 m) to a diameter of 52 mm (40.13-132.59 m), and is, together with the palynological slides, presently housed at the Department of Geology, Lund University.

5 Stratigraphy

The stratigraphical succession in the Röstånga-1 drill core was first studied by Bergström et al. (1999). The stratigraphic units of the core have previously been fairly well exposed along the Kyrkbäcken rivulet in the Röstånga area about 350 m NW of the drilling site (e.g. Pålsson 1996; Bergström et al. 1997). Today, the Kyrkbäcken section is poorly exposed. These units are briefly described and discussed in ascending order (see Fig. 5 and Appendix III).

5.1 Skagen Limestone
(see Appendix I, Figs. 1-3)

The Skagen Limestone is widely distributed in Sweden. It is assigned to the Katian Stage, and previously known as the Ampyx Limestone (Bergström 1982). In the Röstånga-1 core, this unit is ca. 2.5 m thick and underlain by the Sularp Shale (a deeper-water grey and partly silicified mudstone with 33 K-bentonite beds). The Skagen Limestone, in general, shows a substantial lateral variation in thickness, locally and regionally, being ca. 3.7 m thick in Fågelsång (about 34 km SSE of Röstånga; Nilsson 1977), ca. 2 m in the Kyrkbäcken outcrop (about 350 m NW of Röstånga-1 site; Bergström et al. 1997), and ca. 0.6 m thick in the Grötlingbo-1 core from southern Gotland (Ainsaar et al. 2004).

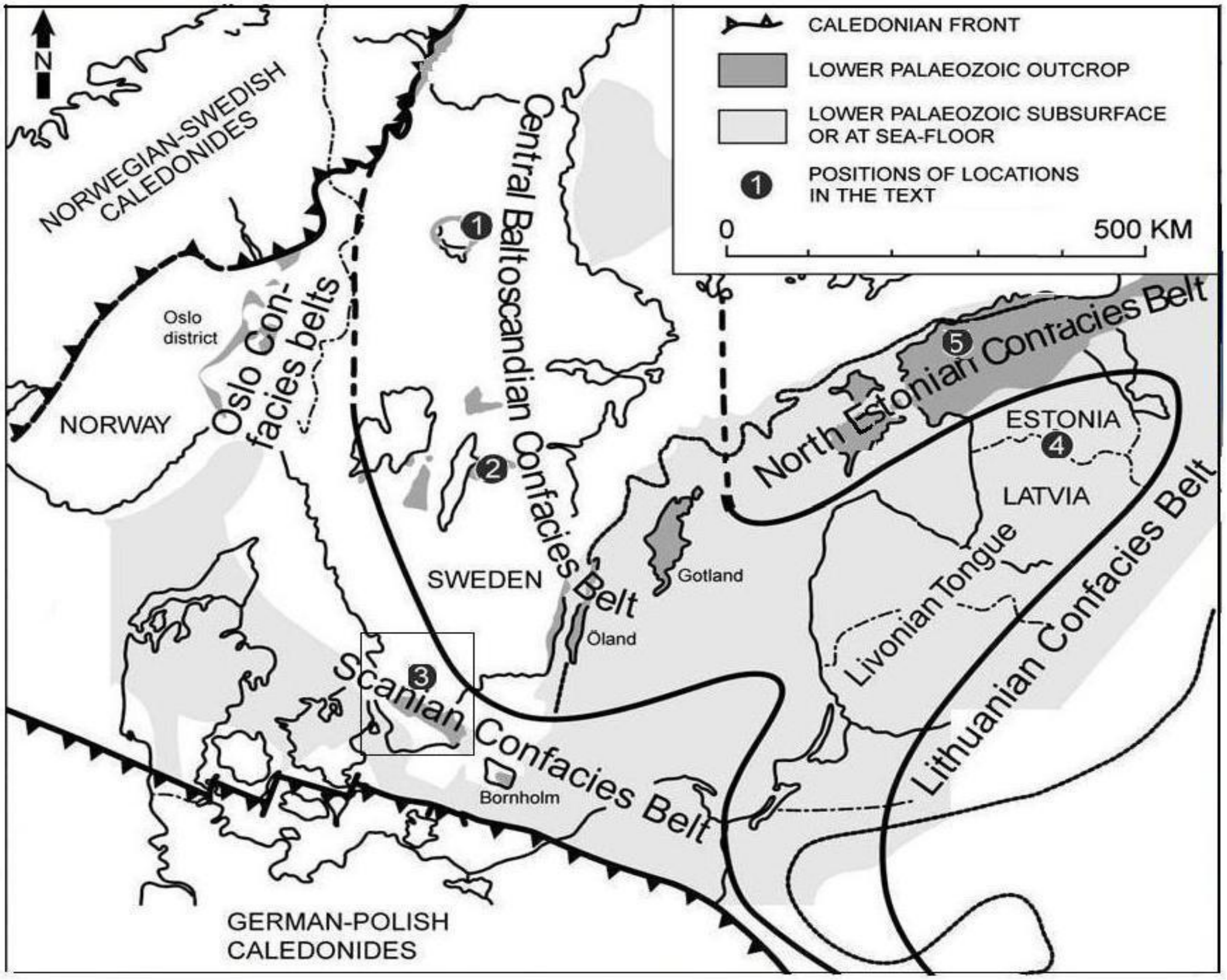

Fig. 3. Map showing the confacies belts of Baltoscandia and areas and localities referred in the text (modified from Calner et al. 2010b). 1– Siljan district, Dalarna. 2– Östergötland. 3– Röstånga area. 4– Valga-10 core, southern Estonia. 5– Rapla core.

In the Röstånga-1 core, the Skagen Limestone is unconformably overlain by the Mossen Formation. The Skagen Limestone is a grey to greenish bedded skeletal limestone, rich in trilobite fragments, alternating with calcareous mudstone. Several prominent palaeokarst surfaces have recently been recorded in the Cambro-Ordovician succession of Sweden, challenging the classical idea of a stable and deep basin (Lehnert et al. 2012). At the top of the Skagen Limestone, there is evidence of solution in the Röstanga-1 core, as indicated by angular- to rounded-shaped solution structures which are the result of karst weathering (supported by the overlying facies). Noteworthy is that the top of the Skagen Limestone (and its equivalents) mark a prominent hiatus in Sweden and in the Estonian Shelf sections (Nõlvak & Grahn 1993; Ainsaar et al. 2004, and references therein; Calner et al. 2010a).

In the Siljan district of central Sweden, Calner *et al.* (2010a) reported an amalgamation of an erosional surface (sequence boundary) and a palaeokarst, marking the top of the middle Katian Kullsberg Limestone which is equivalent to the Skagen Limestone and the base of the Mossen Formation (in the Livonian Basin) as shown by Ainsaar et al. (2004). The two latter units are also present in Scania, southern Sweden (e.g. in the Röstånga-1 core). In the Röstånga-1 core, the Skagen Limestone contains 7 K-bentonite beds with a similar sequence of K-bentonite beds in the Kyrkbäcken outcrop (Bergström et al. 1997, 1999). Generally, major pulses of contemporaneous bentonites are present in southern Sweden and Bornholm. The Skagen Limestone was first interpreted as reflecting a shallowing of the depositional environment, which was probably caused by a eustatic sea level fall recognized in many continents (e.g. Scania; Bergström et al. 1997).

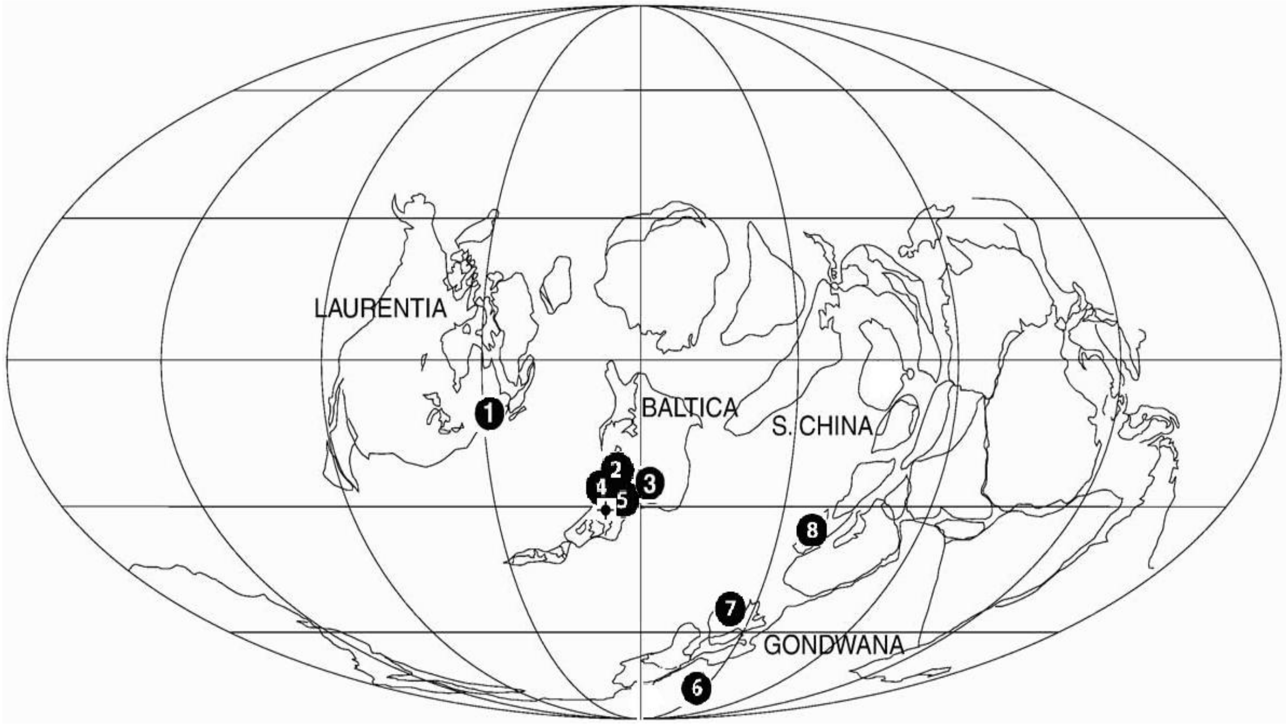

Fig. 4. Map showing the latest Ordovician palaeogeography, latest Katian–Hirnantian, based on Scotese & McKerrow (1991) (modified from Delabroye & Vecoli 2010). Localities and areas mentioned in the text: 1- Anticosti Island, Quebec, Canada; 2- Rapla, northern Estonia; 3- Valga, south Estonia; 4- Gotland Island, Sweden; 5- Holy Cross Mountains, Poland; 6- northeast Libya; 7- Prague Basin, Czech Republic; 8- south Turkey; Cross: Röstånga, south Sweden.

Recently, Calner et al. (2010b) has related this event to a middle Katian glaciation based on the amalgamation with widespread palaeokarst found in the top of the Kullsberg Limestone. This was also evidenced by a widespread palaeokarst across different confacies belts in Baltoscandia. While little is still known about this glaciation event, it seems to have been a short-lived glacial pulse. Furthermore, it was suggested that major Ordovician volcanism (as shown by many prominent K-bentonite beds) caused a cooling event and had a profound effect on Late Ordovician (Mohawkian-Cincinnation) climate during a first (?) Ordovician glaciation in western Laurentia (Buggisch et al. 2010), and was a trigger for increasing karstification due to the formation of acid rains (Keller & Lehnert 2010). This intense volcanism, which was global and concomitant to the tropical carbonate platform growth of the Great Basin, was climaxed by the late Sandbian eruptions, which in turn produced the Deicke and Millbrig K-bentonites and their global equivalents (Keller & Lehnert 2010). For example, the upper boundary of the Dalby Limestone, Sweden, is generally defined by the thick Kinnekulle K-bentonite above which the Skagen Limestone (Sandbian-Katian) overlies. The Sularp Formation of Scania is equivalent to the Dalby Formation. Further correlations would probably discuss the relation of the probably intense volcanism traced contemporaneously in southern Sweden to the glaciation of Calner et al. (2010) and consequently the widespread karstification, taking in account the correlative nature of this short-term glacial event in Laurentia and Baltica, as has been proved by carbon-isotope stratigraphy (see Calner et al. 2010b; Buggisch et al. 2010). Bergström et al. (1997) have shown that the Röstånga area has a unique K-bentonite succession on the entire northern hemisphere. The K-bentonite succession is beyond the scope of this study, but can be a key to the recently-recorded multiple palaeokarst surfaces recorded in Baltoscandia by Lehnert et al. (2012). Further studies are needed to establish whether or not the ca. 59 cm K-bentonite bed just below the Skagen Limestone, or one of the other K-bentonite beds, is representing the prominent Kinnekulle K-bentonite. The latter is a marker bed for regional correlations (Bergström et al. 1995). Bergström et al. (1997) have shown that one possibility is that the Kinnekulle bed is present at Kyrkbäcken. An analysis of the chitinozoan biostratigraphy through the Skagen Limestone in the Kyrkbäcken outcrop has shown the presence of *Desmochitina nodosa* in the lower part of this unit (Grahn & Nõlvak 2007), which suggests the *Spinachitina cervicornis* Biozone of the Keila or early Oandu Stage (Nõlvak & Grahn 1993).

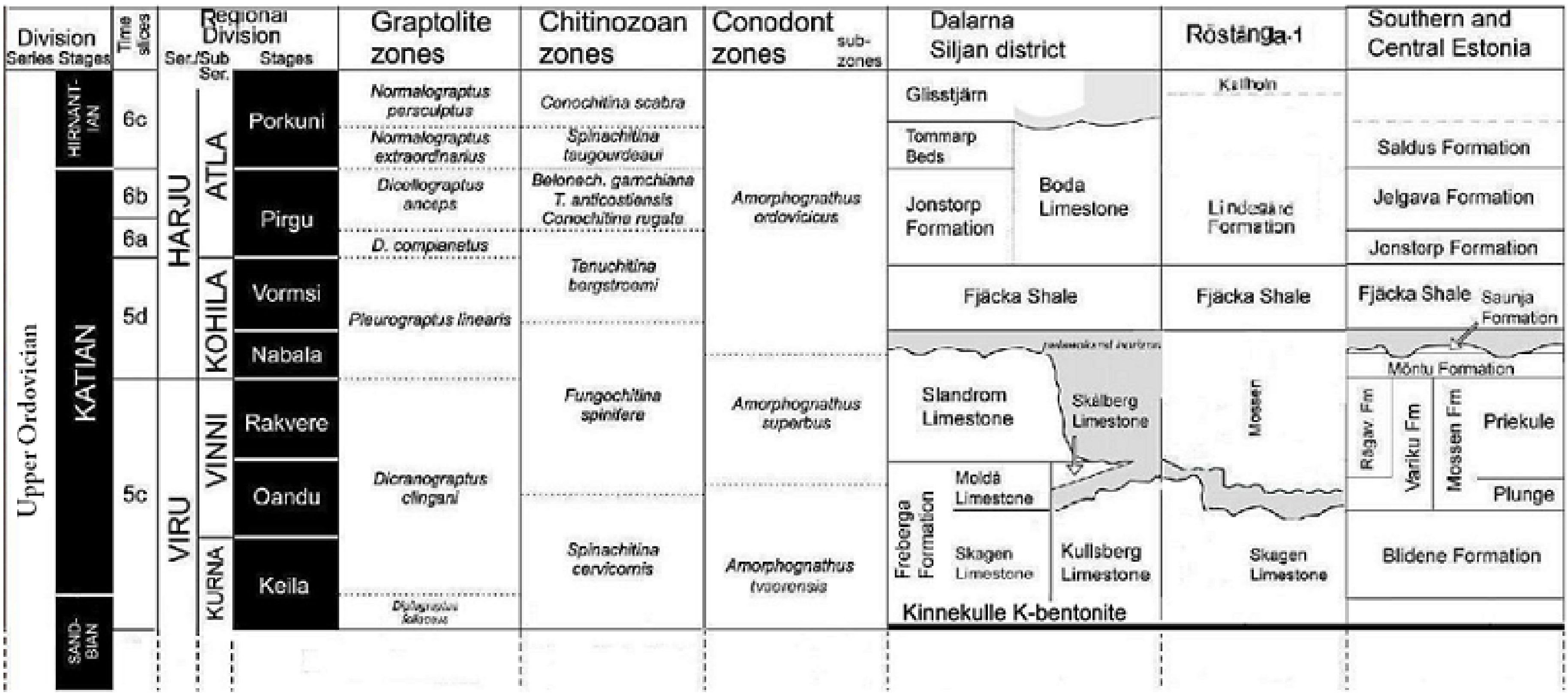

Fig. 5. Stratigraphy of the Upper Sandbian through Hirnantian of Sweden and the East Baltic area (modified from Calner et al. 2010b; see text for discussion).

5.2 Mossen Formation

(see Appendix I, Fig. 2)

The Mossen Formation was originally defined in Västergötland, south-central Sweden as a succession with dark grey or black shale to grey calcareous mudstone by Skoglund (1963). In the Röstånga-1 drill core, the Skagen Limestone is unconformably overlain by the Mossen Formation, which is ca. 0.75 m thick. This unit shows a rapid thinning over short distances, being a ca. 12.75 in Fågelsång (Nilsson 1977) and a ca. 0.95 m in the Kyrkbäcken outcrop (Pålsson 1996). In the Röstånga-1 drill core, the lowermost part of this unit yields rounded to subrounded glauconitic limestone clasts succeeded by strongly bioturbated, coarse-grained, grey calcareous mudstone. Graptolites are generally rare, but brachiopods are common. Noteworthy is the very high abundance of trilobite fragments in this unit at the Kyrkbäcken rivulet (Pålsson 1996). In the Röstånga-1 core, the lowermost part of this unit is probably missing. The bioturbation is attributed to a benthic marine fauna. The unit contains one K-bentonite bed that correlates with a questionable K-bentonite bed in the Kyrkbäcken section identified by Bergström et al. (1997). Generally, the Mossen-Fjäcka formations, which overlie the Skagen Limestone, indicate a return to deeper-water conditions and shows a fining upward succession after a short duration of shallowing and major sea level fall. An analysis of the chitinozoan biostratigraphy in the Mossen Formation, at the Kyrkbäcken outcrop, showed the presence of *Belonechitina robusta* (Grahn & Nõlvak 2007), which is indicative of the *Fungochitina spinifera* Biozone of the late Oandu-early Vormsi Stage (Vandenbroucke 2008). Notably, the recognition of a sequence boundary at the top of the Skagen Limestone/the base of the Mossen Formation in the Scanian Lithofacies Belt, is of a very important significance because this clearly suggests that the glacio-eustatic rate was greater than the subsidence rate at that time (Posamentier & Allen 1993), which will later be accelerated during the Ashgill due to the Avalonia-Baltica collision and the development of foreland basin (Poprawa et al. 1999).

5.3 Fjäcka Shale

(see Appendix I, Fig. 2)

The Mossen Formation is overlain, probably conformably, by the Fjäcka Shale, which is a clearly transgressive unit with a lower contact representing a flooding surface between marine mudstones below and deeper-water marine black shales above. The Fjäcka Shale was described as a grey to black shale and mudstone by Jaanusson (1963) and Skoglund (1963). Generally, the Fjäcka Shale (of Katian Stage age, part of Ka3 Stage Slice; Bergström et al. 2009) is a regionally-distributed graptolitic and organic-rich shale (usually laminated; see also Högström & Ebbestad 2004). It can be locally rich in shelly fossils (e.g. at Fågelsång). In Scania, this unit has been assigned to the Vormsi Stage, marking the transition from the *Fungochitina spinifera* and *Tanuchitina bergstroemi* chitinozoan zones (Grahn & Nõlvak 2007). In the Röstånga-1 core, Grahn & Nõlvak (2007) investigated the Fjäcka Shale, which yielded *Lagenochitina baltica*, a characteristic species indicative of the *Tanuchitina bergstroemi* zone (Nõlvak & Grahn 1993). The graptolites in the Fjäcka Shale are indicative of the *P. linearis* zone (Glimberg 1961); however, *P. linearis* seems to be rare in Sweden (Pålsson 2002). In the Röstånga-1 core, the Fjäcka Shale shows fairly diverse graptolites which are indicative of *P. linearis* zone (see 2 previous work). Furthermore, the Fjäcka Shale is the source rock for oil in the overlying Boda Limestone in the Siljan district (Vlierboom et al. 1986). Stratigraphically, it correlates with the graptolitic Venstøp Formation in the Oslo Region, Norway. In the Röstånga-1 core, the Fjäcka Shale is a ca. 13 m thick, being much thicker than the ca. 3.2 m in Fågelsång (Glimberg 1961) and ca. 3.91 m in the Kyrkbäcken rivulet (Pålsson 1996). In the Röstånga-1 core, the Fjäcka Shale is generally a fine-grained, black to dark grey shale and mudstone interbedded with calcareous shale/mudstone in the upper part. No K-bentonite beds have been recorded; a ca. 9 cm thick ash-like bed (103.28-103.37 m) was proved to be shale by XRD scan (Bergström et al. 1999). The lowermost ca. 3.5 m of the Fjäcka Shale is a black, laminated and graptolitic shale lacking benthic fauna. The preservation of the primary lamination, the lack of a benthic fauna and the very black color (organic-rich), possibly suggest an anoxic depositional environment (Pedersen 1989). According to Leggett (1980), the Lower Palaeozoic anoxic black shales may reflect a deposition in the oxygen minimum zone based on their widespread extent which does not fit into a restricted basin. Caradoc through lower Llandovery coincide with a eustatic transgression and sea-level rise, which in turn was responsible for an increase in surface waters productivity leading to a significant drain on the oxidative potential of the water column (Leggett 1980). The result is an oxygen-deficient water mass and favorable conditions for the preservation of organic carbon. The black shale of the lowermost part of the Fjäcka Shale in the Röstånga-1 core is succeeded by dark grey to black, fine-grained, shales and mudstones. Sparse bioturbation in the mudstone has been observed, reflecting a weakly oxic environment. The shale lacks any bioturbation and is finely laminated, indicating the lack of benthic fauna and slow setting of sediments (see Pedersen 1989). It must be noted that TOC % plays a very important role for interpretation the environment as anoxic or oxic.

One sample (RÖ1-91), at the topmost part of the Fjäcka Shale, has been palynologically studied. It shows highgly degraded organic matter probably because of a very slow average rate of sedimentation, which in turn means sufficient time for degradation. It also strongly suggests deposition in a deep basinal marine environment as indicated by the relatively low diversity, sphaeromorph-dominated assemblage (Molyneux et al. 1996; Montenari & Leppig 2003; Molyneux et al. 2008). The level of lithological change from dark mudstones and shales to light grey or greenish grey mudstone marks the change from the Fjäcka Shale to the overlying Lindegård Mudstone as well as the change from the Fjäcka Shale to the overlying green and gray lower part of the Jonstorp Formation in south-central Sweden (Bergström et al. 1999). This level also corresponds to the *P. linearis* zone - *D. complanatus* zonal boundary (Skoglund 1963). At this level, the change from fine-grained dark facies to coarser-grained light grey silty mudstone to silty shale in the lowermost part of the Lindegård Mudstone is interpreted as a shift from retrogradational to progradational sedimentation. The boundary between the two units is thus interpreted as the maximum flooding surface (mfs). It is clear that the mfs marks the change to increasing sediment supply in certain areas. Marine productivity is generally linked to the absolute frequency (number of palynomorphs/ grams of rock) of Palaeozoic palynomorphs and especially acritarchs (e.g. Stricanne et al. 2006). However, there are several factors, rather than the productivity, affecting the concentration of palynomorphs and phytoplankton, such as palaeoenvironment, sedimentation rate, diagenesis and compaction (see Westphal et al. 2000; Tongiorgi et al. 2003). Furthermore, high productivity does not certainly lead to a high level of preservation (Batten 1996, and references therein). The preservation of organic matter was linked to oxygen deficiency or anoxia (e.g. Tyson 1987). While anoxia has a high probability in the case of high productivity, high productivity is not necessarily connected to anoxia (Tyson & Pearson 1991). Noteworthy is that the grain size of sediments, degree of reworking by currents and storm-wave action, the amount of bioturbation, and the level of oxygen affect also the preservation of the organic matter (Batten 1996). The studied sample, from the topmost Fjäcka Shale, shows a relatively higher abundance (absolute frequency/productivity) as compared to the succeeding samples in the lowermost part of the Lindegård Mudstone. This high productivity is not clear as much as the case in the graptolitic organic-rich black shale of the Kallholn Formation, as will be shown later. There was, however, evidence of weakly oxic environment, as has already been shown above.

5.4 Lindegård Mudstone

(Appendix I, Figs. 4-6)

The term "Lindegård Mudstone" was originally proposed in the Röstånga-1 core by Bergström et al. (1999), and was also previously proposed as a lithostratigraphic unit for the uppermost Ordovician succession in the Lindegård core (Fågelsång area) by Glimberg (1961). According to Bergström et al. (1999), the Lindegård Mudstone (Katian-Hirnantion) replaces the previously used Jerrestad and Tommarp mudstones in Scania, being ca. 50 m thick in its type area at the Fågelsång area. The definition of the new unit is thus grey shales and mudstones between the Fjäcka Shale below and the Kallholn Formation above. The Lindegård Mudstone ranges from the *D. complanatus* zone in the lower part to near the top of the *N. persculptus* zone, so its base marks the boundary between the *P. linearis* and the *D. complanatus* zones. A few K-bentonite beds, just above the level of the appearance of *D. complanatus* have been recorded. These are coeval to the K-bentonite beds in the Jonstorp Formation (Västergötland), which also overlies the Fjäcka Shale in south-central Sweden. In the Röstånga-1 core, the Lindegård Mudstone (27 m) and the lowermost ca. 3.3 m of the Kallholn Formation (i.e. 30.3 m) form the top of the Ordovician System. This Ordovician succession above the Fjäcka Shale is also greater than ca. 50 m in the Fågelsång area. Compared to ca. 13.56 m in the Borenshult-1 core, Östergötland (the reference core in the province; see Bergström et al. 2011), that clearly reflects the increased flexural load and the consequent substantial deepening in the Scanian Lithofacies Belt due to the advancing Caledonian Orogen, depending on the proximity to the active margins of the plate especially that there is no evidence of a lithological change or gap across the O/S boundary in Scania, as has also been demonstrated by Koren et al. (2003). In active tectonic basin settings, the subsidence increases proximal to the orogenic belt, whereas it increases seaward on passive margins (Posamentier & Allen 1993). The lack of a lithological change suggests that the post-*persculptus* fauna/pre-*ascensus* fauna (*N. avitus s.s.* fauna) is of a special importance for the precise

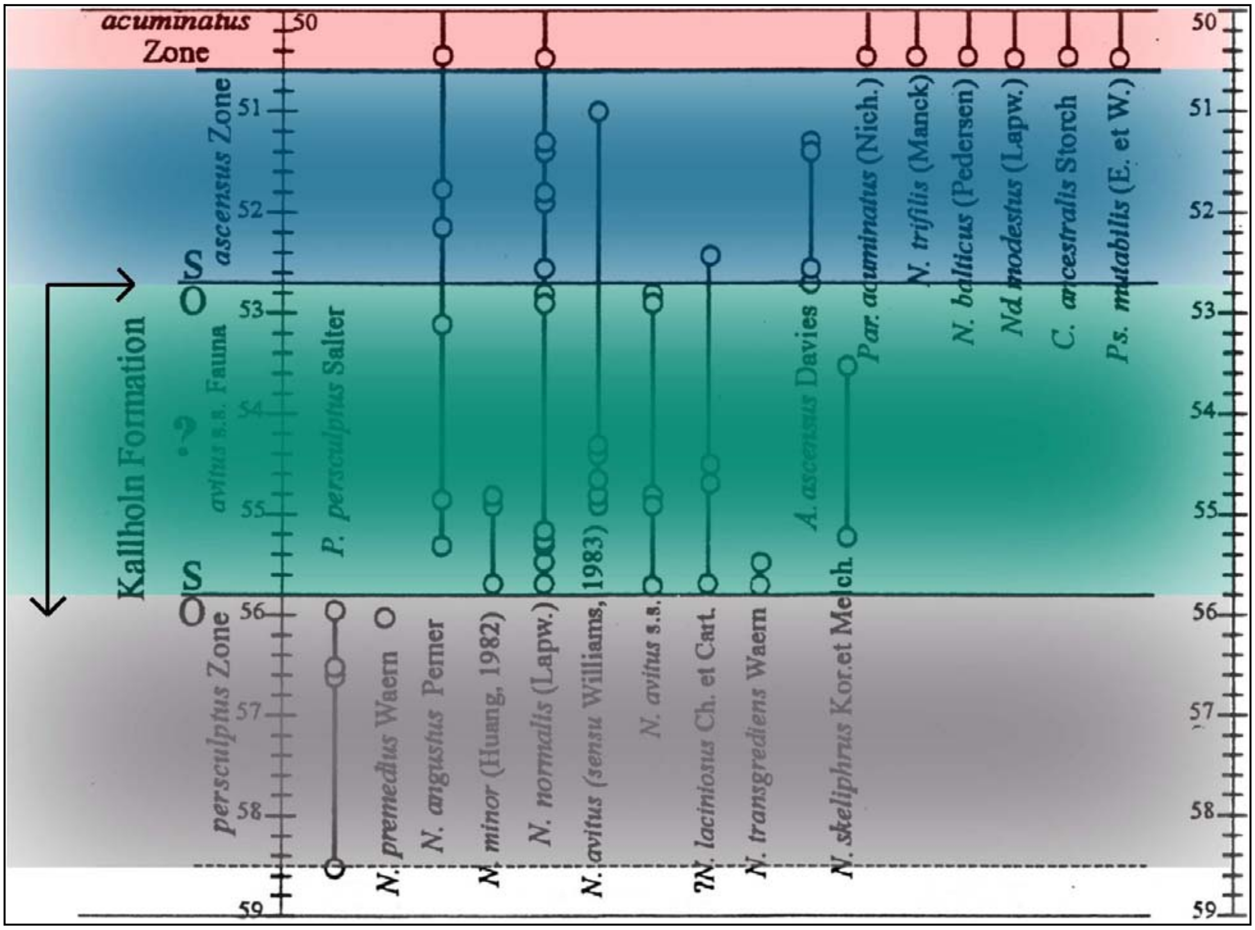

Fig. 6. Graptolite ranges and zones across the Ordovician-Silurian boundary in the Röstånga-1 core (modified from Koren et al. 2003). For discussion, see 2 previous work, the Lindegård Mudstone and the Kallholn Formation. Note the base of the Kallholn Formation is at a depth of 56 m.

identification of the O/S boundary in Scania, because the lack of this fauna in other regions outside Scania, is related to changes in the depositional environments and ecological factors (Koren et al. 2003; Fig. 6).

Following the fine-grained dark clayey facies of the Fjäcka Shale, the lowermost ca. 8.95 m of light grey or greenish grey silty mudstone to silty shale and laminated limestone, at the base of the Lindegård Mudstone, clearly marks a sea-level highstand (i.e. progradational sediments). Weak bioturbation has been observed in the grey mudstone which is capped by ca. 33 cm of greenish silty shale, which is carbonate-rich in the top. This grey bioturbated mudstone has also been recognized in the subsurface of Denmark (Jerrestad Formation; Pedersen 1989). The laminae of this silty shale are thick (2-5 mm), indicating rapid deposition from dense suspension. The carbonate-rich top is possibly caused by the winnowing of the fines together with a coarser-sized supply of sediments, resulting in a higher permeability and carbonate cementation. The lowermost part of the Lindegård Mudstone correlates well with the Highstand System Tract (HST) Jonstorp Formation (e.g. Calner et al. 2010a). The lowermost part of the Lindegård Mudstone overlies the mfs of the Fjäcka Shale, which marks the change from transgression to regression as the shoreline starts to move seaward when the rate of sediment supply starts to exceed the rate of sea level rise at the shoreline (e.g. Embry 2009). Two samples (RÖ1-85 and RÖ1-87), through this part of the Lindegård Mudstone, yielded extremely sparse cryptospores of early land plants (1-2 cryptospores), which denote offshore deep-water shelf environment at a significant distance from shoreline. That supports the sequence stratigraphical interpretation. Following this part of the Lindegård Mudstone, cryptospores will not appear again until the uppermost part of the formation (i.e. Hirnantian). There are two and one questionable K-bentonite beds in the lower part of the Lindegård Mudstone in the Röstånga-1 core (see also Bergström et al. 1999). The upper part of the Lindegård Mudstone is a light to medium grey mudstone and calcareous mudstone/shale. It must be noted that a sequence stratigraphical analysis is hampered by the lack of any lithological change or sedimentological gap because of the substantial deepening of the environment and the increased tectonic subsidence rate indicative of foreland basin development in front of the advancing Caledonian Orogen, as has also been shown by the tectonic subsidence curves of Poprawa et al. (1999). The presence of well-preserved typical Avalonian reworked acritarchs in the Röstånga-1 core indicates detrital Avalonian input in front of the Caledonian Deformation (Caledonian Deformation Front, CDF), as will be shown below. Bergström et al. (1999) noted that there is some mixing of detrital muds with the ash, as proved by XRD analysis of some K-bentonite samples from the Röstånga-1 core. This challenge of the sequence stratigraphy through the foreland setting in front of the advancing orogen (Zone A; see Posamentier & Allen 1993) is mainly because of the high subsidence rate which exceeds the glacio-eustatic rate. Consequently, zone A does not show any a relative sea-level fall but slowing, and then accelerating of relative sea-level rise. This challenge in the foreland basin was linked to the tectonics which put forth strong control on sediments supply and subsidence rates which increase toward the orogenic belt (Jordan & Flemings 1991; Posamentier & Allen 1993). Biostratigraphically, two important graptolite zones were recorded in the Lindegård Mudstone in the Röstånga-1 core. The first graptolite zone is the *Dicellograptus complanatus* Zone marking the transition from the Fjäcka Shale to the Lindegård Mudstone (Pålsson 2001; see above). The other graptolite zone is the *persculptus* Zone (58.50-56.1; Fig. 6) which is just below the latest Hirnantion-earliest Silurian black shale of the Kallholn Formation (Koren et al. 2003). The *persculptus* Zone (58.50-56.1) is important in the following respects (cf. Paris et al. 2000):

- The lowermost part of this zone marks the maximum sea-level fall and the highest value of $\delta^{13}C$.
- The melting of the main ice cap correlates with an early part of the *persculptus* Zone (i.e. the early late Hirnantian Stage). This lower part of the *persculptus* Zone marks a sea-level rise in Baltica and Laurentia (e.g. Kaljo et al. 1999; Finney et al. 1999).
- The rapid sea-level rise (the end-glaciation rise followed the final melting of the ice cap) marks the latest *persculptus* Zone (i.e. the latest Hirnantian Stage).

Sequence stratigraphically, the time of start base-level rise is generally equal to the Correlative Conformity (CC), which is a chronostratigraphical (i.e. time) surface basin-ward, defining the upper boundary of the Falling Stage System Tract, FSST (e.g. Posamentier et al. 1988; Embry 2009). Among the above-mentioned three global events, the last one has been traced palynologically and sequence stratigraphically (sedimentologically) in the Röstånga-1 core. That is clearly plausible, and can be explained by the foreland basin model of Posamentier & Allen (1993). Palynologically, one sample (RÖ1-57), from the uppermost part of the *persculptus* Zone, clearly shows an abrupt increase in productivity, which in turn continues above more or less by the same level (see the Kallholn Formation below for explanation). That is coupled with the disappearance of the sparse cryptospores previously recorded just below this level. Sedimentologically, this level shows a clear fining-upward, from light grey mudstones to dark grey mudstones and shales, marking the gradational contact with the overlying black shale of the Kallholn Formation (at ca. 56 m, uppermost *persculptus* Zone, which rests on mfs as will also be shown below. According to Liu (2005), the anoxic events, in the Upper Cretaceous of the Gulf of Mexico, may occur in two stages of a rising sea-level being at the onset of transgression, and at mfs (maximum sea-level high).

5.5 Kallholn Formation

(Appendix I, Figs. 6-8)

Only the lowermost part of the Kallholn Formation (56-49 m) was studied. In the Röstånga-1 core, the Kallholn Formation ranges from the uppermost Hirnantion to the Lower Silurian. The term "Kallholn Formation" has been proposed to replace the biostratigraphical designations or units of "Rastrites Shale" and "Retiolites Shale" (Bergström & Bergström 1996). That has been applied also in Scania, for instance in the Röstånga -1 core (Bergström et al. 1999). Generally, the Kallholn Formation, in the Röstånga-1 core, shows the most significant thickness in the core being ca. 35 m with 11 K-bentonite beds, like the Llandoverian interval in south-central Sweden and on Bornholm (Bergström et al. 1999). The Lower Silurian part of the Kallholn Formation in the Röstånga-1 core is ca. 31.7 m. This corresponds to (>35 m) in the Øleå section and (>59.5 m) in the Lovisefred core (Scania) (see also Bergström et al. 1999). According to Vejbæk et al. (1994), very rapid subsidence and sedimentation began during the early Llandovery very close to the Caledonian Deformation Front (CDF, e.g. the Danish sector). Bergström et al. (1999) referred to an evidence of a history of deep burial or low-grade metamorphism in the Röstånga-1 core based on the component of illite in illite/smectite (I/S, 87% illite) in the K-bentonite beds. Palynologically, the acritarchs from the Lindegård Mudstone are brownish black-colored, suggesting a Thermal Alteration Index

(TAI) of 4 which is considered to be post-mature with regard to oil generation (e.g. Batten 1996; see below). However, there are many controls rather than the sedimentary burial that might have had an effect on thermal maturities such as magmatic heating (e.g. William et al. 1988). Regarding the investigated part of the Kallholn Formation, sedimentology and palynology, together, strongly suggest anoxic conditions. Sedimentologically, it is similar to the lowermost part of the Fjäcka Shale (see the Fjäcka Shale above). It must also be noted that the Kallholn Formation contains diverse and well-preserved graptolites (i.e. graptolitic, organic-rich, laminated, pyritized black shale). Palynologically, the samples studied from the Kallholn Formation show the high probability of anoxia as a clear high productivity has been observed (see Tyson & Pearson 1991). The palynological assemblage is mainly composed of highly abundant graptolites and sparse sphaeromorph acritarchs (e.g. *Leiosphaeridia* spp. Prasinophyceae), suggesting both zooplanktonic and phytoplanktonic sources for the organic content. The chronostratigraphical definition of this anoxic event is very important to understand and evaluate its occurrence which seems to be linked to a global event coeval to the common Hirnantian-early Silurian black shale (e.g. Leggett 1980; Armstrong et al. 2005; 2009). Lithologically, there is no evidence of a gap in the black shale across the Ordovician-Silurian boundary as was also reported by Koren *in* Bergström et al. (1999). Through the investigated interval (56-49 m) of this black shale, there are three graptolite zones (Bergström et al. 1999; Koren et al. 2003; Fig. 6): the first is part of the latest *persculptus* Zone (58.50-56.10 m; i.e. the latest Hirnantian Stage), the second is the *ascensus* Zone (52.70-50.50 m), and the third is the *acuminatus* Zone (50.50-46.70 m). The base of the Silurian is placed at the base of the *ascensus*-*acuminatus* Zone (i.e. at a depth of 52.70 m). Grahn & Nõlvak (2007) stresssed that the C. *scabra* Zone (chitinozoa) is present in the core as *Conochitina scabra* n. sp. is present in the lowermost part of the Kallholn Formation. These chronostratigraphical assignments simply allow the correlation to the global eustatic sea level rise (Armstrong et al. 2009, and references therein). The origin of this Hirnantian-early Silurian anoxic event was discussed by Armstrong et al. (2005; 2009). Armstrong et al. (2005) showed that low levels of oxygen in the atmosphere-ocean predisposed the Ordovician seas to anoxia as the shelfal basins in which these anoxic black shales formed were greatly restricted, or the glaciation of the Hirnantian was not enough to develop a strong thermohaline circulation which in turn could ventilate the oceans. In the coeval mfs-rested deglacial black shale (highstand) of the Batra Formation (Jordan), Armstrong et al. (2009) provided organic geochemical evidences for an increase in the photic zone productivity during ice melting and a euxinia, through oxidative respiration, extended from the photic zone to the sediment-water interface. Further organic geochemical studies are strongly suggested through the Kallholn Formation to evaluate its occurrence, and to find out the relation of the post-glacial climate and oceanic warming to this anoxic event which comes directly after the latest Hirnantian glaciation and the second largest mass extinction through the Phanerozoic. This will allow high resolution correlations for such global event. Here, it must be noted that the new available data referred to a glaciation episode in Baltoscandia (Calner et al. 2010b) and Laurentia (Buggisch et al. 2010) before a widespread geographical extent of anoxic black shales during Caradoc times (Leggett 1980). In Baltica, a glaciation-related palaeokarst is covered by the organic-rich Fjäcka Shale (Calner et al. 2010b). As was referred above, the anoxic black shale, in the Röstånga-1 core and elsewhere, coincide with eustatic transgression which are deglaciation-related as is clear here. For example, the widespread Fjäcka Shale was defined long before the hypothesis of middle Katian glaciation event in Baltoscandia. This organic-rich black shale (Fjäcka Shale) is a marker bed throughout Baltoscandia, coinciding with a deglaciation-related eustatic transgression, however, little is known about the origin of this black shale event which has a widespread geographical extent. Notwithstanding, the same origin as the latter black shale which marks the latest Hirnantian deglaciation might be considered for further sedimentological, palynological and geochemical studies.

6 Acritarch palynostratigraphy across the Ordovician-Silurian (O/S) boundary

The acritarch assemblages are of moderate diversity and 16 taxa were identified here. A few of these taxa are key-species well suited for stratigraphical purposes which may open the way, not only for local palynozonation, but also for some regional correlation, made the designation of three palynozones possible are within the limit of the sampling resolution (Fig. 7).

6.1 Local palynozone I

The base of this zone in the Röstånga-1 core remains unknown, but it ranges from the lowermost studied sample at a depth of 91 m to its top, which

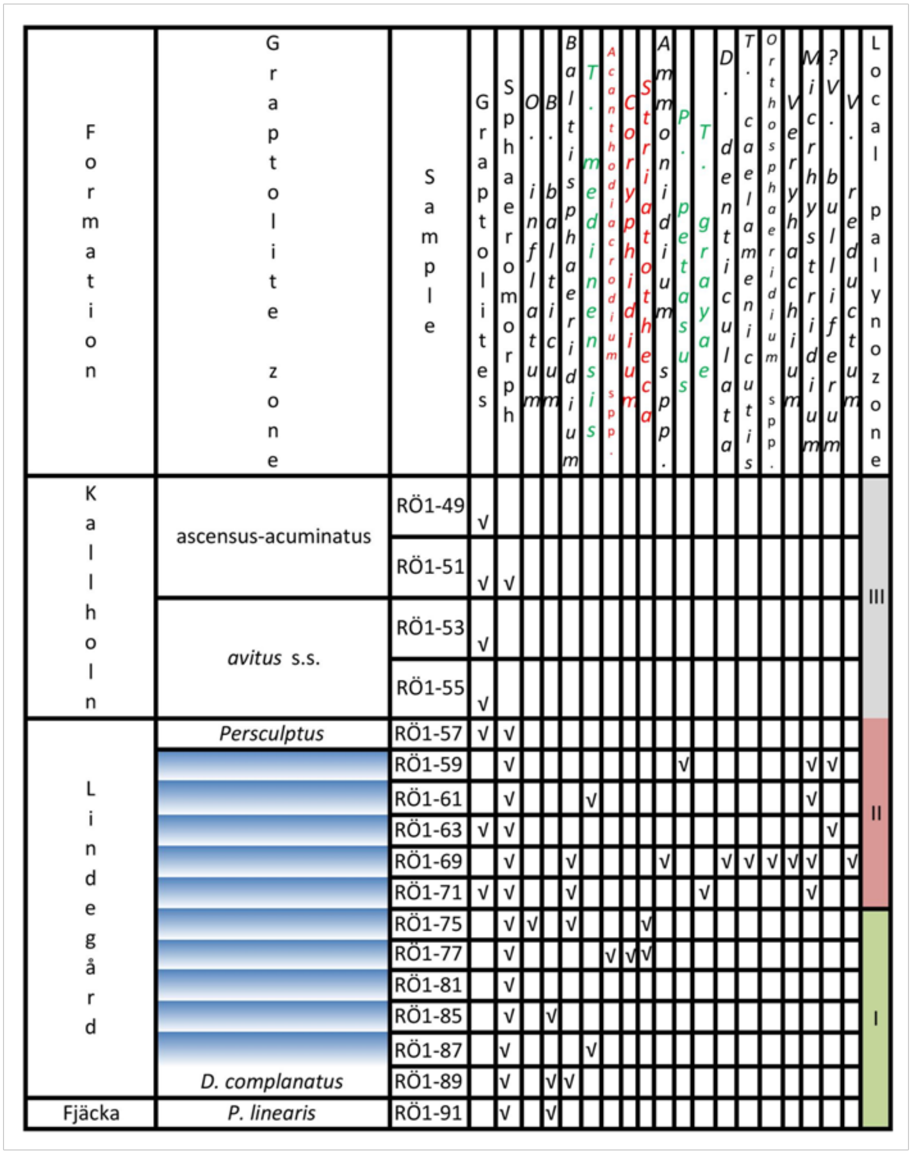

Fig. 7. Acritarch palynostratigraphy across the Ordovician-Silurian boundary in the Röstånga-1 core. Note the green taxa are cryptospores and the red ones are reworked acritarchs.

is probably at a depth of 75 m. This acritarch assemblage zone is characterized by the presence of *Baltisphaeridium*, *Buedingiisphaeridium balticum* and *Orthosphaeridium inflatum*.

6.1.1 Others

In this zone, extremely sparse cryptospores (2) at depths of 87 m and 85 m are present. One single species (*Tetrahedraletes medinensis*) has been identified here. Reworking of Lower-Middle Ordovician acritarchs species such as *Acanthodiacrodium* spp., *Coryphidium* and *Striatotheca* is evident. The latter two species are age-diagnostic and show a clear perigondwanan palaeogeographical affinity as will be shown later.

6.1.2 Age of the zone

This palynozone is probably of late Katian (or pre-Hirnantian Ashgill) age by comparison assemblages from Anticosti Island, Québec, Canada (Jacobson & Achab 1985; Delabroye 2010), Jordan (Keegan et al. 1990), Iran (Ghavidel-Syooki 1996) and Estonia (Delabroye et al. 2011).

6.2 Local palynozone II

6.2.1 Age of the zone

The base of this zone follows directly in Zone I, and the top is tentatively put at a depth of 57 m. It marks a major turn-over, with an appearance of several taxa which show a Silurian affinity such as *Ammonidium* spp., *Diexallophasis denticulata*

(*Evittia remota*) and the first Baltic record of *Tylotopalla caelamenicutis* (characteristic). An unusual occurrence for the large Ordovician genus *Orthosphaeridium* occurs together with the above taxa and shows an extremely small size, which might have related to a climate recovery. Furthermore, long-ranging and tolerant taxa such as *Veryhachium* and *Micrhystridium* have been observed. The acritarch species ?*Veryhachium bulliferum* was further identified, establishing the significance of this species for regional correlations throughout Baltica for this time interval within different lithological units. This zone is probably of early Hirnantian to the latest Hirnantian age based on comparisons with its previously-recorded species in northern Gondwana (Vecoli & Le Hérissé 2004), southern Turkey (Paris et al. 2007), Anticosti Island, Québec, Canada (Delabroye 2010) and Estonia (Delabroye et al. 2011). Furthermore, this zone is possibly correlating to the acritarch Zone (AS3) of Estonia (cf. Delabroye et al. 2011). It is possibly the Baltoscandian equivalent of the acritarch Zone, TAS3 of northern Gondwana "southern Turkey" (cf. Paris et al. 2007).

6.2.2 Others

Extremely sparse but different species of cryptospores (*Tetrahedraletes grayae, Tetrahedraletes medinensis, P. Petasus*) have been observed through this interval. Further, a relatively higher abundance and diversity of scolecodonts (scolecodont peak) coupled with a decrease in the relative abundance of chitinozoans at the base of this zone (within the limit of the sampling resolution) has been detected (see Fig. 8). It must be noted that the sclecodonts (benthos) through the investigated interval (i.e. offshore deep-water environment) are in general extremely sparse (i.e. extremely low absolute abundance).

6.2.3 Discussion

This zone seems to mark a global dramatic event, this so-called "turnover", which is related to the initial stage of the Hirnantian glaciation because of its related major palaeoenvironmental stress (Delabroye et al. 2011, and references therein). The definition of this turnover is the presence of rare precursory species of some genera first appearing in the latest Ordovician but evolving and diversifying during the early Silurian as demonstrated by Delabroye et al. (2011). Generally, the dynamics of phytoplankton (acritarchs) across the O/S boundary has been studied by many workers (e.g. Paris et al. 2000; Vecoli & Le Hérissé 2004; Vecoli 2008; Delabroye et al. 2011). In Algerian Sahara, Paris et al. (2000) have showed that some acritarch and leiosphere species, survived the glaciation whereas others especially the ones with the most complex morphology disappeared. According to the same authors, the morphology of small and simple survivors (e.g. *Veryhachium*, *Michrystridium*, *Evitta*) indicates re-organisation of acritarchs after the Hirnantian glaciation. They also stressed that some Silurian type morphologies appeared already during the Ashgill. As has also been shown by Sheehan (2001), groups with "simple morphology" preferentially survived the extinction. According to Vecoli & Le Hérissé (2004), there was no major extinction event, in the northern Gondwana margin, in a relation to the end-Ordovician mass extinction. Later, Vecoli (2008) reviewed the acritarchs across the O/S boundary globally. According to his review, the pre-glacial Ashgill acritarchs are dominated by species, such as *Orthosphaeridium* and *Baltisphaeridium*, of which an important proportion (excluding e.g. *Orthosphaeridium*) survived the onset of the glaciation. He also noted that a global event of origination and appearance of taxa with a clear Silurian affinity, such as *Tylotopalla* and *Evitta*, counterbalanced the extinction event. Recently, Delabroye et al. (2011) studied the phytoplankton dynamics across the O/S boundary at Anticosti Island, Québec, Canada which was located at low- to mid-palaeolatitudes. Interestingly, major turnovers and diversification events with an appearance of taxa of Silurian affinity, such as *Evitta*, *Ammonidium*, *Tylotopalla* and *Oppilatala*, were also recorded during the early Hirnantian. Then and by the maximum glaciation event (the second stage of glaciation), the typical large Late Ordovician acritarchs, such as *Orthosphaeridium* spp. and large *Baltisphaeridum* spp., disappear. According to the same authors, the post-crisis assemblages exhibit low-diversity acritarchs, dominated by tolerant and long-ranging taxa, such as *Evitta remota* (= *Diexallophasis denticulate*), *Micrhystridium* spp., leiospheres, corresponding to the time of deglaciation at the O/S boundary. It has been noted that the deglaciation-related changes, such as decreasing water salinity, increasing water temperature, and other climatic changes, could have caused a reduction in process length of such taxa (e.g. *Evitta remota*) in parallel to a dwarfism among brachiopod communities since the extinction or climate recovery phases may correlate with a dwarfism (Delabroye et al. 2011, and references therein). According to their study, the palaeoenvironmental pressures and changes (e.g. atmospheric $p\mathrm{CO_2}$, water-mass oxygenation, salinity), which are related to the first large glaciation on Gondwana, may have played a role in this turnover at low latitudes as similar turnovers occurred during the Silurian. Notwithstanding, the effects of this climate cooling were more noticeable on Gondwana (Delabroye et al. 2011). In their important previous study (referred to herein as the Baltic study) on the O/S acritarchs from the Valga-10 core (southern Estonia), Delabroye et al. (2011) demonstrated that these "Silurian affinity" genera during the glaciation (e.g. *Tylotopalla*) are (only) present in Gondwana, however, some of these genera (e.g. *Oppilatala* and *Diexallophasis*) have a cosmopolitan distribution (and a potential for palynozonation), and originally appeared before the glaciation (see also Paris et al. 2000). As has been shown above, this was later challenged by their study on Anticosti Island (Laurentia). The present study also keeps this challenge and demonstrates that there was a probable turnover in a relation to the Hirnantian glaciation at low latitudes (e.g. Baltica) as will be shown here. According to their Baltic study, there were palaeoprovinces during latest Ordovician between Laurentia/Baltica and Gondwana as has been shown by the comparison of phytoplanktonic assemblages. It was justified by limited water-mass exchanges because of the bathymetric ridge rise related to the opening of the Rheic Ocean, coupled with the Hirnantian eustatic sea-level drop. The present study corroborates this hypothesis, as has been shown by the investigated acritarch assemblages; however, the presence of *Tylotopalla* indicates that there was Gondwanan influences, particularly, on the margin of Baltica along the Scanian Lithofacies Belt. According to Paris et al. (2007), this seems plausible since it has also been found Baltoscandian influences among the chitinozoan assemblages belonging to northern Gondwana "southern Turkey, lower palaeolatitude" from the Middle Ordovician onward due to changes related to the rapid northward drift of Avalonia during the Ordovician, and its docking to Baltica by Late Ordovician times. Then, this might justify the presence of typical high latitude perigondwanan species such as *Tylotopalla caelamenicutis* which is very important here for two reasons. The first reason is chronostratigraphical because this record may open the way for the correlation with Gondwanan assemblages. The second reason is that this representative indicates that there was a real turnover in a relation to the Hirnantian Glaciation at low latitudes (Baltica) rather than this phytoplanktonic turnover which was before the glaciation. The thing which is corroborated by the phytoplankton dynamics in Anticosti Island (Canada). Furthermore and according to the Baltic study, the benthos (e.g. scolecodonts, abrupt increase in abundance) and phytoplankton (acritarchs) exhibit increasing diversity near the base of the Hirnantian, whereas, planktonic (chitinozoans) and nektonic (conodonts) has a different pattern by which there is decline in diversity during the earliest Hirnantian and marked increase in the later part of the Hirnantian. This increase in scolecodonts abundance was also corroborated by the analysis of Hints (2001). Consequently, it has alternatively been hypothesized that (1) a favourable (for benthic fauna) shallower and proximal environment during the Hirnantian led to this diversification of the benthic fauna, and/or (2) the planktonic and nektonic fauna suffered rather than the benthic ones. Interestingly, this event can also be traced, in the Röstanga-1 core, within the limit of the sampling resolution, even though, it is not enough clear, as in the shallow-water strata of the Valga-10 core. Then, the latter hypothesis is favourable here because this similar occurrence is clearly through offshore deep-water not shallow-water interval so that it is possibly very significant. This can also be corroborated by the idea that the survivors adapted to the new ecological settings and habitats after the initial pulse of extinction (Sheehan 2001). Alternatively, this scolecodonts peak could reflect an evolutionary trend near the base of the Hirnantian which in turn is not in a relation to the Hirnantian glaciation, being just like the acritarch turnover for some genera before the glaciation. As has been reported in the Valga-10 core, Estonia (Delabroye et al. 2011; the Baltic study), there are 9 species over a total 16 species (i.e. ca. 56%) firstly occur through the abundance peak of scolecodonts near the base of the Hirnantian Stage. If that is all true, further quantitative studies and correlations are strongly suggested to test the possibility to use this "scolecodonts peak", near the base of the Hirnantian, as a proxy for the stage regardless the depositional environment. Finally, the presence of representatives of early land plants different cryptospores, through this zone, would also corroborate the proposed age. They are extremely sparse, suggesting offshore deep-water environment at a significant distance from shoreline, as has also been shown above (see also the geological setting). However, the occurrence of these representatives of cryptospores which have similarities to the coeval ones worldwide provides an evidence for early land plants in this part of Baltica in the Late Ordovician, and indicates homogeneous land plants which tolerated a wide range of climatic conditions (e.g. Wang et al. 1997; Steemans, 2001; Rubinstein & Vaccari 2004; Richardson & Ausich 2007; Vecoli et al. 2011).

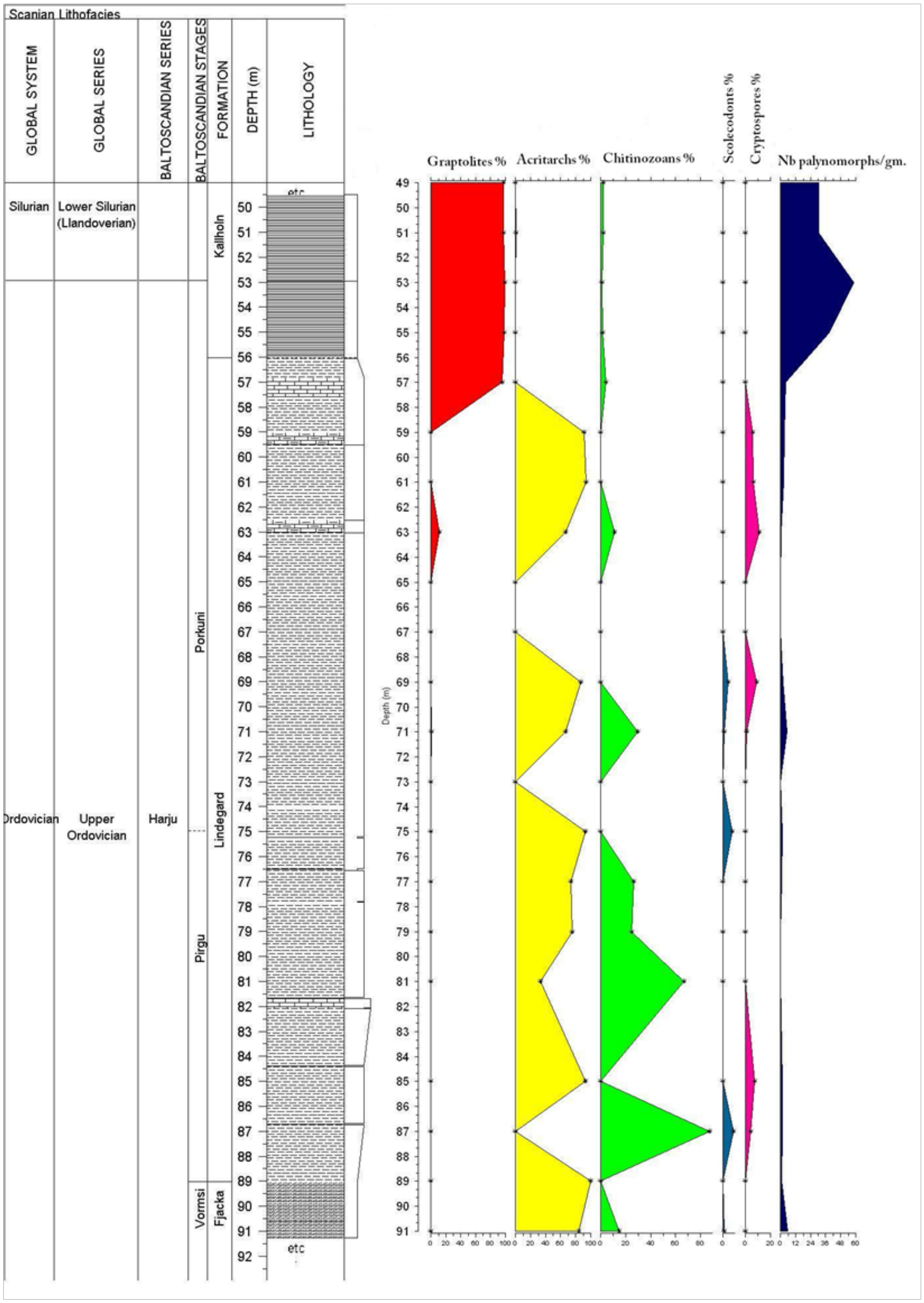

Fig. 8. Palynofacies study through the investigated interval. Note the samples RÖ1-73, RÖ1-67 and RÖ1-65 are barren. For discussion, see the text.

6.3 Local palynozone III

The base of this zone is just above the previous one and its top, in the Röstånga-1 core, remains unknown. It is characterized by the high abundance of graptolites which seems to be responsible for the highest productivity, through the studied interval, as has been shown by the palynofacies study herein (Fig. 8). Furthermore, it is also characterized by the sparse occurrence of sphaeromorph acritarchs (*Leiosphaeridia* spp.).

6.3.1 Age of the zone

This palynozone is probably of latest Hirnantian-early Llandovery (Rhuddanian) age by comparison with its previously-recorded species in Jordan

(Armstrong et al. 2009) and Estonia (Delabroye et al. 2011; the Baltic study). This age assignment is further corroborated by the previously-recorded graptolite zones in the core (Bergström et al. 1999; Koren et al. 2003). Furthermore, this zone might in part be correlated with the acritarch zone (AS4) through the Valga-10 core, southern Estonia (Delabroye et al. 2011; the Baltic study).

6.3.2 Discussion

This zone marks the relatively lowest abundance of acritarchs throughout the investigated interval. This corresponds to the general feature of the acritarch assemblages, through the start of the Silurian, which is low diversity assemblages (dramatic change) mainly dominated by sphaeromorphs (e.g. *Leiosphaeridia* spp.) and tolerant acritarchs as the establishment of eutrophic conditions favoured monospecific algal blooms in a relation to the deglaciation-related transgression (Vecoli 2008; Delabroye et al. 2011 *in* the Baltic study and the Laurentian one of Anticosti Island). According to the same authors and references therein, changes in nutrient supply and anoxic conditions might be related to this early Silurian "crisis". The thing is strongly corroborated here and by Armstrong et al. (2009) who have also showed that euxinia extended into the photic zone, enhancing the carbon preservation, and that the ice melting, coupled with freshwater/nutrients fluxes, caused an enhanced photic zone productivity and organic matter sedimentation (see also the Kallholn Formation above; Leggett 1980). Furthermore, this all seems consistent in terms of sedimentology through the Kallholn Formation through the core.

7 Reworked acritarchs and foreland-type sedimentation

As has previously been referred, highly diagnostic reworked acritarchs of Early-Middle Ordovician age occur together, through the investigated interval, with the other *in situ* ones of latest Ordovician age. The latter acritarchs are of a very important significance in terms of chronostratigraphy and biostratigraphy, however, the reworked ones can also be used for provenance assignments because of the Early-Middle Ordovician provinciality or the palaeogeographical differentiation they exhibit (Vavrdová 1974; McCaffrey et al. 1992; Ribecai & Tongiorgi 1995; Servais 1997; Servais & Fatka 1997; Vecoli & Samuelsson 2001a; 2001b; Servais et al. 2003; Raevskaya et al. 2004; Servais et al. 2008).

Thus, there must essentially be provinciality or differentiation for using these reworked acritarchs as sediment or provenance indicators to avoid any shared phytoplankton otherwise this reworking is less indicative for provenance studies. This sharing could have been because of the palaeogeography during certain time (e.g. Cambrian). Turner (1982) showed that the palynomorphs are susceptible to reworking due to their small size, durable nature of wall, and abundance. Furthermore, the good preservation of reworked acritarchs suggests short distance of transportation and rapid reburial (e.g. Turner 1982; Paris et al. 2007). Particularly, the acritarchs reworking, during the Middle and the Late Ordovician, has been linked to tectonics, and/or marine transgressions (Paris et al. 2007). By and large, such reworking had been highly expected and taken in account since the Röstånga area is located along an important part of the SW margin of the East European Platform within the NW–SE oriented Tornquist Zone marked by major structural features near the border (e.g. uplifts, tilting, thrusts) which in turn can be traced from the North Sea, across Scania, toward the Black Sea (Bergström et al. 1999; see also the geological setting). Along this active tectonic setting, considerable sediment thicknesses reflect the sedimentary filling of rapidly subsiding basin in a relation to the Late Ordovician convergence of Avalonia with Baltica and the formation of foreland basin which started in middle Ashgill (e.g. Poprawa et al. 1999; Vecoli & Samuelsson 2001a; 2001b).

As has just been referred to above, there exist acritarch provinciality or palaeogeographical differentiation, during the Early-Middle Ordovician, by which two palaeoprovinces have been proposed (e.g. Servais et al. 2008). The first palaeoprovince is represented by the cold-water acritarch assemblages, this so-called Perigondwanan (Mediterranean) Palaeoprovince, from e.g. NE Germany, France, Belgium, Spain, Bulgaria, and North Africa, including diagnostic (i.e. absent in Baltica) acritarchs such as *Arbusculidium filamentosum*, *Coryphidium* and *Striatotheca*. The second palaeoprovince is represented by the warm-water acritarch assemblages, this so-called Baltic Palaeoprovince, from e.g. Sweden, Denmark, northeast Poland, and the Holy Cross Mountains. Consequently, the presence of Early-Middle Ordovician reworked acritarchs, of a clear perigondwanan palaeogeographical affinity, suggests reworking from a perigondwanan-related source area with similar taxa, being located south of the East European Platform (i.e. Avalonia; see the systematic palaeontology below). This reworking can also give an evidence for foreland-type sedimentation in the

Röstånga area from probably early middle Ashgill onward. As has already been shown above, the sedimentological and the sequence stratigraphical analysis, through the Röstånga-1 core, clearly corroborates this conclusion, and justifies the presence of these reworked acritarchs. These reworked acritarchs, recovered from the Röstånga-1 core, are broken (corroded) such as *Acanthodiacrodium* spp., or of good preservation such as *Coryphidium* and *Striatotheca* (with preserved striation). Noteworthy is the similar occurrence of these reworked acritarchs in middle Ashgill and Lower Silurian sediments from Bornholm Island, Denmark (Samuelsson et al. 2001; Vecoli & Samuelsson 2001a; 2001b).

8 The Thermal Alteration Index (TAI) and the Acritarchs Alteration Index (AAI)

Many workers have found that thermal alteration (e.g. depth of burial, heat flow, etc.) plays a vital role in petroleum prospecting (Staplin 1969; and references therein). On the other hand, optical analyses for the color of fossils with organic content have been used as palaeotemperature indicators for sedimentary rocks (e.g. Legall et al. 1981; Dorning 1986; Batten 1996; Williams et al. 1998; Armstrong & Brasier 2005; Al-Ameri 2009). Thus, a scale of color ranges for these fossils has been adapted to experimentally-derived temperature ranges, and petroleum zones of generation and destruction. Likewise, calibration of these color alteration indices has been attained by comparing the thermal indicators for different fossil groups (acritarchs: Acritarchs Alteration Index (AAI); conodonts: Color Alteration Index of conodonts (CAI), etc.). As may essentially be clear, this so-called Spore Color Index (SCI) cannot be used on assemblages younger than the Silurian when the vascular plants widely appeared and provided fossils suitable for maturation studies. Furthermore, color standards such as Philips Petroleum Company of Pearson (1990; used herein) have been proposed. Economically, the oil window, the point when maximum hydrocarbon generation occurs during the catagenesis (i.e. mature kerogen; kerogen is insoluble sedimentary organic matter), is indicated by mid-brown colors in most indices (e.g. Armstrong & Brasier 2005). Notwithstanding, it must be noted that the different organic fossils exhibit different colors at any given palaeotemperature, varying with different wall thickness and size, and composition (e.g. Dorning 1986; Williams et al. 1998; and references therein).

Regarding acritarchs, the unaltered specimens are colorless to yellow, and range through increasing dark brown to grey and black. These acritarchs of thin, single, smooth wall, such as *Veryhachium* and *Micrhystridium*, are more appropriate for AAI analysis, while specimens with more than one wall often exhibit differences in color of the inner and outer walls (Dorning 1986). In the Röstånga-1 core, the acritarchs from the Lindegård Mudstone are brownish black-colored, indicating a Thermal Alteration Index (TAI) of 4 which is considered to be post-mature with regard to oil generation.

9 Systematic palaeontology

Genus *Tetrahedraletes* Strother and Traverse emend. Wellman and Richardson 1993

Type species. Tetrahedraletes medinensis Strother and Traverse emend. Wellman and Richardson 1993

Tetrahedraletes grayae

Plate 1, fig. C

1991 *Tetrahedraletes grayii* Strother, pp. 221–222, pl. 1, figs. 1–3

2001 *Tetrahedraletes grayae* Strother 1991 - Steemans, p. 9, fig. 5.15

Dimensions. 33 µm, measured on one specimen.

Occurrence. Lindegård mudstone, sample RÖ1-71.

Remarks. Permanent fused cryptospore tetrad; amb sub-triangular to sub-spherical in shape. The diameter of the present specimen (33 µm) is smaller than the diameter (35 µm) of typical *T. grayae* from the type locality (Strother 1991), but Vecoli et al. (2011) have showed dimensional ranges from 32 to 50 µm.

Previous records. e.g. Upper Caradoc–Lower Telychian: subsurface of northeastern Libya (Richardson 1988). Ashgill: Kosov Fm., Central Bohemia, Czech Republic (Vavrdová 1982); Couches Fort Atkinson Dolomite, McQuokata Group, Illinois, USA (Strother 1991); Oostduinkerke borehole, BrabantMassif, Belgium (Steemans 2001). Katian: Jelgava Fm; Kuili Fm., Valga-10 drillcore; Estonia; Vaureal Fm., Western Anticosti, Anticosti Island, Québec, Canada (Vecoli et al. 2011). Hirnantian: Kuldiga Fm.; Edole Mb.; Saldus Fm., Brocēni Mb., Valga-10 drillcore; Estonia; Ellis Bay Fm., member 1, Western Anticosti, Anticosti Island, Québec, Canada; Becscie Fm., Fox Point Mb., Eastern Anticosti, Anticosti Island, Québec, Canada (Vecoli et al. 2011). Llandovery: Medina Group, Niagara Gorge, Lewiston, New York, USA (Miller and Eames 1982); Jupiter Fm. Anticosti Island, Québec, Canada (Duffield 1985). Early Silurian: Centerville Fm., central Ohio, USA (Taylor 2002).

Tetrahedraletes medinensis
Plate 1, fig. A-B
1979 *Tetrahedraletes medinensis* Strother and Traverse, p. 8, pl. 1, figs. 5, 14–17
1993 *Tetrahedraletes medinensis* (Strother and Traverse) emend. — Wellman and Richardson, p. 165, pl. 2, figs. 8, 10–12
Dimensions. 24.7-27 µm, measured on 2 specimens.
Remarks. Permanent fused tetrads without envelope; individual spores have a subcircular to subtriangular amb, with lines of attachment which are clearly visible on the tetrad surface, and mark the position of contact surface, psilate wall surface.
Previous records. e.g. Caradoc type section: Shropshire, U.K. (Wellman 1996). Caradoc–Ashgill; late Katian-Hirnantian: E1–81 borehole, northeastern Libya (Richardson 1988); När borehole, Gotland, Sweden (Gray 1988; Le Hérissé 1989); Mallowa Salt, Carribuddy Basin, Australia (Foster & Williams 1991); Bedinan Fm., southeastern Turkey (Steemans et al. 1996); Kalpintag Fm., South Xinjiang, China (Wang et al. 1997), Jelgava Fm; Kuili Fm.; Kuldiga Fm., Edole Mb.; Saldus Fm., Brocēni Mb.; Valga-10 drillcore; Estonia (Vecoli et al. 2011). Katian: Vaureal Fm, Western Anticosti, Anticosti Island, Québec, Canada (Vecoli et al. 2011). Hirnantan: upper member of the Salar del Rincón Fm. (Rubinstein and Vaccari 2004); Becscie Fm., Fox Point Member, Eastern Anticosti, Anticosti Island, Québec, Canada (Vecoli et al. 2011). Hirnantian- upper Llandovery: type Llandovery area, southwest Wales (Burgess 1991); Latest Ashgill or earliest Llandovery: Cedaberg Fm., South Africa (Gray et al. 1986).

Group Acritarcha Evitt, 1963

Genus *Diexallophasis* Loeblich 1970
Type-species. Diexallophasis denticulate (Stockmans & Williere) Loeblich, 1970
Diexallophasis denticulate
Plate 2, fig. A
1963 *Baltisphaeridium denticulatum* Stockmans and Willière, p. 458, pl. 1, fig. 4, text-fig. 13.
1970 *Diexallophasis denticulata* (Stockmans & Williere) Loeblich, p. 715. figs 8A–E, 9A–C
1973 *Multiplicisphaeridium denticulatum* (Stockmans & Willière, 1963); Eisenack et al.: 587 –591
Remarks. Spherical vesicle, processes are heteromorphic, strongly variable in ornamentation and tip morphology (Cramer 1970, p. 135-142). The digitate and manate processes that are open to the vesicle are diagnostic. The processes wall is very thick and branching is highly variable. *D. denticulata* is considered to be a junior synonym of *Diexallophasis remota* Deunff, 1955 (Playford 1977) as the processes of *D. remota* are broad and robust.
Dimensions. vesicle diameter 21.7 µm; process length 10.9-15.2 µm; the processes base 3.9-4.3 µm in diameter; number of processes 9, measured on one specimen.
Occurrence. Lindegård mudstone, sample RÖ1-69#2.
Comment. This species ranges from Sandbian–Devonian (Ghavidel-Syooki et al. 2011). It is also common in Silurian strata at other localities (e.g. Gotland, Sweden and Bornholm, Denmark; see Smelror 1991).
Previous records. e.g. Ashgill: the lower Vaureal Formation, Anticosti Island, Quebec, Canada (the *Dicellograptus complanatus* graptolite Zone, Jacobson & Achab 1985); the upper part of Ghelli Fm. the Ghelli area, northeastern Alborz Range (Kopet-Dagh region), Iran (Ghavidel-Syooki 2000). Katian-Hirnantian: the high palaeolatitude of Gondwana (i.e. glacial area), pre-, syn-, and post -glacial times (Vecoli & Le Hérissé 2004); the upper Ellis Bay and lower Brecscie formations, eastern Anticosti outcrops, Québec, Canada (Delabroye 2010). Hirnantian: the Kosov Fm., Prague Basin, Czech Republic (Dufka and Fatka 1993); Hawban Member, Baq'a area, Saudi Arabia (Miller & Al-Ruwaili 2007).

Genus *Tylotopalla* Loeblich 1970
Type species. Tylotopalla digitifera sp. Loeblich 1970
Tylotopalla caelamenicutis
Plate 2, fig. D
1970 *Tylotopalla caelamenicutis* Loeblich, p. 738, figs. 33A-C.
Dimension. Vesicle diameter 27 µm; process length 4 µm, measured on one specimen.
Occurrence. Lindegård mudstone, sample RÖ1-69.
Remarks. Vesicle inflated; spherical to subspherical in outline; granular to microrugulate; with short processes that communicate freely with the vesicle cavity and terminate in a point or in incipient bifurcations with rosette of small spines below their distal end (Loeblich 1970).
Comment. This species ranges from the latest Ordovician (post-glacial Hirnantian) to the mid-Silurian (Vecoli & Le Herissé 2004; see also Delabroye et al. 2011). It is also common to occur in Silurian strata (e.g. the Bardo Stawy outcrop, Holy Cross Mountains, Poland; Masiak et al. 2003) as is the case of *Diexallophasis denticulate* (Vecoli

2008). Consequently, this species exhibits a Silurian affinity (e.g. Le Herissé *in* Paris et al. 2000, p. 98).
Previous records. e.g. Hirnantian: the Kosov Fm., Prague Basin, Czech Republic (Dufka & Fatka 1993); the high palaeolatitude of Gondwana (i.e. glacial area), Hirnantian (syn- and deglacial times; Vecoli & Le Hérissé 2004); the Diyarbakir area, southeastern Turkey (Paris et al. 2007).

Genus *Veryhachium* Deunff 1954 emend. Sarjeant and Stancliffe 1994
Type species. Verhachium trisulcum (Deunff, 1951) ex Deunff, 1959
?Veryhachium bulliferum
Plate 2, fig. H
1970 *?Veryhachium hamii* Loeblich; Wright and Meyer 1981, pp. 29–30, plate 3, figure N
2011 *?Veryhachium bulliferum* Delabroye, Vecoli, Hints and Servais, P. 22, Plate 14, figures 5–10, Plate 15, figure 1
Diagnosis. Rhombohedral and thick-walled vesicle; homomorphic processes with large base but thinning towards the tip, sometimes one to three processes arise perpendicularly from both sides of vesicle body due to flattening of specimen . Process-vesicle junction is curved and progressive. Processes are filled by same material as vesicle wall, with several small circular hollow parts.
Dimensions. Vesicle diameter 34 µm; process length 15 µm; width at the half of the process 1.7 µm, measured on one specimen.
Occurrence. Lindegård mudstone, sample RÖ1-59.
Comment. The presence of *?Veryhachium bulliferum* reflects the regional significance of this species for regional correlations throughout Baltica through the Hirnantian Stage.
Previous records. Uppermost Ordovician: the När borehole, southern Gotland, Sweden (Le Hérissé 1989a), upper Katian-Hirnantian: from the upper Pirgu Regional Stage (Jelgava, Parojeva and Kulli formations) to the top of the Porkuni Regional Stage (Kuldiga and Saldus formations), Valga-10-drill core, southern Estonia (Delabroye et al. 2011).

Veryhachium reductum
Plate 2, fig. B
1959 *Veryhachium reductum* Deunff, p. 27, pl. 1, figs. 1, 3, 8, 10-12,16-17
1965 *Veryhachium reductum* (Deunff, 1959) Downie and Sarjeant, p.152, Pl. II, Figs 12 & 13; emend.
Dimension. Length of vesicle sides 26 (27) 34 µm x 27 (33) 39 µm, measured on 3 specimens
Occurrence. Lindegård mudstone, sample RÖ1-69.
Emended diagnosis. A species having a large vesicle (sides larger than 25µm). The spines are shorter than the longest side of the vesicle, with taper smoothly from a broad base to a pointed tip. Eilyma laevigate to granulate (Stancliffe & Sarjeant 1994).
Remarks. Vesicle is hollow and triangular in outline, with sides that are straight or slightly concave. *Veryhachium reductum* is different from *Veryhachium trispinosu* which has spines longer than the longest side of the vesicle (sides also larger than 25µm) (Stancliffe & Sarjeant 1994).
Previous records. e.g. Ashgill: The Zalesie Nowe succession, Holy Cross Mountains, southern Poland (Kremer 2001). Hirnantian: the lower and Dargaz diamictites, the Zagros Mountains, Iran (Ghavidel-Syooki et al. 2011).
Comment. The Genus *Veryhachium* is among the long-ranging taxa (e.g. Stancliffe & Sarjeant 1994; Vecoli 2008). It is known also to occur in Gotland, Sweden through Silurian (e.g. Stricanne et al. 2004; 2006).

Genus *Orthosphaeridium* Eisenack 1968
Type species. Orthosphaeridium rectangulare (Eisenack) Eisenack, 1968, p. 92, pl. 25, fig. 1 (=*Baltisphaeridium rectangulare* Eisenack 1963, p. 211, pl. 20, figs. 1-3; 10a-b).
Orthosphaeridium inflatum
Plate 2, fig. E
1970 *Orthosphaeridium inflatum* Loeblich, p. 733-734, figs. 29 A-E.
Dimensions. Vesicle diameter 68 µm; process length 24.8 µm, measured on one specimen.
Remarks. Vesicle is subspherical to subquadrate in outline, smooth; processes delineate from vesicle cavity but do not communicate internally with it due to thick proximal plugs, basal constriction and tapering to acuminate tips are not observed making it different from *Orthosphaeridium rectangulare* (Eisenack) Eisenack 1968 which has a smooth rectangular vesicle, process wall thick. Excystment is by vesicle splitting in half, each half bearing two processes, half-vesicle having broken apart along the median split. Then, the taxonomic separation between *O. inflatum* and *O. rectangulare* was herein kept (see also Jacobson & Achab 1985).
Occurrence. Lindegård mudstone, sample RÖ1-75.
Previous records. e.g. Ashgill: the Vaureal Formation, Anticosti Island, Quebec, Canada (the *Dicelllograptus complanatus* graptolite Zone, Jacobson & Achab 1985); the Well WS-3, Jordan (Keegan et al. 1990); the upper part of Ghelli Formation, southwest of Shahrud (Kuh-e-Kharbash), North Iran (Ghavidel-Syooki 2006).
Comment. Orthosphaeridium inflatum sp. is diagnostic of and possibly restricted to the *Dicellog-*

raptus complanatus graptolite zone (Jacobson & Achab 1985). Thus, *O. inflatum* is restricted to the Ashgill (Keegan et al. 1990). On the other hand, *Orthosphaeridium* sp. (typical Ordovician) is generally dominated in pre-glacial Ashgillian sediments but it disappears through the early Silurian (e.g. Vecoli 2008).

Orthosphaeridium spp.
Plate 2, fig. F
Remarks. Vesicle is inflated and subcircular in outline, processes distinct, elongate, straight to curved, delineated from the vesicle; expanding slightly, then tapering to acuminate tips; neither the smooth rectangular vesicle of *O. rectangular* nor the granulate spherical vesicle of *O. insculptum* are observed. The present specimen is different also from the Mid Ordovician *O. vibrissiferum*, the Upper Ordovician *O. chondrododora*, *O. inflatum* and *O. rectangular* as they all have only four processes, whereas, this specimen shows 6 processes.
Dimension. Vesicle diameter 28.4 µm; process length 7.9-23.2 µm, number of processes 6; measured on one specimen.
Occurrence. Lindegård mudstone, sample RÖ1-69#2.

Genus *Buedingisphaeridium* Schaarschmidt 1963, emend. Staplin *et al.,* 1965, Lister 1970
Type species. Buedingiisphaeridium permicum Schaarschmidt 1963, p. 70, pl. 20, figs. 4-6; text-fig. 26.
Buedingiisphaeridium balticum Plate 2, fig. I
1991 *Buedingiisphaeridium balticum* Uutela and Tynni, P. 47, Pl. V, fig. 53
Remarks. Vesicle spherical, thin-walled and shagrinate. The vesicle is covered by regular hollow pyramidal outgrowth. There was also a solid nipple on the top of this outgrowth observed on one specimen, as usually occurs on the specimens of Uutela & Tynni (1991). The present specimen shows a comparable vesicle diameter, as shown by Uutela & Tynni (1991).
Dimension. Vesicle diameter 23.7 (25.8) 31.1 µm, measured on 7 specimens.
Occurrence. Lindegård mudstone, sample RÖ1-91, RÖ1-89 and RÖ1-85.
Previous records. e.g. Ordovician Baltic erratics: Finland (*Buedingiisphaeridium* sp.; Uutela 1989), the Lower to Upper ordovician (Kunda Regional Stage to Pirgu Regional Stage): Sillaoru Fm. to. Adila Fm., Rapla borehole, Estonia (Uutela & Tynni 1991). Katian (Pirgu Regional Stage): Jelgava Fm.; Paroveja Fm.; Kuili Fm., Valga-10 drill core, southern Estonia (Delabroye et al. 2011). Hirnantian: the upper Ellis Bay Fm.; eatern Anticosti outcrops; Québec; Canada (Delabroye 2010), Porkuni Regional Stage of Kuldiga Fm.; Saldus Fm., Valga-10 drill core, southern Estonia (Delabroye et al. 2011).

Genus *Acanthodiacrodium* Timofeev, 1958 emend. Deflandre and Deflandre-Rigaud, 1962
Type species. Acanthodiacrodium dentiferum Timofeev 1958, pl. 1, fig. 2, pl. 3, fig. 2
Acanthodiacrodium spp.
Plate 3, fig. C
Remarks. The present specimen has thick wall and very low solid processes (protuberances) which are not connected to the interior of the vesicle.
Occurrence. Lindegård mudstone, sample RÖ1-77.
Dimension. Vesicle diameter 27 µm, measured on one specimen.
Comment. This species is interpreted herein as reworked acritarch which occurs together with other diagnostic acritarchs such as *Striatotheca* and *Coryphidium. Acanthodiacrodium* spp. is consistent with an Early to Middle Ordovician age and usually dominates the assemblages from Avalonia and Gondowana with other diacromorph acritarchs (e.g. McCaffrey et al. 1992 and references therein; Le Hérissé et al. 2007; Molyneux 2009).

Genus *Striatotheca Burmann, 1970*
Type species. Striatotheca principalis Burmann, 1970
Striatotheca
Plate 3, fig. A
Diagnosis. Tetragonal or polygonal central body, hollow processes at the corners without basal constriction passing into gradually tapering. The central body and the processes are provided with a striate sculpture which is arranged in a fan shape. The four-sided shape may be altered by concave arch. Additional deviations come from the sides shortening, the processes reduction, and the unequal development of processes (Burmann 1970). The ornamentation by striae or ribs is here clearly visible.
Occurrence. Lindegård mudstone, sample RÖ1-77 & sample RÖ1-75.
Dimension. Vesicle diameter 26.3 µm, maximum length of process 8.4µm, measured on 2 specimens.
Comment. The *Striatotheca* is typically of Llanvirn age and normally not recorded in post-Caradoc strata (e.g. Vecoli 2008) so that the presence of this species in uppermost Ordovician strata is possibly a consequence of sediment reworking in the upper part of the Lindegård mudstone. The first indisputable occurrence of *Striatotheca* is close to the base of the Arenigian with widespread occurrence during the Arenigian and the Llanvirnian, whereas

the Upper Ordovician and Silurian occurrences of *Striatotheca* may be a result of reworking (Servais 1997).

Genus *Coryphidium* Vavrdová 1972 emend. Servais, Li, Molyneux and Vecoli 2008
Type species. *Coryphidium bohemicum* Vavrdová 1972
Coryphidium
Plate 3, fig. B
Emended diagnosis. Vesicle is quadrangular, pillow-shaped with rounded corners. The vesicle sides are straight, convex or concave. Sculptural ridges are usually present and cover almost the entire vesicle wall; they are mostly more or less parallel to the sides. The processes are numerous and of various length and morphology which is simple and sharp-tipped, or distally branched or truncated. They tend to be either concentrated at the corners of the vesicle, or distributed more widely and at random across the surface of the vesicle (Servais et al. 2008).
Occurrence. Lindegård mudstone, sample RÖ1-77 (it occurs together with *Striatotheca*).
Dimension. Vesicle diameter 27.9 µm, processes length 1.1-2.6 µm.
Comment. The frequently recorded genus *Coryphidium* Vavrdová 1972 first appears in the uppermost Tremadocian *Araneograptus murrayi* graptolite Biozone and is common through the upper Lower Ordovician and the Middle Ordovician, whereas, the Upper Ordovician occurrences might be a result of reworking (Servais et al. 2008). *Coryphidium* is palaeogeographically an indicator of the Perigondwanan acritarch palaeoprovince during the Early/Middle Ordovician, and is absent in Baltica (e.g. Raevskaya et al. 2004; Servais et al. 2008). As is the case of *Striatotheca*, *Coryphidium* is completely lacking in the coeval Arenigian assemblages from e.g. Horns Udde Quarry, Oland, Sweden (Ribecai & Tongiorgi 1995). Thus, *Coryphidium* is palaeogeographically diagnostic and important (e.g. Servais & Fatka 1997; Servais et al. 2003, 2008). In the Röstånga-1 core, the presence of this species in uppermost Ordovician strata suggests sediment reworking, as is the case of the diagnostic *Striatotheca*.

10 Discussion

The present integrated study has revealed the potential of the Scanian Lithofacies Belt in its reference succession through the O/S boundary at the Röstånga area to be regionally and globally correlated. Thus, the sedimentary succession was here linked to regional and global events based on sedimentological and stratigraphical correlations. While the Röstånga-1 core is considered one of the most important core drillings and intensely studied sedimentary successions in Baltoscandia, a dramatic scenario for the Lower Palaeozoic of Baltoscandia is not ruled out herein. However, a conclusive account seems to be early, but the regional and global stratigraphical comparisons would possibly support this dramatic scenario.

An intense and global Ordovician volcanism caused major pulses of contemporaneous bentonite beds in Baltoscandia (e.g. southern Sweden, Bornholm) and Laurentia. Unique and several K-bentonite beds developed at Röstånga area (Bergström et al. 1997). This intense volcanism was climaxed by a short-lived glacial pulse and a major eustatic sea level fall. That in turn led to a eustatic regression and a development of a sequence boundary which was rapidly succeeded by a return to deeper-water conditions expressed in the Mossen-Fjäcka succession. Thus, several palaeokarst surfaces developed and have been preserved in Baltoscandia and Laurentia. Notably, the glacioeustatic rate was greater than the subsidence rate at that time in Scania, and consequently the Skagen Limestone was unconformably overlain by the deeper-water sedimentary succession with solution structures at the top. Anoxic deglacial black shales, which coincide with a flooding surface at the base of the Fjäcka Shale, developed regionally and mark a high palaeo-productivity and preservation. In the Röstånga-1 core, this is traced in the lowermost part by black, laminated and graptolitic shale which lacks any benthic fauna or bioturbation. This Fjäcka Shale is the source rock for the oil in the overlying Boda Limestone in central Sweden (Vlierboom et al. 1986). Furthermore, it rests on an unconformity and a palaeokarst surface which is in turn a glaciation-related (Calner et al. 2010b). Following the Fjäcka Shale, the onset of the Lindegård Musdtone, which correlates to the Jonstorp Formation in central Sweden, marks sea-level highstand and a stable environment in the basin.

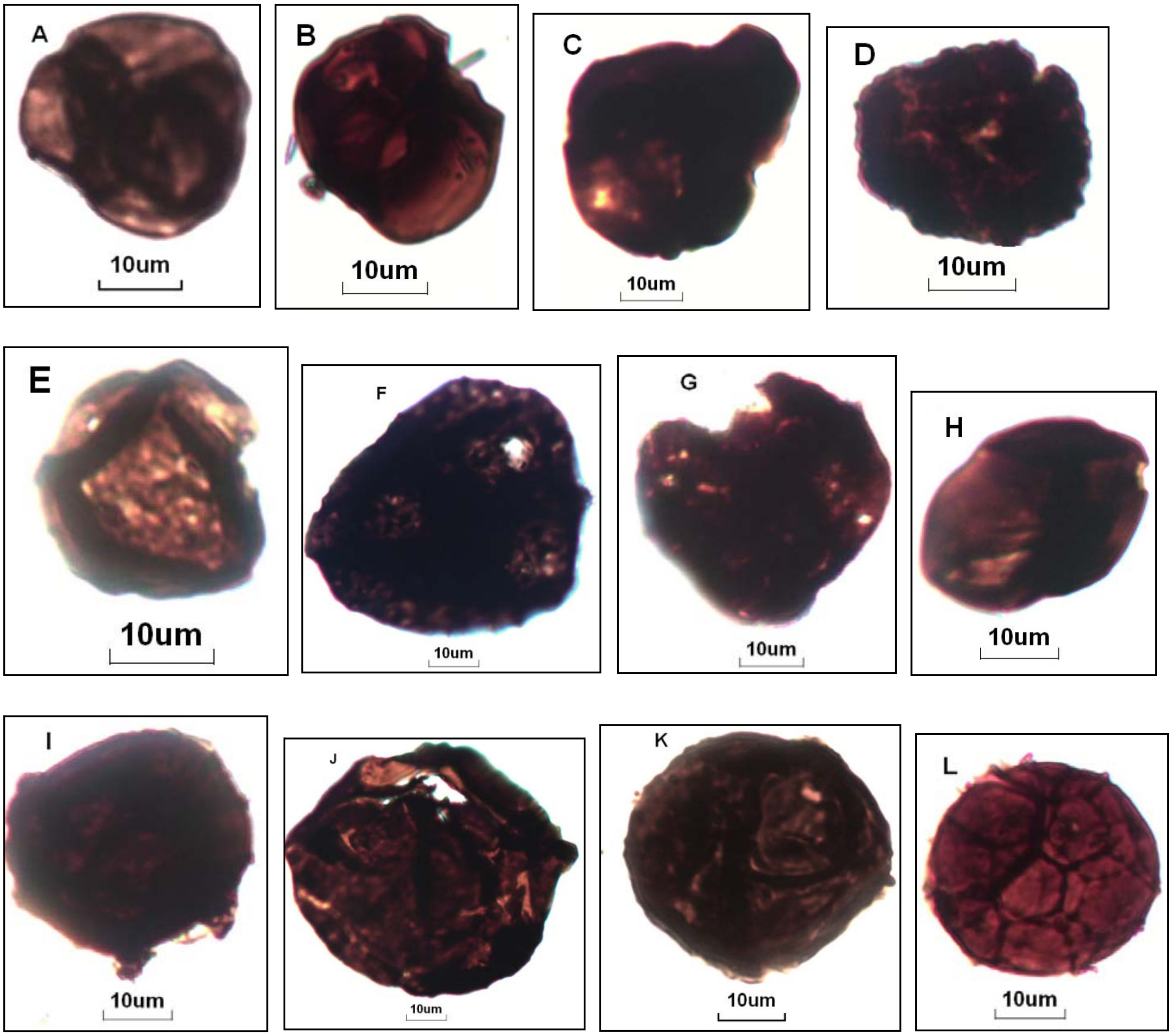

Plate 1

A-B, *Tetrahedraletes medinensis* (Strother & Traverse) Wellman & Richardson 1993.

C, *Tetrahedraletes grayae* Strother 1991.

E, *Pseudodyadospora petasus* Wellman & Richardson 1993.

D, Questionable species.

F-I, Cryptospores.

J-L, Sphaeromorph acritarchs.

J-K, *Leiosphaeridia* spp.

L, *Dictyotidium* sp.

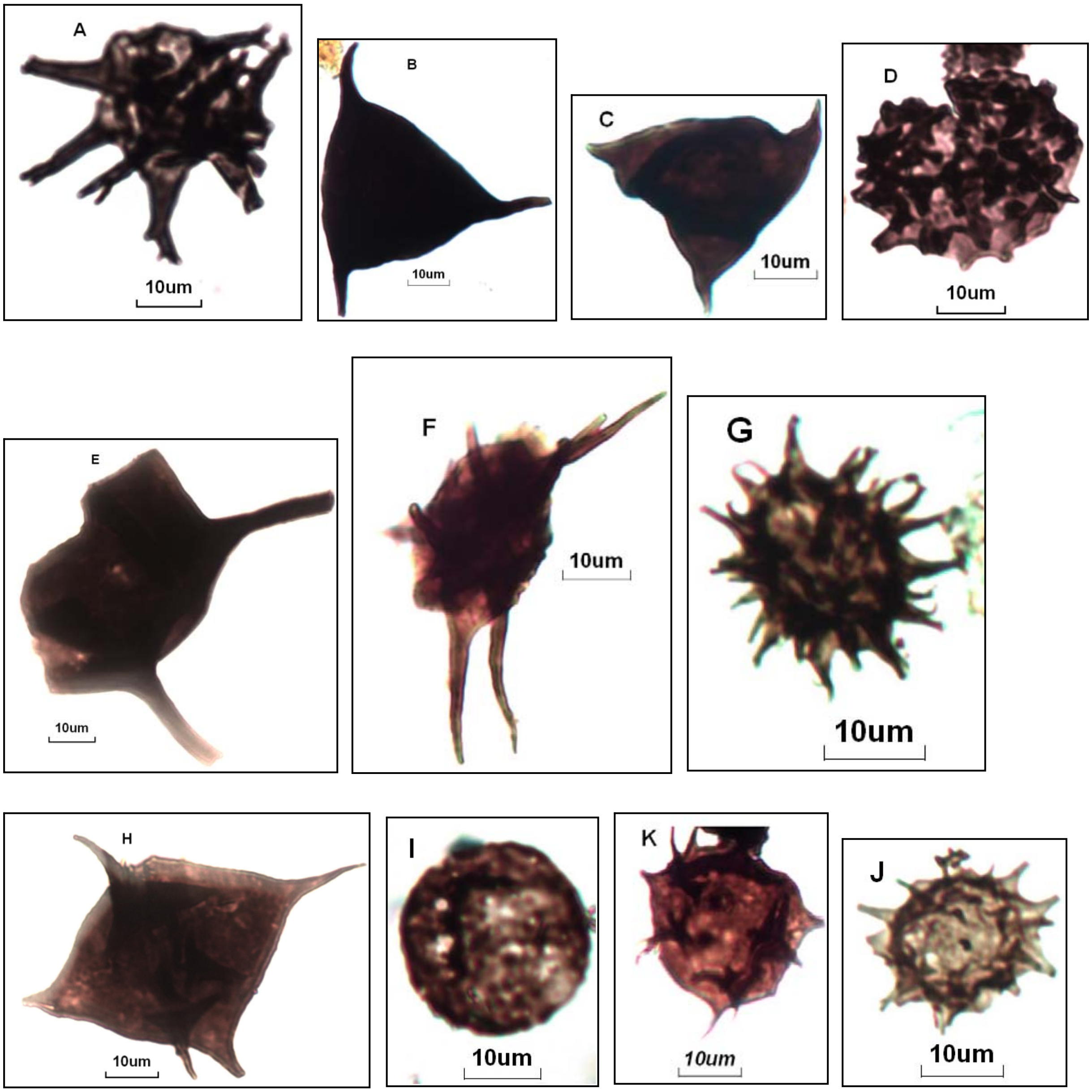

Plate 2

A, *Diexallophasis denticulate* (Stockmans & Willière) Loeblich 1970.

B, *Veryhachium reductum* (Deunff) Downie & Sarjeant 1965. C, *Veryhachium* sp.

D, *Tylotopalla caelamenicutis* Loeblich 1970.

E, *Orthosphaeridium inflatum* Loeblich 1970.

F, *Orthosphaeridium* spp.

G, *Ammonidium* spp.

H, *?Veryhachium bulliferum* Delabroye, Vecoli, Hints & Servais 2011.

I, *Buedingiisphaeridium balticum* Uutela & Tynni 1991.

K-J*, Micrhystridium* sp.

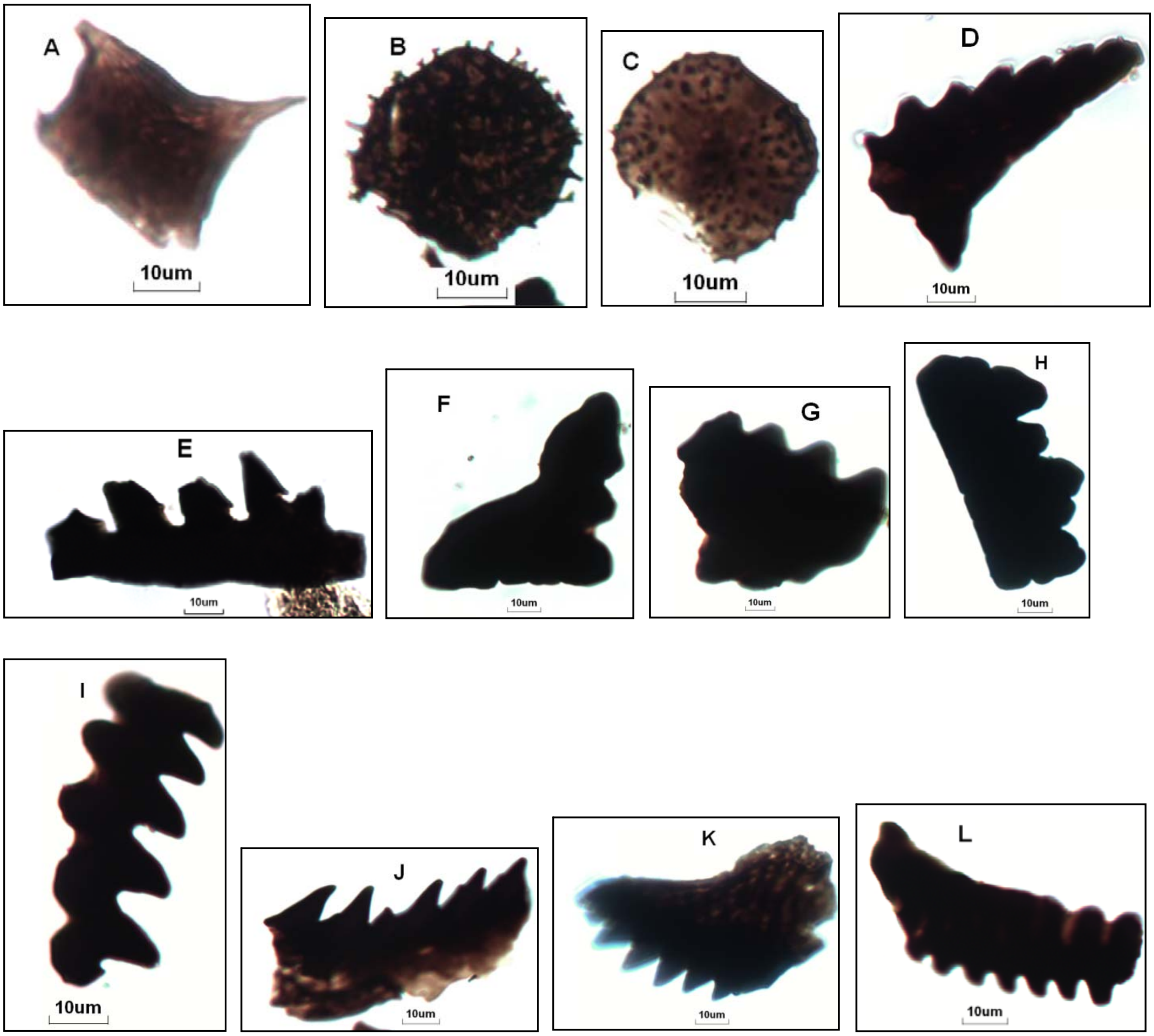

Plate 3

A, *Striatotheca* sp.
B, *Coryphidium* sp.
C, *Acanthodiacrodium* spp.
D-L, Scolecodonts.
D, RÖ1-91; R8-2.
E, RÖ1-89; J33.
F, RÖ1-87; H42.
G, RÖ1-87; N28-2.
H, RÖ1-75; P37.
I, RÖ1-75; W47.
J, RÖ1-71; U37-3.
K, RÖ1-69; G46.
L, RÖ1-75; N41-1

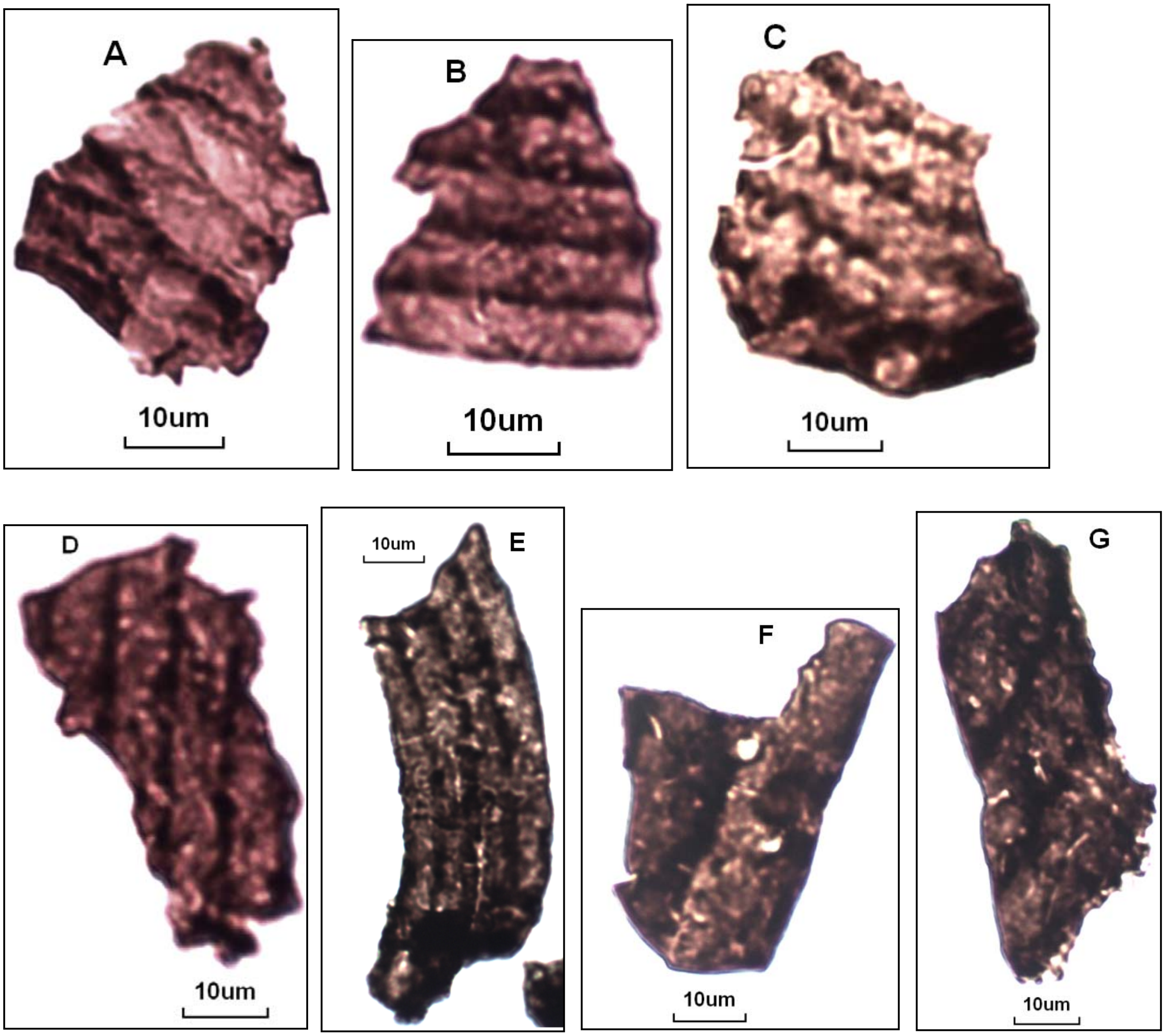

Plate 4

A-G, Graptolites.
A, RÖ1-49; D13.
B, RÖ1-49; F26.
C, RÖ1-53; M42-2.
D, RÖ1-49; D16.
E, RÖ1-49; S17-3.
F, RÖ1-49; G45-3.
G, RÖ1-53; L20.

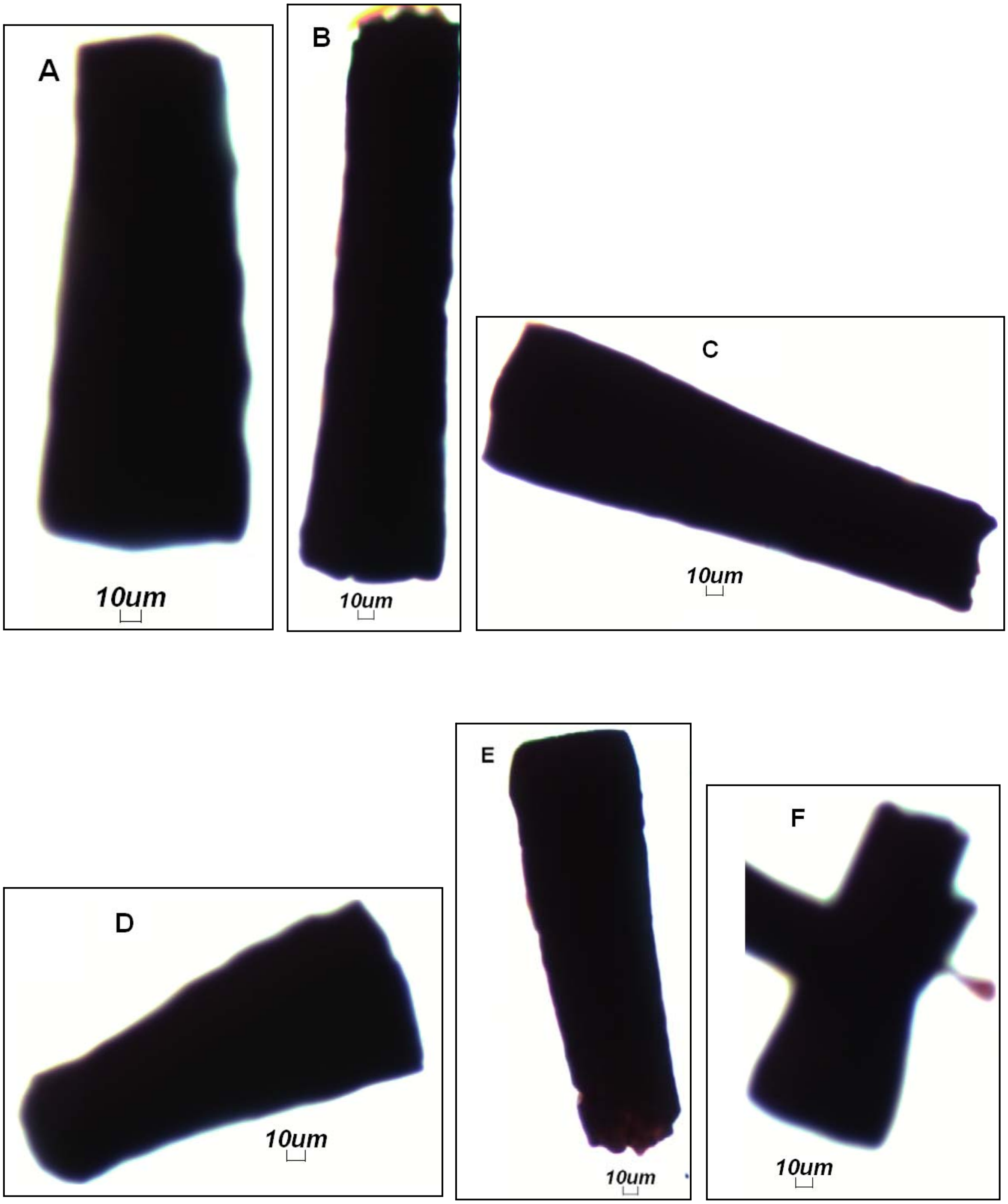

Plate 5

A-F, Chitinozoans.
A, RÖ1-71; R18-2.
B, RÖ1-71; U29-2.
C, RÖ1-71; H34-3.
D, RÖ1-71; Q29-2.
E, RÖ1-71; L32-2.
F, RÖ1-71; V32-1.

Thus, the shoreline started to move seaward as the rate of sediment supply started to exceed the rate of sea level rise at the shoreline. Interestingly, the lower part of the Lindegård Mudstone, in the Röstånga-1 core, through the lower local palynozobe I, proposed herein, provides the oldest evidence of early land plants of Baltica. The evidence continues, through the local palynozone II (i.e. Hirnantian), proposed herein, by different cryptospores which have similarities to the coeval ones worldwide indicating homogeneous land plants which tolerated a wide range of climatic conditions (e.g. Wang et al. 1997; Steemans, 2001; Rubinstein & Vaccari 2004; Richardson & Ausich 2007; Vecoli et al. 2011). Through the upper part of the local palynozone I, another dramatic and regional event is variously traced herein. The Avalonia-Baltica collision, the consequent significant closure of the Tornquist Sea and the foreland character and sedimentation took place. Thus, tectonically caused deepening of the environment and increased tectonic subsidence and flexure loading along the margin of Baltica caused significant sediment thicknesses seen in the Röstånga-1 core and elsewhere when thicknesses are compared to the intracratonic part of the basin. Thus, the Scanian Lithofacies Belt is developed with its deep facies in contrast to the shallower carbonates of this intracratonic part. In addition to the significant thicknesses, several marks have been recorded herein in the Röstånga-1 core. Through the upper part of the local palynozone I, through the lower part of the Lindegård Mudstone, diagnostic Early-Middle Ordovician reworked acritarchs have indicated a detrital Avalonian sedimentary input in front of the Caledonian Deformation and provided an evidence for foreland-type sedimentation. This foreland setting in front of the advancing orogen put forth strong control on sediments supply, and caused a development for foreland-zone A with slowing and then accelerating of relative sea level rise without any relative sea level fall and prevented any lithological change or gap through the Hirnantian. While the lowermost part of the *persculptus* zone globally marks the maximum sea level fall, tracing of such major eustatic sea level change was unsuccessful through this part of this zone through the Lindegård Mudstone. Across another dramatic and biostratigraphical event, there was also no gap or lithological change. This event is marked by the occurrence of long-ranging and tolerant taxa such as *Veryhachium* and *Micrhystridium* and a major micro-phytoplankton turnover recognized by the appearance of several taxa which show a Silurian affinity such as *Ammonidium* spp., *Diexallophasis denticulate* and the first Baltic record of *Tylotopalla caelamenicutis*. The latter species has clearly proved that this real turnover is in a relation to the Hirnantian glaciation rather than this turnover which was before the glaciation. While the acritarchs assemblage in the Röstånga-1 core corroborates the idea that there were palaeoprovinces during the latest Ordovician between Laurentia/Baltica and Gondowana due to the opening of the Rheic Ocean and the Hirnantian eustatic sea-level drop, this occurrence of *Tylotopalla* indicates that there might be Gondwanan influences particularly on the margin of Baltica due to the rapid northward drift of Avalonia and its docking to Baltica by Late Ordovician times. The local palynozone II has mainly been based on this dramatic turnover and the occurrence of long-ranging and tolerant taxa. It is worth to refer that acritarch palynostratigraphy may play a role in the Scanian Lithofacies Belt which has the most ambiguous successions in terms of chronostratigraphy (Katian -Hirnantian Stages) because of the geological limitation of many potential methods such as sequence stratigraphy, stable-isotope stratigraphy and conodont biostratigraphy. Other things have been discussed in the local palynozone II and showed the regional similarity of the palynofacies pattern near the base of this palynozone (see above). The Kallholn Formation, through the local palynozone III, rests on a mfs and coincides with a eustatic sea level rise related to the Hirnatian deglaciation, marking a new anoxic black shale and high productivity. This local palynozone III marks the relatively lowest abundance of acritarchs and corresponds to the general feature of the acritarch assemblages through the start of the Silurian. Anoxic conditions might be related to this early Silurian "crisis". Last, the acritarchs from the Lindegård Mudstone are brownish black-colored, indicating a Thermal Alteration Index (TAI) of 4 which is considered to be post-mature with regard to oil generation. There are many controls such as the sedimentary burial and magmatic heating might have had an effect on thermal maturity.

11 Concluding remarks

The Scanian Lithofacies Belt comprises Ordovician rocks preserved along the Tornquist Zone at the SW margin of the palaeocontinent Baltica in Scania, the southernmost province of Sweden, and on the Danish island of Bornholm. These sediments are dominated by deep marine graptolitic shales and mudstones, with subordinate limestone levels.

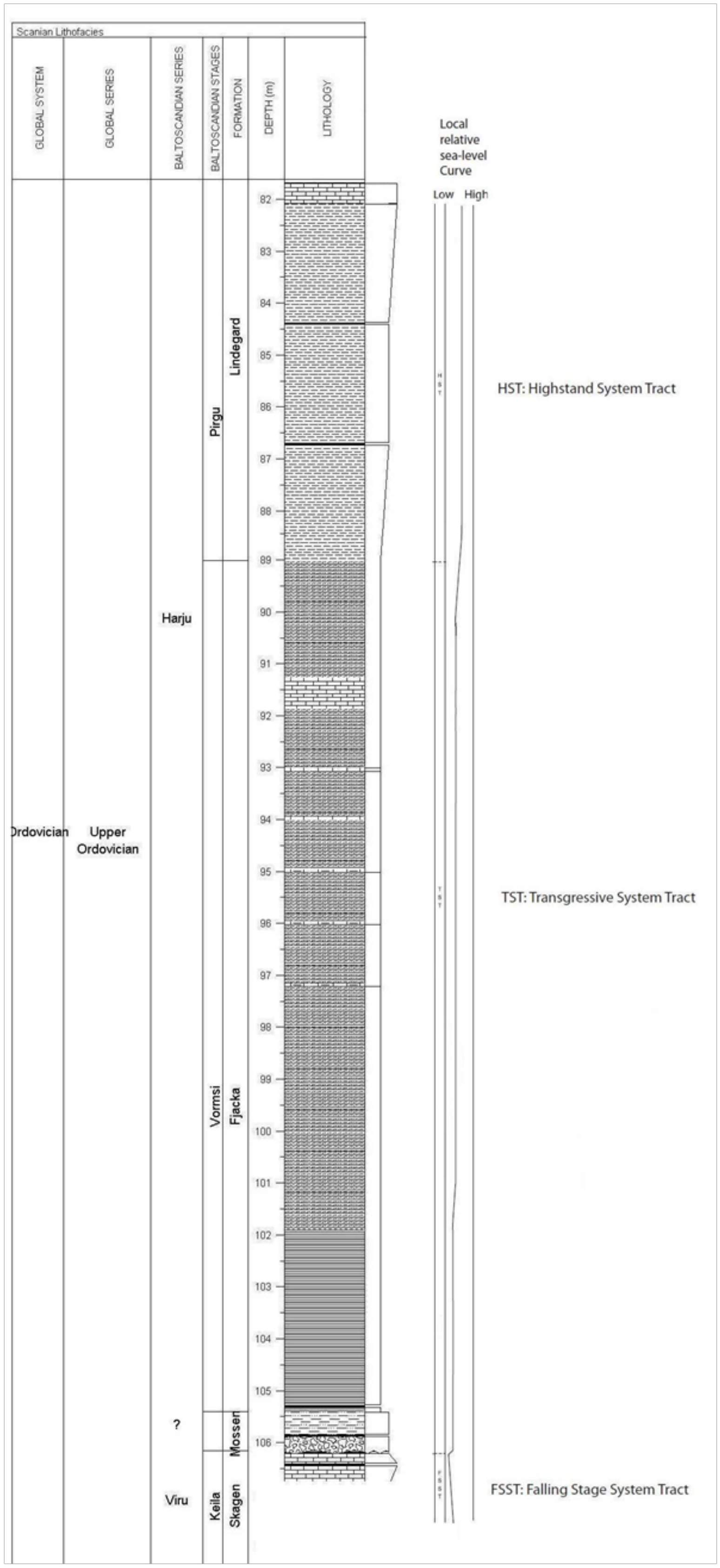

Fig. 9. Local relative sea-level curve and the sequence stratigraphical interpretation through the Skagen-Mossen-Fjäcka-Lindegård formations.

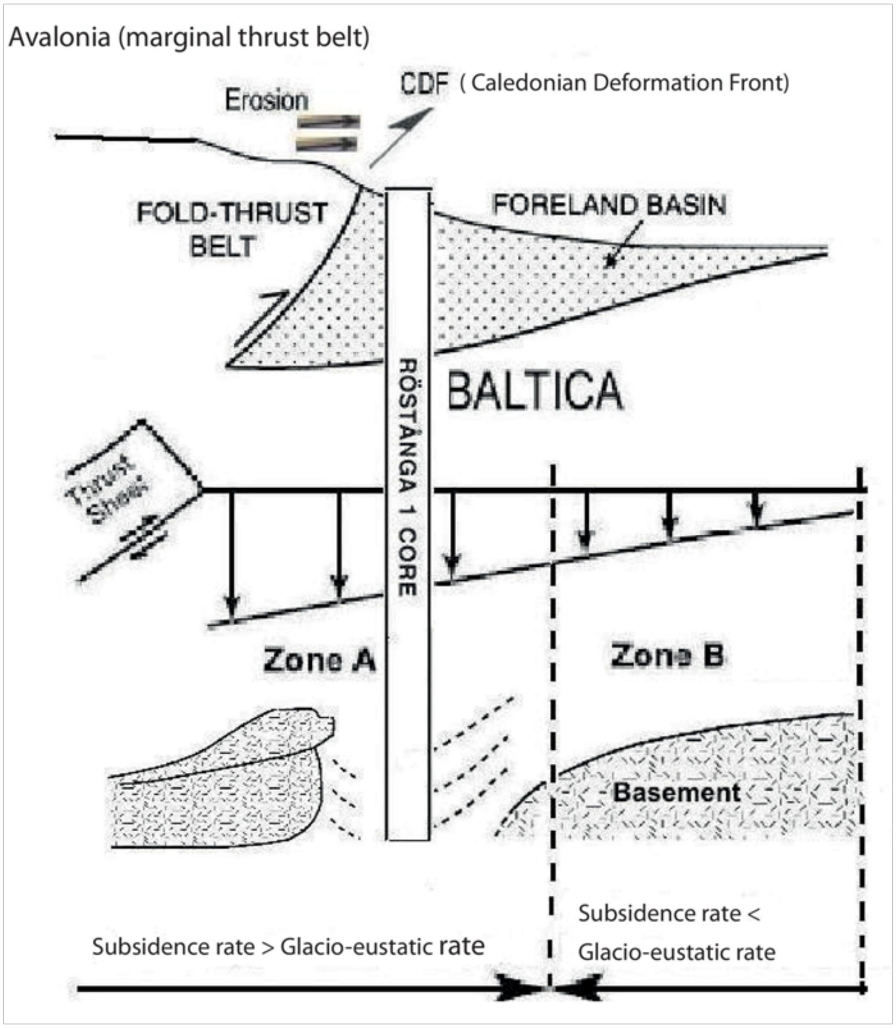

Fig. 10. A model for the sedimentary basin. Note that this model can not be applied, at least, at a level corresponding to the top of the Skagen Limestone or at a level earlier than that. For discussion, see the text.

	Low to Mid Latitudes						
	Laurentia	Baltica					Perigondwana (Arabian Plate)
	❶	❷	❸	❹	❺	✦	❽
?Veryhachium bulliferum			√	√		√	
Buedingiisphaeridium balticum	√	√	√	√		√	
Orthosphaeridium inflatum	√					√	
*Diexallophasis denticulata**	√				?	√	
Veryhachium reductum					√	√	
Micrhystridium	√	√	√	√	√	√	√
Leiosphaeridia spp.	√	√	√	√		√	
Tylotopalla caelamenicutis *						√	√
Ammonidium spp.*	√		√			√	

Fig. 11. Some acritarch species identified in the Röstånga-1 core, and thought to be important for regional correlation and future (standard) biozonation through the uppermost Ordovician (uppermost Katian–Hirnantian) strata of low- to mid-latitudes. The species which are marked by * show a clear Silurian affinity. See Fig. 4 to locate these sites on the latest Ordovician palaeogeography map 1- Anticosti Island, Quebec, Canada (Laurentia). Note in Baltica that 2- Rapla drill core, northern Estonia is located in the North Estonian Confacies (see Uutela & Tynni 1991). 3- Valga-10 drill core, southern Estonia is located in the transitional deposit environment close to the border between the Estonian shelf

and the Livonian Basin (see Delabroye et al. 2011). 4- Gotland Island, Sweden is located in the Central Baltoscandian Confacies belt (*sensu* Jaanusson 1995). 5- Holy Cross Mountains sections, Poland correspond to deep basin facies of graptolite-bearing sediments (see Bednarczyk 1998; Kremer 2001; Masiak et al. 2003). Cross: Röstånga-1 drill core, south Sweden is located in the Scanian Lithofacies Belt (Jaanusson 1995; formerly the Scanian Confacies Belt, cf. Jaanusson 1976). 8- south Turkey (Perigondwana, Arabian Plate). Acritarchs data available from Duffield & Legault (1981), Jacobson & Achab (1985), Martin (1988) and Delabroye et al. (2011) for Anticosti Island, Uutela & Tynni (1991) for Rapla drill core, Delabroye et al. (2011) for Valga-10 drill core, Le Hérissé (1989a) and Eiserhardt (1992) for Gotland, Kremer (2001) and Masiak et al. (2003) for Holy Cross Mountains sections and Paris et al. (2007) for south Turkey.

The present study is a multiproxy analysis of the sediments from the Röstånga-1 core, considered an excellent upper Middle Ordovician-Lower Silurian reference for southernmost Sweden. The studied succession spans the Ordovician-Silurian boundary represented by the 6 units: Sularp, Skagen, Mossen, Fjäcka, Lindegård and Kallholn formations. The sediments were studied for sedimentology, sequence stratigraphy, palynology and biostratigraphy, which subsequently served for; sedimentary basin analysis and regional correlations. The following concluding remarks summarize the main results from this study, suggesting a dramatic scenario for the Lower Palaeozoic of Baltoscandia:

- An intense and global Ordovician volcanism caused major pulses of contemporaneous K-bentonite beds, and was climaxed by a short-lived glacial pulse and a major eustatic sea level fall (Fig. 9). That in turn led to a eustatic regression and a development of a sequence boundary and solution structures at the top of Skagen Limestone (early middle Katian). This was rapidly followed by a return to deeper-water conditions expressed through the Mossen-Fjäcka succession. Notably, the glacio-eustatic rate/influence was greater than the subsidence rate at that time in Scania.
- The basal part of the Fjäcka Shale (Katian age) consists of anoxic black shales with evidence of a flooding surface (as result of deglaciation) at the base of the Fjäcka Shale. This serves as a regional marker horizon, reflecting a high paleo-productivity and preservation. In the Röstånga-1 core, this is traced by black, laminated and graptolitic shale which lacks any benthic fauna or bioturbation.
- The succession follows with the Lindegård Mudstone, which marks a sea-level high stand and a stable environment in the basin at the boundary between the Fjäcka Shale and the Lindegård Mudstone. The lower part of the later unit correlates to the Jonstorp Formation in central Sweden. This lower part of the Lindegård Mudstone, comprising the informal palynozone I, proposed herein, provides the oldest evidence for early land plants in Baltica. The sparse occurrence of cryptospores suggests offshore deep-water shelf environment at a significant distance from shoreline.
- The evidence continues, through the local palynozone II (i.e. Hirnantian), proposed herein, by different cryptospore taxa. Although the cryptospore assemblage is sparse, these same taxa are encountered in coeval assemblages globally possibly indicating homogeneous land plant assemblages, which tolerated a wide range of climatic conditions.
- Through the upper part of the local palynozone I (late Katian; pre-Hirnantian Ashgill), another regional event is traced herein. Diagnostic Early-Middle Ordovician reworked acritarchs indicated a detrital Avalonian sedimentary input in front of the Caledonian Deformation, and provided an evidence for foreland-type sedimentation (Fig. 10). This foreland setting in front of the advancing orogen put forth strong control on sediments supply, and caused a development for foreland-zone A with slowing and then accelerating of relative sea level rise without any relative sea level fall. This prevented any lithological change or gap through the Hirnantian.
- Across another biostratigraphical event, there was also no gap or lithological change. This event is marked by the occurrence of long-ranging and tolerant taxa such as *Veryhachium* and *Micrhystridium* and a major microphytoplankton turnover recognized by the appearance of several taxa with a Silurian affinity such as *Ammonidium* spp., *Diexallophasis denticulate* and the first Baltic record of *Tylotopalla caelamenicutis*. The occurrence of the latter species indicates that the turnover is related to the Hirnantian glaciation.
- The local palynozone II has mainly been based on this turnover and the occurrence of long-ranging and tolerant acritarch taxa. This palynozone has possibly a Gondwanan equivalent through the Hirnantian Stage. Therefore, acritarch stratigraphy is an important tool not only for dating, but also for palaeoenvironmental interpretations within the Scanian Lithofacies Belt, which has the most ambiguous successions in terms of chronostratigraphy (Katian-

Hirnantian stages; Fig. 11). Other geological methods such as sequence stratigraphy, stable-isotope stratigraphy and conodont biostratigraphy have limitations when it concerns dating.

- The palynofacies results reveal a relatively high abundance and diversity of scolecodonts (scolecodont peak) coupled with a decrease in the relative abundance of chitinozoans at the base of the local palynozone II (Hirnantian), reflecting a regional similarity with previous results.
- The Kallholn Formation, comprising the local palynozone III, rests on a mfs and coincides with a eustatic sea level rise related to the Hirnantian deglaciation, marking a new anoxic black shale and high palaeo-productivity. In the Röstanga-1 core, the Kallholn Formation is graptolitic, organic-rich, laminated and pyritized black shale. The local palynozone III (latest Hirnantian-early Llandovery (Rhuddanian) marks the relatively lowest abundance of acritarchs, and corresponds to the general feature of the acritarch assemblages through the start of the Silurian. Anoxic conditions might be related to this early Silurian "crisis".
- The acritarchs from the Lindegård Mudstone are brownish black-colored, indicating a Thermal Alteration Index (TAI) of 4 which is considered to be post-mature with regard to oil generation. There are many controls such as sedimentary burial and magmatic heating might have had an effect on thermal maturity.

12 Acknowledgements

First of all, I would like to thank my kind teacher Vivi Vajda for the interest and encouragement she has given during this project. She always behaves as a kind friend. Per Ahlberg is thanked for providing an access to the Röstånga core and for helping to move the core from the department stores. Mikael Calner is thanked for reviewing the stratigraphy part. He also arranged for a polished slab to study the Skagen Limestone. Furthermore, they all provided me with some articles. Git Ahlberg is thanked for her help in the laboratory. Kristina Mehlqvist is thanked for reviewing the taxonomy of some cryptospores. I am grateful to Claudia Rubinstein (Argentina) for discussing the taxonomy of some acritarchs and cryptospores during her visit to Lund. Jörg Maletz (Germany) is thanked for his interest with the graptolite succession in the core. Carl Alwmark is also thanked for offering the help during the SEM session which has been challenged. I was sponsored by a joint Egyptian-European grant (L020901652) over the last two years for master studies in Geology at Lund University. Petter Pilesjö, director of Lund University's GIS Centre, is thanked for many things. Due to an early sponsorship by Chevron Corporation, I have been given a free access to some journals and old literature. I would like to thank my kind friends. I would like to send deep thanks to my family and especially my parents. They always inspire, support and encourage me.

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Appendix I

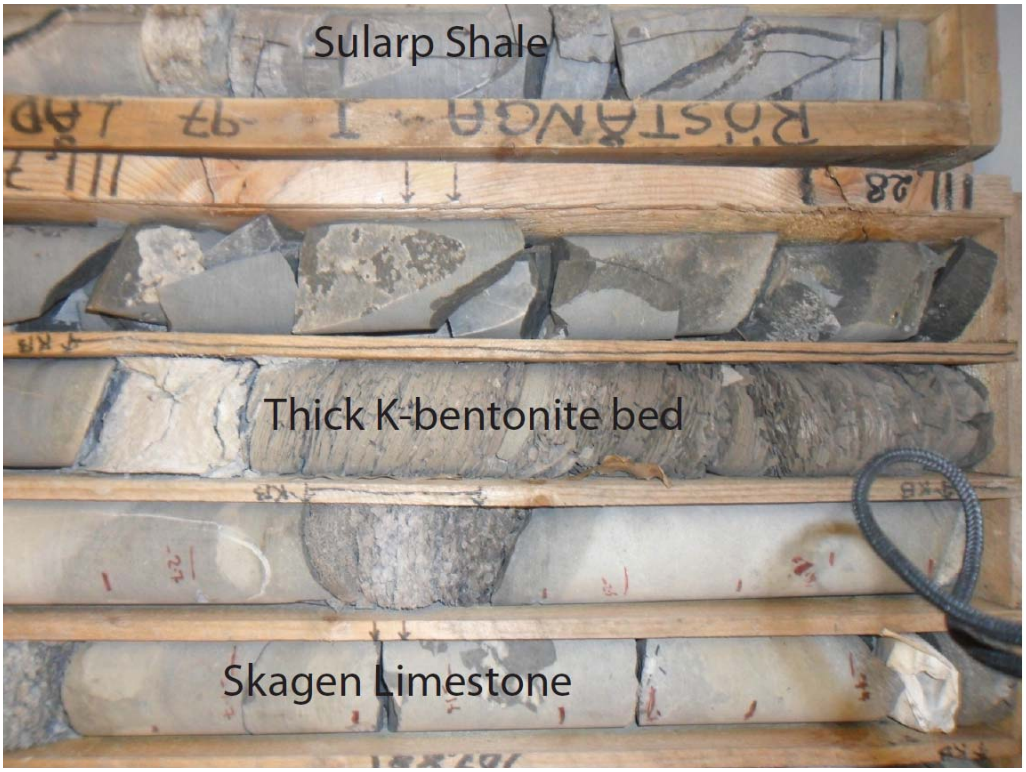


Fig.1. The Sularp Shale and the Skagen Limestone. Note the yellowish clay beds (K-bentonite beds).

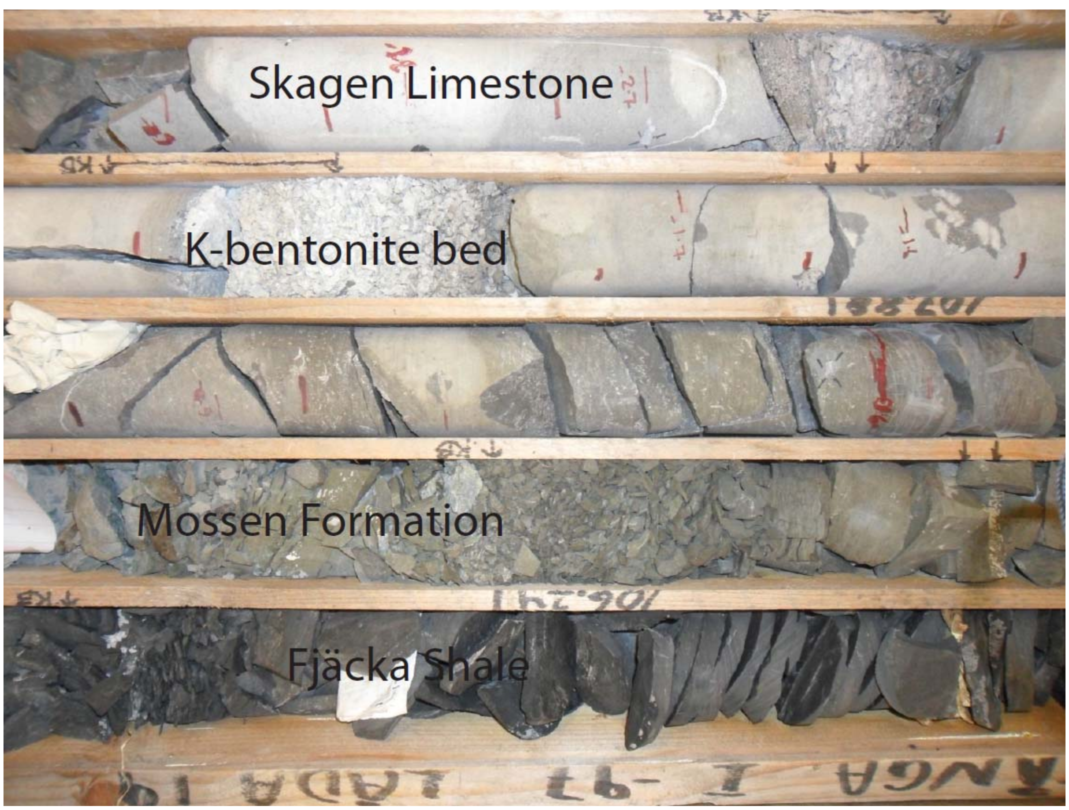


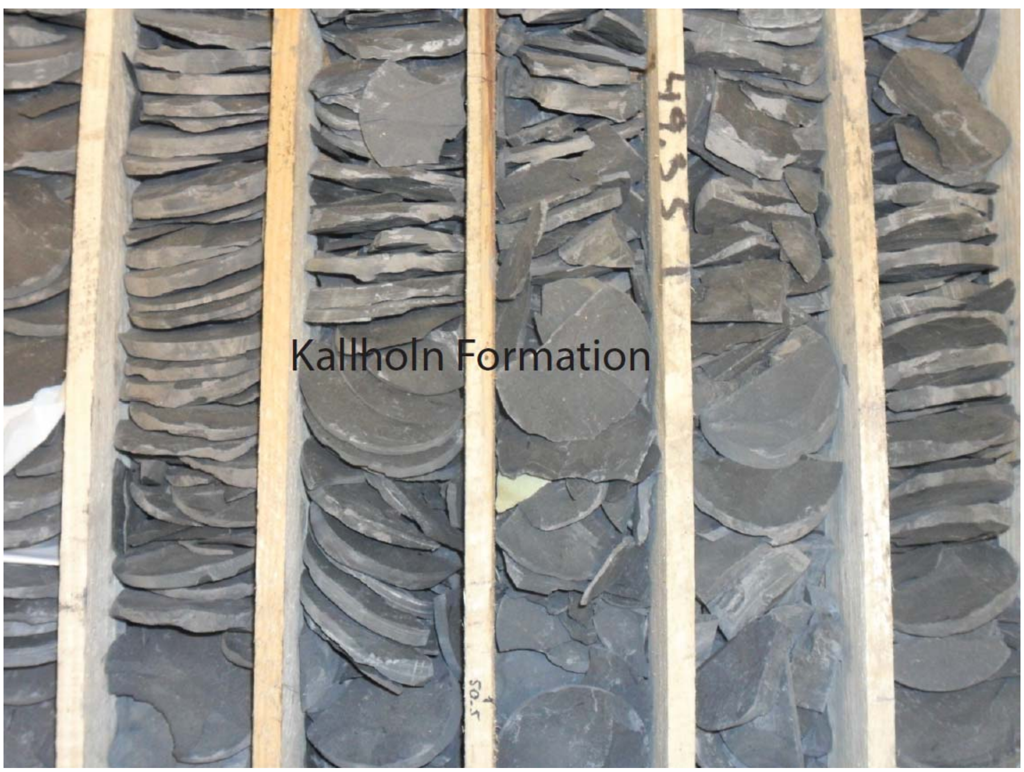
Fig. 2. The Skagen Limestone, the Mossen Formation and the Fjäcka Shale. Note 1) the K-bentonite beds in the Skagen Limestone, 2) the Mossen Formation consists of clasts of glauconitic limestone and strongly bioturbated grey mudstone and 3) the Fjäcka Shale is a dark grey to black, laminated and graptolitic shale.

Fig. 3. Polished slab showing the disconformity and solution structures at the top of the Skagen Limestone.

Fig. 4. The Lindegård Mudstone consists of a light grey and massive mudstone.

Fig. 5. Greenish silty shale that is carbonate-rich to the top. Note that the laminae are thick (2-5 mm).

Fig. 6. The gradational contact or interval between the Lindegård Mudstone and the Kallholn Formation. The boundary is arbitrarily placed at a depth of ca. 56 m in the uppermost part of the *persculptus* Zone.



Figs. 7. and 8. Fissile, laminated, graptolitic, dark grey black shale of the Kallholn Formation.

Appendix II

List of species

1- *Tetrahedraletes medinensis* (Strother & Traverse) Wellman & Richardson 1993. Plate 1, Fig. A (Sample RÖ1-87; O32); Fig. B (RÖ1-61; F19).
2- *Tetrahedraletes grayae* Strother 1991. Plate 1, Fig. C (Sample RÖ1-71; U13-2).
3- *Pseudodyadospora petasus* Wellman & Richardson 1993. Plate 1, Fig. E (Sample RÖ1-59; E42-2).
4- *Leiosphaeridia* spp. Plate 1, Fig. J (Sample RÖ1-51; R36-1); Fig. K (Sample RÖ1-59; F11).
5- *Dictyotidium* sp. Plate 1, Fig. L (Sample RÖ1-63; O40-1).
6- *Diexallophasis denticulate* (Stockmans & Willière) Loeblich 1970. Plate 2, Fig. A (Sample RÖ1 -69; T44).
7- *Veryhachium reductum* (Deunff) Downie & Sarjeant 1965. Plate 2, Fig. B (Sample RÖ1-69; M29-3).
8- *Veryhachium* sp. Plate 2, Fig. C (Sample RÖ1-69; U27).
9- *Tylotopalla caelamenicutis* Loeblich 1970. Plate 2, Fig. D (Sample RÖ1-69; H41).
10- *Orthosphaeridium inflatum* Loeblich 1970. Plate 2, Fig. E (Sample RÖ1-75; M38-2).
11- *Orthosphaeridium* spp. Plate 2, Fig. F (Sample RÖ1-69; S30-4).
12- *Ammonidium* spp. Plate 2, Fig. G (Sample RÖ1-69; V47).
13- *?Veryhachium bulliferum* Delabroye, Vecoli, Hints & Servais 2011. Plate 2, Fig. H (Sample RÖ1-59; G10).
14- *Buedingiisphaeridium balticum* Uutela & Tynni 1991. Plate 2, Fig. I (Sample RÖ1-91; H37-1).
15- *Micrhystridium* sp. Plate 2, Fig. K (Sample RÖ1-71; D24); Fig. J (Sample RÖ1-71; U18-1).
16- *Striatotheca* sp. Plate 3, Fig. A (Sample RÖ1-77; X40-1).
17- *Coryphidium* sp. Plate 3, Fig. B (Sample RÖ1-77; L34-3).
18- *Acanthodiacrodium* spp. Plate 3, Fig. C (Sample RÖ1-77; M38).

Appendix III

Fig.1. Lithologic succession and stratigraphy of the Röstånga-1 core. Note that the appearance of *D. complanatus* (Ka4 Stage Slice) is at a depth of 88.56 m. The oldest *Tetrahedraletes medinensis* (Strother & Traverse) Wellman & Richardson 1993 was recovered from the Lindegård Mudstone at a depth of 87 m.


Scanian Lithofacies
GLOBAL SYSTEM
GLOBAL SERIES
BALTOSCANDIAN SERIES
BALTOSCANDIAN STAGES
FORMATION
DEPTH (m)
LITHOLOGY
LIMESTONES
mud
wacke
pack
grain
rud & bound
MUD
SAND
GRAVEL
clay
silt
vf
f
m
c
vc
gran
peb
cobb
boul
BIOTURBATION
STRUCTURES / FOSSILS
NOTES
etc
Continued
HST
Silurian
Lower Silurian (Llandoverian)
Kallholn
Depth = 52.7 m, acuminatus Zone (Ordovician-Silurian boundary)
Porkuni
Harju
Lindegard
Katian-Himantian boundary ?
Pirgu
HST
K-b ?
D. complanatus Graptolite Zone
Ordovician
Upper Ordovician
Vormsi
Fjacka
TST
P. linearis Graptolite Zone
?
Mossen
Unconformity (Sequence Boundary, SB)
Viru
Keila
Skagen
Skeletal limestone rich in trilobite fragments
Haljala
Sularp
etc
Continued
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Lithologies
K-bentonite (K-b)
Light to medium gray mudstone
Limestone
Clasts of glauconitic limestone
Gray bioturbated calcareous mudstone
Dark gray to black shale
Dark gray to greenish mudstone and shale
Calcareous mudstone
Symbols
Shells
Intense bioturbation
Minor bioturbation
Cryptospore
Base Boundaries
Erosion
Gradational

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