DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2013/7

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Summary

The Alum Shale Formation (ASF) of Scandinavia is a highly organic rich unit (5-25 % TOC) deposited in an epicontinental sea on the western fringe of Baltica. The greater part of the ASF consists of finely laminated, non-bioturbated, pyrite-rich mudstone, deposited under oxygen depleted conditions. This depositional regime lasted from the Mid Cambrian into the Early Ordovician i.e. nearly 30 my. Baltica was at that time located on intermediate latitudes south of Equator and characterized by a cool temperate climate probably with much storm activity. The sea level was high from the mid Mid Cambrian onwards and all of Scandinavia was inundated. The coast was located in western Russia most of the time.

The ASF is distributed from the St Petersburg Region (Russia) in the east to the Middle or even Upper Allochthon in the west (representing a palaeo-position offshore western Norway) and from Denmark in the south to northernmost Norway in the north and the unit originally covered some 1.000.000 km^2. It ranges in thickness from 15-25 m across much of Sweden and is up to about 80-100 m in Scania (southern Sweden) and the Oslo area (southern Norway). Locally the ASF even approaches a thickness of 180 m offshore Denmark. From the southern Scandinavian depocenter(s) the formation thins towards the margins of Baltica both southwards and westwards.

The ASF was deposited on the outer shelf from about the storm wave base and further outboard. The sea floor was exceptionally flat, probably with an average slope below 1-2 m per km. The bottom environment was generally dysoxic, maybe occasionally anoxic, leading to enrichment of the sediment by pyrite as well as a number of trace elements, notably uranium, molybdenum, vanadium and nickel. Limestone is common in the ASF and occurs as concretions and beds that constitute up to 50% of the formational thickness in central Sweden vs only 5-10 % in southernmost Sweden, Denmark and southern Norway. This distribution reflects recurrent erosional events on the mid shelf caused by lowering of the storm wave base associated with sea level falls. Storm driven erosion recycled the unconsolidated Alum Shale mud and left behind limestone and limestone conglomerates; some of the limestone consists of trilobite hash winnowed from the mud.

In the offshore areas where the ASF is thickest the average accumulation rate was only 4-6 mm per 1000 yrs (compacted thickness). The profound sediment starvation was a result of the thorough late Precambrian peneplanisation of Baltica (no topography in the hinterland) in combination with the extensive flooding of the craton (small land area).

An abundant, low-diverse, specialized fauna, dominated by trilobites, was adapted to cope with the dysaerobic bottom environment and a very detailed trilobite biostratigraphy has been developed comprising three Middle Cambrian superzones subdivided into 8 zones and seven Furongian superzones subdivided into 26 zones. Six graptolites zones are recognized in the Tremadocian. The average biozonal duration is c. 750.000 yrs.

The long-lasting dysoxic conditions in the epicontinental sea was due to a reduced oxygen level in the Cambrian hydro- and atmosphere on a global scale, likely further amplified by uplifted margins of Baltica creating local silled basin conditions. The general oxygen level in the epicontinental sea decreased during the Mid Cambrian with a major hike in dysoxidity through the Furongian. The oxygen level rose again from the late Furongian and into the Tremadocian, unrelated to changes in general depth of deposition.

Most of Poland was uplifted during deposition of the ASF and changing isostatic movements affected different parts of Baltoscandia during the Mid Cambrian-Tremadocian (both uplift and localized subsidence). The so-called Hawke Bay Event was associated with uplift of Scandinavia; different parts of the uplifted area subsided progressively and differentially during the early Mid Cambrian and the Hawke Bay unconformity is as a result

diachronous. Sub-regional uplift events took place in the mid Mid Cambrian and latest Furongian, in both cases lasting for several million years. The intra-plate movements most likely reflect subtle isostatic responses triggered by concurrent plate tectonic changes. The axis Estonia-Åland-central Sweden seems to have been an especially mobile zone.

A Mid Cambrian–Tremadocian sea level curve is reconstructed and a preliminary sequence stratigraphy is outlined comprising 21 third order sequences (the oldest is Early Cambrian) forming two second order supersequences. The average duration of the sequences is 1.5 my. It is not possible to recognize fourth order subsequences (parasequences) in this offshore depositional environment. The sea level was comparatively low early in the Mid Cambrian and clastic supply from the east was high. Progradation shifted the coastline westwards almost reaching mainland Sweden. Alum Shale low in organic matter was at the same time deposited in westernmost Scandinavia with clastics supplied from the west and maybe also from south central Scandinavia which was still uplifted as a result of the Hawke Bay Event. A major sea level rise in the mid Mid Cambrian displaced the coastline into Russia and deposition of Alum Shale spread across the greater part of Scandinavia as the Hawke Bay uplift subsided. The sea level rose towards the close of the Mid Cambrian to drop again in the early Furongian, which constitutes a second order lowstand. The sea level rose once more in the late half of the Furongian with a highstand peak during the *P. minor* Superzone. Following a transient latest Furongian lowstand a strong sea level rise characterized the earliest Ordovician, at which stage deposition of Alum Shale reached its greatest extent. The eastwards spreading of Alum Shale deposition was, however, also to some extent the result of local subsidence. After a mid Tremadocian moderate lowstand interval a new sea level rise took place in the late Tremadocian, but Alum Shale deposition was eventually terminated by the major late Tremadocian sea level fall referred to as the Ceratopyge Regressive Event and which likely coincided with disappearance of the uplifted western margin of Baltica.

1. Introduction

This report contains a geological synthesis of the Alum Shale formation prepared to Total E&P. The maps and illustrations cited in this synthesis are presented in the accompanying report 'Nielsen & Schovsbo 2013. Alum Shale maps and diagrams. GEUS Report 2013/6'.

The Alum Shale Formation of Scandinavia is a remarkable unit deposited under low oxygen conditions lasting for nearly 30 my (early Mid Cambrian – earliest Ordovician). The formation, which contains 5-25% organic carbon, is different from all other black shale intervals seen in the Lower Palaeozoic of Baltoscandia. It is, in fact, different from most other black shales seen in the world. The content of various trace elements in the Alum Shale is thus unusually high, the unit is very rich in fossils despite obviously representing deposition in an oxygen restricted environment, limestone is common, and the unit is very widely distributed, yet it is greatly condensed (maximum average accumulation rates were 4-6 mm per 1000 yrs). The facies originally blanketed the western part of Baltoscandia and roughly covered an area measuring c. 2000 km north-south and up to c. 1500 km east-west (Fig. 1). Breaking the distribution down into subareas the original areal distribution can be calculated to about 1 mill. km^2. The western fringes of Baltica are now concealed below the Caledonian orogen and the Lower Palaeozoic strata that were deposited in this area are telescoped into the mountain chain. The Alum Shale acted as decollement level and, hence, is typically strongly disturbed in the orogen (Fig. 2). Despite its wide distribution, the Alum Shale is unknown from the German-Polish branch of the Caledonides and the formation is absent in the greater part of Poland, which is another peculiar feature of the unit considering that the Lower Palaeozoic succession of Poland in the main is closely comparable to that of southernmost Scandinavia.

The Alum Shale has generally been interpreted as a relatively shallow water deposit (e.g. Westergård 1922, Thickpenny 1984, 1987), and the facies has even been considered extending to the nearshore environment (Hansen 1945, Henningsmoen 1957). More recently Dworatzek (1987) argued for a greater depth of deposition in an outer shelf setting and we concur with his interpretation and infer that the Alum Shale Sea was dysoxic below the storm wave base or at times even from above the storm wave base. The outer shelf sea floor was probably to some extent covered by bacterial mats and the sediment itself was anoxic from immediately below the sea floor and, accordingly, hostile for infauna. As a result bioturbation is very rare in the Alum Shale, and the sedimentary lamination is typically preserved. The outlined depositional scenario inevitably leads to the conclusion that uniformtarian conditions did not prevail in the Mid Cambrian–late Tremadocian: there must have been significantly less oxygen dissolved in the oceans and much less oxygen in the atmosphere than in the modern world. If the Cambrian atmosphere contained oxygen comparable to modern levels simple diffusion would have led to a much higher oxygen concentration in the Alum Shale Sea.

A characteristic feature of the Alum Shale Formation is the presence of bituminous limestone lenses and layers, so-called orsten or anthraconite; for a review of the trivial names of the limestone, see Berg-Madsen (1989). The abundance of limestone increases in an adlittoral direction and limestone accounts for a substantial part of the Alum Shale Formation in south-central and eastern Sweden. Intraformational conglomerates also occur at several levels in various tracts of Sweden (Westergård 1922, Martinsson 1974, Dworatzek 1987). The limestone- and conglomerate distribution is ascribed to recurrent changes in sea level that regularly lowered the storm wave base, and these episodes were associated with extensive erosive events across the mid shelf. As the unconsolidated Alum Shale mud was reworked, the harder limestones were left behind, either as conglomerates or as resistant thicker beds preventing further erosion of the mud. As a result two lithofacies can be recognized (Fig. 3): A thinner midshelf limestone-rich Alum Shale facies (mostly < 25 m total formational thickness) with up to 50% limestones and common thin intraformational conglomerates and a thicker offshore facies (> 25 m total formational thicklness) with 5-10 % limestone and no or only rare conglomerates.

The Alum Shale is thickest along the platform periphery, measuring 80-100 metres in Scania and parts of the Oslo area, with a recorded maximum thickness of 178 m in the Danish offshore well Terne-1. The average net accumulation rate – up to 4-6 mm per 1000 yrs in southernmost Scandinavia – was exceedingly low and almost comparable to present-day pelagic deposition (the cited figure is compacted thickness, however). The low average accumulation rate reflects that the sedimentary supply in fact was very low - all of Scandinavia was flooded and the main clastic source area was located somewhere in Russia - in combination with regular reworking of unconsolidated Alum Shale mud across much of Sweden during sea level lowstands, where the average accumulation rate as a result was c. 1 mm per 1000 yrs (Lindström 1971). This low figure is, however, irrelevant, as much time is not represented in the sedimentary record. A revised depositional model for the Alum Shale is outlined by Nielsen & Schovsbo (in prep.); it is cited in extenso below. Thin intercalations of silt, ranging in thickness from one-grain to 1 cm, are locally common in the Middle Cambrian and Tremadocian Alum Shale. They are interpreted as distal tempestites.

Initially some sediment was supplied from a western source in the early Mid Cambrian and maybe also from the uplifted part of southern Scandianvia, but from the late Mid Cambrian the principal clastic source area was located in Russia-Ukraine and little or no sediment were supplied from the incipient Caledonian collision zones to the west and south. This pattern shifted immediately after deposition of the Alum Shale and during the Ordovician-Silurian an increasing amount of clastics derived from the Caledonian collision zone (Bjørlykke 1974, Schovsbo 2003). During the Ordovician clastic supply from the west was dominant (cf. the "competitive sedimentation model" outlined by Jaanusson 1982).

The black, pyrite-rich Alum Shale was obviously deposited under low-oxygen conditions, but, even so, the shale contains an abundant fossil fauna. Trilobites are dominant, but brachiopods and a few other groups are also intermittently present. Many authors have suggested that the comparatively diverse Middle Cambrian Alum Shale trilobite fauna must have been able to cope with lowered oxygen levels, whereas the Furongian Alum Shale environment in general has been inferred 'stagnant'/anoxic, and the low diverse fauna has been considered pelagic or epipelagic (e.g. Bergström 1973) or even allochtonous (Dworatzek 1987). In view of the fact that the relative composition of the Furongian trilobite fauna exhibits consistent regional facies differences within Scandinavia and that the olenid trilobites everywhere in the world occurs exclusively in black shale environments, a pelagic way of living appears improbable and we infer that olenids were benthic or nekto-benthic and adapted to cope with low oxygen conditions. It is, however, uncertain whether the presence of shelly benthos reflects short-lived oxygenation events, punctuating general anoxic conditions, or prolonged periods with bottom life under dysoxic conditions. Intermittent absence of calcareous shells may relate to early dissolution rather than absence of life in the environment, an aspect that clearly must be considered in palaeoecological analysis (cf. Schovsbo 2001).

The low sedimentation rate in combination with the generally dysoxic/anoxic depositional regime led to syngenetic trace element enrichment of the Alum Shale, for instance of uranium (up to 300 ppm), vanadium (up to 5000 ppm), and molybdenum (up to 200 ppm). The enrichment of individual trace elements is characteristic of certain stratigraphic intervals, but in particular the Furongian shows strong enrichments. Uranium is thus, broadly speaking, preferentially enriched in the Furongian *Peltura minor* and *P. scarabaeoides* superzones, whereas vanadium is preferentially enriched in the Lower Ordovician part of the formation. The geochemistry of the Alum Shale has been intensively studied because of the economical interests attached to the uranium content as well as the source rock potential for hydrocarbons. Previous geochemical investigations are reviewed by Armands (1972) and Andersson et al. (1985).

A first attempt to unravel Cambrian and earliest Tremadocian sea level changes as well as sub-regional isostatic uplifts during deposition are provided in the present report. Interpretation is based on a combination of regional distribution of individual parts of the Alum Shale (“cratonwards onlap”), lithology (e.g. distribution of conglomerates and high energy bioclastic limestones, detached stranded lowstand units etc.), geochemistry (palaeo-oxygenation) and faunal data (depth controlled biofacies). It is, however, a difficult task because of the incompleteness of the Alum Shale in the shallower part of the basin and the extremely uniform appearance of the more complete Alum Shale in the deeper part of the basin.

It is emphasized that the Alum Shale Formation at closer inspection is much less homogenous than immediately apparent. Thus the organic and trace element contents are not uniformly distributed throughout the unit, the fossil fauna shows vertical and lateral differences in composition and the shale shows systematic regional differences in distribution of individual stratigraphic intervals. For hydrocarbon exploration the Furongian interval is the most interesting, showing the highest levels of organic content, whereas the Middle Cambrian interval is less interesting, showing relatively low organic contant. The Ordovician Alum Shale is characterized by intermediate values.

2. Stratigraphical framework

2.1. Chronostratigraphy

Four global Cambrian series are in the process of being introduced, replacing the traditional tri-partite subdivision of the system (i.e. Lower/Early, Middle/Mid, Upper/Late). The oldest global series has been formally named the Terreneuvian (Landing et al. 2007) and the youngest series is named the Furongian (see Shergold & Cooper 2004, Babcock & Peng 2007). These new units correspond to the lower half of the traditional Lower Cambrian and most of the traditional Upper Cambrian, respectively (Fig. 4). Pending the introduction of proper formal names for series 2 and 3, corresponding to the upper half of the traditional Lower and the Middle Cambrian, respectively, we maintain using the terminology Early/Lower Cambrian (including the Terreneuvian) and Mid/Middle Cambrian, whereas we adopt the Furongian, which by and large corresponds to the Late/Upper Cambrian as traditionally defined in Scandinavia except that the *Agnostus pisiformis* Zone now is assigned to the Middle Cambrian. The four Cambrian series will eventually be subdivided into 10 global stages; not all of them have been formally named as yet (Figs 3–5). Local Baltoscandian stage names are available for the Lower Cambrian (see Nielsen & Schovsbo 2011 for review and discussion) and the late Furongian-Tremadocian is separated as the Pakerort Stage in the East Baltic area, but no local Scandinavian stage names are available for the Middle Cambrian-Tremadocian (Fig. 4).

2.2. Biostratigraphy

The Alum Shale Fm is very rich in fossils, notably trilobites, and a detailed zonation has been established for the unit. Trilobites are generally rare in the Tremadocian and the upper part of the Alum Shale Formation is mostly correlated using graptolites.

Middle Cambrian

A durable Middle Cambrian trilobite zonation was outlined by Westergård (1936, 1946) comprising 8 agnostid zones and 2 polymerid zones, constituting 3 superzones in modern terminology. Westergård's zonation has recently been modified by uniting his *Ptychagnostus atavus* and *Hypagnostus brevifrons* zones into the *Acidusus atavus* Zone (Axheimer & Ahlberg 2003; Weidner & Nielsen, 2009, in press a). However, the *P. atavus* and *H. brevifrons* zones sensu Westergård largely correspond to the informal lower and upper parts of the amended *A. atavus* Zone (cf. Fig. 5). Further, the designation *Goniagnostus nathorsti* Zone is used instead of the *Ptychagnostus lundgreni* Zone (e.g. Høyberget & Bruton 2008). Some of the generic names have also been changed as a result of taxonomic revision. Please note that the generic assignment of agnostid trilobites is a contentious issue and several species are assigned to different genera by different stratigraphers; zonal designations varies accordingly. The *A. pisiformis* Zone has traditionally been assigned to the Upper Cambrian; it is pre-Furongian and here temporarily assigned to the Middle Cambrian awaiting the formal introduction of a new name for the new Cambrian Series 3. The average duration of the individual Middle Cambrian trilobite zones is about 1.2 my.

Furongian

A very detailed trilobite zonation comprising 7 trilobites zones and 31 subzones was outlined for the Furongian by Henningsmoen (1957), to a large extent based on work by Westergård

(1922, 1947a). This zonation has recently been revised by Terfelt et al. (2008, 2010), Høyberget & Bruton (2012) and Weidner & Nielsen (in press b). Terfelt et al. (2010) suggested elevating the subzones to zonal rank and abandon the hitherto used longer-ranging zones. Weidner & Nielsen (in press b) accepted the ranking of former subzones as zones, but preferred to treat the traditional subzones as superzones rather than discarding them. This viewpoint is followed here (Fig. 6). The number of Furongian zones is now reduced to 26 (Fig. 5); the average duration of the biozones is < 500.000 yrs.

The superzones are usually readily identified, also by non-specialists, whereas the refined zonation requires detailed identification of key taxa by specialists in order to be recognized. For the moment it is actually uncertain precisely which zones are present in some districts of Sweden (Fig. 7). For drill-cores the older wide-ranging units are also more practicable. Weidner & Nielsen (in press b) proposed renaming the youngest Furongian unit the *Acerocarina* Superzone, replacing the name *Acerocare* Zone sensu Henningsmoen (1957). This terminology is adopted here[1].

Tremadocian

Currently 7 graptolites zones are discerned in the Tremadocian Alum Shale; the zonation is discussed by Westergård (1909), Bulman (1954), Tjernvik (1958), Spjeldnæs (1963), Bruton et al. (1982, 1988) and Cooper (1999). A plexus of *Rhabdinopora* species (formerly *Dictyonema*) is characteristic of the lower Tremadocian. The oldest zones are graptolithic only in the Oslo area (Bulman 1954, Bruton et al. 1988) and partly so in Scania, where it has been referred to as the *R. desmograptoides* Zone (Tjernvik 1958). In the course of the prominent earliest Ordovician sea level rise the offshore graptolithic facies spread across Baltoscandia.

Conodont and acritarch zonations

Euconodonts turned up in the Furongian and are often common in the limestones of the Alum Shale Formation (e.g. Andres 1981, Müller & Hinz 1991), especially in central Sweden whereas conodonts are poorly preserved and comparatively infrequent in the more offshore facies (Stouge pers. com. 2012). Some zones have been established (Fig. 6), but so far most investigators have focused on taxonomic issues rather than the biostratigraphic utility of conodonts and a detailed calibration of the trilobite and conodont zonations has not yet been

[1] Further revision of the zonation is in progress: Changing the rank of the zones introduced by Westergård (1922, 1947) and modified by Henningsmoen (1957) to superzonal level is straight-forward except with regard to the boundary between the *Protopeltura praecursor*/*Peltura minor* zones. For unknown reasons Henningsmoen (1957) defined the lower boundary of the *Peltura minor* zone at the base of the *Ctenopyge similis* Subzone [now Zone], despite the circumstance that *P. minor* itself does not occur below the overlying *Ctenopyge spectabilis* Subzone [now Zone]. It may be considered an academic formality, but according to modern standards this is not permissible and a formal redefinition is necessary. Work is in progress (Nielsen et al., in prep) redefing the *Protopeltura praecursor*, *Peltura minor* and *P. scarabaeoides* zones sensu Henningsmoen (1957), and the plan is to introduced a new *Protopeltura* Superzone, replacing the *P. praecursor* zone as well as the lower part of the *P. minor* zone, and a new *Peltura* Superzone, replacing the upper part of the *P. minor* zone and the entire *P. scarabaeoides* zone. The new superzonal boundary coincides, as far as can be established, with the base of the new Cambrian stage 10 (Fig. 4). The planned new terminology will also align the naming style of the Furonigian superzones so they all are named after a characteristic genus.

made. Work is in progress by Bagnoli & Stouge on conodont faunas from the Furongian of Västergötland and Öland.

Acritarchs are known from the Alum Shale of Öland (Bagnoli et al. 1988, Milia et al 1989, Ribecai & Tongiorgi 1997) but the established zonation is crude. So far no acritarchs have been published from offshore Alum Shale facies.

2.3. Lithostratigraphy

We here adopt the lithostratigraphic nomenclature proposed by Nielsen & Schovsbo (2006), see Fig. 8. The Alum Shale is recognized as a formation and the traditional name is retained, despite not referring to a geographic site, because it is deeply entrenched in the literature. A number of readily identified widespread thin limestones and conglomerates within the unit are referred to as formally named beds: Forsemölla Limestone Bed, Acrothele Granulata Conglomerate, Exsulans Limestone Bed, Hyolithes Limestone Bed, Andrarum Limestone Bed, Exporrecta Conglomerate Bed, Kakeled Limestone Bed and Incipiens Limestone Bed (see Nielsen & Schovsbo 2006 for details).

2.4. Remarks on applied correlation of the Alum Shale in the Danish area

Trilobites are in general very common in the Alum Shale Fm in southernmost Scandinavia, both within the shale itself and in the intercalated limestones. The trilobites are flattened and normally dissolved in the shale, why they occasionally may be difficult to identify, whereas they typically are well-preserved in the limestones. On this basis it has been possible to outline a fairly detailed biostratigraphy for most scientific drill-cores (5.5 cm diameter) obtained in Scania-Bornholm just by identifying the trilobites incidently exposed on the bedding planes without further splitting the cores and this is expected to be feasible also in deep wells in the Danish area. Theoretically conodonts extracted from the limestones by dissolution may also be used in wells, but the conodont yield is low in offshore Alum Shale facies, and in practice trilobites are expected to provide the best tool for biostratigraphy. The acritarch stratigraphy is crude and currently poorly defined, compared with the trilobite zonation, and acritarchs are likely badly preserved (or even not preserved) in the deeply buried Alum Shale subsurface Denmark.

The Tremadocian interval of the Alum Shale, especially the basal part, is normally very rich in dendroid graptolites. Species identification is notoriously difficult, but the profuse occurrence of *Rhabdinopora* s.l. at the base of the Tremadocian is usually readily identified, and is an excellent proxy for the base of the Ordovician. The Danish area is located so distally on the palaeoshelf that even the oldest *R. preparabola* and *R. parabola* zones likely are developed in graptolite facies, like in the Oslo area (cf. Bulman 1954). The graptolites of the mid-Tremadocian *A. tenellus* Zone – which usually is also very rich in inarticulate brachiopods that may occur in large quantities ("Brachiopod beds") – are without much difficulty identified even by non-specialist.

3. Presentday distribution of the Alum Shale Formation

Within Scandinavia undeformed Lower Palaeozoic rocks are found in an area bounded to the northwest, west and southwest by the Caledonian Deformation Front (Fig. 1). The once continuous Alum Shale Formation is now preserved in a number of outliers and impact craters across south-central Sweden, in the Bothnian Bay, and below the overthrusted units along the Caledonian Deformation Front. Alum Shale is also known from the block faulted Lower Palaeozoic succession preserved subsurface of southernmost Sweden and Denmark. A more uninterrupted package of Lower Palaeozoic strata is preserved subsurface of the Baltic Sea east of Bornholm-Öland, but the Alum Shale peters out eastwards, and does not enter Latvia-Lithuania-Kaliningrad, whereas the formation has been encountered in drill holes in northeastern Poland. However, further south the unit is absent in the greater part of mainland Poland (Fig. 1). A tongue of Ordovician Alum Shale extends into northern Estonia and further eastwards into the St. Petersburg Region, Russia. Westwards the Alum Shale continues into the Caledonian terrain, but here acted as decollement level for the overthrusted units, and the Alum Shale Formation is usually strongly tectonized and locally also metamorphosed in the orogenic belt. Hence, thickness data from the Caledonian terrain, if available at all, are notoriously unreliable. Only spotty occurrences of surviving fossils are known from the Alum Shale within the Caledonides, but the formation can be recognized by its geochemical signature and dark black colour. The Alum Shale Formation can thus be traced at least 200 km westwards of the present Caledonian front in Sweden-Norway (Bergström & Gee 1985). It appears that the Alum Shale thinned on the distal outer part of the Scandinavian shelf and the unit is absent in the allochthonous successions representing the outermost shelf setting facing the Iapetus Ocean (Fig. 7). The Alum Shale also thinned along the southern edge of Scandinavia.

The Teisseyre-Tornquist fault Zone (TTZ) straddling Poland and Ukraine defines the boundary between the relatively stable Precambrian East European Shield and the younger Central European Complex. The northwestern extension of the TTZ into southern Scandinavia, the Sorgenfrei-Tornquist Zone (STZ), is an intercratonic fault zone (EUGENO-S 1988), which was active mainly from the Late Palaeozoic onwards. The Alum Shale Formation is, however, significantly thicker in this zone (Fig. 7), but whether this is indicative of increased subsidence in an incipient STZ or reflects an intra-plate flexure relating to the Caledonian orogen to the south is uncertain. Upcoming thickness data from the planned TOTAL well in northern Jutland may finally clarify this uncertainty.

The southern plate margin of Baltica can be traced from the TTZ in Poland as a deep-seated structure through northern Poland-Germany, the so-called Elbe line (Thybo 2001 and references therein). During the Caledonian collision slices of Avalonian derivation were thrusted onto Baltica; their northern extent in southern Denmark is referred to as the Caledonian Deformation Front (CDF) (Fig. 1). No Alum Shale is known from the German-Polish Caledonides, but no deep wells in the Caledonian terrain has been extended to the basement and instead terminate in more or less intensively metamorphic Ordovician rocks (e.g. Hoffman 1990).

4. Geological setting

Scandinavia is located on the old craton called Baltica and which stretches from the Urals to west of Norway and from the Black Sea to northernmost Russia (see e.g. Cocks & Torsvik 2005). Baltica formed during a series of Precambrian orogenies, the youngest taking place c. 1 billion yrs ago. After that the craton was subjected to intensive erosion and peneplanisation during the late Precambrian. Various phases of Neoproterozoic rifting resulted in the development of local basins in Baltoscandia; for references and location, see Nielsen & Schovsbo (2011). A large rift system, the Volhyn–Orcha Rift, straddled Ukraine–SE Poland–Byelorussia–western Russia (Fig. 9) and when rifting ceased, a sag-basin developed in which earliest Cambrian deposition took place. However, shortly into the Cambrian the basin inverted (see Nielsen & Schovsbo 2011 and references therein) and deposition ceased until the Mid Cambrian (compare Mens et al. 1990). The Hedmark Rift in southwestern Norway was probably also affected by mild Early Cambrian inversion (see Nielsen & Schovsbo 2011), but no effects on Mid Cambrian-Furongian deposition have been recognized. No other Scandinavian Neoproterozoic rift systems seem to have influenced Cambrian deposition (Nielsen & Schovsbo 2011).

The multiple Neoproterozoic rifting eventually resulted in continental break-up and sea-floor spreading commenced west of Scandinavia at around 580 Ma (Hartz & Torsvik, 2002, see also Cocks & Torsvik, 2005). At some stage during the Cambrian-Ordovician this ocean began to close again. Onset of subduction in the Iapetus Ocean separating Baltica from Lauretia is commonly assumed to be signalled by the Finnmarkian deformation phase (metamorphism dated at c. 505–480 my), as locally recognized in the Caledonides, but Greiling et al. (1999, p. 141) reasoned that subduction likely was initiated about 10 myr earlier than the metamorphic ages, i.e. approximately at the Early/Mid Cambrian boundary as currently dated. We suspect that this change in plate tectonic regime is signalled by the highly atypical regional isostatic uplift referred to as the Hawke Bay Event in Baltoscandia (see section 8.1).

The onset of closure of the Tornquist Sea (by some authors referred to as the Ran Ocean) between Avalonia/Gondwana and Baltica commenced in the late Early Ordovician according to Fortey & Cocks (2003 and references therein) whereas Landing (2005 and references therein) suggested that Avalonia rifted off Gondwana considerably earlier. Despite these differences of interpretation there is a consensus of opinion that the Cambrian and Early Ordovician subduction zones to the present south and west of Baltica were situated at considerable distances from the continent and dipped in opposite directions, and the shelf edges in peripheral Scandinavia were, accordingly, passive (Bergström & Gee 1985; Greiling et al. 1999). Along the northern and eastern margins of Baltica the Timanide orogeny took place during the Ediacaran and Cambrian. An associated foreland basin straddled northernmost Norway (see Nielsen & Schovsbo 2011 and references therein) and the area was characterized by rapid subsidence and high terrigenous influx throughout the Cambrian. The substantial sedimentary supply deriving from the orogenic zone to the northeast was trapped in the foreland basin, and the ongoing collision had virtually no influence on the conditions in the epicontinental sea covering large parts of Scandinavia except possibly in the form of transient local isostatic adjustments (Section 8).

The Scandinavian shelf was exceptionally flat reflecting thorough late Precambrian peneplanisation and lack of tectonic activity. Active subsidence was in general extremely limited but minor local or sub-regional isostatic events – both subsidence and uplift - did, however, occur from time to time (Section 8). These isostatic movements, despite being only in the size order of but a few tens of metres, controlled in concert with eustasy the facies distribution.

Indications of volcanic activity are unknown from the Cambrian of Scandinavia except for a few bentonites observed in the Lower Cambrian of Bornholm (Nielsen et al. 2006). Additional sparse bentonites occur in the upper part of the Tremadocian in the Oslo area and central Sweden (unpublished), but an increase in bentonite occurrence, deriving from volcanic eruptions associated with the ongoing Caledonian collision, is not evident before the Mid Ordovician (Darriwilian). It is reasonable to assume, however, that the Timanide Orogeny (northernmost Baltica) was associated with volcanism (cf. Nikishin et al. 1996; Gee & Pease 2004 and references therein) but no effects on the Alum Shale Sea have been recognized.

5. Palaeogeography

Baltica was during the Cambrian positioned south of Equator in temperate latitudes and isolated from other major continents (Torsvik & Rehström 2001; Cocks & Torsvik 2005 and references therein). This interpretation is corroborated by the scarsity of carbonates in the stratigraphic column, suggesting a cool temperate climate prior to the Mid Ordovician. The cited authors suggest that the Baltica was turned almost upside-down at the beginning of the Cambrian, and then rotated clock-wise throughout this period, but the possible effects on the depositional environment in the 'piggy-backed' epicontinental Alum Shale Sea has not been considered in this report. When referring to points of the compass in this report we always imply presentday coordinates.

Baltica became deeply eroded during the latest Precambrian, and thus was extensively peneplanised at the dawn of the Cambrian. The topography of local irregularities is typically 10-20 m and 50 m at the most (see Nielsen & Schovsbo 2011 for references). We estimate, based on calculations of Early Cambrian sea level changes (unpubl.), that the average slope of the peneplain at the time of initial transgression was in the size order of only 1-2 m per km. The shelf slope was likely even lower later on, as the blanket of lower Cambrian sediments levelled out much of the original topography. The regional average slope of the Alum Shale Sea floor may thus have been <1 m per km and maybe as low as 0.1 m per km (see section 10).

Repeated pulses of rising sea level during the Early Cambrian were associated with stepwise transgression of the fringes of Baltica and eventually the greater part of Scandinavia became inundated (Nielsen & Schovsbo 2011). However, throughout the Early Cambrian a sediment-producing land area straddled the axis of mainland Sweden and, most of the time, also southernmost Norway. An extensive regional isostatic uplift, referred to as the Hawke Bay Event, took place at the Early/Mid Cambrian boundary (Nielsen & Schovsbo in prep.) coinciding with a major eustatic sea level lowstand, and in the aftermath of this event the Scandinavian land area disappeared due to a combination of renewed sea level rise and differential local subsidence. Scandinavia thus became totally transgressed shortly into the Mid Cambrian and from then on and well into the Ordovician the epicontinental sea floor sloped gently westwards across Scandinavia, generally speaking. In southernmost Scandinavia the slope seems to have been broadly southwards. Minor isostatic uplift events did, however, interfere with this general pattern, see section 8. Due to the extensive flooding the sediment-producing land area closest to Scandinavia was most of the time located in western Russia. The clastic supply to the epicontinental sea covering western Baltica therefore became extremely stunted, and the sediment that actually reached the Alum Shale Sea may to some extent have been windborn. The isolated Baltic craton surrounded by wide oceans was also effectively cut off from extra-cratonic sedimentary supply during the Cambrian-Early Ordovician. Under other circumstances with a plate position in warmer water, carbonate deposition would undoubtedly have taken place in the relatively shallow epeiric sea. Condensed carbonate deposition became more widespread after the Alum Shale regime terminated, and characterize the Ordovician of the Baltic region ("Orthoceras Limestone facies") probably because the continent moved closer towards Equator.

6. Lithofacies distribution: A new depositional model for the Alum Shale

We infer that the Alum Shale was deposited from the storm wave base and deeper. Hence deposition from some 40-70 m and down to maybe more than 200 m is a plausible guesstimate for the depth of deposition. For remarks on how deep the storm wave base was, see section 10.

Five main factors controlled deposition in the Alum Shale Sea:

1) The profound flatness of the craton
2) The extremely limited supply of sediment
3) The palaeogeographic position in comparatively high latitudes (i.e. relatively cool water without lime production)
4) The low oxygen level in the sea from the Mid Cambrian onwards (locally enhanced global phenomenon, see below)
5) Changes in sea level controlling the position of the storm wave base.

The two first mentioned factors resulted from the severe late Precambrian peneplanisation of Baltica in combination with the Cambrian 1st order sea level rise, eventually leaving only parts of Ukraine and western Russia as land-areas (Fig. 43A). The setting with deposition in an extremely sediment starved, dysoxic, level-bottom epicontinental sea covering large parts of the craton has no modern analogues. The organic production appears to have been low in the Cambrian sea, and the high organic content of the Alum Shale reflects the lack of clastic supply in combination with restrained degradation due to low oxygen conditions at the sea floor.

We distinguish five depositional phases in the Cambrian to Early Ordovician interval of Scandinavia (Nielsen & Schovsbo 2011; in prep.). The phases reflect a progressive sedimentary starvation in the course of the Cambrian transgression in combination with increasing offshore dysoxidity during the Mid Cambrian onwards. Deposition of Alum Shale commenced in the early Mid Cambrian during Depositional Phase 3 (henceforth referred to as DP3) and expanded during depositional phases 4 and 5 (= DP4, DP5). Since the definition of DP3, DP4 and DP5 are unpublished as yet, their characterization is sited here in extenso (from unpubl. manuscript by Nielsen & Schovsbo on the Hawke Bay Event, slightly modified). For decription of DP1-DP2, see Nielsen & Schovsbo (2011).

6.1. Depositional Phase 3 (early Mid Cambrian): Transient increase in clastic supply and onset of oxygen shortage

The Early Cambrian was characterized by decreasing clastic supply to the epicontinental sea due to progressing inundation of Scandinavia (DP1-DP2, see Nielsen & Schovsbo, 2011). As a result progradation diminished in the later half of the Early Cambrian and eustasy became the principal factor controlling the local depth of deposition in Scandinavia. This trend was interrupted by the widespread regression referred to as the Hawke Bay Event at the close of the Early Cambrian (for details, see section 8.1). This event reflects a regional uplift of Scandinavia seemingly coinciding with a major eustatic lowering of sea level. Afterwards, while the Hawke Bay unconformity still developed in western and southern Scandinavia because of uplift, the eastern sector of the Baltoscandian epicontinental sea was characterized by a significant increase in clastic supply during the earliest Mid Cambrian. The sediment derived almost exclusively from eastern land areas, unlike earlier, where Scandinavian supply also played a significant role (cf. Nielsen & Schovsbo, 2011). This is remarkable since the greater part of Scandinavia was uplifted, but reflects that the area, despite the uplift, became flooded by the sea shortly into the Mid Cambrian. The uplifted relict sea bed is shown by cross-hatching in Figs 40–41; it was seemingly not subjected to much erosion, although small-scale mining of older sediments probably did occur as indicated by the greater thickness of sequence MC3-2 on Öland in comparison with Gotland (cf. Fig. 49). The minimal erosion probably reflects that the sea-floor, despite being uplifted a few tens of metres, still was exceedingly flat. At the same time some sediment was supplied from a western source (maybe recycled Lower Cambrian sand on the uplifted western margin of Baltica) as demonstrated by the incursion of Middle Cambrian sandstone in the Lower Allochthon of Sunfjell, southern Norway (Nickelsen et al. 1985, see also Fig. 26). This is the reason why there are two Middle Cambrian depocenters: one in the Baltic Sea (see Fig. 44) and one in southwestern Scandinavia (Fig. 28).

The greater clastic supply during DP3 was mainly due to a low sea level and progressive infilling from the east of the available accomodation space in the Baltic area. Prograding units of relatively coarse sediment eventually reached as far west as Öland (Äleklinta Mbr, T. gibbus Zone). The general lithofacies trends were the same as previously with nearshore to shallow marine sands, mid shelf siltstones (with numerous interdigiting storm beds) and offshore mudstones (Fig. 10). However, in comparison with the upper Lower Cambrian, the comparatively thick lower Middle Cambrian succession tends to be less glauconitic, likely reflecting lesser condensation.

During DP3 the offshore mudstones turned dark grey to blackish due to an increased content of organic matter, signalling dysoxic conditions in the bottom environment (Alum Shale facies). This facies was fringed shorewards (distal inner shelf) by grey-greenish mudstones. These mudstones and locally even the Alum Shale facies contain thin sandy and silty distal storm beds. We are under the distinct impression that the dysoxic zone expanded during the Mid Cambrian and spread to shallower environments (Fig. 11), but local dysoxia in Baltoscandia may also reflect poor ventilation due to silled basin conditions. The latter effect seems to have been responsible for the earliest incursions of Alum Shale in south central Sweden behind the residual "Hawke Bay uplift" (cf. Fig. 12). Deposition of Alum Shale also commenced west of the central Scandinavian uplift and we regard it likely that the western and southern margins of Baltica also were upturned associated with the Hawke Bay Event, forming a sill.

Rapid sea level rises were typically associated with the formation of thin cool-water bioclastic limestones in Scandinavia (Fig. 13) like in the later part of the Early Cambrian (see DP2 described by Nielsen & Schovsbo, 2011). Similar limestones have not been reported from the East Baltic area. These limestones (see e.g. Alvaro et al. 2010) are in most cases sandwiched by offshore mudstones, yet they characteristically contain a fossil fauna, which is significantly more diverse than those of the surrounding mudstones, and it is evident that there was no shortage of oxygen on the sea floor when the limestones were deposited. Since the limestones invariably formed in the aftermath of prominent sea level lowstands they were most likely deposited in shallower water than the surrounding mudstones (the fragmentation of the shelly fossils also witness high energy conditions) and evidently above the dysoxic zone and within reach of storm waves. However, it is also possible that stratification of the water column collapsed during the initial sea level rise or the preceding lowstand. Consequently, the ventilation even in the deeper parts of the shelf may have been good and allowed an oxygen-demanding diverse benthic fauna to invade the sea-floor. This factor was perhaps even more important for the formation of the limestones than clastic starvation associated with rising sea level since the clastic supply was very low at all times in the relatively offshore settings where these limestones occur. If the Alum Shale depositional environment was a silled basin, a rising sea level perhaps also led to incursion of well-ventilated water masses across the sill during strong sea level rise, temporarily improving the oxygen conditions in the bottom environment during early transgression. Locally, notably in south central Sweden, Fe-oolites formed during drowning events, likely in shallower water than the limestones (compare regional distribution of limestones and Fe-oolites in the Lower Cambrian, see Nielsen & Schovsbo 2011, p. 216).

6.2. Depositional Phase 4 (mid-late Mid Cambrian): Sedimentary starvation and widespread dysoxia

The depositional rates plummeted in the mid Mid Cambrian (latest Triplagnostus gibbus Zone - Acidusus atavus Zone) due to a significant sea level rise shifting the coastline far eastwards into Russia. This change marks the onset of DP4, and which lasted until the Furongian. Roughly at the same time – locally slightly later – deposition resumed in most areas of Scandinavia in the aftermath of the Hawke Bay 'Event'. Coeval nearshore sands were deposited in western Russia, Lithuania and Estonia, but the precise age of these units, which are typically thin (but a few metres) and bounded by major hiati, are uncertain (see for instance Puura 1996, Jankaukas 2002). The sandstones are taken to represent 'stranded' lowstand sands rather than indicating the position of the shoreline during maximum flooding conditions, i.e. it is inferred that the nearshore coarse clastic belt shifted abruptly basinwards associated with major sea level falls, resulting in deposition of detached non-glauconitic lowstand sands on the midshelf. We envisage that deposition of these sand units took place during late lowstand, connected with incipient sea level rise.

The greater part of the inner shelf was characterized by net sedimentary bypass. This condition may theoretically reflect frequent storm reworking, which regularly removed the sparse sediment that settled during fair-weather conditions and transported it outboard with lasting deposition from below the level where storm waves/surges were able to effectively 'sweep' the sea floor. However, alternatively and more likely recurrent erosive episodes with outboard transport of sediment occurred in connection with falling sea level and lowstands. Such events also caused reworking of the former outer shelf mudstones because of the associated lowering of the storm wave base and the winnowing/erosion events resulted in the formation of thin conglomeratic lags and shell-beds on the mid-shelf. The well-known widespread 'Obolus beds' of Estonia-western Russia (e.g. Puura, 1996) are for instance taken to represent such lag deposits. We envisage that these fossils were winnowed from unconsolidated mud that was eroded away in connection with falling stage and lowstand events. Associated calcite shelled fossils are not preserved due to dissolution. The more offshore conglomerates, typifying Scandinavia, are often amalgamated with glauconitic and phosphorite-bearing cool-water limestones that formed during the ensuing sea level rise as described above.

Rapid sea level rises were also during this depositional phase associated with the formation of thin cool-water bioclastic limestones (see DP3 above). With the general sea level rise into the later part of the Mid Cambrian the dark coloured, organic-rich outer shelf mudstones spread across central Sweden and eventually reached as far east as Gotland.

6.3. Depositional Phase 5 (Furongian-late Tremadocian): Extreme sedimentary starvation and intensified dysoxia

Oxygen depletion in the Alum Shale Sea intensified markedly associated with the globally recognized SPICE isotopic event at the base of the Furongian (Fig. 11) and even the distal part of the inner Baltoscandian shelf became dysoxic. The reason for this global oxygen crisis is unknown (Saltzman et al. 2000); it marks the onset of DP5. Because of the dysoxic state of the water column the offshore mudstones (Alum Shale facies) are greatly enriched in various trace elements (e.g., U, V, Mo, see Armands 1972, Andersson et al. 1985), much more so than during the earlier (and later) depositional phases.

Onset of the SPICE isotopic event coinsided with a lowering of sea level, hence incursion of offshore low-oxic water masses onto the shelf cannot be the explanation of the lowered oxygen in the depositional environment. On a 2nd order level the sea level stayed relatively low in the early Furongian to rise significantly in the later half of Furongian. It further rose into the Early Tremadocian at which stage deposition of Alum Shale had its greatest extent in Baltoscandia. Due to the extensive inundation of the craton the clastic supply to the epicontinental sea was extremely low.

Like during DP4 the coastline was positioned far east of Scandinavia and outboard of the nearshore zone the inner shelf was characterized by net sedimentary bypass (see description of DP4). As far as can be established all sediment derived from the east. Major regressions were associated with deposition of detached lowstand sands on the mid shelf, see description of DP4.

Deposition of very organic-rich mudstones (Alum Shale facies) took place from the distal part of the inner shelf, where only major storms affected the bottom environment, i.e. probably from some 40-50 m of water depth and at least no deeper than 60-80 m, as well as further offshore. The organic content is up to 25 wt% (Schovsbo 2002 and references therein) reflecting preservation of organic matter due to a low oxygen level in the depositional environment.

Major sea level falls were associated with severe reworking of Alum Shale mud because of the coupled lowering of the storm wave base. This resulted in lag deposits comprising conglomeratic bituminous limestone (reworked abraded carbonate concretions) as well as formation of bioclastic 'olenid' limestones consisting of olenid trilobite hash winnowed from the unconsolidated mud (Fig. 14). Reworking was often stopped by erosion-resistant limestone beds. Of these the most well known is the Kakeled Limestone Bed (= the 'Great stinkstone bed' of older literature, e.g. Westergård 1922 and Dworatzek 1987, see Fig. 15) which formed across much of Sweden during a long-lasting composite 2nd order lowstand in the early Furongian.

No 'transgressive' bioclastic limestones formed during drownings (compare DP2 [Nielsen & Schovsbo 2011] and DP4), most likely because a diverse shelly fauna could not thrive in the dysoxic environment, and drownings were in most cases (below the mid Tremadocian) not associated with the formation of phosphorite or glaucony, possibly because the low oxygen level somehow prevented precipitation.

Geochemical data and taphonomy (dissolution of calcite tests, see Schovsbo 2001) suggest a progressive rise in general oxygen level in the bottom environment from the latest Furongian and through the Tremadocian. It is possible but remains speculative that the enhanced ventilation reflects gradually increased exchange of oceanic water masses due to ongoing downwarp of the western margin of Baltica (in turn somehow associated with plate tectonics). DP5 was terminated by the prominent CRE Lowstand in the late Tremadocian (see Nielsen 2004), after which stage 'transgressive' limestones reappeared in the stratigraphic column (e.g. Bjørkåsholmen Fm and equivalent units) and deposition of Alum Shale stopped.

6.4. Limestones in the Alum Shale

The Alum Shale Formation contains lenses and layers of bituminous limestone (Fig. 3), referred to as anthraconite, orsten or stinkstone in the literature (for a review of terminology, see Berg-Madsen 1989). The lenses are early concretions formed before or during initial compaction whereas layers of stinkstone may be early diagenetic or primary bioclastic limestone, in the latter case consisting of winnowed broken shell material of olenid trilobites (Fig. 14). This olenid bioclastic limestone are common in central Sweden, Jämtland and on Öland and is rare or absent in the offshore facies in Scania-Bornholm.

The largest lensoid concretions attain a diameter of 2 metres and a height of about 1 metre, whereas individual limestone layers rarely are more than half a metre thick; amalgamated stacked units may form thicker beds (Fig. 16). The carbonate content in the concretions varies between 60 and 90 wt% (Buchardt & Nielsen 1985), whereas background carbonate content in the Alum Shale is low (< 10 wt%). Crystal-size generally increases outwards in the concretions, and usually an outer layer consists of cm-large prismatic calcite crystals displaying cone-in-cone structure (e.g. Hansen 1938; Hadding 1958; Dworatzek 1987). Dating of a uranium-rich lens from the *Peltura scarabaeoides* Superzone on Öland indicates a concretionary growth extending for some 35 million years (Israelson et al. 1996).

The limestone abundance generally speaking increases in an adlittoral direction. Thus limestone makes up as much as 50% of the Alum Shale Formation in central Sweden, whereas limestones account for only about 5-10 % of the formational thickness in the marginal facies of Bornholm-Scania-Oslo. At some levels, and predominantly in central and eastern Sweden, the limestone has been reworked, leading to the formation of intraformational conglomerates (Martinsson 1974, Dworatzek 1987). Often these conglomerates have been the nucleus of further concretionary growth. We have observed horizons where concretions must have been standing above the sea-floor due to winnowing of the mud around them concomitant with dissolution, i.e. the first step in forming a conglomerate (Fig. 17).

Examples of disruption of limestone layers due to degassing of the underlying shale are also common where the 'big orsten bank' is developed, and have been described by Dworatzek (1987).

The formation of diagenetic limestone, which has been subject to some discussion (e.g. Hansen 1938, 1945; Hadding 1958; Henningsmoen 1974; Dworatzek 1987; Thickpenny 1984), was obviously related to levels in the sediment, where pore-water carbonate supersaturation occurred. Carbon isotopes studies of the concretions reveal that the carbonate is a mixture of carbonate derived from the sulphate reduction zone and oxidized methane derived from the methane reduction zone (Buchardt & Nielsen 1985). Local supersaturation of calcium carbonate may develop in the sediment by decay of organic matter or by nucleation onto skeletal carbonate. High abundance of calcareous shells in a horizon may thus be speculated to trigger carbonate precipitation (Thickpenny 1984), and the fact that trilobites often are found in great profusion within the fine-grained concretions might be taken to support this notion. Fossils are, however, found also in the shale as imprints - and, more conspicuously, some diagenetic limestones are unfossiliferous. We doubt that the formation of carbonate concretions were controlled by fossil abundance and their presence in concretions is considered to be merely "preservation by chance". We infer that limestone concretions often formed in connection with slow or no deposition. This would focus the base of the sulfate reduction zone, where biological reactions produce supersaturation, resulting in a fixed carbonate precipitation at a certain level in the sediment (cf. Canfield & Raiswell 1991). Such offshore sedimentary still-stands may in theory reflect low sedimentrary supply during strongly rising sea level (i.e. precipitation below a drowning surface) but further study is needed to test this hypothesis.

6.5. Barite

Barite and pseudomorphs after barite (now calcite-pyrite intergrowths) are very common in the Alum Shale Formation (Callisen 1914; Westergård 1922; Hadding 1958). Small 'needles' of rhomb-shaped barite (often replaced by calcite-pyrite or simply dissolved) occur in great masses in some intervals of the Furongian (Fig. 18), whereas larger nodules, typically up to fist size, are common in the Tremadocian (e.g. Hede 1951, Tjernvik 1958). Barite also locally occurs in great quantity in the basal part of the overlying Tøyen Shale. It is puzzling that a sulphate like barite occurs so abundantly in an anoxic-euxenic diagenetic environment otherwise dominated by sulphides and the fact that barite is very abundant at some levels and uncommon or absent at others have nourished a suspicion that its distribution somewhow has a bearing on synsedimentary palaeoenvironmental conditions. The current working hypothesis is, however, that precipitation of barite had a connection with early methane produced by bacteria. If so, the presence or absence of barite has no direct bearing on the depositional palaeoenvironment byt reflects diagenetic processes.

7. Palaeoecology

The Alum Shale palaeoenvironment has been inferred anoxic/'stagnant' by the majority of previous authors (e.g., Hansen 1945; Henningsmoen 1958; Thickpenny 1984, 1987; Dworatzek 1987). This interpretation is, however, challenged by the presence of an abundant, albeit low-diverse fossil fauna, dominated by trilobites (Fig. 19). Dworatzek (1987) considered that the fauna with few exceptions is allochtonous, and derived from higher, better oxygenated areas of the shelf. This scenario is, however, unlikely for several reasons. Firstly it is peculiar that the fossil faunas remained so monotonous and did not mix with assemblages from other environments during transport. Müller & Hinz (1991 pp. 8-9) pointed for instance to the general non-record of mollusks in the Furongian Alum Shale. Secondly, the Alum Shale faunas are very widely distributed, requiring transport distances of up to 1000 km from the conjectural living areas. Thirdly, there is generally no sorting by size, which almost inevitably would result from transportation (see e.g. Eklöf et al. 1999 and Fig. 20). Fourthly, the olenid trilobites were thin-shelled and not likely to survive long transportation. We regard the fossil faunas of the Alum Shale as largely autochtonous. Agitation and winnowing of shells at the sea-floor evidently occurred at some levels (e.g, coquinas connected to 'big orsten bank', skeletal limestones of the *Peltura* superzones of Västergötland and Öland etc.), but the transport distance was likely insignificant. We also note that the sea floor was essentially flat, which is another impediment for efficient long-distance transport of skeletal parts.

The presence of an autochthon benthic fauna thus suggests that oxygen was present in the Alum Shale depositional environment, but it remains unresolved whether the trilobitic intervals reflect short lived oxygenation events or prolonged dysoxia but with enough oxygen for a specialized fauna to exist. We believe the latter and emphasize the importance of distinguishing between euxinic (oxygen free environments with free H2S), anoxic (no oxygen), dysoxic (deficient oxygen) and oxic conditions. The respective biofacies are referred to as anaerobic, dysaerobic and aerobic (e.g. Wignall 1994). However, this terminology was developed for stable slope facies, and such setting is not directly comparable with the potentially more rapidly changing oxygen conditions on the shelf. Such environments have been referred to as poikiloaerobic (Oschmann 1991), where not alone the oxygen level but also the duration of oxygenic periods controls the fauna. Nonetheless, we interpret an incresing diversity of benthic trilobites in the Alum Shale as indicating higher general oxygen level and which in turn is taken to indicate a lower depth of deposition. Diversity figures compiled from the literature and unpublished student theses have been used as supplementary data for reconstructing the Mid Cambrian-Tremadocian sea level although the tedious details on diversity and faunal distribution are not discussed in this report.

7.1. Taphonomy

The Alum Shale trilobite fauna is predominantly preserved within the carbonate concretions and layers in most districts of Sweden, whereas the calcite tests usually are dissolved in the surrounding shales (e.g. Westergård 1922, p. 5). Trilobite imprints in shale are common only in Scania-Bornholm and the Oslo area. However, non-fossiliferous shale is also seen in the offshore facies and relatively thick 'barren intervals' often separate the individual biozones (e.g. Westergård 1942, 1944; Schovsbo 2001; Terfelt 2006, see Fig. 21). These recurrent non-fossiliferous intervals could be suspected representing anoxic interludes without bottom life, but somewhat surprising, the geochemical signature suggests that dysoxia was less intense during deposition of the barren intervals (Schovsbo 2001). The absence of calcite shelled fossils is inferred signalling repeated episodes with raised oxygen levels in the bottom environment, causing frequent re-oxidation of pyrite in the uppermost part of the Alum Shale mud, in turn leading to early dissolution of calcite tests. Subsequent compaction obliterated all traces of the ghost fossils and as a result the trilobites left no imprint in the sedimentary record. It is a working hypothesis that the non-fossiliferous intervals signal sea level lowstands. The Tremadocian Alum Shale may be seen as one extensive 'barren interval' as calcite shelled fossils are not preserved (with few exceptions).

7.2. Faunal composition and palaeoecology: a supplementary tool for sea level reconstructions

The Middle Cambrian-Furongian Alum Shale fauna is strongly dominated by trilobites, which usually occur in great profusion. The trilobites have been described in numerous papers by Grönwall (1902), Westergård (1909, 1922, 1936, 1946, 1947a-b, 1948, 1950, 1953), Poulsen (1923), Kaufmann (1933a,b, 1935), Henningsmoen (1957), Clarkson (1973), Axheimer & Ahlberg (2003), Terfelt et al. (2008, 2010), Weidner & Nielsen (in press a, b) and various earlier authors. Other macrofossil groups present include brachiopods, ostracods, porifera a.o. in addition to mikroscopic fossils such as conodonts, crustaceans, etc. However, we here solely focus on trilobites and brachiopods. Palaeoecological analysis is relevant for unraveling palaeoenvironmental changes relating to depth changes, notably in the offshore environment, characterized by a monotonous lithology. It is thus a supplementary tool for sequence stratigraphical interpretation.

Agnostid and olenid trilobites epitomize the Alum Shale fossil macrofauna, but a range of other trilobites is present as well, being more common in the Middle Cambrian than in the Furongian. Very few trilobites have been described from the Tremadocian Alum Shale, where the calcite fauna is inferred dissolved early (see section 7.1.). The persistent pattern of olenid trilobites occurring in black shales and associated limestones throughout the world strongly suggests that they were adapted to cope with oxygen-deficient environments (e.g. Henningsmoen 1957; Fortey 1974, 1975, 1980, 1985). However, interpretations of whether the olenids were benthic, nektonic, epipelagic or pelagic are disparate (e.g. Henningsmoen 1957, Öpik 1963, Bergström 1973, Fortey 1975, 1985). This disagreement also concerns agnostids, which by most authors have been considered pelagic (e.g., Robison 1972), an interpretation contested by Fortey (1980 p. 23) and Nielsen (1995, 1997). In our opinion the strong olenid-agnostid affinity with black shale environments, and only subordinate occurrence in other environments, suggests that a near-surface pelagic way of living is unlikely for the simple reason that a wider environmental spead, irrespective of bottom conditions, then were to be expected. The absence of bioturbation in the Alum Shale does not exclude the presence of a fauna living on the substrate (for remarks on the probable presence of bacterial mats, see section 10).

We tentatively divide the trilobites present in the Alum Shale among five groups, embracing 1) 'normal' trilobites, 2) agnostids, 3) *Olenus*-type olenids, 4) *Peltura*-type olenids, and, 5) *Ctenopyge*-type olenids (Fig. 22). Most agnostids and all olenid trilobites were opportunistic and adapted to live under dysoxic conditions. Adaptions included high spat production and fast growth, whenever the conditions were favourable.

'Normal' trilobites

This heterogeneous group comprises trilobites not specifically adapted to black shale facies although these taxa obviously were tolerant of lowered oxygen levels. The labelling of all non-olenid/agnostid trilobites as 'normal' is obviously a gross simplification but for the present purpose these benthic trilobites are either exotic elements not typical of the Alum Shale environment or, as far as can be established, they occur only in upper dysoxic intervals, hence the designation ‘normal’ is most convenient. Such trilobites are in particular common in the Middle Cambrian, where several taxa occur in the Alum Shale as well as in the contemporanous better oxygenated silt- and mudstones deposited in shallower water. The presence of representatives of this group is considered diagnostic of upper dysoxic or fully oxic conditions.

Agnostid trilobites

Agnostid trilobites are very common and diverse in the Middle Cambrian Alum Shale, but rapidly decrease in diversity in the Furongian. They occur only sporadically above the *Olenus* Superzone (Westergård 1922; Ahlberg & Ahlgren 1996, 2000). Because of their pronounced association with black shales (often *a priori* considered deposited under anoxic conditions), their small size and the almost pandemic distribution of some species, agnostids have been inferred pelagic and adapted to the oceanic environment (for an authoritative review, see Robison 1972). This interpretation has gained widespread acceptance, but the same arguments may be taken as indicating adaption to survival in dysoxic environments (Nielsen 1995, 1997). The alternative interpretation is underpinned by the observation that Cambrian agnostids usually occur associated with some 'normal' benthic trilobites, and the agnostid diversity decreases in black shales without the ‘normal’ trilobite faunal component. Also, if agnostids were pelagic, it is peculiar that they are so strongly associated with black shale environments – a wider spread irrespective of bottom conditions should be anticipated. Some agnostid species exhibit an almost pandemic distribution – for which reason they are excellent biostratigraphic markers - hence their ability to migrate was certainly extraordinary.

Agnostids lived enrolled (Müller & Walossek 1987; see also Robison 1972), and may be compared to ostracods. The latter group is largely bottom-dwelling.

Olenus-type olenid trilobites

Olenid trilobites with comparatively flat carapace, thin test, narrow axis, short genal spines and mostly short or no thoracic spines are referred to as '*Olenus*-type'. The cephala typically shows genal cecae.

This group of trilobites is considered benthic and adapted to lower dysoxic conditions than the agnostids. The proportionally narrow and not particularly vaulted axis suggests that appendages were not designed for swimming (compare *Peltura*-type). The thin test is a likely adaption for improved respiration (cf. Jell 1978). The distribution of *Parabolina*, the members of which occasionally are comparatively large-sized, suggest adaption to higher oxygen levels than most other *Olenus*-type representatives. This also concerns *Leptoplastides*, but which is very rare in the Scandinavian Alum Shale.

Peltura-type olenid trilobites

Olenid trilobites with comparatively strongly vaulted carapace, broad axis, short or no genal spines and no thoracic spines are referred to as '*Peltura*-type'. The eyes tend to be small and marginal or sub-marginal, situated forwardly (see Clarkson 1973).

Members of this group are considered active swimmers (cf. Richter 1919 p. 229; Henningsmoen 1957 p. 78). The broad axis is taken as a requirement for attachment of powerful muscles, a prerequisite for swimming. The tendency of the eyes to become marginal plus the rather strong convexity of the skeleton are taken as additional indications of a swimming way of life. The functional rationale behind the diminishing eye-size is unknown, but it is a feature seen in other swimming trilobites as well (Fortey 1985, p. 228). The well-known Ordovician genus *Triarthrus* exhibits the same general morphology, and is the only species of *Peltura*-type for which the ventral soft parts have been described. It is remarkable that the appendages of *T. eatoni* (see e.g. Cisne 1975) are extending beyond the lateral edges of the dorsal shield, which is unusual among trilobites. Henningsmoen (1957, p. 81) suggested that the large gills may have enabled *Triarthrus* to live in waters with a low oxygen content; at the same time it is possible that the exopodites acted as swimming apparatus. Besides, a swimming trilobite would have had little use of dorsal protection, so there was no functional need for restricting the appendages below the shield.

Because of their occurrence pattern and morphology, *Peltura* and allies are considered nekto-benthic; some broad-axed Tremadocian forms may have been fully nektonic (cf. Fortey 1975, p. 343).

***Ctenopyge*-type olenid trilobites**

Smallish, extraordinarily convex, spinose olenid trilobites with very narrow axis, and long genal and thoracic spines are referred to as '*Ctenopyge*-type'. The genal spines are typically situated forwardly on the librigena, the eyes are proportionally larger and more sphaerical than in the other olenid types (Lindström 1901, Clarkson 1973), the preglabellar field is extremely short or not defined, and a frontal median arch is distinct.

The well-developed spines of this group are interpreted as devices for preventing sinking in the water column through frictional retardation; at the same time the very narrow axis indicates that representatives of this group probably were not provided with powerful appendages. The genal spines even pointed downwards in *Sphaerophthalmus humilis* (see Clarkson 1973, fig. 8), providing strong evidence for a fully pelagic way of living. Alternatively the spines were used to keep a distance from the poisonous bottom sediment in which case the well-developed frontal arch may have been instrumental for permitting a water flow beneath the animal for respiration.

The members of this group, notably *Ctenopyge*, are characteristic of offshore lower dysoxic environments, and they may have been mesopelagic.

7.3. Towards the definition of biofacies

The Alum Shale trilobite assemblages show distinctive geographical and stratigraphical differences in composition and which is taken to reflect a decreasing oxygen level with depth. The general diversity of trilobites thus desceases with decreasing oxygen content, agnostid trilobites are common and diverse in upper dysoxic facies but become infrequent in low dysoxic environments, and olenid trilobites are divided into three morphotypes of which *Ctenopyge*-types are dominating in the most offshore, low dysoxic environments and *Olenus*-types are dominating in or even restricted to (*Parabolina*) upper dysoxic environments (Fig. 23).

No biofacies per se are defined in this report, but the trilobite distribution has been used in a quasi-qualitative way for calibrating and adjusting the reconstructed sea level curve.

8. Cambrian tectonism and isostasy

The Baltoscandian platform was by and large tectonically quiescent during the Cambrian, and active subsidence of this old, mature craton was minimal. However, fissures in the basement, filled with Cambrian sediments, attest to intermittent periods of earthquake activity. For the greater part the ages of the mostly sand-filled fissures are unknown (see Nielsen & Schovsbo 2011 for references) but the general notion, supported by a few fossil findings, that they are all of Early Cambrian age was contested by Martinsson (1968). It has also become increasingly evident that several sub-regional hiati within the Alum Shale Formation must be due to transient local isostatic movements during deposition. These movements were likely only in the size order of a few tens of metres, but they had, nonetheless, a profound impact on deposition, likely because of the otherwise extremely uniform flat bottom topography.

It is relevant to identify tectonic/isostatic disturbances in order not to confuse their effects with sea level driven events and it is obviously also important to unravel their control on the local thickness variations of the Alum Shale Formation.

Mid Cambrian-Tremadocian isostatic and tectonic disturbances in Baltoscandia are indicated by:

- Fissure fillings in the basement on the isle of Åland between Finland and Sweden which are dated as mid to late Furongian (Martinsson 1968; Holmer & Popov 1990) or earliest Ordovician (Tynni 1982). Theoretically they may be associated with the nearby Lumparn impact crater. If so, large impacts and associated disturbances may be added to the plethora of potential anomalies in the Alum Shale depositional environment. The early Middle Cambrian shale at Ritland in SW Norway (see Henningsmoen 1952, Bruton & Harper 2000) was deposited in a large crater created at around the Early/Mid Cambrian transition. However, we are most inclined to interpret the fissure fillings on Åland as earth quake related (see below).
- Fissure fillings in the basement near Göteborg, Sweden, contain both Middle Cambrian and Furongian limestone and Alum Shale (Martinsson 1968, Samuelson 1975). The youngest dateable sediments in these fissures represent the *Olenus* Superzone. This must be taken as a maximum date for the formation of the fissures. The fissures strike WNW-ESE.
- The numerous spectacular 'Funnel Grabens' seen in the Lower Cambrian sandstone of Scania (Lindström 1967) reflect earthquake-events, releasing water-soaked sand trapped at depth and which closer to the surface led to the formation of relatively large crater-like subsidence funnels (Fig. 24). At least two phases of collapse occurrred, the first one in mid Early Cambrian time and a second one in the Furongian *Olenus truncatus* Zone or slightly later (see Lindström 1967). The collapse structures are associated with fractures striking WNW-ESE.
- The development of the upper Middle Cambrian deviates strongly between the neighbouring districts Närke and Östergötland in south central Sweden (Fig. 7; for summary, see Martinsson 1974). In Närke the *A. oelandicus* Superzone and locally the *T. gibbus* Zone is thus directly overlain by the Exporrecta Conglomerate. The deviating stratigraphy indicates late Mid Cambrian uplift of Närke relative to Östergötland.
- A veneer of Tremadocian Alum Shale rests on the Furongian *Peltura minor* Superzone at Hunneberg, Västergötland (Westergård 1922), and which is indicative of a late Furongian erosive event.

- No Tremadocian Alum Shale is present in the Autochthon of Jämtland, where the youngest preserved level usually is the *P. minor* Superzone (Karis 1998). Tremadocian Alum Shale occurs locally in the Parautochthon and the Lower Allochthon in the area.
- Late Furongian erosion/non-deposition has hitherto been ascribed to the Acerocare Regressive Event, a major sea level fall at the close of the Furongian (see below). However, the *Peltura costata* Zone (*Acerocarina* Superzone) on Kinnekulle, Västergötland, contains redeposited trilobites from the basal *Acerocarina* Superzone, the *P. scarabaeoides* Superzone and the *P. minor* Superzone (Weidner & Nielsen in press b). Hence, erosion of Alum Shale mud and winnowing of trilobite tests seems to have taken place in the vicinity in the late Furongian.
- Local incursions of sandstone, the Skåningstorp Sandstone, in the basal Tremadocian of Östergötland, Sweden, indicate exposure and erosion of nearby Lower Cambrian sandstone or basement. Feldspar occurs as well as 2-3 mm large quartz grains, suggesting erosion of basement. The *Acerocarina* Superzone is absent in the district and the Tremadocian in general rests on the *P. scarabaeoides* Superzone (which mostly is rather thin), but locally it rests on the *P. minor* or the *Leptoplastus* Superzone. This pattern is clearly indicative of a late Furongian erosive event which in the vicinity must have been more severe than in Östergötland. Sandstone of Early Tremadocian age is also known from Siljan and northern Öland.
- The youngest Alum Shale in the Hummeln impact crater, Småland, represents the *A. pisiformis* Zone (Westergård 1922). This is suggestive of uplift and erosion post-dating the *A. pisiformis* Zone.
- There is a marked difference in thickness of the Alum Shale Formation between the three deep wells Falsterborev-1, Hölviksnäs-1 and Hammarlöv-1 in SW Scania in comparison with the two deep wells Håslöv-1 and Eskildstorp-1, located less than 10 km further north (Fig. 25). The difference reflects condensation of the upper part of the Furongian (c. 10 m) and the Tremadocian (c. 10 m). The abrupt change may be due to a growth fault.
- The youngest Tremadocian graptolite zone is strongly condensed in Scania and on Bornholm (in comparison with e.g. the Oslo area), suggestive of late Tremadocian uplift of southernmost Scandinavia.
- No Tremadocian Alum Shale is developed in NE Poland, where Furongian Alum Shale was deposited, which may be an indication of Tremadocian uplift, if not interpreted as erosion during a sea level lowstand (e.g. the CRE).
- Tremadocian Alum Shale is also missing in many sections across Sweden and in southernmost Norway. This may be due to erosion during the prominent Ceratopyge Regressive Event or due to local Tremadocian uplift.
- The Alum Shale Formation peters out westwards in Norway (Fig. 25), which in part may reflect that the sedimentary supply derived from an eastern land area, but at the same time Tremadocian Alum Shale is locally present in the Lower, Middle and Upper Allochthon (Fig. 26), indicating a westwards spread of Alum Shale deposition concomitant with the strong Early Ordovician sea level rise which everything else equal should displace the clastic source area further east. This paradox is taken to indicate that uplift played a part in the westwards thinning of the Alum Shale during the Mid Cambrian-Furongian.
- The southwards thinning of the Alum Shale Formation in Denmark-southernmost Sweden likely reflects an uplifted southern margin of Baltica (Figs 27–28).
- The Alum Shale Fm is absent in the greater part of Poland (Fig. 25), where the Lower Palaeozoic succession otherwise is quite closely comparable to that of southern

Scandinavia both below and above the Alum Shale. This is suggestive of transient uplift of most of (eventually all of) Poland during the late Mid Cambrian-Furongian-Tremadocian.

- On a greater scale the regional subsidence pattern shifted between deposition of the Middle Cambrian and the Furongian and again between the Furongian and the Tremadocian (see Fig. 29 vs Fig. 30 vs Fig. 31), suggesting regional isostatic changes, which in turn may reflect stress changes relating to ongoing plate tectonism.
- The absence of post-Lontova (next oldest stage in the Cambrian, see Fig. 4) Lower Cambrian in large parts of Estonia (Fig. 32) is ascribed to an uplift that took place during the mid to late Mid Cambrian and which caused extensive erosion. The dating is constrained by the local onlap of Middle Cambrian sandstone (Fig. 33) directly onto Lontova deposits in Russia (see Puura 1996 for stratigraphic details). The discordance is here illustrated in Fig. 34. The southern flank of the uplift is deliniated by the erosional limits of Lower and Middle Cambrian units across Estonia.
- On Hardangervidda in southern Norway the 30-40 m thick Alum Shale (locally assigned to the Bjørnbo Mbr of the Låven Fm) is overlain by a coarsening upward unit, the 10-60 m thick Buanut Mbr, comprising black shales intercalated with sandstone beds, in turn overlain by quartz sandstone, the Holberg Quartzite, mostly 15-25 m but up to 60 m thick (Fig. 35) (Andresen 1978). Greatest thicknesses are seen to the east and south. The sandstone must be of Ordovician age as the graptolite *Rhabdinopora* have been found in the upper part of the local Alum Shale (Størmer 1940; Andresen 1978). The incoming of sand reflects an uplift of southernmost Norway, the so-called Telemark Land (e.g. Rasmussen et al. 2011).

The analysis of the plethora of observations enumerated above is complex and still in its infancy, but it appears that at least three phases of tectonic/isostatic unrest affected Baltoscandia during deposition of the Alum Shale, in addition the the so-called Hawke Bay Event which took place at around the Early/Mid Cambrian boundary but with long-lasting effects extending well into the Mid Cambrian. These events are briefly discussed below; they are summarized in Figs 36–38.

8.1. Hawke Bay Event

This event, as identified in Scandinavia, reflects a regional latest Early Cambrian epierogenic uplift apparently coinciding with a major eustatic sea level fall (Fig. 39). The uplifted areas – initially all of Scandinavia – gradually and differentially subsided during the early Mid Cambrian (Figs 40-41). As a result the Hawke Bay unconformity is most extensive in western and southernmost Scandinavia where the uplift persisted for longest time. It is estimated that the uplift locally lasted for as much as 6-7 Ma. The seemingly rapid epierogenic uplift may have been triggered by stress-induced density changes in the mantle linked to major plate-tectonic adjustments (cf. Cathles & Hallam 1991), and we strongly suspect that the event signals onset of subduction in the ocean adjacent to Baltica (Iapetus or Ægir). It is stressed that the “residual” uplifted area in Scandinavia became flooded shortly into the Mid Cambrian (*P. praecurrens* Zone) but that deposition in most cases did not resumed before subsidence of the individual areas in the aftermath of the Hawke Bay Event. This inference is based on the local presence of condensed autigen Middle Cambrian sediments (glauconite, limestone), in for instance Östergötland (Kvarntorp Mbr) and on Bornholm (amalgamated Forsemölla and Exsulans limestones), see Nielsen & Schovsbo (in prep.) for details. These condensed sediments evidence that the areas must have been inundated, despite generally characterized by non-deposition. The "residual" Hawke Bay uplift with inferred relict sea floor is shown as hatched areas on the palaeogeographical maps Figs 40–41.

When the Hawke Bay uplift eventually abated – during the late *A. atavus* Chronozone – Alum Shale deposition characterized most of Scandinavia (Norway, Denmark, Sweden east of Gotland).

8.2. Mid to late Mid Cambrian sub-regional uplift(s)

Estonia-westernmost Russia (St. Petersburg region) must have been uplifted between deposition of the early Mid Cambrian Ruhnu Formation (*A. oelandicus* Superzone age) and the Mid Cambrian Sablinka Fm which in Estonia may have correspond to the Paala Formation (precise Mid Cambrian age of both units uncertain, but they are believed to represent lowstand sand associated with the Andrarum Lowstand, see section 9.3). The uplift is demonstrated by the unconformable onlap of Mid Cambrian-Furongian-Tremadocian sandstone units (Paala/Sablinka, Ulgäse/Ladoga and Kallavera/Tosna formations [Estonian/Russian unit names]) directly onto eroded Lower Cambrian (Lontova, Tiskre and Lükati formations) in northern Estonia and the St. Petersburg region (e.g. Mens et al. 1990; Puura 1996). The southern flank of the uplift is deliniated by the erosional limits of Lower and Middle Cambrian strata in Estonia, subcropping below Furongian-Ordovician units (see Figs 32 and 42).

An uplift of Estonia during the *P. paradoxissimus* or the *P. forchhammeri* Superzone has not previously been recognized. The uplift was associated with intense local erosion of much greater scale than during the other isostatic events discussed below.

We believe that the uplift extended westwards from Estonia as indicated on Fig. 43A, causing extensive erosion of the Lower Cambrian in much this area. The Lower Cambrian plus the lower part of the Middle Cambrian must originally have been > 100 m thick in the Åland area (see regional thickness trends of the Lower Cambrian in Nielsen & Schovsbo 2011, fig. 2 and Fig. 44). We consider it most obvious to ascribe it to the same erosive event that affected Estonia prior to the late Furongian. Now only a few tens of metres are preserved down-faulted in the Lumparn crater (see Bergman et al. 1982). The effects of uplift are traceable northwards into the Bothnian Sea where the Ordovician limestones rest with a slight angular unconformity on older strata (see Söderberg 1993, fig. 2).

If the uplift continued into Swedish territory it is simplest to assume that it also affected the Närke district, explaining the different development between the Middle Cambrian in Närke vs Östergötland. This is a highly interesting perspective as it corroborates the inferred timing of the event: it predates deposition of the Exporrecta Conglomerate (Andrarum Lowstand), resting unconformably on the incomplete older Middle Cambrian strata (youngest preserved strata: *T. gibbus* Zone).

In Jämtland the Furongian Alum Shale Fm is more stratigraphically complete westwards, southwards and northwards of the Storsjö area (Karis 1998 p. 140) which in theory may define the western extension of the uplift. Overall the topography seems to have been levelled out by the end of the Mid Cambrian.

It is relevant to consider whether an elongate east-west oriented uplift from Estonia to Jämtland changed the general regional slope from east-west to a local north-south in the southern part of Scandinavia. This could be the reason for the changes in regional distribution of the Middle Cambrian and Furongian Alum Shale (Fig. 29 vs Fig. 30). The local slope was certainly roughly north-south on Öland during the Furongian (cf. Westergård 1922).

We also infer that most of Poland was uplifted at about this time. By comparison with Scandinavia it is peculiar that the Alum Shale Fm does not extend southwards along the Baltica margin into the Polish sector and the absence of upper Middle Cambrian and

Furongian Alum Shale in the Lublin Slope is particularly intriguing and strongly suggestive of transient uplift. Regarding dating it should, however, be kept in mind that some Middle Cambrian strata may have been removed by erosion during the uplift.

8.3. Late Furongian sub-regional uplift(s) and tectonism

The mid Furongian palaeogeography is shown in Fig. 43B. It is, however, evident that westernmost Västergötland and the Autochthon of Jämtland were affected by uplift and non-deposition/erosion in the late Furongian. The *P. minor* Superzone is thus directly overlain by a veneer of Ordovician Alum Shale at Hunneberg (Westergård 1922). The same condition is seen at several sites in the autochthon of Jämtland (Karis 1998), where Furongian Alum Shale younger than the *P. minor* Zone in general is absent. The recently investigated *Acerocarina* Superzone at Kinnekulle, Västergötland (Weidner & Nielsen in press b), contains several reworked trilobites from the basal *Acerocarina* Superzone, the *Peltura scarabaeoides* Superzone and, rarely, even the *P. minor* Superzone. This demonstraters that active erosion of Furongian Alum Shale with winnowing of trilobite skeletons took place in the vicinity at the same time as Alum Shale was deposited during *Peltura costata* Zone time at Kinnekulle.

Deep erosion of Lower Cambrian sandstone and basement is likely also the reason why sandstone, the Skåningstorp Sandstone, suddenly appears in the Alum Shale Fm at the base of the Ordovician in Östergötland (Fig. 8, see Nielsen & Schovsbo 2006 for references). Coeval sandstone is not seen in the nearby districts of Närke (no Tremadocian) or Västergötland (Alum Shale locally preserved), suggesting a source area to the southeast of Östergötland. Tremadocian "Obolus sandstone" is also known from northern Öland and it is possible that Småland was uplifted in the late Furongian. Interestingly, ice-rafted limestone deriving from the Hummeln impact crater in eastern Småland suggests that the level preserved in the crater is the *A. pisiformis* Zone (Westergård 1922). Again this may be taken as an indication of uplift-related erosion of Furongian strata. However, other souces of the Skåninsgtorp Sandstone may be contemplated, for instance the "Åland-Siljan" uplifted ridge. Basal Tremadocian sandstone is also known from the Bothnian Bay (Thorslund & Axberg 1979) and the Siljan area (Holmer & Popov 1990 and references therein).

There is a marked difference in thickness of the Alum Shale Formation in SW Scania between the Falsterbo Rev-1, Hölviksnäs-1 and Hammarlöv-1 deep wells and the two more northerly located Håslöv-1 and Eskildstorp-1 wells. The distance between Håslöv-1 and Hölviksnäs-1 is just c. 6 km, yet the Alum Shale Formation exhibits a 20 m difference in thickness. This difference reflects condensation of the upper part of the Furongian (c. 10 m) and the Tremadocian (c. 10 m). The jump in thickness may reflect growth fault controlled subsidence.

The Scanian 'Funnel Grabens' (see Lindström 1967) and the fissure fillings in the Göteborg area mentioned above may be taken to suggest that earthquakes occurred in the Furongian and maybe they were contemporaneous with the late Furongian uplift of parts of Sweden. The sand filled fissures in the basement on Åland contain mid-late Furongian brachiopods and acritarchs taken to indicate an Early Ordovician age (se above) and are also suggestive of earth quake activity at around the Furongian/Ordovician boundary (it is currently very difficult to ascertain whether acritarchs indicate *Acerocarina* Superzone or early Tremadocian).

8.4. Tremadocian isostasy

The distribution pattern of Tremadocian Alum Shale differs from that of the Furongian Alum Shale (Fig. 30 vs Fig. 31, see also Fig. 43B–C). This may partly be due to the strong earliest Ordovician rise in sea level (section 9.5) but it also appears that a regional shift in subsidence pattern took place. The most notable shift is the incursion of Alum Shale into northern Estonia-westernmost Russia (Fig. 45). This tongue of Alum Shale roughly coincides with the location of the mid Mid Cambrian uplift (section 8.2 and Fig. 38), suggesting that this uplift eventually subsided. Onlap of Furongian units along the flanks of the uplift in Estonia suggest that this subsidence took place in the very latest Furongian or earliest Tremadocian (Fig. 35). This local subsidence complicates assessing the Tremadocian sea level stand relative to the height of earlier sea levels.

Ordovician Alum Shale is, unlike Furongian Alum Shale, inferred present even in the far-travelled Middle Allochthon of southern Norway (dating is inferred, however, based on comparison with fossiliferous Lower Allochthon), suggesting subsidence of the western margins of Baltica. Fossiliferous Tremadocian black shales have been reported from the Upper Allochthon of eastern Trøndelag, Norway (Gee 1981 and references therein). This spread of deposition possibly heralded the late Tremadocian disappearance of the sill along the western fringe of Baltica.

Tremadocian Alum Shale is absent in Närke and most of Västergötland, many places in Jämtland and locally in southernmost Norway (Fig. 31). At least some of this absence may be due to erosion during the Ceratopyeg Regressive Event, lowering the storm wave base, but it is alternatively possible that central Sweden-southern Norway was uplifted early in the Tremadocian, as sketched in Fig. 38. The Furongian Alum Shale is at Brattefors, Kinnekulle, cut by peculiar funnels, filled with upper Tremadocian sediment otherwise absent in the area (Teves & Lindström 1988; Löfgren 1997). It is uncertain how the funnels formed; because the upper Tremadocian plug fill rests on disturbed but not entirely disrupted Furongian Alum Shale, Teves & Lindström (1988) excluded rapid release of methane. The fact that the upper Tremadocian plug fill rests directly on Furongian demonstrates that no lower Tremadocian Alum Shale was present in the area *prior* to the Ceratopyge Regressive Event, suggesting that the early Tremadocian was a non-depositional period, in turn corroborating uplift. The sediment filling the funnels formed on location (glauconite). If the local funnels reflect tectonic disturbance, it took place shortly into the late Tremadocian. Collapse structures are also reported from the Lower Cambrian of Närke (Karis & Magnusson 1972; Bengtson 1976) and these post-Mid Cambrian structures may be of the same age.

The uppermost part of the Tremadocian Alum Shale is strongly condensed on Bornholm and in parts of Scania (Hede 1951; Tjernvik 1958; von Janson 1979), indicating late Tremadocian uplift of the southern margin of Baltica. Tremadocian uplift seemingly also affected NE Poland where no Tremadocian Alum Shale is developed.

The late Tremadocian and very prominent CRE lowstand marks the end of the Alum Shale depositional environment. Subsequently the bottom environment in the epicontinental sea covering all of Scandinavia was much better oxygenated. This fundamental change indicates that the CRE was not just another major lowstand and we assume that the event also marks the disappearance of the sill along the western margin of Baltica that created poor exchange of water masses in the Alum Shale Sea.

9. Sequence stratigraphy and sea level changes

It has not previously been attempted to appraise the Cambrian sea level changes of Baltoscandia, except that regressions routinely have been invoked as explanation of hiati in the stratigraphic succession. As a starting point for addressing sea level changes we emphasize that

- the craton was by and large tectonically quiescent
- active subsidence was insignificant (local minor anomalies are discussed above)
- the craton was exceptionally flat
- the sedimentary supply was exceedingly limited from shortly into the Mid Cambrian onwards and the available accomodation space was never exhausted
- all hiati recognized in the Alum Shale Formation formed submarine

The strongly reduced sedimentary supply was the result of the peneplaned stated of the craton in combination with extensive flooding, leaving only small land-areas above sea level and they were distant from Scandinavia. As sedimentary processes and isostasy in general had insignificant influence on the local depth of deposition in the Alum Shale Sea, eustasy was the principal controlling factor. When referring to sea level, we therefore imply eustasy, unless otherwise stated.

We adopt the same approach to sequence stratigraphy as Nielsen & Schovsbo (2011) and, accordingly, define sequences as transgressive-regressive units bounded by maximum regressive surfaces and their correlative offshore conformities. We also adopt the same naming style for sequences using two capital letters as a mnemonic abbreviation of age, e.g. MC [Middle Cambrian], followed by a number, e.g. 3-4. The prefixes LC, MC, FU and TR refer to Lower Cambrian, Middle Cambrian, Furongian and Tremadocian, respectively. The sequence name MC3-4 for example refers to Middle Cambrian, supersequence 3, sequence 4. Fourth order sequences (subsequences in the terminology of Nielsen & Schovsbo 2011) are labeled A, B etc, e.g. MC3-3A, MC3-3B etc., but it is in general not possible to recognize fourth order sequences in the relatively deep Alum Shale environment.

Much of the standard sequence stratigraphical terminology is superfluous in the present setting due to the insignificant sedimentary influence on the local depth and the successions are in general so condensed and lithologically uniform that it is impossible to distinguish system tracts. Most of the Alum Shale across mainland Sweden represents transgressive and highstand events; non-deposition and erosion characterize falling stage and lowstand intervals. Synoptic sections of sequences are shown in Fig. 46.

The vertical time scale for the sea level curve is constructed by adopting the most recently published datings of the global stage boundaries (Peng et al. 2012). The biozones within each stage have then been plotted as of equal duration which obviously is an oversimplification, but the only option for the time being in the absence of more detailed datings. It is attempted to assess the size order of the sea level oscillations in metres, based on the assumption that the effective storm wave base was located at around 70 m. This is a comparatively deep SWB; it is derived from unpublished modeling of Early Cambrian sea level changes in Scandinavia (Nielsen in prep.). If the SWB was shallower across the central part of Sweden - it may theoretically have been shallower on the central parts of the craton than closer to the margins (cf. Keulegan & Krumbein 1949) - then the constructed Furongian–Tremadocian oscillations may be of smaller amplitude than shown. However, Allison & Wells (2006) suggested that storm reworking down to 100 m is possible even in epieric seas. A sea level rise of ≈200 m from the Hawke Bay Event (full regression) to the early

Tremadocian, which was one of the most major highstands of the Ordovician (Nielsen 2004), also appears plausible and maybe even on the low side.

9.1. Early Cambrian

It is beyond the purpose of this report to enter a discussion of Early Cambrian sea level changes and sequence stratigraphy, but the general Early Cambrian development is briefly sketched in order provide a background for discussing the Alum Shale Formation.

During the initial Cambrian transgression the sedimentary supply was much higher in Scandinavia than during deposition of the Alum Shale and the general oxygenation level was significantly higher in the bottom environment on the outer shelf, where even red coloured sediments regularly were deposited (see e.g. Nielsen & Schovsbo 2011, fig. 42). A comprehensive Lower Cambrian sequence stratigraphical frame was outlined for Scandinavia by Nielsen & Schovsbo (2011), but they did not discuss the underlying sea level changes as such (see, however, Nielsen & Schovsbo 2011, fig. 13). Overall, the sea level rose significantly during the Early Cambrian, likely in the size order of 200 m, maybe even more. The prominent 1st order sea level rise comprises numerous 3rd order pulses punctuated by a series of falls. Nielsen & Schovsbo (2011) recognized two Lower Cambrian supersequences divided into 14 third order sequences in turn comprising numerous fourth order sequences. The resulting average duration of the third order sequences was c. 2 myr. However, this figure covers older sequences showing an average duration of c. 3 myr, and younger sequences with an average duration of only 1.5 myr. The inconsistency probably reflects incompleteness of the basal Cambrian succession.

9.2. Early-Mid Cambrian transition: Hawke Bay Event

The Hawke Bay Event – as recognized in Baltoscandia – is briefly outlined in section 8.1., based on unpublished work by Nielsen & Schovsbo (in prep.). The complex event comprises uplift of Scandinavia seemingly overprinting a major simultaneous eustatic sea level fall. The result was widespread full regression in most or all of Scandinavia (Fig. 39). It is currently uncertain whether the regression is precisely corresponding to the Hawke Bay Event recognized in Laurentia as indicated by using the same name (introduced to Scandinavia by Bergström 1981; Bergström & Ahlberg 1981). Intercontinental correlation is crude in this stratigraphical interval and the late Early Cambrian När Lowstand (see Nielsen & Schovsbo 2011) may be (mis?)identified as the Hawke Bay Event in some regions of the world. It may prove that the Hawke Bay Event as recognized in Scandinavia does not correspond to the Laurentian event.

Conglomerates containing extraformational clasts suggest that large parts of at least Sweden were above sea level during the initial phase of the Hawke Bay lowstand whereas the marginal areas of Baltica, e.g. Scania, may have remained inundated throughout the event, but deposition was interrupted because of uplift (for details, see Nielsen & Schovsbo in prep.). The Hawke Bay regional unconformity forms the upper boundary of Cambrian Supersequence 2 sensu Nielsen & Schovsbo (2011), and the base of the Alum Shale Formation in most areas of Scandinavia (Fig. 8). Due to the uplift, or rather, the slow and differential subsidence in the aftermath of the uplift, the Hawke Bay “Event” is diachronous and of longest duration in western Scandinavia. Due to the differential early Mid Cambrian subsidence sequences of different age onlap the Hawke Bay unconformity across Scandinavia (Fig. 47). When the uplift eventually disappeared in the mid Mid Cambrian, the Early Cambrian elongate high, straddling the long axis of mainland Sweden-southern Norway (see Nielsen & Schovsbo 2011, fig. 83), disappeared, evidencing that the post-Hawke Bay subsidence did not just bring the area back to its previous state – most of Scandinavia subsided further, the central part likely in the size order of some 200 m. For further remarks on the Hawke Bay Event, see section 8.1.

Findings of trilobites of Lower Cambrian aspect in the oldest sequence of Supersequence 3 (see Nielsen & Schovsbo in prep. for details), indicate that the Hawke Bay Event commenced in the late Early Cambrian like in Laurentia and Spain (e.g. Alvaro & Vennin 1998). Accordingly, the oldest sequence of Supersequence 3 is here referred to as LC3-1; it comprises 3 subsequences. As this sequence – which forms the basal part of the Mossberga Mbr of the Borgholm Fm in the Gotland area (Fig. 48) - is of little relevance for the Alum Shale Formation it is not discussed any further.

9.3. Mid Cambrian

In the aftermath of the Hawke Bay Event - while the Hawke Bay unconformity was still developing across most of southern Scandinavia due to uplift – the sea level rose but stayed moderately low. At this early stage in the Mid Cambrian a high amount of sediment was supplied from the east and progradation shifted the coastline westwards (depositional phase 3). These prograding packages (Deimena Fm and coeval units in the East Baltic area, the Borgholm Fm in eastern Sweden) are, in comparison with the Alum Shale Formation, relatively coarse-grained and mostly deposited under well-ventilated bottom conditions. There seems to be about five latest Early Cambrian – early Mid Cambrian sequences in Lithuania (Nielsen & Schovsbo in prep.), but there is no biostratigraphic control on the correlation of individual sequences and correlation remains model-driven, in particular between the East Baltic area and Sweden (Fig. 49). For this reason we are uncertain exactly how many sequences are developed.

In westernmost Scandinavia (Lower Allochthon in southern Norway and Jämtland, e.g. Karis 1998) the Hawke Bay unconformity is overlain by mudstone deposited during the *A. pinus*–*P. praecurrens* Zone (sequence MC3-3 and/or MC3-4) and we assume that all of Scandinavia, including the still uplifted areas, became flooded at this stage. The mudstone in southern Norway and Jämtland is dark grayish and rather lean in organic content, yet it is still most convenient to assign it to the Alum Shale Formation. Slightly later, probably during deposition of sequence MC3-5, deposition of greenish mudstone commenced in Östergötland and Närke due to subsidence of the area after the Hawke Bay Event. The local strongly glauconitic Kvarntorp Mbr with several phosphorite conglomerates may represent strongly condensed strata corresponding to sequence MC3-3 and/or MC3-4. It is possible that Poland was still not uplifted (Fig. 37B–C), permitting free inflow of oceanic water masses so that the oxygen deficiency in the eastern part of the epicontinental sea was still not very pronounced.

A forced regression towards the close of the *A. oelandicus* Superzone is signalled by the Faludden Sandstone Mbr in the Gotland area, demonstrating that the coastal zone reached the area (Figs 48, 50). The event is referred to as the Faludden Lowstand and it marks the boundary between sequences MC3-5 and MC3-6. Subsequent progradation shifted the coastline as far west as Öland (Äleklinta Mbr, sequence MC3-6, see Figs 49, 51) and during another lowstand (Mid-*gibbus* Lowstand), halfway through the *T. gibbus* Zone, the coastline ran just west of the Öland area. This lowstand marks the boundary between sequences MC3-6 and MC3-7.

The sea level rises that followed the Faludden and the Mid-*gibbus* lowstand events were seemingly fast and in both cases associated with deposition of conglomeratic ‘transgressive’ limestone beds (Forsemölla Lmst and Exsulans Lmst, respectively; for regional distribution see Fig. 8). Deposition of Alum Shale started in Scania during deposition of sequence MC3-6 due to subsidence of the area after the Hawke Bay Event. Locally in Scania is even seen a vestige of sequence MC3-5 (see Nielsen & Schovsbo in prep. for references). Incursions of Alum Shale are locally seen in Östergötland during deposition of sequence MC3-6 (Figs 12, 52).

The sea level rose strongly in the aftermath of the Mid-*gibbus* lowstand with a major hike at the base of the *A. atavus* Zone which eventually shifted the coastline far into Russia, inundating the inverted Orcha-Volchyn Rift in Russia-Latvia-Lithuania for the first time since the earliest Cambrian (upper part of Cirma Superformation/Paneriai Fm, cf. Mens et al. 1990). As a result of the major transgression sedimentary supply was lowered radically to the epicontinental sea and this is the onset of depositional phase 4. The Hawke Bay uplift finally disapperared during deposition of sequence MC3-7 and most of Scandinavia was characterized by deposition of Alum Shale, except Östergötland-Närke, where mostly greenish mudstone was deposited (Bårstad Mbr of the Borgholm Fm, Fig. 52). The strong sea level rise at the base of the *A. atavus* Zone is locally accompanied by deposition of (unnamed) 'transgressive limestones' (Västergötland, Bornholm), but this horizon does not form a coherent regional marker bed comparable to the older Exsulans and Forsemölla limestones and which is slightly puzzling as this sea level rise was a very prominent event. But maybe living conditions on the sea floor for the shelly animals that produced the lime were less favourable than previously because the environment became too deep. There is no lithological or faunal indications of a shallowing between the *T. gibbus*/*A. atavus* zones although we suspect there may have been one. From the *A. atavus* Zone onwards the entire inner shelf from Öland eastwards to the Russian border became, with few exceptions, a zone of net non-deposition.

The geochemical signature of the Scanian Alum Shale (vanadium/nickel ratio) indicates a transient shallowing in the upper part of the *A. atavus* Zone, followed by a new sea level rise into the *P. punctuosus* Zone, there seemingly reaching a higher level than previously. This pattern is corroborated by faunal data: the trilobite assemblage seen in the Scanian Alum Shale is of low diversity and almost without "normal" trilobites (e.g. Axheimer & Ahlberg 2003, Ahlberg et al. 2008). The sea level lowstand in the late *A. atavus* Zone is taken to mark the boundary between sequences MC3-7 and MC3-8. The sequence boundary is in many places marked by a limestone bed, e.g. in Västergötland although we emphasize that this unnamed bed is not a 'transgressive limestone' and rather should be seen as an erosion resistant bed preventing further erosion during the Andrarum Lowstand (see below); it was referred to as the 'Hypagnostus limestone bank' by Weidner et al. (2004, fig 2). The upper part is conglomeratic (Hadding 1958, pp. 84-85). There are no other lithological changes to support the sequence stratigraphical interpretation. Another impediment for interpretation is the circumstance that the *P. punctuosus* Zone is absent on the shallower part of the platform (central Sweden, Öland, most of Jämtland) due to erosion associated with the prominent Andrarum Lowstand (Fig. 7).

The "*P. punctuosus* highstand" was followed by a shallowing (judging from geochemical data from the Scanian Alum Shale as well as invasion of polymerid trilobites into the Alum Shale environment of Scania-Bornholm), and which culminated in a major lowstand resulting in widespread erosion across much of the platform. In Västergötland (Falbygden-Kinnekulle) the event was associated with deposition of local pockets of conglomeratic limestone (erosional lag deposit), up to 0.15 m thick, containing a mixed *nathorsti-punctuosus* fauna (Weidner et al. 2004). The *G. nathorsti* Zone is absent on Öland and in most of Jämtland. Winnowing of Alum Shale mud also occurred in Scania-Bornholm where the Hyolithes Limestone contains much reworked trilobite/hyolithes skeletal debris. On Bornholm this bed contains a mixed fauna including elements from the *P. punctuosus* and *G. nathorsti* faunas (cf. Berg-Madsen 1985). This major lowstand is taken to mark the boundary between supersequences 3 and 4. The overlying Hyolithes Limestone (sequence MC1-1) is dark, rather anthraconitic and is thus not a typical 'transgressive' limestone. There were clearly better oxygenated conditions at the sea floor during deposition of the overlying Andrarum Limestone. For this reason we are in doubt whether the supersequence boundary rather should be defined at the base of the Andrarum Limestone, which is a typical 'transgressive' limestone. However, the Hyolithes Limestone is typically separated from the Andrarum Limestone by a thin Alum Shale, and it appears that local reworking in Scania-Bornholm was significantly stronger associated with the lowstand below the Hyolithes Limestone; no reworked shell-lag is seen incorporated in the Andrarum Limestone. On this basis the lowstand at the base of the Hyolithes Limestone is judged as of larger amplitude than the lowstand at the base of the Andrarum Limestone, although that lowstand introduced better oxygenated conditions at the sea floor. But maybe there was lesser Alum Shale to rework during the lowstand preceeding deposition of the Andrarum Limestone, and, hence, fewer fossils to concentrate. Sometimes the thin Alum Shale separating the Hyolithes Limestone from the Andrarum Limestone was eroded away during the lowstand at the base of the Andrarum Limestone and then the Hyolithes and Andrarum limestones are amalgamated.

The major lowstands at the base of the Hyolithes and Andrarum limestones were associated with non-deposition/erosion across most of Sweden and is signalled by the widespread Exporrecta Conglomerate. The following strong sea level rise was associated with deposition of the 'transgressive' Andrarum Limestone, best known from Scania-Bornholm. It is also locally developed in Västergötland (Weidner et al. 2004 and references therein), Ritland, southwestern Norway (Bruton & Harper 2000) and in the Lower Allochthon of Synfjell, Norway, where it occurs amalgamated with the Exsulans Limestone (unpublished data; the composite limestone unit is referred to as the Skinnaløkstølen Limestone on Fig. 26). The succession deposited during the 2nd order "Andrarum Lowstand" is more expanded in the Krekling area, southern Norway (Brøgger 1878), where no 'transgressive' limestone is developed (Fig. 12). The interval is seemingly also expanded in the Terne well offshore Denmark, although some limestone seems to be developed there).

The shallow marine Sablinka Fm (up to 20 m of sand, mostly less, Fig. 34) in the St. Petersburg area (see e.g. Puura 1996) may represent a detached lowstand sand unit connected to the Andrarum Lowstand, but there is no tight biostratigraphic constrain on correlation and interpretation remains model-driven. The Paala Fm of Estonia may be an equivalent unit.

The drowning signalled by the Andrarum Limestone accelerated into the upper part of the *L. laevigata* Zone and this major sea level rise re-established the Alum Shale depositional regime across much of Scandinavia in the late part of the Mid Cambrian (*L. laevigata* and *A. pisiformis* zones). A drowning "surface" (condensed interval with numerous pyrite laminae) is well developed in the Alum Shale on Bornholm immediately above the Andrarum Limestone (Fig. 53).

A moderate shallowing separated the *L. laevigata* Zone from the *A. pisiformis* Zone, locally associated with increased faunal diversity (Wallerius 1895; Bengtsson 1999), and changes in the vanadium/nickel ratio in the Alum Shale of Scania also outline the shallowing. It remains uncertain how much erosion this intermittent shallowing caused, but it may be responsible for the local instances where the *A. pisiformis* Zone directly overlies the Exporrecta Conglomerate as for instance seen on southern Öland (Westergård 1944). The lowstand is taken to mark the boundary between sequences MC4-1/MC4-2.

Renewed sea level rise during the *A. pisiformis* Zone shifted the Alum Shale facies at least as far eastwards as Gotland (cf. Ahlberg 1989); this was maximum highstand of the Middle Cambrian. The true original eastwards distribution of the Alum Shale is obviously difficult to establish due to the erosive character of the following lowstands.

9.4. Furongian

The upper part of the *A. pisiformis* Zone is on the shallower part of the platform characterized by qoquinoid limestone beds containing a profusion of reworked *A. pisiformis*. The skeletal parts exhibit size sorting (Fig. 20) and preferred orientation (Eklöf et al. 1999, Terfelt 2003) suggestive of occasional storm re-working of the Alum Shale mud, in turn taken to indicate a falling sea level bringing the sea floor within reach of storm events. Reworking intensified upwards and the top of the *A. pisiformis* Zone forms the lower part of the Kakeled Bed ("Great orsten bank" of previous literature; it is here illustrated in Fig. 15). Terfelt (2003) even reported thin pockets of quartz sand within the uppermost *A. pisiformis* Zone on Kinnekulle, Västergötland, but we have not been able to confirm his observation. A sea level lowstand between the *A. pisiformis* Zone and the *Olenus* Superzone is, accordingly, inferred and it marks the boundary between sequences MC4-2 and FU4-3. During the lowstand the sea floor in all of central Sweden, Öland and the autochthon of Jämtland were within reach of storm reworking and only condensed limestone was deposited (Fig. 7).

The sea level probably rose slightly in the early Furongian, but the shelf remained within reach of storm activity across most of Sweden. The Kakeled Bed thus typically straddles the top of the *A. pisiformis* Zone, as well as the *Olenus*, *Parabolina* and *Leptoplastus* superzones, and this marker bed is considered representing a 2nd order sea level lowstand, informally referred to as the *Olenus-Parabolina* lowstand.

The iterative narrowings of *Olenus* species described by Kaufmann (1933a,b, 1935) probably reflect successive events of ventilation of the bottom environment in Scania-Bornholm during the earliest Furongian, but whether these events reflect sea level cycles remain speculative; they are ignored here. The older zones of the *Olenus* Superzone are more widely distributed in Scandinavia than the youngest zone (Westergård 1922, 1947a) – and the latter is also strongly expanded in Scania (see Fig. 27 and Westergård 1922). This is taken to indicate a lowering of the sea level towards the close of the *Olenus* Superzone with non-deposition across the greater part of the platform and outboard transport of the mud. The upper part of the *Olenus* Superzone is a "barren interval" devoid of calcite shelled fossils in Scania (Fig. 21) and this horizon is taken to mark peak lowstand (see remarks in section 7.1.). This lowstand separated deposition of sequences FU4-3 / FU4-4.

The *Parabolina* Superzone typically forms part of the Kakeled Bed in several districts of Sweden, suggesting that the sea level stayed low. The contemporaneous fauna described from Jämtland includes brachiopods of 'Middle Cambrian' aspect (Bergström 1980). The *Parabolina* Superzone also contains the highest number of 'normal' trilobites recorded from the Furongian Alum Shale Formation and brachiopods are extremely common, occasionally even rock-forming (Fig. 19i). The marginal successions, e.g. in Scania, are on the other hand expanded (see e.g. Westergård 1922). All these observations indicate that the sea level remained low during the *Parabolina* Superzone. The *P. spinulosa* Zone is much more widely distributed than the *P. brevispina* Zone (Fig. 7), and is in some districts developed as shale. This indicates that the sea level overall rose towards the end of the *Parabolina* Superzone and was lower in the *P. brevispina* Zone. Geochemical data (vanadium/(nickel ratio) from the Alum Shale of Scania, suggest, however, that the sea level rose into the *P. brevispina* Zone, but then fell again in the upper part of the zone and this lowstand is here taken to separate deposition of sequences FU3-3/FU3-4. The lowstand was associated with deposition of brachiopod coquinas on for instance Bornholm (see Hansen 1945, p. 19), suggesting that the local sea floor temporarily was within reach of storm activity. However, unravelling 3rd order sea level changes during the *Olenus-Parabolina* 2nd order lowstand remains uncertain because the interval is so strongly condensed in most sections from mainland Sweden.

The Petseri Fm (up to 11 m of sandstone) in southern Estonia and the Ülgase Fm (up to 14 m thick sandstone) in northern Estonia may represent detached lowstand sands deposited during this 2nd order event (for stratigraphic details, see Mens et al. 1990, Puura 1996).

The *Leptoplastus* Superzone is, generally speaking, a condensed maximum drowning "surface", reflecting renewed sea level rise in the wake of the major *Olenus-Parabolina* lowstand. Many zones of the *Leptoplastus* Superzone are missing across much of Sweden, locally even in the Oslo region (Fig. 7), and which at face value is suggestive of non-deposition or erosion during a lowstand (or, rather, two lowstands, one at the base and one at the top of the superzone). This is, however, believed to be an artifact of preservation. The *Leptoplastus* Superzone is the thinnest of all the Furongian superzones (e.g. Fig. 27) and several of the constituting thin zones are characterized by just one olenid species and we believe that some of the index fossils for one reason or the other have not been found except in a few sections (if no limestones are present the fossils are not preserved). The *Leptoplastus* Superzone is everywhere thin, at most some 3 m, but across much of central Sweden it strongly condensed and sometimes represented only by isolated pockets of fossiliferous limestone in the uppermost part of the Kakeled Bed. Sections in Oslo (unpublished) and Scania (Ahlberg et al. 2006) do not indicate significant depth changes in the depositional environment during deposition of the *Leptoplastus* Superzone and we tentatively infer a gradually rising sea level during the superzone. It was probably a much shorter time interval than indicated in the diagram Fig. 54, which is constructed allotting the same duration to all biozones within a stage.

The increase in depth of deposition continued into the *P. praecursor* Superzone, at which stage 'normal' Alum Shale deposition commensed throughout central Sweden, suggesting that the region now came below storm wave base. The widespread absence of the *C. similis* Zone at the base of the *P. minor* Superzone could be taken to indicate a transient shallowing but the zoen is thin and the index fossils rare, so it is susopected that its absence is an artifact of the fossil record. There are no faunal, lithological or geochemical indications of a shallowing at this level. Maximum flooding during the Furongian took place in the middle part of the *P. minor* Superzone at which stage strongly condensed, TOC-rich Alum Shale was deposited. This thin unit is conspicuous on gamma logs.

The sea level briefly fell again briefly in the uppermost part of *C. tumida* Zone and this event is well-constrained. The vanadium-nickel data from Scania clearly indicate this oxygenation event and brachiopods and agnostids appear at this level in the Scanian Alum Shale (Westergård 1922, Christensen 2003). In Västergötland a horizon in the *P. minor* Superzone shows exhumed, partially dissolved limestone concretions, some still erect, other tilted over (Fig. 17). It is obvious that c. 0.5 m of Alum Shale was removed in the local Alum Shale environment.

The sea level rose again and remained high in the lower part of the *P. scarabaeoides* Superzone, which is also developed as Alum Shale across Sweden (cf. Westergård 1922). At the same time this part of the Alum Shale is comparatively condensed in Scania, reflecting that most sediment was trapped further inboard on the shelf. Thus the zone is typically thicker in central Sweden than in Scania, despite minor erosion during the subsequent *Acerocarina* Superzone (see below).

Faunal changes (representatives of *Parabolina* again became common, *Ctenopyge* largely disappeared) and presence of numerous limestone beds consisting of winnowed trilobite hash in central Sweden and Öland show that the sea level fell again in the upper part of the *P. scarabaeoides* Superzone. At this stage *Peltura*-type trilobites became common in the Alum Shale in Scania (Westergård 1922; Christensen 2003). The youngest *P. paradoxa* Zone is developed only in the offshore areas of Scandinavia and is here relatively thick; it is separated from the *Acerocarina* Superzone by a "barren interval" in Scania (Fig. 21), taken to mark peak lowstand (see remarks in section 7.1). Accordingly, we infer that the later half of the *P. scarabaeoides* Superzone was a lowstand and which seemingly culminated at the close of the superzone. This lowstand is taken to mark the boundary between sequences FU4-7 and FU4-8. The shallowing may correspond to the socalled Lange Ranch eustatic event (Miller 1992, Nicoll et al., 1992).

The Tsitre Fm in northern Estonia (less than 10 m thick sandstone) may be a detached lowstand sand associated with this second order lowstand (for stratigraphic details, see Puura 1996, Mens & Pirrus 1997).

The ensuing *Acerocarina* Superzone is absent in the greater part of central Sweden and Öland. This general absence has been ascribed to a low sea level, referred to as the *Acerocare* Regressive Event by Erdtman (1986), but which was considered a misnomer by Nicoll et al. (1992), who suggested restricting this term to the terminal Furongian lowstand during the *A. ecorne* Zone. The shown sea level curve (Fig. 54) is drawn according to variations in the Vanadium/Nickel ratio within the Scanian Alum Shale, the presence of several "barren intervals" in the Scanian succession (Fig. 21, see remarks in section 7.1) and the presence of the *P. costata* Zone on Kinnekulle, Västergötland, and on southern Öland. There is a very good internal accordance between these data. The *P. costata* Zone on Kinnekulle has recently been reinvestigated by Weidner & Nielsen (in press b). It contains a range of reworked trilobites including *Peltura transiens,* characteristic of the *A. granulate* Zone at the base of the *Acerocarina* Superzone, and which thus seems to have been deposited somewhere in the vicinity, probably further downslope westwards. We therefore infer that the sea level rose again in the *Acerocarina* Superzone to reach a temporary maximum in the *P. costata* Zone after which time it fell again and it seemingly reached a new lowstand towards to the close of the *Acerocarina* Superzone, here referred to as the Acerocare Regressive Event (ARE).

Overall, the *Acerocarina* Superzone is interpreted as a 2nd order lowstand interval. The lower part of the sandy Kallavere Formation (total thickness up to 20 m) in Estonia, which is quite well-dated by conodonts, corresponds in age to this lowstand and is inferred representing a detached lowstand sand unit. The upper part of the Kallavera Fm was deposited during the initial Tremadocian transgression.

9.5. Tremadocian

Calcite shelled fossils are in general very rare in the Tremadocian Alum Shale, likely due to early dissolution (cf. section 7.1). This indicates repeated oxygenation of the sea floor during deposition and a relatively high oxygen content in the bottom environment (albeit still dysoxic). This is corroborated by geochemical evidence (vanadium/nickel ratio), suggesting higher general oxygenation during deposition in the Tremadocian than during most of the Furongian (Schovsbo 2001). The generally higher oxygen conditions in the Tremadocian is seemingly unrelated to sea level changes (i.e. does not reflect a generally lower depth of deposition), but deprives us the possiblity of using facies dependent trilobites for constraining depth changes during deposition.

The lower part of the Tremadocian is characterised by prolific occurrence of graptolites (*Rhapdinopora* spp.). Thin horizons with high concentrations of graptolites are taken to signal drowning events (maximum drowning surfaces). According to this line of interpretation, the faunal abundance data from the Flagabro drillcore of southeastern Scania, Sweden (Tjernvik 1958, fig. 3) suggest 4 rapid sea level rises in the early Tremadocian. This is corroborated by the detailed occurrence data from the Alum Shale at Tøyen, Oslo (Bulman 1954, pp. 14-28), also showing that *P. parabola, P. socialis* and *P. flabelliformis* occur abundantly in three thin successive levels, followed by more horizons with *flabelliformis* and other species higher up. The inferred rises are taken to signal 3rd order sea level changes, but the sequences are very strongly condensed in this offshore environment (average accumulation rate was c. 1 mm per 1000 yrs). There seems to be two flooding surfaces within the *R. flabelliformis* Zone, which here tentatively is ranked as 4th order cyclicity but maybe one more sequence is represented. For the moment 3 early Tremadocian sequences are recognized (labelled TR4-9 to TR4-11).

The name Stonehenge Transgression is available for the early Tremadocian sea level rise (Taylor et al., 1992). It may be that the Black Mountain Eustatic Event (BMEE) sensu Miller (1984) (not Nicoll et al., 1992) matches the *socialis* level, which apparently is roughly coinciding with the incoming of the conodont *C. angulatus* (Cooper 1999). This remains uncertain, however, and the available names may refer to the same event.

The major 2nd order sea level rise at the beginning of Tremadocian lead to a spread of Alum Shale deposition into the East Baltic area (Türisalu Formation), notably during the *R. socialis* time (see Kaljo & Kivimägi 1976). The upper part of the Kallavere Formation seems to be deposited during the initial sea level rise of the Ordovician. There is little question, however, that the eastwards spread of Alum Shale deposition not only was due to a major sea level rise, but also reflects local collapse of the Mid Cambrian uplift “ridge” that still had a slight positive relief in the Furongian (Fig, 38). We emphasize that this makes it difficult to scale the Tremadocian sea level rise/highstands relative to earlier highstands.

A westwards spread of deposition is also seen in the Tremadocian (see Fig. 30 vs Fig. 31). Pockets of Alum Shale representing the *R. socialis* Zone have also been recorded in the Siljan area, Sweden (Jaanusson 1982b).

A gradual sea level lowering is inferred at the base of the *Adelograptus* Zone, based on the faunal change seen e.g. in the Flagabro drillcore (Tjernvik 1958) and associated lithological changes, as also seen on Bornholm, Denmark (see Nicoll et al. 1992). This shallowing heralded a longer-lasting lowstand during the *Adelograptus* Zone throughout which the sea level lowered further. Most of the *Adelograptus* Zone is non-graptolitic in the Oslo area, which is interpreted as a result of increased biological activity at the sea floor and lack of preservation. Graptolites also disappear upwards in the zone in Scania and brachiopods then become very abundant, forming the so-called Brachiopod beds (Hede 1951). Note that the brachiopod beds are characterised entirely by phosphatic shelled brachiopods whereas calcite shells probably were dissolved. During the mid-Tremadocian peak lowstand, called the *Peltocare Regressive* Event (PRE) by Erdtmann (1986), a thin dark limestone with a sparse trilobite fauna was deposited in the Oslo area (the Incipiens Limestone; see Nielsen & Schovsbo 2006 for references). It is currently unsettled whether this thin limestone unit is ‘transgressive’; it may well be. In that case it signals the sea level rise in the aftermath of the lowstand and the designation *Peltocare Regressive* Event is strictly speaking a misnomer. The vanadium/nickel ratio of the Scanian Alum Shale corroborates the outlined interpretation for the early Tremadocian.

The *Peltocare* Regressive Event was followed by a new drowning. The amplitude of this rise is poorly constrained, but deposition of Alum Shale seems to have continued in Estonia. The sea level gradually lowered again in the late Tremadocian. This general lowering was punctuated by a very short-lived drowning event immediately below the Bjørkåsholmen Formation [= the Ceratopyge Limestone of older literature] in the Oslo area, where graptolites again are concentrated in a thin interval see Erdtmann 1965, Spjeldnæs 1985). At this level is also seen a very thin Alum Shale at the top of glauconite beds in the collapse structures at Brattefors in central Sweden (for general setting, see Teves & Lindström 1988; Löfgren 1997 for conodont dating). Another very short drowning event in the basal part of the Bjørkåsholmen Fm is signalled by incoming of Olenid trilobites throughout the Oslo region (cf. Ebbestad 1999).

There are no indications of a break in deposition between the lower and upper part of the Alum Shale in Estonia marking the Peltocare Regressive Event, but a hiatus may be rather inconspicuous in soft mudstone. A silty/sandy intercalation is present in the middle part of the Alum Shale in western Estonia (Pukkonen & Rammo 1992). The late Tremadocian part of the Alum Shale in Estonia with *Kiaerograptus* contains thin sandy layers (probably distal storm beds), indicating a shallower depositional environment than during the early Tremadocian.

Deposition of Alum Shale was terminated by the conspicuous so-called Ceratopyge Regressive Event (CRE of Erdtmann 1986). It is, however a misnomer, as the Ceratopyge limetone [now Bjørkåsholmen Fm] is a 'transgressive limestone' comparable to the Exsulans and Andrarum limestones of the Middle Cambrian. The lowstand took place at the base of the limestone and was associated with non-deposition in the offshore areas. Across much of central Sweden the base of the Bjørkåsholmen Fm is developed as a major unconformity due to significant erosion during the sea level lowstand and likely also local Tremadocian uplift (Fig. 38H). Tremadocian Alum Shale is thus absent across much of Västergötland and entirely so in Närke. Tremadocian Alum Shale is also absent at most localities in Jämtland. Whether this reflects erosion during the CRE or non-deposition/erosion due to uplift (or a combination) is currently unsettled.

10. Discussion

The Alum Shale Formation of Scandinavia differs from all other black shales present in the Lower Palaeozoic of Baltoscandia – or the world for that matter – by being extraordinarily rich in organic matter and trace elements, yet it contains abundant limestone in some areas and is overall rich in shelly fossils. Coeval less condensed Alum Shale-like deposits are known e.g. from the microcontinent Avalonia (UK, Newfoundland) (e.g. Martin and Dean, 1981; Brasier et al. 1992) but they are not nearly as enriched in trace elements or organic matter. The widespread distribution on a global scale of notably Furongian black shales but also Middle Cambrian and Tremadocian shales (e.g. Berry & Wilde 1978, Leggett 1980) suggest that the general oxygen level in the atmos- and hydrosphere was far below modern values during this time interval. However, the uniqueness of the Alum Shale Formation indicates that local conditions also somehow amplified the dysoxidity in the epicontinental sea covering western Baltica. We infer a setting with uplifted outer margins of Baltica which created barriers impeding the free exchange of water masses and for this reason the general global dysoxidity became further amplified within the epicontinental Alum Shale Sea. The uplift of the margins most likely reflects isostasy related to concurrent plate tectonic processes, maybe ridge push. We note that deposition of Alum Shale commenced in the aftermath of the Hawke Bay Event (isostatic uplift concurrent with eustatic sea level lowstand, see above), which is strongly suspected to mark the onset of subduction in the ocean adjacent to Baltica (Nielsen & Schovsbo in prep.).

Deposition of the Alum Shale was terminated by the prominent sea level lowstand referred to as the Ceratopyge Lowstand Event (CRE) in the late Tremadocian (Nielsen 2004 and references therein). However, like the Hawke Bay lowstand this cannot just have been a eustatic event – then deposition of Alum Shale should have resumed as the sea level again rose. But from then on no Alum Shale-like depositional environment reappeared in Scandinavia and at the same time clastic supply from a western source commenced. This is taken to indicate that the prominent Ceratopyge Regressive Event was associated with downwarp of the western margin of Baltica, probably because the active Caledonian collision zones shifted to a position closer to Baltica. However, it may further be speculated that the CRE, which was one of the most major lowstands in the entire Ordovician and comprised several rapid pulses of changing sea level (Nielsen 2004), reflects a glacial period that theoretically may have been associated with more vigorious global oceanic circulation enhancing the general oxygenation level in the oceans. This scenario remains, however, speculative.

The uplifted southern margin of Baltica did not disappear at the same time, on the contrary it appears that southernmost Scandinavia was uplifted shortly prior to the CRE event. The uplift must have been minor, though, as the Alum Shale of the area was not within reach of storm waves during the prominent CRE lowstand.

Deposition of the Alum Shale Formation was thus in our interpretation bracketed by local tectonic events which in combination with a generally low global oxygen level in the Mid Cambrian-Tremadocian and notably during the Furongian was responsible for this unique depositional phase in Scandianavia.

Alum Shale was deposited from about the storm wave base and further outboard, i.e. on the outer shelf. Unpublished modeling of Early Cambrian sea level changes (Nielsen unpubl.) suggests that the effective storm wave base may have been as deep as 70-80 m, at least along the margins of Baltica and this may also have been the case later on in the Cambrian. This is maybe not so surprising taking into consideration that Baltica probably was located in the southern storm belt with a long free stretch to the nearest neighbouring continent. Hence storms are likely to have played an important role in the depositional environment, especially because the sedimentary supply was extremely limited with ample time for repeated storm reworking. The slope gradient of the subcambrian peneplain was also calculated by Nielsen (unpubl.), suggesting an average slope as low as 1-2 m per km. That figure was actually derived from a sea level curve, constructed on the premise that accommodation space was exclusively created by eustatic sea level rises during the Early Cambrian and which seems not to have been the case (local subsidence occurred adjacent to inversion zones). The average figure is therefore likely exaggerated and may in reality have been as low as 0.5-1 m per km. Since much original topography was leveled out by the thick blanket of Lower Cambrian sediments, the slope gradient of the epicontinental sea may later on have been even lower. If the Furongian sand packages described from Estonia represent detached lowstand sands (see section 9.4) deposited close to the shore during incipient sea level rise, as we consider them to be, at the same time as central Sweden was within reach of storm waves during the lowstands, rough calculations of the average sea floor slope between Estonia and central Sweden (some 550 km, assuming a deep SWB at 70-80 m) suggest an average slope as low as 0.1 m per km. It may of course be objected that the transect from Estonia to central Sweden was oblique to the true slope (the conditions on the isle of Öland for instance indicates a ≈ north-south slope), but an extremely low slope of the sea floor is corroborated by the extraordinary great width of the inner shelf, characterized by non-deposition, and which seems to have been as much as 600-700 km wide. These rough calculations are relevant for assessing the effects and scale of sea level changes during deposition of the Alum Shale. Whatever the true slope was, we stress that the sea floor of the Alum Shale Sea was exceedingly flat.

The storm wave base was lowered during sea level lowstands and which led to submarine erosion of the Alum Shale mud deposited between the original storm wave base and the lowered storm wave base. Winnowing removed the unconsolidated mud and left behind the more resistant limestone and shell debris or was stopped at durable limestone beds preventing further erosion, and as a result the relative proportion of limestone and intraformational conglomerates increase in an adlittoral direction in the Alum Shale facies (see e.g. Fig. 16). Many of the limestone beds consist of abraded trilobite hash winnowed from the mud. The reworked mud was transported outboard and deposited below the storm wave base. Recurrent lowstands were associated with repeated episodes of winnowing creating the marked difference between the stratigraphically rather incomplete, limestone-rich Alum Shale facies characterizing the shallower parts of the epicontinental sea and the expanded, relatively limestone-poor (mainly concretions) Alum Shale deposited further offshore.

The inner shelf shorewards of the Alum Shale environment was characterized by net sedimentary bypass. The sedimentary supply was undoubtedly overall low and most likely also rather fine-grained as suggested by the general absence of sandstones of any noteworthy thickness, but the total absence of sediments across large reaches of the inner shelf requires reworking as fine-grained sediment must have settled there during fair-weather conditions. It is possible that the normal back-ground sedimentation was regularly interrupted by reworking during storms with outboard transport of the suspended material. Lasting deposition simply may not have occurred above the normal storm wave base, except close to the shore. Alternatively it is possible that most of the redeposition took place during sea level lowstands, significantly increasing the energy level in the inner shelf area. Or maybe a combination of these factors was at play. At any rate a large sector of the inner palaeo-shelf, several hundreds of kilometers wide, is largely devoid of a sedimentary record.

Thin units of Middle Cambrian-Furongian-Tremadocian fine-grained sandstones are described from the East Baltic region (for summary, see Puura1996) and they have been taken to indicate the approximate position of the shore during deposition of the Alum Shale (e.g. Buchardt et al. 1997). However, we interpret these units as detached lowstand sands deposited during incipient sea level rise in the aftermath of major sea level lowstands. If this inference is correct, the coastal zone was most of the time during deposition of the Alum Shale located even further eastwards, i.e. somewhere in Russia. Because of the wide belt of non-deposition, separating the Alum Shale from the nearshore coarser clastic deposition, in combination with the direct onlapping of Alum Shale onto the basement in some areas of Scandinavia, e.g. Oslo-Jämtland, there has been a tendency of inferring a coastline not far eastwards of the Alum Shale area (e.g., Westergård 1922 p. 108, Hansen 1945, Henningsmoen 1957 p. 62), an interpretation with which we disagree.

The high content of organic matter and pyrite in the Alum Shale in combination with the preserved lamination have led most previous authors to conclude that the depositional environment was anoxic. This is, however, at odds with the presence of a prolific fossil fauna and we emphasize the need for distinguishing between dysoxic and anoxic conditions. Black shales cannot routinely be taken as an indication of anoxia in the palaeoenvironment although anoxia obviously prevailed within the sediment from just below the sea floor. It remains an open question whether the presence of life – which obviously was specialized to live under low oxygen conditions – reflects "blooms" during short lived oxygenation events or general dysoxia but with enough oxygen present to permit an opportunistic fauna to survive most of the time. We are inclined to favour the latter scenario. It is in this context relevant to emphasize that present-day dysoxic bottom environments typically are characterized by bacterial mats (Wignall, 1994), and there is no reason to believe that the Alum Shale bottom was a poorly defined soupy water/sediment transition. The outline of pyrite "smudges" on Alum Shale bedding planes often resembles modern bacterial mats (cf. Fig. 55, showing these structurs in the younger Dicellograptus Shale). Anoxic and probably even euxinic conditions prevailed within the sediment from immediately below the sea floor/bacterial mats, preventing an infauna to destroy the fine sedimentary lamination. In order to survive in this harsh bottom environment, the opportunistic fauna had a large spat production that rapidly developed in profusion whenever the conditions permitted, like typical for many opportunistic animals. Especially the agnostid trilobites also seems to have had long-lived larvae – another obvious advantage for surviving under difficult conditions as at least some larvae were likely to reach areas to settle successfully in. At the same time these survival strategies made the agnostid and olenid trilobites excellent widespread index fossils useful for biostratigraphy.

The Alum Shale Formation appears very homogenous at a first glance, but at closer examination a range of intraformational differences become evident. The regional differences in proportion of limestone content are already addressed above. But also the trace element and organic content exhibit systematic stratigraphical differences. The Furongian Alum Shale thus exhibits the highest enrichment in both trace elements and organic matter, wheras the Middle Cambrian Alum Shale is significantly more lean in organic matter (average 4.9 % vs 10.3 % for Alum Shale in Scania) and contains much lower concentrations of trace elements. The Tremadocian Alum Shale exhibits intermediate values. This persistent pattern is ascribed to general differences in dysoxidity in the depositional environment with lowest oxygen levels in the Furongian (Fig. 11). The consistent pattern can be used for stratigraphical correlation, based on geochemsistry and log interpretation in wells, and it is also relevant for shale gas exploration as the Furongian shales obviously has highest economical potential.

The Alum Shale Formation is also characterized by several regional hiati developed across Sweden (Fig. 7). The Alum Shale of Scania-Oslo (and likely also most of western Denmark) is the stratigraphically most complete without obvious gaps. The regional hiati is ascribed to non-deposition and erosion during sea level lowstands, as discussed above. It is vital to keep in mind that highstand intervals also may be missing in the sedimentary record due to erosion during a subsequent lowstand which is critical when trying to decipher sea level oscillations from the preserved sediments. This condition makes it difficult to rely on coastwards migration of the Alum Shale facies for reconstructing an "onlap curve". The missing time intervals are represented in the offshore areas, often as relatively expanded sections, but here the lithology is very monotonous and unravelling sea level changes require detailed palaeontologcal and geochemical data. Reconstructing the sea level changes and establishing a sequence stratigraphy is thus a task fraud with difficulties in this offshore environment and conventional approaches are of little use.

The task is further complicated by local stratigraphic anomalies due to transient uplifts in some areas, associated with non-deposition and erosion, sometime even severe erosion. These local uplift events are still not fully understood and their temporal and geographical delimitations remain to be studied carefully, but we assume that they were intracratonic isostatic responses to ongoing plate tectonic in the adjacent oceans. It is beyond the scope of the present report to discuss conditions outside Baltica, but it is striking to note that the Alum Shale-like Elliot Cove and Clarensville formations on Random Island, Newfoundland, Canada (> 1.6 km thick) are separated by a late Furongian gap comprising the upper half of the *Peltura scarabaeoides* Superzone as well as the entire *Acerocarina* Superzone (except maybe the uppermost *Acerocare ecorne* Zone) (Poulsen & Nielsen in prep). This disturbance in a setting on the opposite site of the Tornquist Ocean matches the late Furongian gap seen in Baltica. Also, the successions preserved in the Holy Cross Mts in southern Poland, likely representing deposition on a microcontinent adjacent to Baltica, record tectonic disturbances at the end of the Mid Cambrian and within the Tremadocian (e.g. Trela 2010), corroborating that plate tectonic events did take place at the same time as isostatic movements occurred in Baltica. This important perspective bears further investigations.

The newly constructed isopach maps clearly show that the depositional pattern differered between the Middle Cambrian, Furongian and Tremadocian (Figs 29–31) and the inferred isostatic disturbances are likely controlling these differences. The Alum Shale Formation is strongly disturbed (folded and internally stacked) in the Caledonian orogen and thickness data are generally unreliable. It appears, however, that there were two depocentres in the central part of the Caledonides divided by one or, more likely, several highs, corresponding to the tectonic windows (Fig. 25). The windows thus seem to reflect original basement highs.

Through most of the Tremadocian the western plate margin seems to have been progressively subsiding, leading to a westwards migration of the Alum Shale facies, and this may have caused the observed gradual increased ventilation of the epicontinental sea covering Scandinavia. Eventually the western uplift seems to have disappeared associated with the CRE in the late Tremadocian.

The 2nd order sea level changes are summarized below (see section 11 and Fig. 56). The repeated rapid sea level oscillations seen in Supersequence 3 and lower part of Supersequence 4 probably reflect glacio-eustasy. The late Tremadocian Ceratopyge Regressive Event is also strongly believed to reflect a glacial interval.

The lowering of the sea level at the base of the Furongian was associated with an intensification of the dysoxic conditions in the Alum Shale Sea, as indicated in Fig. 11. In theory a lowering of sea level may have caused decreasing exchange of water masses across the sills along the margins of Baltica, amplifying the oxygen shortage in the bottom environment of the Alum Shale Sea, but the dysoxidity remained low also when the sea level rose later in the Furongian. Hence, restricted circulation was likely not the main reason for the hike in dysoxidity seen at the base of the Furongian and this was probably a global phenomenon (the SPICE Event, see Saltzman et al. 2000).

It is unclear whether the sea level during the late Furongian "*P. minor* highstand" reached the same high level as during the late Mid Cambrian *A. pisiformis* Zone. Interpretation is hampered by the changing basinal outline so observed shorewards migration of the Alum Shale facies is difficult rely upon. At face value the sea level was highest during deposition of the *A. pisiformis* Zone with most widespread deposition of Alum Shale. It is also not clear whether the sea level reached an even higher level during the early Tremadocian or whether the wider distribution of Ordovician Alum Shale deposition is due to isostatic subsidence, notably of the Estonia-Åland ridge (cf. Fig. 38).

It has been claimed that the sea level overall was low during the late Furongian *Acerocarina* Superzone (the Acerocare Regressive Event of previous literature, see Nicoll et al. 1992 for references) but erosion associated with the late Furongian uplift and the Ceratopyge Regressive Event may in theory be partly or entirely responsible. However, if the conditions at Kinnekulle, Västergötland, are representative, a highstand may be inferred for the *P. costata* Zone shortly into the *Acerocarina* Superzone and which exactly matches geochemical data from the Scanian Alum Shale, suggesting increased dysoxidity shortly into the superzone.

10.1. The Alum Shale Formation in Denmark: How thick?

The Alum Shale Formation subsurface Denmark is expected to compare well with the lithology of the Alum Shale known from Scania, i.e. by being relatively expanded and by showing low concentration of (mainly concretionary) limestone. At present the formation has been encountered only in the two deep wells Slagelse-1 and Terne-1.

The Alum Shale is seemingly rather thin in the Slagelse well. The gamma-log from this old well is of poor quality and low resolution, but facilitates a crude interpretation of the Alum Shale. We have accepted this interpretation in the present report but it cannot be excluded that parts of the Alum Shale in fact are faulted out in this well. The issue has significant economical relevance as the organic-rich Furongian interval is the most interesting for shale-gas exploration and that interval is relatively thin on southern Zealand if the succession in the Slagelse-1 well is representative for the area.

The offshore well Terne-1, located in Kattegat, contains on the other hand an expanded Alum Shale section which according to interpretation based on logs and cuttings is 178 m thick. It seems to be in particular the Middle Cambrian section that is unusually expanded. It is uncertain how to extrapolate the thickness trends from the Terne-1 well and southern Norway into northern Jutland, see maps shown in Figs 25 and 29–31. Each map is deliberately drawn independently from the other maps, and for this reason they are not entirely internally consistent, but they thereby illustrate the uncertainty how to extend the thickness trends into northern Jutland. Because northern Jutland lies within the NW-SE striking Tornquist fault Zone, it is tempting to infer a NW trend of the thick Alum Shale from the Terne-1 well, but maybe the main controlling factor was the east-west striking southern margin of Baltica. Also, a thinning of the Alum Shale towards the western plate margin must be anticipated, as seen in southern Norway. The principal question is from which point in Denmark this westwards thinning starts and which is of utmost relevance for predicting the thickness of the Alum Shale Formation below northern Jutland.

The abrupt change of thickness of the Alum Shale Formation seen between the five deep wells in SW Scania (see section 8.3) suggests that local subsidence may have been fault controlled. The thickness of the Alum Shale thus decreases 20 m within just 6 km. A significant denser data coverage is needed to reveal whether or not such abrupt thickness changes also occur in the Danish area. The precise direction of the potential growth fault in

SW Scania is highly relevant for a shale-gas play in northern Zealand, if the fault happens to extend into the Danish area.

From an academic point of view the new well in northern Jutland will provide exiting new data, constraining the mapping and eventully furnishing evidence whether an incipient Tornquist Zone influenced subsidence in the Alum Shale Sea or not. But it may turn out that the Alum Shale Formation is much thinner in northern Jutland than hoped for; the unit is only some 45 m at Rognstranda in southern Norway (Fig. 25).

The Alum Shale is overlain by a thick unit of quartz sandstone in SW Norway, the socalæled Holberg Quartzite (Andresen 1978). This sand must derive from a land area in southnmost Norway, the socalled Telemark Land (see Rasmussen et al. 2011). The precise position and size of this land area are unknown (Fig. 38H). It is even a remote possibility that the Alum Shale is overlain by sandstone in northern Jutland.

11. Conclusion

- The Alum Shale Formation is a comparatively condensed unit, up to 100-180 m thick but mostly much thinner, deposited under low oxygen conditions in an epicontinental sea that covered all of Scandinavia for a period of almost 30 my from the Mid Cambrian to the late Tremadocian.
- The general oxygen level was low on a global scale at that time, but was probably locally amplified in the Alum Shale Sea by uplift of the margins of Baltica, creating silled basin conditions.
- The late Early Cambrian – mid Mid Cambrian Hawke Bay "Event" involved uplift of Scandinavia, initially concomittent with a eustatic sea level lowstand. The uplifted areas slowly and differentially subsided into the Mid Cambrian and in some areas the uplift lasted for 5-6 my. The uplifted areas were flooded shortly into the Mid Cambrian but were characterized by non-deposition. It is likely that the western margin of Baltica also was uplifted during the Hawke Bay Event and silled the Alum Shale Sea (see below). The Hawke Bay uplift event may be an example of rapid isostasy due to stress changes in the mantle (cf. Cathles & Hallam 1991). The event likely marks the onset of subduction in the ocean (Iapetus or Ægir) adjacent to Baltica.
- The late Tremadocian Ceratopyge Regressive Event was a prominent, multiphased lowstand that marks the end of the Alum Shale depositional regime. It likely reflects glacioeustasy. The event probably coincided with disappearance of the uplift western margin of Baltica. However, the western margin probably gradually subsided during the Tremadocian, leading to slowly improved ventilation of the Alum Shale environment and a westwards spread of Alum Shale deposition. The development is taken to reflect that the incipient Caledonian collision zone shifted closer to Baltica. From the latest Tremadocian onwards Baltica received increasing clastic supply from a western source.
- Faunal and geochemical data are indicative of decreasing oxygen concentrations in the Alum Shale Sea during the Mid Cambrian with a major hike in dysoxidity from the base of the Furongian onwards. During the Furongian dysoxic conditions even prevailed on the inner shelf above storm wave base. The oxygen level rose again from the late Furongian to the end of the late Tremadocian, unrelated to changes in general depth of deposition. Because the dysoxidity was highest during the Furongian this interval has the highest economic potential, both with regard to hydrocarbons, but also with regard to e.g. Uranium.
- Alum Shale was deposited from about the storm wave base and deeper. The inner shelf above storm wave base was characterized by net sedimentary bypass. The shore was distant and located somewhere in Russia most of the time. Shallow marine sandstones were deposited close to the shore. The shallow marine sandstones known from Estonia and the St. Petersburg area are interpreted as detached lowstand sands, deposited during incipient sea level rise in the aftermath of major lowstands.
- Some sediment were supplied from a western source (mining of Lower Cambrian sand on the uplifted margin?) early in the Mid Cambrian and at the same time some sediment may have been supplied from the uplifted parts of Scandinavia (Hawke Bay Event) but by far most sediment derived from an eastern source. From the late Mid Cambrian onwards all sediment derived from an eastern source; as far as can

be established no sediment were supplied from the Calidonian collision zone.

- The sea floor was sub-horizontal; the average slope is estimated at < 1 m per km.
- Recurrent sea level falls led to lowering of the storm wave base, in turn causing erosion of the Alum Shale mud located in the zone between the original position of the storm wave base and the lowered position. The sedimentary record from the shallower parts of the Alum Shale Sea is therefore characterized by numerous hiati, intraformational conglomerates and a high proportion of limestones that consists of winnowed concretions and bioclatic units, formed by trilobite test winnowed from the resuspended mud.
- The distal offshore Alum Shale environment is characterized by thicker Alum Shale without internal hiati and much less limestone.
- The palaeoenvironment must have contained oxygen, at least occasionally, permitting a specialized fauna to thrive. We believethat the depositional environment was dysoxic, not anoxic, most of the time. A high reolution biozonation is based on the common presence of rapidly evolving trilobites.
- The Alum Shale mud was anoxic, probably euxenic, from just below the sea floor and no infauna disturbed the fine sedimentary lamination. The sea floor was probably covered by bacterial mats.
- Multiple local isostatic events, probably reflecting ongoing plate tectonic processes in the adjacent ocean, were associated with temporal changes in basinal subsidence. Local uplifts (Hawke Bay Event, mid Mid Cambrian, late Furongian, late Tremadocian) were associated with non-deposition and often also erosion.
- Subsidence in concert with a strongly rising sea level was responsible for incursion of Tremadocian Alum Shale into northern Estonia-westernmost Russia.
- On a 2^{nd} order scale (Fig. 56) the sea level was low early in the Mid Cambrian to rise significantly in the middle part of the Mid Cambrian, associated with a spread of Alum Shale deposition. After a series of major lowstands in the late Mid Cambrian, likely signalling a glacial episode and forming a 2^{nd} order sea level lowstand, the sea level rose prominently towards the close of the Mid Cambrian, resulting in deposition of a rather uniform blanket of Alum Shale across much of Scandinavia, even reaching as far eastwards as Gotland. A new drop of sea level at the base of the Furongian heralded a 2^{nd} order lowstand during the *Olenus* and *Parabolina* superzones. During this lowstand sedimentation was repeatedly interrupted across mainland Sweden and virtually only limestone was deposited. The sea level rose again through the *Leptoplastus* and *P. praecursor* superzones to reach a maximum highstand in the *P. minor* Superzone. The sea level remained high in the early part of the *P. scarabaeoides* Superzone to lower towards the end of the zone, forming a 2^{nd} order lowstand. The sea level rose shortly again in the early part of the *Acerocarina* Superzone but then fell again towards the end of the Furongian. This 2^{nd} order lowstand was terminated by a major sea level rise in the earliest Ordovician, comprising several pulses. During the early Tremadocian highstand deposition of Alum Shale even encroached into northern Estonia and western Russia and this stage seemingly marks the highest sea level during deposition of the Alum Shale. The transient isostatic uplifts and subsidence events make it difficult, however, to calibrate the late Mid Cambrian, mid Furongian and early Tremadocian highstand levels internally.
- After a mid Tremadocian moderate lowstand the sea level rose again, before the Alum Shale depositional interval eventually was terminated by the prominent Ceratopyge Regressive Event in the late Tremadocian.

12. References

Ahlberg, P. & Ahlgren, J. 1996: Agnostids from the Upper Cambrian of Västergötland, Sweden. GFF 118, pp. 129–140.

Ahlberg, P. & Ahlgren, J. 2000: *Lotagnostus? mystacinus*, a rare agnostid from the Upper Cambrian of Sweden. Acta Palaeontologica Polonica 45 (1), pp. 91–96.

Ahlberg, P. 1989: Cambrian stratigraphy of the När 1 deep well, Gotland. Geologiska Föreningen i Stockholm Förhandlingar 111 (2), 137–148.

Ahlberg, P., P., Månsson, K., Clarkson, E.N.K. & Taylor, C.M. 2006: Faunal turnovers and trilobite morphologies in the upper Cambrian *Leptoplastus* Zone at Andrarum, southern Sweden, Lethaia 39 (2), pp. 97–110.

Ahlberg, P., Axheimer, N, Babcock, L.E., Eriksson, M.E., Schmitz, B. & Terfelt, F. 2008: Cambrian high-resolution biostratigraphy and carbon isotope chemostratigraphy in Scania, Sweden: first record of the SPICE and DICE excursions in Scandinavia. Lethaia 42 (1), pp. 2–16.

Allison, P.A: & Wells, M.R. 2006: Circulation in large ancient epicontinental seas: What was different and why? Palaios 21, pp. 513–515.

Alvaro, J.J. & Vennin, E. 1998: Stratigraphic signature of a terminal Early Cambrian regressive event in the Iberian Peninsula. Canadian Journal of Earth Sciences, Ottawa, 35 (4), pp. 402–411.

Alvaro, J.J., Ahlberg, P. & Axheimer, N. 2010: Skeletal carbonate productivity and phosphogenesis at the lower–middle Cambrian transition of Scania, southern Sweden. Geological Magazine 147 (1), pp. 59–76.

Andersson, A., Dalmeny, B., Gee, D.G. & Small, S. 1985: The Scandinavian Alum Shales. Sveriges Geologiska Undersökning, Serie Ca 56, pp. 1–50.

Armands, G. 1972: Geochemical studies of uranium, molybdenum and vanadium in a Swedish Alum Shale. Stockholm contribution in Geology 27, pp. 1–148.

Andres, D. 1981: Beziehungen zwischen kambrischen Conodonten und Euconodonten. Berliner Geowissenschaftliche Abhandlungen A 32, pp. 19–31. [In German].

Andresen, A. 1978: Lithostratigraphy of the autochthonous-parautochthonous lower Palaeozoic metasediments on Hardangervidda, South Norway. Norges Geologiske Undersøgelse 338, pp. 59–69.

Axheimer, N. & Ahlberg, P. 2003: A core drilling through Cambrian strata at Almbackan, Scania, S. Sweden: trilobites and stratigraphical assessment. GFF 125 (3), pp. 139–156.

Babcock, L. E. & Peng, S. C. 2007. Cambrian chronostratigraphy: current state and future plans. Palaeogeography, Palaeoclimatology, Palaeoecology 254, pp. 62–66.

Bagnoli, G., Stouge, S. & Tongiorgi, M. 1988: Acritarchs and conodonts from the Cambro-Ordovician Furuhäll (Köpingsklint) section (Öland, Sweden). Rivista Italiana di Paleontologia e Stratigrafia 94 (2), pp. 163–248.

Bengtson, P. 1976: Brecciastrukturer i Närkes lingulidsandsten. Abstract XII Nordic Geological Winter Meeting. Geology Department of the University of Gothenburg 4.

Bengtsson, A. 1999: Trilobites and bradoriid arthropods from the Middle and Upper Cambrian at Gudhem in Västergötland, Sweden. Examensarbete i geologi vid Lunds Universitet 106, pp. 1–21.

Berg-Madsen, V. 1985: The Middle Cambrian of Bornholm, Denmark: A stratigraphical revision of the lower alum shale and associated anthraconites. Geologiska Föreningens i Stockholm Förhandlingar 106 (4) (for 1984), pp. 357–376.

Berg-Madsen, V. 1989: Origin and usage of the geological terms orsten, stinkstone and anthraconite. Archives of Natural History 16 (2), pp. 191–208.

Bergman, L., Tynni, R. & Winterhalter, B. 1982: Paleozoic sediments in the rapakivi area of the Aland Islands. Geological Survey of Finland Bulletin 317, 132 pp.

Bergström, J. & Ahlberg, P. 1981: Uppermost Lower Cambrian biostratigraphy in Scania, Sweden. GFF 103, pp. 192–214.

Bergström, J. & Gee, D.G. 1985: The Cambrian in Scandinavia. In Gee, D.G. & Sturt, B.A. (eds) The Caledonide Orogen – Scandinavia and Related Areas, pp. 247–270. Wiley, Chichester.

Bergström, J. 1973: Organization, life, and systematics of trilobites. Fossils and Strata 2, 69 pp.

Bergström, J. 1980: The Caledonian margin of the Fennoscandian shield during the Cambrian. In Wones, D.R. (ed.) The Caledonides in the U.S.A. Department of Geological Science, Virginia Polytechnical Institute and University, Memoir 2, pp. 9–13.

Bergström, J. 1981: Middle and upper Cambrian biostratigraphy and sedimentation in south central Jämtland, Sweden. GFF 102, pp. 373–376.

Berry, W.B.N. & Wilde, P. 1978: Progressive ventilation of the oceans - an explanation for the distribution of the Lower Paleozoic black shales. American Journal of Science 278 (3), pp. 257–275.

Bjørlykke, K. 1974: Depositional history and geochemical composition of Lower Palaeozoic epicontinental sediments from the Oslo Region. Norges Geologiske Undersøkelse 305, pp. 1–81.

Brangulis, A. 1985: The Vendian and Cambrian of Latvia. Riga, Zinathe. 136 pp. [In Russian].

Brasier, M. D., Ingham J. K. & Rushton, A. W. A. 1992: Cambrian. Geological Society, London, Memoirs 13, pp. 13–18.

Brøgger, W.C. 1878: Om paradoxidesskiferene ved Krekling. Nyt Magazin for Naturvidenskaberne, Oslo 24, 18–88. [In Norwegian].

Bruton, D. L. & Harper, D.A.T. 2000: A mid-Cambrian shelly fauna from Ritland, western Norway and its palaeogeographical implications. Bulletin of the Geological Society of Denmark 47, pp. 29–51.

Bruton, D.L., Erdtmann, B.-D. & Koch, L. 1982: The Nærsnes section, Oslo Region, Norway: a candidate for the Cambrian-Ordovician boundary stratotype at the base of the Tremadoc Series. In Basset, M.G, Dean, W.T. (eds.): The Cambrian-Ordovician boundary: sections, fossils distributions, and correlations. National Museum of Wales, Geological Series 3, pp. 61–69.

Bruton, D.L., Koch, L. & Repetski, J.E. 1988: The Nærsnæs section, Oslo Region, Norway: trilobite, graptolite and conodont fossils reviewed. Geological Magazine 125 (4), pp. 451–455.

Buchardt, B. & Nielsen, A.T. 1985: Carbon and oxygen isotope composition of Cambro-Silurian limestone and anthraconite from Bornholm: evidence for deep burial diagenesis. Bulletin of the geological Society of Denmark 33, pp. 415–435.

Buchardt, B., Nielsen, A.T., Schovsbo, N.H. 1997. Alun Skiferen i Skandinavien. Geologisk Tidsskrift 3, pp. 1–30. [In Danish].

Bulman, O. M. B. 1954: The graptolite fauna of the Dictyonema Shale of the Oslo Region, Norsk Geologisk Tidsskrift 33, pp. 1–40.

Callisen, K. 1914: Tenformede Tungspatkrystaller ("Pseudo-Gaylussit" og "Pseudo-Pirssonit") i Alunskiferen. Meddelelser fra Dansk Geologisk Forening 4, pp. 245–258. [In Danish].

Canfield, D.E. & Raiswell, R. 1991: Carbonate precipitation and dissolution; Its relevance to fossil preservation. In Allison, A. & Briggs, D.E.G. (eds.): Taphonomy; releasing the data locked in the fossile record. Plenum Press, New York. pp. 441–453.

Christensen, C.D., 2003. *Peltura* Zonen (Øvre Kambrium) i Skåne, Sverige. Unpublished Cand. Scient. thesis, University of Copenhagen. 137 pp. [In Danish].

Cathles, L.M. & Hallam, A. 1991: Stress-induced changes in plate density, vail sequences, epeirogeny, and short-lived global sea level fluctuations. Tectonics 10 (4), pp. 659–671.

Cisne, J. L. 1975: Anatomy of *Triarthrus* and the relationships of the Trilobita. Fossils and Strata 4, pp. 45–63.

Clarkson, E.N.K. 1973: Morphology and evolution of the eye in Upper Cambrian Olenidae (Trilobita). Palaeontology 16, pp. 735–763.

Cocks, L.R.M. & Torsvik, T.H. 2005. Baltica from the late Precambrian to mid-Palaeozoic times: the gain and loss of a terrane's identity. Earth Science Reviews 72, pp. 39–66.

Cooper, R.A. 1999: Ecostratigraphy, zonation and global correlation of earliest Ordovician planktic graptolites. Lethaia 32 (1), pp. 1–14.

Dworatzek, M. 1987: Sedimentology and petrology of carbonates intercalations in the Upper Cambrian Olenid Shale facies of southern Sweden. Sveriges Geologiska Undersökning, Ser. C 819, pp. 1–71.

Ebbestad, J.O.R. 1999: Trilobites of the Tremadoc Bjørkåsholmen Formation in the Oslo Region, Norway. Fossils and Strata 47, 118 pp.

Eklöf, J., Rydell, J., Fröjmark, J., Johansson, M. & Seilacher, A. 1999: Orientation of agnostid shields in Alum Shale (Upper Cambrian): Implications for the depositional environment. GFF 121, pp. 301–306.

Erdtmann, B.-D. 1965: Outline stratigraphy of graptolite-bearing 3b (Lower Ordovician) strata in the Oslo region, Norway. Investigations of a section at Tøyen, Oslo. Norsk Geologisk Tidsskrift 45, pp. 481–547.

Erdtmann, B.-D. 1986: Early Ordovician eustatic cycles and their bearing on punctuations in early nematophorid (planktic) graptolite evolution. In O.H. Walliser (ed.) Global Bio-Event. Lecture Notes in Earth Sciences 8, pp 139–152.

EUGENO-S working group 1988: Crustal structure and tectonic evolution of the transition between the Baltic Shield and the north German Caledonides (The EUGENO-S Project). Tectonophysics 150, pp. 253–348

Fortey, R.A., Cocks, L.R.M. 2003: Palaeontological evidence bearing on the global Ordovician–Silurian continental reconstructions. Earth Science Reviews 61, pp. 245–307.

Fortey, R. A. 1974: The Ordovician trilobites of Spitsbergen I. Olenidae. Norsk Polarinstitutt Skrifter 160, pp. 1–81.

Fortey R.A. 1975: Early Ordovician trilobite communities. Fossils and Strata 4, pp. 339–360.

Fortey, R.A. 1980: The Ordovician trilobites of Spitsbergen III. Remaining trilobites of the Valhallfonna Formation. Norsk Polarinstitutt Skrifter 171, pp. 1–163.

Gee, D.G. 1981: The *Dictyonema*-bearing phyllites at Nordaunevoll, eastern Trøndelag, Norway. Norsk Geologisk Tidsskrift 61, pp. 93–95.

Gee, D.G. & Pease, V. (Eds.) 2004: The Neoproterozoic Timanide Orogen of eastern Baltica. Memoirs of the Geological Society of London 30. 260 pp.

Greiling, R.O., Jensen, S. & Smith, A.G.1999: Ediacaran–Cambrian subsidence of the passive margin of western Baltica — application of new stratigraphic data from the Scandinavian Caledonian margin. Norsk Geologisk Tidsskrift 79, pp. 133–144.

Griegelis, A.A. 1991. Geology and geomorphology of the Baltic Sea. “Nedra” Leningrad Branch. 420 pp. [In Russian].

Grönwall, K.A. 1902: Bornholms Paradoxideslag og deres fauna. Danmarks Geologiske Undersøgelse, Ser. II 13, pp. 1–230. [In Danish].

Hadding, A. 1958: The pre-Quaternary sedimentary rocks of Sweden: VII. Cambrian and Ordovician limestones. Lunds Universitets Årsskrift, N.F. 2, 54(5), pp. 1–262

Hagenfeldt, S.E., 1994. The Cambrian File Haidar and Borgholm Formations in the central Baltic and south central Sweden. Stockholm Contributions in Geology 43, pp. 69–110.

Hansen, K. 1938: Strukturen i nogle bornholmske Kalksten. Meddelelser fra Dansk Geologisk Forening 9, pp. 327–335. [In Danish].

Hansen, K., 1945. The middle and upper Cambrian sedimentary rocks of Bornholm. Danmarks Geologiske Undersøgelse II. Række 72, pp. 1–81.

Hartz, E.H. & Torsvik, T.H. 2002: Baltica upside down: a new plate tectonic model for Rodinia and the Iapetus Ocean. Geology 30, pp. 255–258.

Hede, J. E. 1951: Boring through Middle Ordovician-Upper Cambrian strata in the Fågelsång district, Scania (Sweden); I. Succession encountered in the boring. Lunds Universitets Årsskrift, N. F., Avd. 2, 46(7), 84 pp

Heinsalu, H. & Viira, V. 1997. Pakerort Stage. In Raukas, A. & Teedumäe, A., (eds): Geology and Mineral Resources of Estonia, pp. 52–58. Estonian Academy Publishers, Tallinn.

Henningsmoen, G. 1952. Early middle Cambrian fauna from Rogaland, SW Norway (*Paradoxides oelandicus* stage=1 cα). Norsk Geologisk Tidsskrift 30, pp. 13–31.

Henningsmoen, G. 1957: The trilobite family Olenidae, with description of Norwegian material and remarks on the Olenid and Tremadocian Series. Norsk Videnskaps-Akademi i Oslo, Skrifter 1. Matematisk-Naturvidenskapelig Klasse 1, 303 pp.

Henningsmoen, G. 1958: The Upper Cambrian faunas of Norway. With descriptions of non-olenid invertebrate fossils. Norsk Geologisk Tidsskrift 38, pp. 179–196.

Henningsmoen, G. 1974: A comment. Origin of limestone nodules in the Lower Palaeozoic of the Oslo Region. Norsk Geologisk Tidsskrift 54, pp. 401–412.

Hoffman, N. 1990: Der präpermische Untergrund der Mitteleuropäischen Senke: Fakten und Hypothesen. Niedersächsische Akademie der Geowissenschaften veröffentlichungen 4, 19–75. [In German].

Holmer, L.E. & Popov, L.E. 1990: The acrotretacean brachiopod *Ceratreta tanneri* (Metzger) from the Upper Cambrian of Baltoscandia. Geologiska Föreningens i Stockholm Förhandlingar 112, pp. 249–263.

Høyberget, M. & Bruton, D. L. 2008: Middle Cambrian trilobites of the suborders Agnostina and Eodiscina from the Oslo Region, Norway. Palaeontographica. Abteilung A, Palaozoologie, Stratigraphie 286, pp. 1–87.

Høyberget, M. & Bruton, D. L. 2012: Revision of the trilobite genus *Sphaerophthalmus* and relatives from the Furongian (Cambrian) Alum Shale Formation, Oslo Region, Norway. Norsk Geologisk Tidsskrift 92 (4), pp. 433–450.

Israelson, C., Halliday, A.N. & Buchardt, B. 1996: U-Pb dating of calcite concretions from Cambrian black shales and the Phanerozoic time scale. Earth and Planetary Science Letters 141, pp. 153–159.

Jaanusson, V., 1982: Introduction to the Ordovician. In Bruton, D.L. & Williams, S.H. (eds): Field Excursion Guide. IV International Symposium on the Ordovician System: Palaeontological Contributions from the University of Oslo 295, pp. 1–9.

Jaanusson, V., 1982b: The Siljan District. In Bruton, D.L., Williams, S.H. (eds): Field Excursion Guide. IV International Symposium on the Ordovician System: Palaeontological Contributions from the University of Oslo 295, pp. 15–42.

Jankauskas, T.V., 2002: Cambrian Stratigraphy of Lithuanis. Institute of Geology of Lithuania, Vilnius University. 233 pp.

Jell, P.A. 1978: Trilobite respiration and genal caeca. Alcheringa 2, pp. 251–260.

Kaljo, D. & Kivimågi, E. 1976: Zonal Stratigraphy of the Estonian Tremadocian In Kaljo, D. & Koren, T. (eds): Graptolites and Stratigraphy. Academy of Sciences of Estonian SSR, Institute of Geology, Tallinn, pp. 56–63.

Karis, L. 1998: Jämtlands östlige fjällberggrund. In Karis, L., Strömberg, A.G.B. (eds): Beskrivning till berggrundskartan över Jämtlands län Del 2: Fjälldelen. Sveriges Geologiska Undersökning Research Papers Ca 53, pp. 6–178. [In Swedish].

Karis, L. & Magnusson, E. 1972: Paleozoisk berggrund. In P.H. Lindegårdh, H. Hübner, H. Wikman, L. Karis & E. Magnusson: beskrivning till berggrundsgeologiska kartbladet Örebro NV. Sveriges Geologiska Undersökning Serie Af 102, pp. 156–186. [In Swedish].

Kaufmann, R. 1933a: Variationsstatistische Untersuchungen über die "Artabwandlung" und "Artumbildung" an der Oberkambrischen Trilobitengattung *Olenus* Dalm. Abhandlungen aus dem geologisch-palaeontologischen Institut der Universität Greifswald 10, pp. 1–55. [In German].

Kaufmann, R. 1933b: Die Einstufung der *Olenus*-Arten von Bornholm. Paläontologische Zeitschrift 15, pp.57–63. [In German].

Kaufmann, R. 1935: Exakt-statistische Biostratigraphie der *Olenus*-Arten von Südöland. Geologiska Foreningens i Stockholm Förhandlingar 57, pp. 19–28. [In German].

Keulegan, G.H. & Krumbein, W.C. 1949: Stable configuration of bottom slope in a shallow sea and its bearing on geological processes: American American Geophysical Union Transactions 30 (6), pp. 855–861.

Landing, E. 2005: Early Paleozoic Avalon-Gondwana unity: an obituary-response to "Palaeontological evidence bearing on global Ordovician-Silurian continental reconstructions". Edited by R.A. Fortey and L.R.M. Cocks. Earth-Science Reviews 69, pp. 169–175.

Landing, E., Peng, S.C., Babcock, L.E., Geyer, G., Moczydlowska Vidal, M. 2007: Global standard names for the Lowermost Cambrian Series and Stage. Episodes 30, pp. 287–299.

Leggett, J.K. 1980: British Lower Palaeozoic black shales and their palaeo-oceanographic significance. Journal of the Geological Society, London 137, pp. 139–156.

Lindström, G. 1901: Researches of the visual organs of the trilobites. Kongliga Svenska vetenskapsakademiens handlingar 34, pp. 6–86.

Lindström, M. 1967: “Funnel Grabens” and Early Paleozoic Tectonism in South Sweden Geological Society of America Bulletin 78 (9), pp. 1137–1154.

Lindström, M. 1971: Vom Anfang, Hochstand und Ende eines Epikontinentalmeeres. Geologische Rundschau 60, pp. 419–438. [In German].

Löfgren, A. 1997: Conodont faunas from the upper Tremadoc at Brattefors, south-central Sweden, and reconstruction of the Paltodus apparatus. GFF 119 (4), pp. 257–266.

Martin, F. & Dean, W.T. 1981: Middle and Upper Cambrian and Lower Ordovician acritarchs from Random Island, Eastern Newfoundland. Geological Survey Canada Bulletin 343, 30 pp.

Martinsson, A., 1968. Cambrian palaeontology of Fennoscandian basement fissures. Lethaia 1, pp. 137–155.

Martinsson, A. 1974: The Cambrian of Norden. In Holland, C.H. (ed.): Cambrian of the British Isles, Norden and Spitsbergen. Lower Palaeozoic Rocks of the World 2. John Wiley and Sons, London. pp. 185–283.

Michelsen, O. & Nielsen, L.H. 1991: Well records on the Phanerozoic stratigraphy in the Fennoscandian Border Zone, Denmark. Hans-1, Sæby-1 and Terne-1 wells. Danmarks Geologiske Undersøgelse, Ser. A 29, pp. 1–37.

Mens, K. & Pirrus, E. 1997. Cambrian. In Raukas, A., Teedumäe, A. (eds): Geology and Mineral Resources of Estonia. Estonian Academy Publishers, Tallinn, pp. 39–51.

Mens, K., Bergström, J. & Lendzion, K. 1990. The Cambrian System on the East European platform. International Union of Geological Sciences 25, pp. 1–73.

Milia, A. D., Ribecai, C. & Tongiorgi, M. 1989: Late Cambrian Acritarchs from the *Peltura scarabaeoides* Zone at Degerhamn (Öland, Sweden). Palaeontographia Italica LXXVI, 56 pp.

Miller, J.F. 1984: Cambrian and earliest Ordovician conodont evolution biofacies, and provincialism. In Clark, D.L. (ed.): Conodont Biofacies and Provincialism. Geological Society of America, Special Paper 196, pp. 43–68.

Miller, J.F. 1992: The Lange Ranch Eustatic Event: A regressive-transgressive couplet near the base of the Ordovician System. In Webby, B. D. & Laurie, J.R., editors, Global Perspectives on Ordovician Geology. A.A. Balkema, Rotterdam, pp. 395–407.

Müller, K.J. & Hinz, I. 1991: Upper Cambrian conodonts from Sweden. Fossils & Strata 28, 153 pp.

Müller, K. J. & Walossek. D. 1987: Morphology, ontogeny and life habit of *Agnostus pisiformis* from the Upper Cambrian of Sweden. Fossils and Strata 19, 124 pp.

Nickelsen, R.P., Hossack, J.R., Garton, M., Repetsky, J. 1985. Late Precambrian to Ordovician stratigraphy and correlation in the Valdres and Synnfjell thrust sheets of the Valdres area, southern Norwegian Caledonides; with some comments on sedimentation. In Gee, D.G., Sturt, B.A. (eds): The Caledonian Orogen — Scandinavia and Related Areas. John Wiley and Sons Ltd, Chichester, pp. 369–378.

Nicoll, R.S., Nielsen, A.T., Laurie, J.R. & Shergold, J.H. 1992: Preliminary correlation of latest Cambrian to Early Ordovician sea level events in Australia and Scandinavia. In Webby, B.D. & Laurie, J.R. (eds.): Global Perspectives on Ordovician Geology. Balkema, Rotterdam, pp. 381–394.

Nielsen, A.T. & Schovsbo, N.H. 2006: Cambrian to basal Ordovician lithostratigraphy in southern Scandinavia. Bulletin. Geological Society of Denmark 53, pp. 47–92.

Nielsen, A.T. & Schovsbo, N.H. 2011: The Lower Cambrian of Scandinavia: Depositional environment, sequence stratigraphy and palaeogeography. Earth-Science Reviews 107, pp. 207-310.

Nielsen, A.T. & Schovsbo, N.H. in prep.: The Lower-Middle Cambrian 'Hawke Bay regressive Event' in Baltoscandia: Epeirogenic uplift in response to plate tectonics and/or eustasy? [Manuscript].

Nielsen, A.T. 1995: Trilobite systematics, biostratigraphy and palaeoecology of the Lower Ordovician Komstad limestone and Huk Formations, Southern Scandinavia. Fossils & Strata 38, 376 pp.

Nielsen, A.T. 1997: A review of Ordovician agnostid genera (Trilobita). Transactions of the Royal Society of Edinburgh 87, pp. 463–501.

Nielsen, A.T. 2004: Ordovician sea level changes: A Baltoscandian perspective. In Webby, B.D., Droser, M.L., Paris, F. & Percival, I. (eds): The Great Ordovician Biodiversification Event: New York, Columbia University Press, pp. 84–93.

Nielsen, A.T., Klitten, K. & Hansen, H.P.B. 2006: Borggård-1: En ny stratigrafisk kerneboring på Bornholm. Geologisk Nyt 6, pp. 18–24. [In Danish].

Nikishin, A.M., Ziegler, P.A., Stephenson, R.A., Cloetingh, S.A.P.L., Furne, A.V., Fokin, P.A., Ershov, A.V., Yershov, A.V., Bolotov, S.N., Korotaev, M.V., Koratayev, M.V., Alekseev, A.S., Alekseyev, A.S., Gorbachev, V.I., Shipilov, E.V., Lankreijer, A., Bembinova, E.Yu., Shalimov, I.V. 1996. Late Precambrian to Triassic history of the East European Craton; dynamics of sedimentary basin evolution. Tectonophysics 268, pp. 23–63.

Öpik, A.A. 1963: Early Upper Cambrian fossils from Queensland. Australian Bureau of Mineral Resources, Geology and Geophysics Bulletin 64, pp. 1–133.

Oschmann, W. 1991: Anaerobic-poikiloaerobic-aerobic: a new zonation for modern and ancient neritic redox facies. In Einsele, G., Ricken, W. & Seilacher, A. (eds): Events and cycles in stratigraphy, pp. 565–571. Springer-Verlag, Heidelberg.

Peng, S., Babcock, L.E. & Cooper, R.A. 2012: The Cambrian Period. In Gradstein, F. M., Ogg, J. G., Schmitz M. & Ogg, G. (eds): The Geologic Time Scale 2012, Chapter 19. Elsevier.

Poulsen, C. 1923: Bornholms Olenuslag og deres Fauna. Danmarks Geologiske Undersøgelse, Ser. II 40, pp. 1–83. [In Danish].

Pukkonen, E. & Rammo, M. 1992: Distribution of Molybdenum and Uranium the Tremadoc Graptolitic Argillite (Dictyonema Shale) of North-Western Estonia. Bulletin of Geological Survey of Estonia 2 (1), pp. 3–15.

Pukkonen, E. & Buchardt, B. 1994: The *Dictyonema* shale of Estonia. Final reports III, Pre-Westphalian Source Rocks in northwest Europe. Geological Institute, Copenhagen. 37 pp.

Puura, I. 1996: Lingulate brachiopods and biostratigraphy of the Cambrian Ordovician boundary beds in Baltoscandia. Doctoral Thesis, Uppsala University.

Rasmussen, J.A, Nielsen, A.T. & Harper D.A.T. 2011: An unusual Mid-Ordovician island environment on the western edge of Baltica: New palaeoecological and palaeobiographical data from Hardangervidda, southern Norway. In J.C. Gutierrez-Marco, I. Rabano & D. Garcia-Belido (eds): Ordovician of the World. Cuadernos del Museo Geominero, 14. Instituto Geologico y Minero de Espana, Madrid, pp. 455–462.

Richter, R. 1919: Von Bau und Leben der Trilobiten. Senckenbergiana wissenschaftliche Mitteilungen hrsg. von der Senckenbergischen naturforschenden Gesellschaft in Frankfurt a. M. 1, pp. 213–38. [In German].

Ribecai, C. & Tongiorgi, M. 1997: *Lusatia dramatica*, a distinctive new species from the Upper Cambrian of Öland (Sweden). In R. Wicander (ed.): Festschrift in honour of Loeblich and Tappan. Review of Palaeobotany and Palynology 98, pp. 27–32.

Robison, R.A. 1972: Hypostoma of agnostid trilobites. Lethaia 5 (2), pp. 239–248.

Saltzman, M.R., Ripperdan, R.L., Brasier, M.D., Lohmann, K.C., Robison, R.A., Chang, W.T., Peng, S., Ergaliev, E.K., & Runnegar, B. 2000: A global carbon isotope excursion (SPICE) during the Late Cambrian: relation to trilobite extinctions, organic-matter burial and sea level. Palaeogeography, Palaeoclimatology, Palaeoecology 162, pp. 211–223

Samuelson, L. 1975: Palaeozoic fissure filling and tectonism of the Göteborg area, southwestern Sweden. Sverige Geologiska Undersokning 69, pp. 3–43

Schovsbo, N.H. 2001: Why barren intervals? A taphonomic case study of the Scandinavian Alum Shale and its faunas. Lethaia 34 (4), pp. 271–285.

Schovsbo, N.H. 2003: The geochemistry of lower Palaeozoic sediments deposited on the margins of Baltica. Bulletin of the Geological Sociaty of Denmark 50, pp. 11–27.

Shergold, J. H. & Cooper, R. A. 2004: The Cambrian Period. In F. M. Gradstein, J. G. Ogg, and A. Smith, eds. A geologic timescale, pp. 147–164. Cambridge University Press, Cambridge.

Söderberg, P. 1993: Seismic stratigraphy, tectonics and gas migration in the Åland Sea, northern Baltic proper. Stockholm Contributions in Geology 43 (1), pp. 1–67.

Spjeldnæs, N. 1963: Some Upper Tremadocian graptolites from Norway. Palaeontology 6, pp. 121–131.

Spjeldnæs, N. 1985: Excursion-Guide Oslo. Graptolite Working Group of the International Palaeontological Association, Copenhagen 1985, 13 pp.

Størmer, L. 1940: Dictyonema shales outside the Oslo Region. Norsk Geologisk Tidsskrift 20, pp. 161–179.

Taylor, J.F., Repetski, J.E. & Orndorff, R.C. 1992: The Stonehenge transgression: A rapid submergence of the central Appalachian platform in the Early Ordovician. In Webby, B.D., and J.R. Laurie, (eds.), Global Perspectives on Ordovician Geology, pp. 409–418. Proceedings of the Sixth International Symposium on the Ordovician System, Balkema, Rotterdam.

Terfelt, F. 2003: Upper Cambrian trilobite biostratigraphy and taphonomy at Kakeled on Kinnekulle, Västergötland, Sweden. Acta Palaeontologica Polonica 48 (3), pp. 409–416.

Terfelt, F. 2006: Synthesis. Upper middle Cambrian through Furongian of Scandinavia with focus on trilobites, palaeoenvironments and correlations. Lund University Doctoral thesis 11, pp. 1–19.

Terfelt, F., Eriksson, M. E., Ahlberg, P. & Babcock, L. E. 2008: Furongian (Cambrian) biostratigraphy of Scandinavia – a revision. Norwegian Journal of Geology 88, pp. 73–87.

Terfelt, F., Ahlberg, P. & Eriksson, M.E. 2010: Complete record of Furongian polymerid trilobites and agnostoids of Scandinavia – a biostratigraphical scheme. Lethaia 44 (1), pp. 8–14.

Teves, R. & Lindström, M. 1988: The Brattefors plugs: Collapse structures initiated during a Tremadocian regression. Geologiska Föreningen i Stockholm Förhandlingar 110 (1), pp. 55–66.

Thickpenny, A. 1984: The sedimentology of the Swedish Alum Shales. In Stow, D.A.V. & Piper, D.J.W. (eds.): Fine-Grained Sediments: Deep-Water Processes and Facies, pp. 511–525. Geological Society Special Publication No. 15.

Thickpenny, A. 1987: Palaeo-oceanography and depositional environment of the Scandinavian Alum Shales: sedimentological and geochemical evidence. In Leggett, J.K. & Zuffa, G.G. (eds): Marine clastic sedimentology. Graham & Trotman, London. pp. 156–171.

Thorslund, P. & Axberg, S. 1979: Geology of the southern Bothnian Sea. Part I. Bulletin of the Geological Institutions of the University of Uppsala, N.S. 8, pp. 35–62.

Thybo, H. 2001: Crustal structure along the EGT profile across the Tornquist Fan interpreted from seismic, gravity and magnetic data. Tectonophysics 334, pp. 155–190.

Tjernvik, T. E. 1958: The Tremadocian beds at Flagabro in South-Eastern Scania (Sweden). Geologisk Föreningen i Stockholm Forhandlingar 80, pp. 259–276.

Torsvik, T.H. & Rehström, E.F. 2001: Cambrian palaeomagnetic data from Baltica; implications for true polar wander and Cambrian palaeogeography. Journal of the Geological Society of London 158, pp. 321–329.

Trela, W. 2010: Outline of Geology of the Holy Cross Mountains. In: CIMP 2010 FIELD TRIP GUIDEBOOK, Institute of Geological Sciences, Polish Academy of Sciences, pp. 4–8.

Tynni, R. 1982: On Palaeozoic microfossils in clastic dykes on the Åland islands and in the core samples of Lumparn. Geological Survey of Finland Bulletin 317, pp. 35–94.

von Jansson, C. 1979: Zur Biostratigraphie des Tremadociums auf Bornholm. Unpublished Diplomarbeit, Königsberg. 55 pp. [In German].

Wallerius, I. D. 1895: Undersökningar öfver zonen med *Agnostus laevigatus* i Vestergötland, jämte en inledande öfversikt af Vestergötlands samtliga Paradoxideslager. Lund: Gleerupska Universitetsbokhandeln, pp. 1–72. [In Swedish]

Weidner, T. R., Ahlberg, P., Axheimer, N. & Clarkson, E. N. K. 2004: The middle Cambrian *Ptychagnostus punctuosus* and *Goniagnostus nathorsti* zones in Västergötland, Sweden. Bulletin of the Geological Society of Denmark 50, pp. 39–45.

Weidner, T. & Nielsen, A.T. 2009: The Middle Cambrian *Paradoxides paradoxissimus* Superzone on Öland, Sweden. GFF 131, pp. 253–268.

Weidner, T. & Nielsen, A.T. in press a: A highly diverse trilobite fauna with Avalonian affinities from the Middle Cambrian *Acidusus atavus* Zone (Drumian Stage) of Bornholm, Denmark. Journal of Systematic Palaeontology.

Weidner, T. & Nielsen, A.T. in press b: The late Cambrian (Furongian) *Acerocarina* Superzone (new name) on Kinnekulle, Västergötland, Sweden. GFF.

Westergård, A.H. 1909: Studier öfver Dictyograptusskifferen och dess gränslager. Meddelelser fra Lunds Geologiske Fältklubb, Ser. B 4, Lund, 79 pp. [In Swedish].

Westergård, A.H. 1922: Sveriges Olenidskiffer. Sveriges Geologiska Undersökning, Ser. Ca 18, 205 pp. [In Swedish].

Westergård, A.H. 1936: *Paradoxides oelandicus* beds of Öland: with the account of a diamond boring through the Cambrian at Mossberga. Sveriges Geologiska Undersökning Ser. C 394, pp. 1–66.

Westergård, A.H. 1940: Nye djupborrningar genom äldste ordovicium och kambrium i Östergötland och Närke. Sveriges Geologiska Undersökning Ser. C 437, pp. 1–72. [In Swedish].

Westergård, A.H. 1942: Stratigraphic results of the borings through the Alum Shales of Scania made in 1941-42. Lunds Geologiska Fältklubb 185, pp. 1–20.

Westergård, A.H. 1944: Borrningar genom Skånes Alunskiffer. Sveriges Geologiska Undersökning, Ser. C 459, pp. 1–37. [In Swedish].

Westergård, A.H. 1946: Agnostidea of the Middle Cambrian of Sweden. Sveriges Geologiska Undersökning, Ser. C 477, pp. 1-140, pls. 1–16.

Westergård, A.H. 1947a: Supplementary notes on the Upper Cambrian trilobites of Sweden. Sveriges Geologiska Undersökning, Ser. C 489, pp. 1-28, pls. 1–3.

Westergård, A.H. 1947b: Nya data rörande alunskifferlagret på Öland. Sveriges Geologiska Undersökning Ser. C 483, pp. 1–12. [In Swedish].

Westergård, A.H. 1948: Non-agnostidean trilobites of the Middle Cambrian of Sweden. I. Sveriges Geologiska Undersökning, Ser. C 498, pp. 1–32.

Westergård, A.H. 1950: Non-agnostidean trilobites of the Middle Cambrian of Sweden. 2. Sveriges Geologiska Undersökning, Ser. C 511, pp. 1–57.

Westergård, A.H. 1953: Non-agnostidean trilobites of the Middle Cambrian of Sweden. 2. Sveriges Geologiska Undersökning, Ser. C 526, pp. 1–59.

Wignall, P.B. 1994: Black shales. Geology and Geophysics Monograph Series 30. Clarendon Press, Oxford. 127 pp.