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Holocene stratigraphy of the Archipelago Sea, northern Baltic Sea: the definitions and descriptions of the Dragsfjärd, Korppoo and Nauvo Alloformations

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Abstract A formal stratigraphic division is proposed for the Holocene succession of the Archipelago Sea, northern Baltic Sea. Marine geological investigations, including high-resolution acoustic profiles as well as sedimentologic and stratigraphic studies, have been carried out. More than 100 km of acoustic survey lines together with 8 up to 6 m long sediment cores were collected. Correlations between the acoustic profiles and the cores reveal that the Holocene succession is interrupted by two distinctive unconformities. This allows the definition and description of three allostratigraphic units: the Dragsfjärd Alloformation, Korppoo Alloformation and Nauvo Alloformation. The Korppoo Alloformation is subdivided into the Trollskär Allomember and Sandön Allomember based on an acoustic discontinuity.

Keywords *Acoustic profiling, stratigraphy, Holocene, Archipelago Sea, Baltic Sea.*

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INTRODUCTION

During its late Quaternary history, the Baltic Sea has successive lacustrine and brackish-water stages, known as the Baltic Ice Lake, the Yoldia Sea, the Ancylus Lake, the Litorina Sea and the present Baltic Sea (Sauramo 1958; Winterhalter et al. 1981; Björck 1995). Conventionally, the Baltic Sea Basin (BSB) stratigraphy has been divided into units corresponding to these environmental stages. The definitions of the environmental stages, however, are based on mixed criteria such as shore displacement, biostratigraphy and lithostratigraphy, depending on established practices in the respective circum-Baltic countries. As a consequence, the identification of the stratigraphic units in the BSB is far from unambiguous. This has led to increasing criticism of the conventional stratigraphic division (e.g. Hyvärinen 1988; Gibbard 1992). Furthermore, the term stage is internationally reserved for chronostratigraphic units that can be recognized on a global scale (Salvador 1994; Murphy & Salvador 1999; North American Commission on Stratigraphic Nomenclature 2005).

Due to the complex interactions between the retreat of the (last) Weichselian continental ice-sheet, glacio-isostatic rebound and eustatic sea-level changes, the onsets of the individual Baltic Sea stages have been diachronous, and the characteristics of the stages and the corresponding sediments differ around the BSB (Winterhalter et al. 1981; Björck 1995). For example, the Ancylus Lake deposits from the southern BSB are lithologically and biologically different from the Ancylus Lake deposits from the northern BSB. In addition, especially in shallow coastal areas, complex topography results in marked lateral variation in the lithologic character (e.g. laminated to homogeneous) of the Litorina Sea deposits. It is apparent, therefore, that the conventional stratigraphic division and naming practice, although it may be implicitly understood by many Baltic Sea geologists, is not particularly well suited for inter-regional correlation. Nor does it support more detailed understanding of depositional processes extensive acoustic surveys, the extent of the proposed stratigraphic units is known well enough, and the units are defined formally. However, the units are defined for the Archipelago Sea area only. Their extension beyond this area and possible correlation to conventional stratigraphic units in the BSB needs to be considered in the future.

Within the presented framework, the Dragsfjärd Alloformation, Korppoo Alloformation and Nauvo Alloformation, together with their Gullkrona Graben type area, are formally defined and described. The Korppoo Alloformation is further subdivided into the Trollskär Allomember and the Sandön Allomember. All these units can be easily identified and traced in acoustic profiles. The aim is to provide means for easy and unambiguous sediment identification, mapping and correlation. The usage of formal stratigraphic terminology allows a geologist coming from outside the area to understand the local stratigraphy without putting an effort into studying the division principles first. The purpose of this paper is to define and describe the proposed units; dated sediment chronologies together with a more thorough discussion on their depositional environments will appear in a future article.

GEOLOGICAL SETTING

The Archipelago Sea is an expansive mosaic of multitudes of islands and adjacent sub-basins (Fig. 1). The average water depth is only 23 m, but some deeps reach over 100 m. The sea is essentially tideless, but irregular water level fluctuations of up to 1 m occur due to variations in wind and atmospheric pressure. The sedimentation pattern is complicated by the glacio-isostatic land uplift (3-4 mm per year, Mäkinen & Saaranen 1998), resulting in a slowly changing balance between the areas of accumulation, transportation and erosion.

The (last) Weichselian ice margin left behind glacial till and glaciofluvial deposits. Longitudinal eskers and the huge transverse Salpausselkä ice-marginal formations shape the morphology in the NNW direction of the ice sheet retreat. This substratum is covered successively by varved glaciolacustrine silts and clays, by lacustrine transition clays and, finally, by brackish-water, organic-rich muds (Gripenberg 1934; Heino 1973; Häkkinen 1990; Kotilainen 1991). On acoustic profiles, the glaciolacustrine and transition deposits follow conformably the substratum irregularities to an "astonishing degree", while the muds are distributed more irregularly with a tendency towards "basin fill" (Winterhalter 1972). Most of the Archipelago Sea resides on the north side of the Second Salpausselkä (Fig. 1). Because the ice margin retreat from the Second Salpausselkä was more or less simultaneous with the final drainage of the Baltic Ice-Lake (Sauramo 1958), most of the area was deglaciated during the Yoldia Sea stage (Winterhalter et al. 1981; Björck 1995). The glacio-isostatic land uplift was extremely rapid immediately after the deglaciation, but the land uplift rate has been decreasing since (Glückert 1995). The area has been essentially regressional throughout the Holocene, except for two short-lived transgressions.

The Gullkrona Graben was formed during the Paleoproterozoic Svecokarelian orogeny (Edelman 1949). Today, it is visible in maps as a large depression characterized by numerous small islands (Fig. 1). The islands are rocky, except for the sand and gravel islands associated with the (mostly) submarine Third Salpausselkä and Trollholm Esker ice-marginal formations that transverse the area (Häkkinen 1990). The water depths barely exceed 60 m, but the bedrock surface reaches down to as deep as 150 m below sea surface. The thickness of the Holocene sediments reaches several tens of metres at some locations.

MATERIAL AND METHODS

Fieldwork. High-resolution acoustic data and eight sediment cores were collected onboard the Finnish R/V's Aranda (September 2002 and 2003) and Geola (August 2004) (Fig. 1, Table 1). Acoustic data was

Table 1. Coring location, depth and type of the sediment cores used in this study (PC = long piston corer, VH = vibrohammer corer).

Core	Sampling date	Latitude (WGS84)	Longitude (WGS84)	Water depth (m)	Corer	Recovery (m)
AS6-VH1	26 Sep. 2002	59°39.75N	21°57.48E	66	VH	4.38
AS6-VH2	26 Sep. 2002	59°39.75N	21°57.11E	64	VH	4.68
AS2-VH2	27 Sep. 2002	60°03.31N	22°17.49E	34	VH	4.38
AS2-VH3	27 Sep. 2002	60°02.85N	22°17.84E	32	VH	5.52
AS2-PC4	23 Sep. 2003	60°02.60N	22°17.71E	32	PC	5.97
AS5-PC2	25 Sep. 2003	60°18.47N	22°30.03E	33	PC	5.56
AS3-PC1	26 Sep. 2003	60°13.27N	22°25.98E	19	PC	4.23
MGTK-04-13	5 Aug. 2004	60°03.73N	21°21.36E	37	VH	5.04

and environmental change in the BSB; lithologic and biologic changes do not always occur at the same level in sediments, and these criteria should strictly be kept separated. Therefore, a more unambiguous stratigraphic division of the BSB sediments is required.

In this paper, a new stratigraphic division is proposed for the Holocene succession of the Archipelago Sea, northern Baltic Sea. The visual character of sediments has been selected as means for identifying the sediment units because it can be readily studied from the sediment cores. However, since lateral lithologic transitions are characteristic for these sediments, their stratigraphic division based on lithostratigraphic principles is problematic (e.g. Walker 1992; Eyles et al. 1998; Hiscott & Aksu 2002). Therefore, the succession has been divided into sediment units based on distinctive unconformities (breaks in sedimentation) observed in the cores. Within the bounding unconformities of these units, lithologic variation is allowed. Furthermore, the diachronous depositional history of the BSB makes the correlation of sediments difficult, but, when the stratigraphic units are defined based on distinctive unconformities, the diachronous changes are easier to follow. These unconformity-bounded units could be called either synthems, following the International Stratigraphic Guide (ISG) (Salvador 1994; Murphy & Salvador 1999), or allostratigraphic units, following the North American Stratigraphic Code (NASC) (North American Commission on Stratigraphic Nomenclature 2005). The term synthem has received very limited acceptance and use, however, and its usage is discouraged by Murphy & Salvador (1999). Instead, allostratigraphic units have a widely accepted meaning (e.g. Walker 1992; Miall 1997), and, therefore, the allostratigraphic principles are used in the proposed stratigraphic division. In addition, allostratigraphic units can be given ranks (allogroup, alloformation, allomember), which is not possible with synthems. The proposed allostratigraphic units are descriptive units and do not have genetic connotations as sequence stratigraphy does.

The ISG strongly recommends the formal definition of stratigraphic units when the units can be described in detail and their lateral extent is known. Based on the

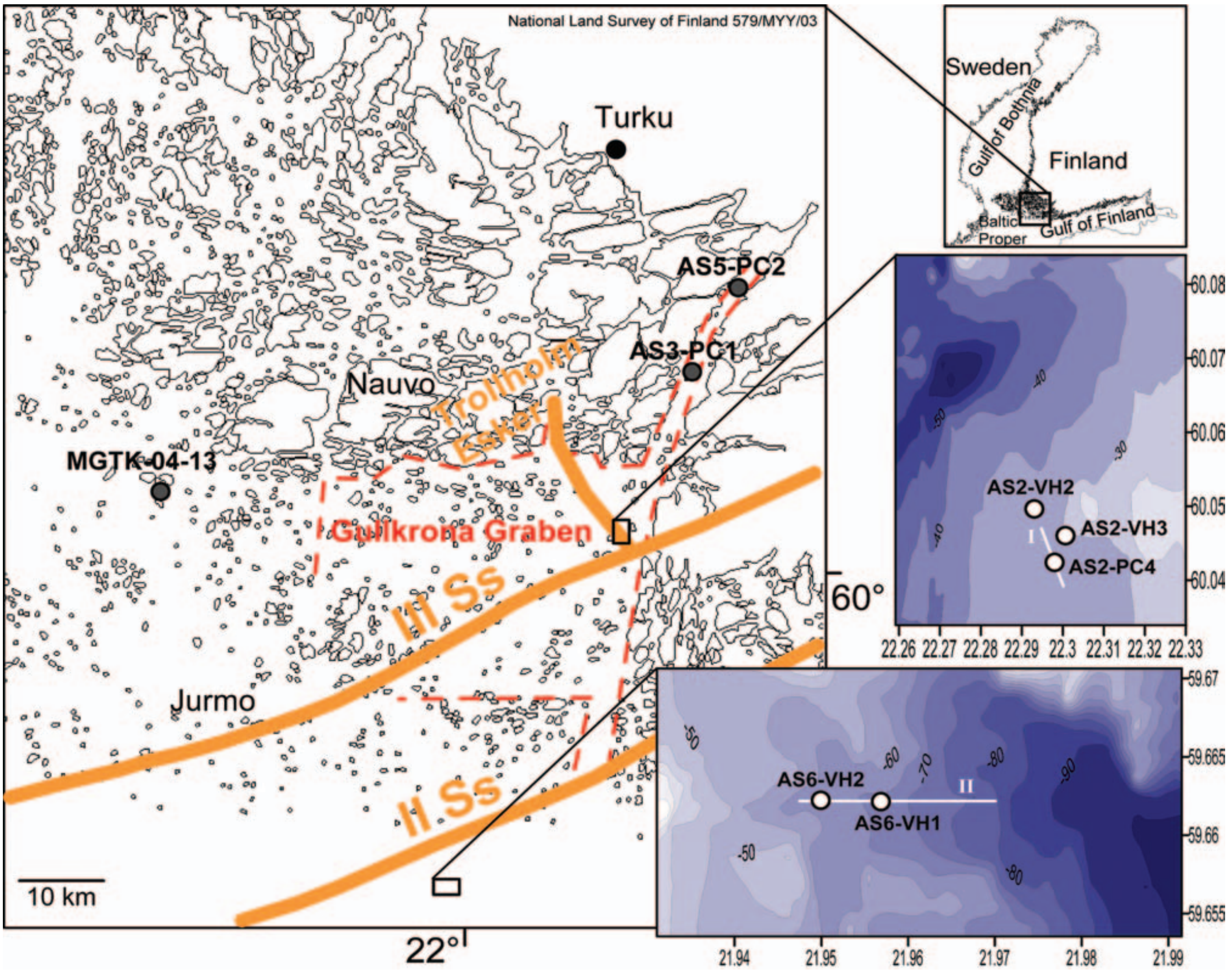

Fig. 1. Map of the study area and sampling sites. Contoured bathymetric maps are presented for the locations where multiple sediment cores were collected. Roman numbered white lines in the bathymetric maps indicate the acoustic profiles illustrated in Figs. 2 & 6. Positions for the Trollholm Esker, Second Salpausselkä (II Ss) and Third Salpausselkä (III Ss) formations are from Söderberg (1988) and Häkkinen (1990). Dashed lines outline the Gullkrona Graben (Edelman 1949).

recorded and stored digitally by using an MD DSS sub-bottom profiling system operating in a pinger mode at a frequency of 12 kHz. Altogether more than 100 km of acoustic survey line was collected, with each echopulse fixed to DGPS positioning data. The acoustic profiles were used in the careful selection of sampling locations. The retrieved sediment cores were up to 6 m long, and, therefore, they were cut into ca. 150 cm long sections for transportation. Cores AS2-PC4 and MGTK-04-13 were opened, described and sub-sampled onboard. The other cores were opened and studied ashore.

Application of acoustic data. Since different types of soft sediments have different types of acoustic properties, it is possible to distinguish these in acoustic profiles. However, the high frequency acoustic signal utilized in the present study does not penetrate into bedrock, till, gravel or even sand. Therefore, the bedrock and the coarse sediments deposited before the glaciolacustrine sediments are referred to here as a substratum.

Bathymetric maps for the areas where multiple cores were collected were drawn on the basis of the acoustic surveys (Fig. 1). The water depths were digitised from the acoustic profiles by using the MDPS 4.1 software. The bottom surface was interpolated by using the Kriging algorithm in the Golden Software Surfer 7 program. Sound velocity used for water was 1480 m s^{-1}. The same sound velocity was used for the sediments as well, even though a higher value (1600 m s^{-1}) would have been more correct. However, in the cores up to 6 m in length, the error in the depth estimates is < 10%.

Analysis of sediment cores. The core sections were cut and trimmed for description and digital photography. The bulk magnetic susceptibility (κ) was measured at 5 mm intervals by using a Bartington MS2E1 Surface Scanning Sensor. Sediment colour was recorded based on the Munsell colour chart. Continuous sub-samples for X-ray radiographs were collected by pressing 50 cm long plastic liners 1-4 cm in cross section into the sediment surface. Sub-samples (volume of 2 cm^3) for dry bulk density (DBD) and weight loss on ignition (LOI) analyses were taken with an open-tip syringe. DBD was determined after drying the samples at 105°C for 12 h, and LOI after ashing at 550°C for 2.5 h. Sub-samples were also collected for grains size distribution analyses, which were done with a Micromeritics 5000 ET sedigraph equipment. At major lithologic boundaries, the sub-samples were collected every 1 cm and their grain size distribution was analysed by using a Coulter LS 200 laser diffractometer.

X-ray radiographs were taken with a Philips constant potential 102 L system on an AGFA Structurix D7Pb film by using a focal distance of 100 cm, a focal spot size of 0.4-0.4 mm, a 6 mA tube current, a 40 kV load and 2.5 minutes exposure time. The developed films were scanned at 1200 dpi resolution and the contrast was enhanced using Canvas 8 and Corel Photo-Paint 10 in order to reveal structures hardly discernible to the naked eye. The small sizes of the trace fossils and the low density differences in the sediments allowed their distinction to the ichnogenous level only.

RESULTS

The acoustic profiles reveal four distinctive acoustic units and two distinctive erosional horizons (Fig. 2). They all are traceable across the Archipelago Sea, and, therefore, constitute a firm basis for the division of the acoustic stratigraphy. The penetration of the acoustic signal is generally good, but in the areas of high sediment thickness, as well as in gas bearing sediments, acoustic turbidity is common.

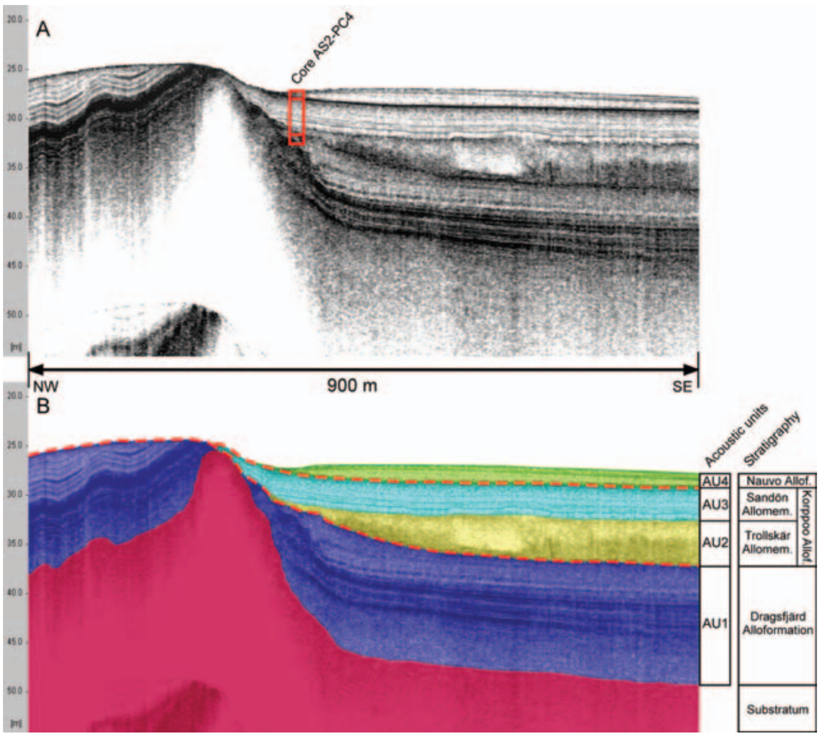

Fig. 2. Acoustic profile (A) with an interpretation (B) over the AS2-PC4 coring site (Transect I in Fig. 1). The sampling location and erosional contacts in the core AS2-PC4 are indicated in red. Vertical scale is in metres below sea surface. Dashed lines indicate erosional surfaces.

As revealed by visual examination, and verified by the X-ray radiographs, the sediment cores are characterized by 2 distinctive erosional contacts (Fig. 3). These contacts correlate well with the erosional horizons in the acoustic profiles (Fig. 2). This allows the definition of three unconformity-bounded allostratigraphic units: the Dragsfjärd Alloformation, Korppoo Alloformation and Nauvo Alloformation. The Korppoo Alloformation is subdivided into the Trollskär Allomember and the Sandön Allomember based on an acoustic discontinuity. All the stratigraphic units are traceable with acoustic surveys outside the Archipelago Sea toward the Gulf of Bothnia, the Baltic Proper and the Gulf of Finland.

Dragsfjärd Alloformation

The Dragsfjärd Alloformation is named after the municipality where its Gullkrona Graben type area is located. The alloformation corresponds to the acoustic unit AU1 (Fig. 2). The lower bounding surface is sometimes difficult to determine in areas where the deposits are too thick for the acoustic signal to penetrate. None of the cores reached the lower boundary, but based on the acoustic profiles, the unit bounds at its bottom to the substratum. The unit thickness is about 9 m in the Gullkrona Graben area. Its internal reflection configuration and external form indicate conformable deposition over the underlying topography. In places, however, the reflection structure is cut at the upper boundary, indicating an erosional truncation. This is especially common when the unit is exposed at the seafloor, but the truncations are observed also where subsequent deposits cover the unit.

The stratotype of the Dragsfjärd Alloformation is represented by the basal part of the core AS2-PC4 (Table 2, Fig. 4a). These deposits are observed also in the cores AS2-VH3 and MGTK-04-13 (Figs. 4b & 5a). The differing lithologies of the cores indicate marked lateral variation. Some generalizations can be made, however. The thickness of the rhythmic couplets together with the grain size difference between the couplet layers decrease upward. The rhythmic structure becomes less distinctive toward the upper part of the succession, where it varies between indistinct and well developed. Small dropstones are found at various depths. Silt-covered erosional horizons are common, especially in the upper part of the unit. The presence of black ferrous monosulphide banding varies depending on the locality. The upper boundary of the alloformation is sharp (Fig. 3a), reflecting the erosional nature of the upper boundary of AU1. However, the Trollskär Allomember (see below) overlies the Dragsfjärd Alloformation in all of the studied cores, but the acoustic surveys reveal that Trollskär Allomember is missing in some (shallower) areas. It remains unclear if this unconformity is erosional also where the Trollskär Allomember is missing, but it is expected to be at least non-depositional in those areas.

The alloformation is devoid of trace fossils (Fig. 4a). The κ values are high (> 20 * 10^{-6} SI) and increase with the grain size. The coarser end of the couplet layers and the silt layers covering the erosional horizons give the highest κ readings, while in the homogeneous to weakly laminated intervals the κ values are generally lower. LOI values are low (< 4 % dw) and decrease with the increasing grain size. The highest LOI values are observed in the homogeneous and weakly laminated intervals. DBD values are high (> 0.7 kg m^{-3}) and behave opposite to LOI.

A distinct horizon of dark, tiny (< 1 mm), grains is observed in the cores AS2-PC4 and MGTK-04-13 at the depths of 504 cm and 376 cm, respectively (Figs. 4a & 5a). The horizon coincides with an exceptionally strong κ peak. In addition, an interval of black, diffuse monosulphide mottling is observed in the same cores at the depth intervals of 538-547 cm and 414-420 cm, respectively.

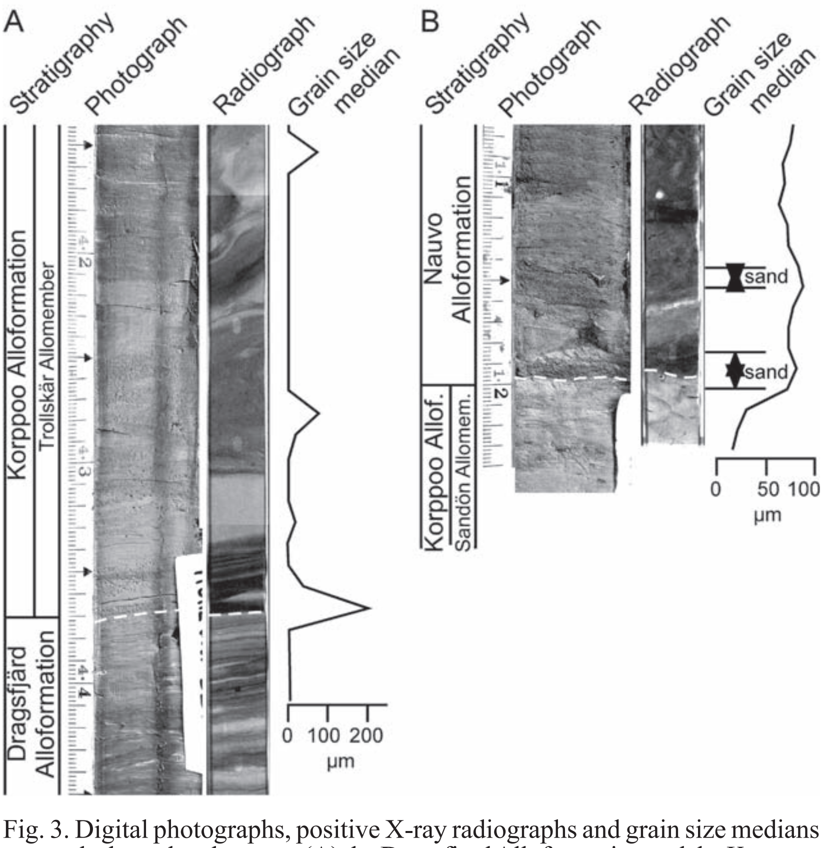

Fig. 3. Digital photographs, positive X-ray radiographs and grain size medians across the boundary between (A) the Dragsfjärd Alloformation and the Korppoo Alloformation, and (B) the Korppoo Alloformation and the Nauvo Alloformation (core AS2-PC4). Vertical scale is in centimetres below core top.

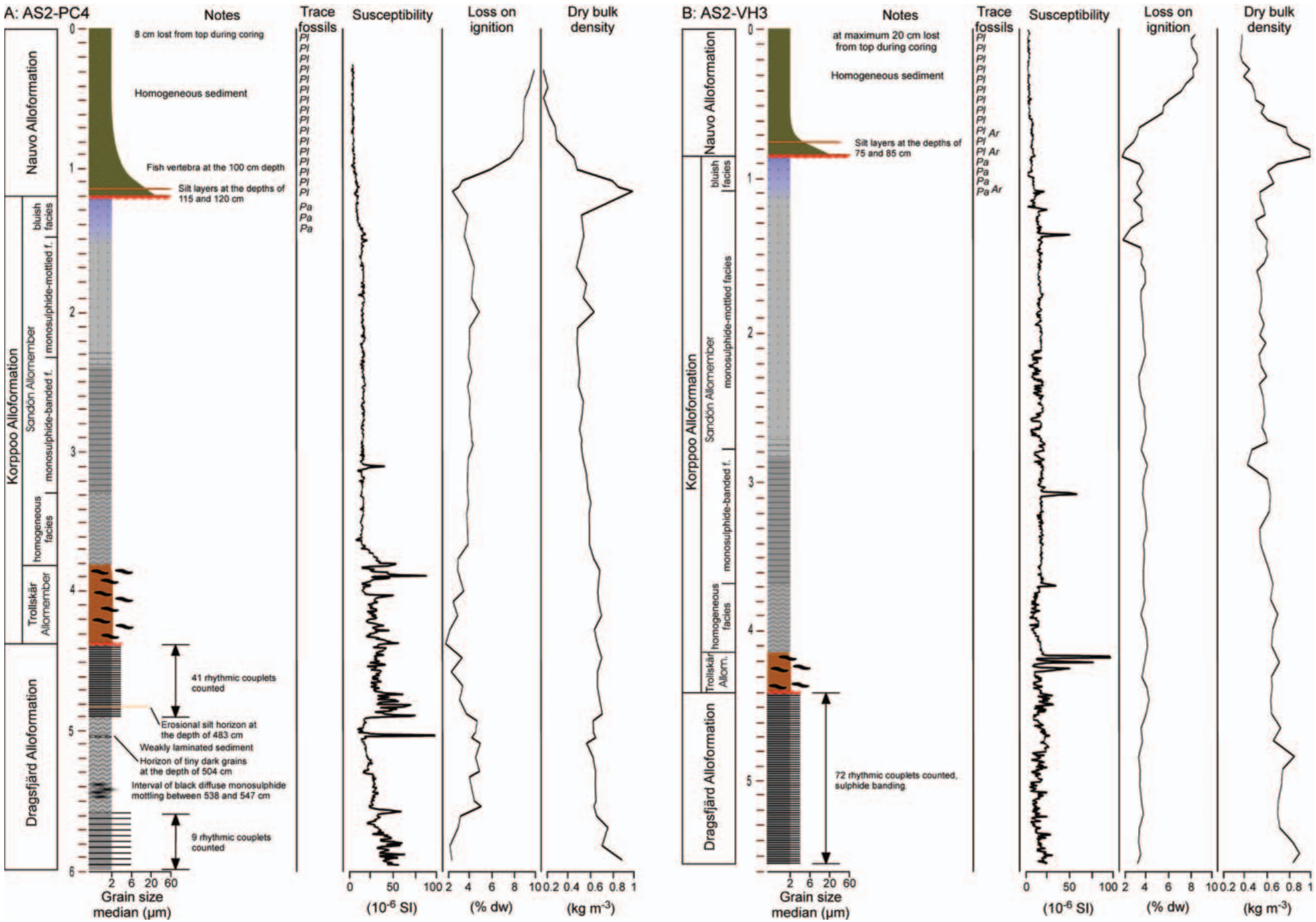

Fig. 4. Lithologic description of the cores AS2-PC4 (A) and AS2-VH3 (B) supplemented by trace fossils, susceptibility, loss on ignition and dry bulk density data. Trace fossils: Ar = *Arenicolites*, Pa = *Palaeophycus*, Pl = *Planolites*, Te = *Teichichnus*, Lo = *Lockeia*.

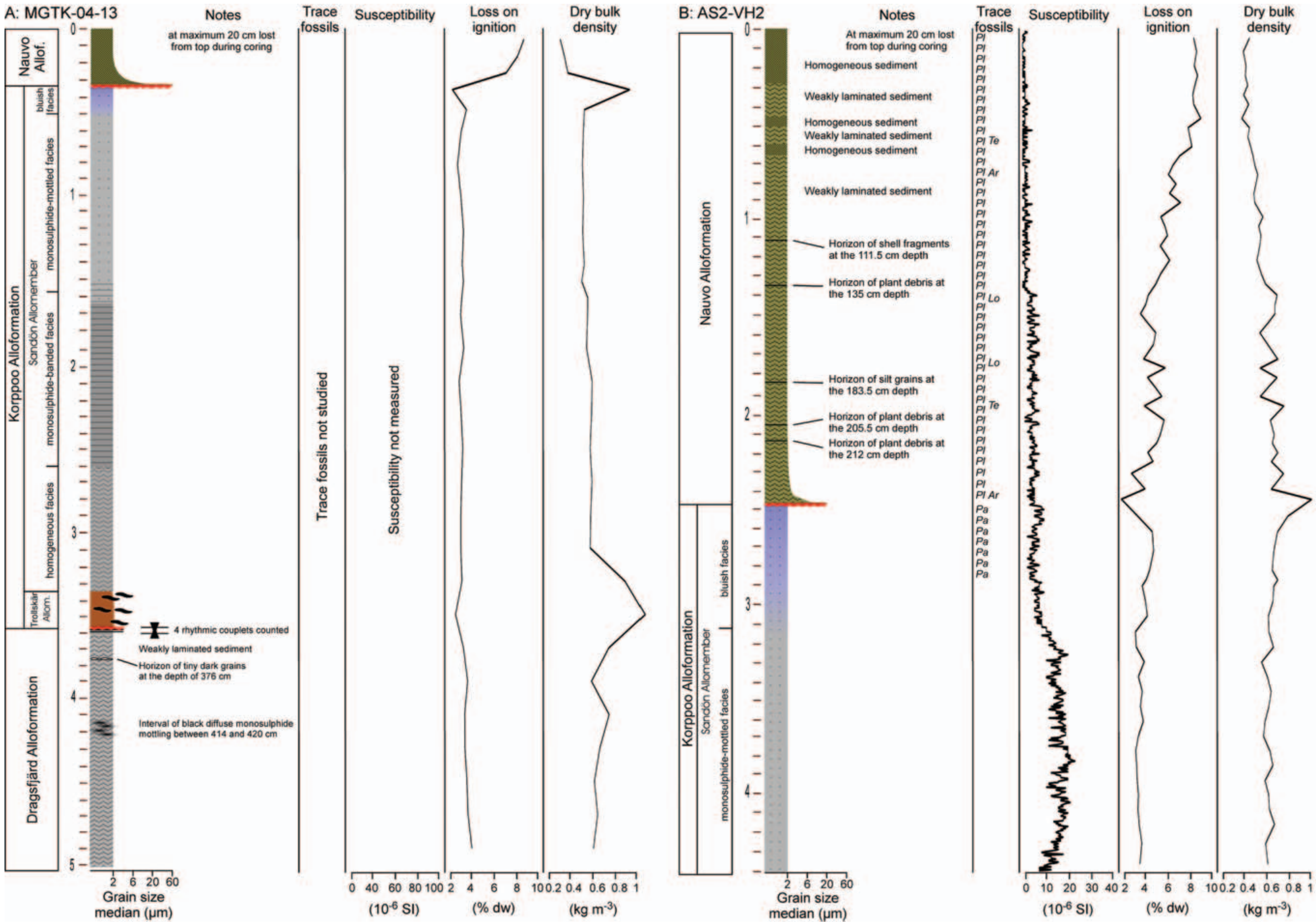

Fig. 5. Lithologic description of the cores MGTK-04-13 (A) and AS2-VH2 (B) supplemented by trace fossils, susceptibility, loss on ignition and dry bulk density data. Trace fossils: Ar = *Arenicolites*, Pa = *Palaeophycus*, Pl = *Planolites*, Te = *Teichichnus*, Lo = *Lockeia*.

Table 2. Lithologic description of the Dragsfjärd Alloformation deposits in the sediment cores.

AS2-PC4 (Stratotype) Core depth (cm). Description.	**AS2-VH3** Core depth (cm). Description.	**MGTK-04-13** Core depth (cm). Description.
<u>491-437.</u> Rhythmically alternating fine and coarse layers. At the upper boundary, the primary structure is cut indicating an erosional contact. The brownish-grey (5GY4/1) coarse layers consist of silt, while the grey (5Y4/1) fine layers are clay. Altogether 41 rhythmic couplets are counted, their thickness varying between 1 and 2 cm. An erosional horizon of silt is observed at the 483 cm depth. <u>559-491.</u> Weakly laminated brownish-grey clay. Sharp upper contact. An interval of black (N3) diffuse mottling presumably by monosulphide is observed between 547 and 538 cm. A distinct horizon of dark tiny grains is observed at 504 cm. The horizon is characterized by the black diffuse mottling as well. <u>598-559.</u> Altogether 9 rhythmic couplets are counted, their thickness decreasing upward. The brownish coarse layers consist of silt, while the grey fine layers are clay	<u>555-440</u>. The entire sequence is rhythmically laminated. At the upper boundary, the structure is cut indicating an erosional contact. Altogether 72 couplets are counted, their thickness varying between 1 and 2 cm. The sequence is characterized by black diffuse monosulphide banding. The bands are usually located at the base of the fine layers, but they occur within the fine and coarse layers as well. The unit bottom is not reached.	<u>360-357.</u> Four rhythmic couplets counted. At the upper boundary the structure is cut indicating an erosional contact. <u>504-360.</u> Weakly developed lamination. Sharp upper contact. An interval of black monosulphide mottling is observed between 420 and 414 cm. A distinct horizon of dark tiny grains is observed at the 376 cm depth. The unit bottom is not reached.

Korppoo Alloformation

The Korppoo Alloformation is named after a municipality close to its Gullkrona Graben type area. The alloformation is bounded by the two unconformities and consists of AU2 and AU3 (Fig. 2). The AU2 is characterized by internal reflections that vary from transparent to chaotic (Fig. 2). Sometimes lumps of laminated sediments are seen supported in the matrix. Its external form is basin fill. The unit thickness varies from undistinguishable in the elevated areas up to 15 m in the topographic depressions, being usually about 4-5 m. AU2 is not observed at the offshore AS6 site (Fig. 6).

According to the internal reflections, AU3 was deposited conformably on the underlying topography in the basal part of the unit, but the structure grades upward to transparent (Fig. 2). Its external form is conformal to the underlying topography. The unit thickness in the Gullkrona Graben is about 7 m, but it increases seawards. In places, the reflection structure is truncated at the upper boundary. The reflection configuration and the form of AU3, therefore, resemble those of AU1, but the reflector angles are slightly smoother due to the levelling of the underlying topography by AU2.

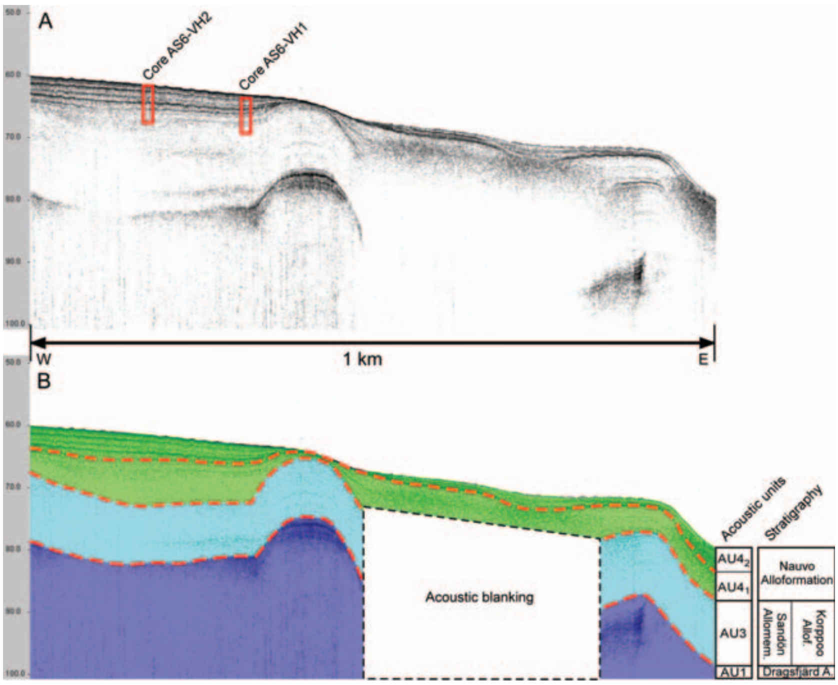

Fig. 6. Acoustic profile (A) with an interpretation (B) over the AS6 coring site (Transect II in Fig. 1). The sampling locations of the cores AS6-VH1 and AS6-VH2 are indicated. Vertical scale is in metres below sea surface. Dashed lines indicate erosional surfaces.

The stratotype of the Korppoo Alloformation is represented by the middle part of the core AS2-PC4 (Table 3, Fig. 4a). Almost identical lithologic variation is observed in the cores AS2-VH3 and MGTK-04-13 (Figs. 4b & 5a). The upper part of the alloformation is observed also in the cores AS2-VH2, AS3-PC1 and AS5-PC2 (Figs. 5b & 7). The lithologic change from the deformed sediments to the homogeneous sediments at the basal part of the alloformation correlates with the AU2/AU3 boundary (Figs. 2 & 4a). Because this correlation allows these different sediments to be recognized in acoustic profiles, the Korppoo Alloformation is subdivided into the Trollskär Allomember (AU2) and Sandön Allomember (AU3). Their contact is gradational in the studied cores, which, strictly speaking, would not allow their separation based on allostratigraphic principles. However, the boundary is a distinct acoustic discontinuity, which indicates a marked change in sedimentation processes at this level. Compaction shear and other consolidation processes, as well as the irregular AU2 surface due to the redeposited sediment lumps may also add to the acoustic character of this contact. Thus, even though it is not a real unconformity, the boundary nevertheless represents a marked change in sedimentation processes, and, therefore, the subdivision into allomembers is justified.

The Trollskär Allomember is named after an island closest to the stratotype coring site. Its deformed nature is obvious in both the sediment structure and the acoustic character of AU2 (Table 3; Figs. 2 & 3a). The primary sediment structure alternates between homogeneous and laminated, with the lamina oriented in arbitrary directions. This indicates that the unit is partly composed of redeposited sediment lumps. AU2 is not observed at the offshore AS6 coring site, which suggests that the unit is restricted in the Gulf of Finland to its westernmost part.

The Sandön Allomember is named after an island close to the stratotype coring site. The allomember corresponds to AU3 (Fig. 2). Its lithologic succession shows a marked consistency between the cores, which allows its subdivision into facies (Table 3; Fig. 4a). The succession begins with a weakly laminated to homogeneous clay facies, which abruptly changes into a monosulphide-banded clay facies. The banding is gradually replaced upward by a diffuse monosulphide-mottled clay facies abundant in pyrite-marcasite concretions, which, in turn, gradates into a bluish-grey clay facies. The bluish facies is missing entirely in the core AS5-PC2, where it has probably been eroded away (Fig. 7b). The top boundary of the Sandön Allomember is truncated (Fig. 3b), reflecting the erosional character of the upper boundary of AU3.

The first trace fossils appear just above the lower boundary of the bluish-grey facies, and cover the rest of the succession (Fig. 4a). The trace assemblage is Palaeophycus-dominated (2-5 mm in diameter); rare *Arenicolites* (2-9 mm in diameter) are also observed. The contrast of the burrow linings is enhanced by mineral precipitation, probably pyrite.

The κ values are variable, but frequently exceed 40 $* 10^{-6}$ SI in the Trollskär Allomember (Fig. 4a). LOI values are low (< 3 % dw) and DBD values high (~ 0.7 kg m^{-3}). At the base of the Sandön Allomember, the κ values show a gradual decrease, but the values increase slightly again toward the monosulphide-banded facies. From there on, the κ values remain relatively constant (~ 15 $* 10^{-6}$ SI), except for the occasional peaks associated with the sulphides, until they gradually decrease below 10 $* 10^{-6}$ SI at the base of the bluish-grey facies. LOI values increase to ~ 4 % dw at the base of the Sandön Allomember, remain relatively constant in the overlying succession, and increase again in the bluish-grey facies. DBD values decrease at the base of the allomember to < 0.6 kg m^{-3} and remain relatively constant thereupon.

Nauvo Alloformation

The Nauvo Alloformation is named after a municipality close to its Gullkrona Graben type area. The alloformation corresponds to the acoustic unit AU4 (Figs. 2 & 6). AU4 covers large parts of the seafloor in the Archipelago Sea. Frequent convex to onlap reflectors characterize its internal reflection configuration. Its external form is basin fill. The unit thickness varies considerably. Usually it is several metres, but in the topographic depressions the thickness can reach 20 m. Where underwater channels occur, the unit can be several metres thick on one flank, while completely missing on the other. Its upper boundary is truncated in places. Sometimes strong reflectors cut through the internal structure, dividing the unit into subunits with the orientation of the overlying reflectors differing from that of the subunit below (see for example the subunits $AU4_1$ and $AU4_2$ in Fig. 6). The lateral extent of such cross-cutting reflectors is restricted, typically less than the respective sub-basin.

The stratotype of the Nauvo Alloformation is represented by the upper part of the core AS2-VH2 (Table 4, Fig. 5b). Comparable successions are observed in the cores AS6-VH1 and AS6-VH2, but they do not reach the unit bottom (Fig. 8a,b). Also the cores AS2-VH3, AS2-PC4, AS3-PC1 and AS5-PC5 include these deposits. The succession is characterized by a strong lithologic variability. A 1-2 cm thick silt (or in places fine sand), layer usually overlies its base (Fig. 3b). At some locations, there can be several of these layers. Above the silt layers, the succession consists of alternating light greenish-grey, homogeneous mud and dark greenish-grey, thinly laminated mud intervals with irregular vertical extent. The sediments are more laminated where the unit thickness is higher. Tiny plant remains are abundant in these deposits, and the odour of H_2S is evident. Pyrite concretions are abundant as well, but they are smaller than those of the Sandön Allomember. Thin layers of plant debris or coarser minerogenic material frequently interrupt the succession. *Macoma baltica* valves are common. The topmost sediments are of very low viscosity.

The trace fossil assemblage includes *Planolites* (1-5 mm in diameter), *Arenicolites* (1-3 mm in diameter), *Lockeia* and *Teichichnus* (Fig. 5b). The traces are not

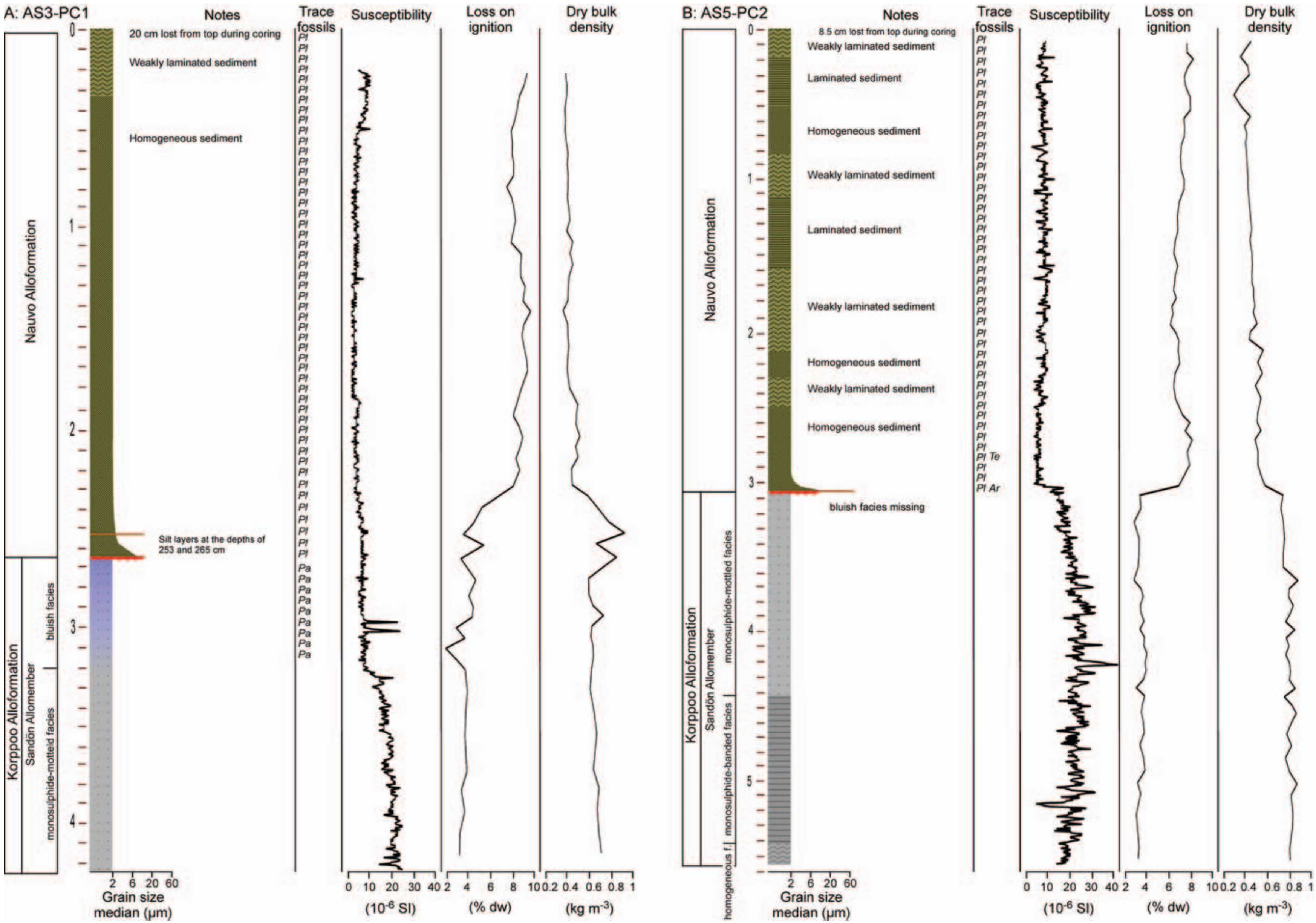

Fig. 7. Lithologic description of the cores AS3-PC1 (A) and AS5-PC2 (B) supplemented by trace fossils, susceptibility, loss on ignition and dry bulk density data. Trace fossils: Ar = *Arenicolites*, Pa = *Palaeophycus*, Pl = *Planolites*, Te = *Teichichnus*, Lo = *Lockeia*.

Table 3. Lithologic description of the Korppoo Alloformation deposits in the sediment cores.

Allomember	facies	AS2-PC4 (Stratotype) Core depth (cm). Description.	AS2-VH2 Core depth (cm) Remarks.	AS2-VH3 Core depth (cm) Remarks.	AS3-PC1 Core depth (cm) Remarks.	AS5-PC2 Core depth (cm) Remarks.	MGTK-04-13 Core depth (cm) Remarks.
Sandön Allomember	bluish-grey facies	148-120. Brownish-grey (5GY4/1) homogeneous clay characterized by a bluish tint, which strengthens upward. Some black (N3) diffuse monosulphide mottling and pyrite-marcasite concretions. The upper boundary is sharp.	312-247. Sharp upper boundary.	108-85. Sharp upper boundary.	320-265. Sharp upper boundary.	The unit is missing completely.	50-33. Sharp upper boundary.
	monosulphide-mottled facies	232-148. Grey (5Y4/1) homogeneous clay. Distinct black (N3) diffuse monosulphide mottling. Pyrite-marcasite concretions are abundant. The upper contact is indicated by the gradual appearance of a bluish tint.	440-312. The unit bottom is not reached.	278-108	423-320. The unit bottom is not reached.	441-307. Sharp upper boundary.	157-50
	monosulphide-banded facies	329-232. Grey homogeneous clay. Distinct black banding presumably by monosulphide. At the upper contact, the banding is gradually replaced by diffuse monosulphide mottling and the increasing occurrence of pyrite-marcasite concretions.		368-278		541-441	260-157
	homogeneous facies	381-329. Grey, weakly laminated to homogeneous clay. Sporadic black monosulphide mottling. The upper contact is indicated by the lowermost black band.		414-368		556-541. The unit bottom is not reached.	334-260
Trollskär Allomember		437-381. Brownish-grey to grey clay with silt lenses. Primary structure is homogeneous to laminated. The orientation of the lamination alternates between horizontal to vertical. The upper boundary is gradual.		440-414			357-334

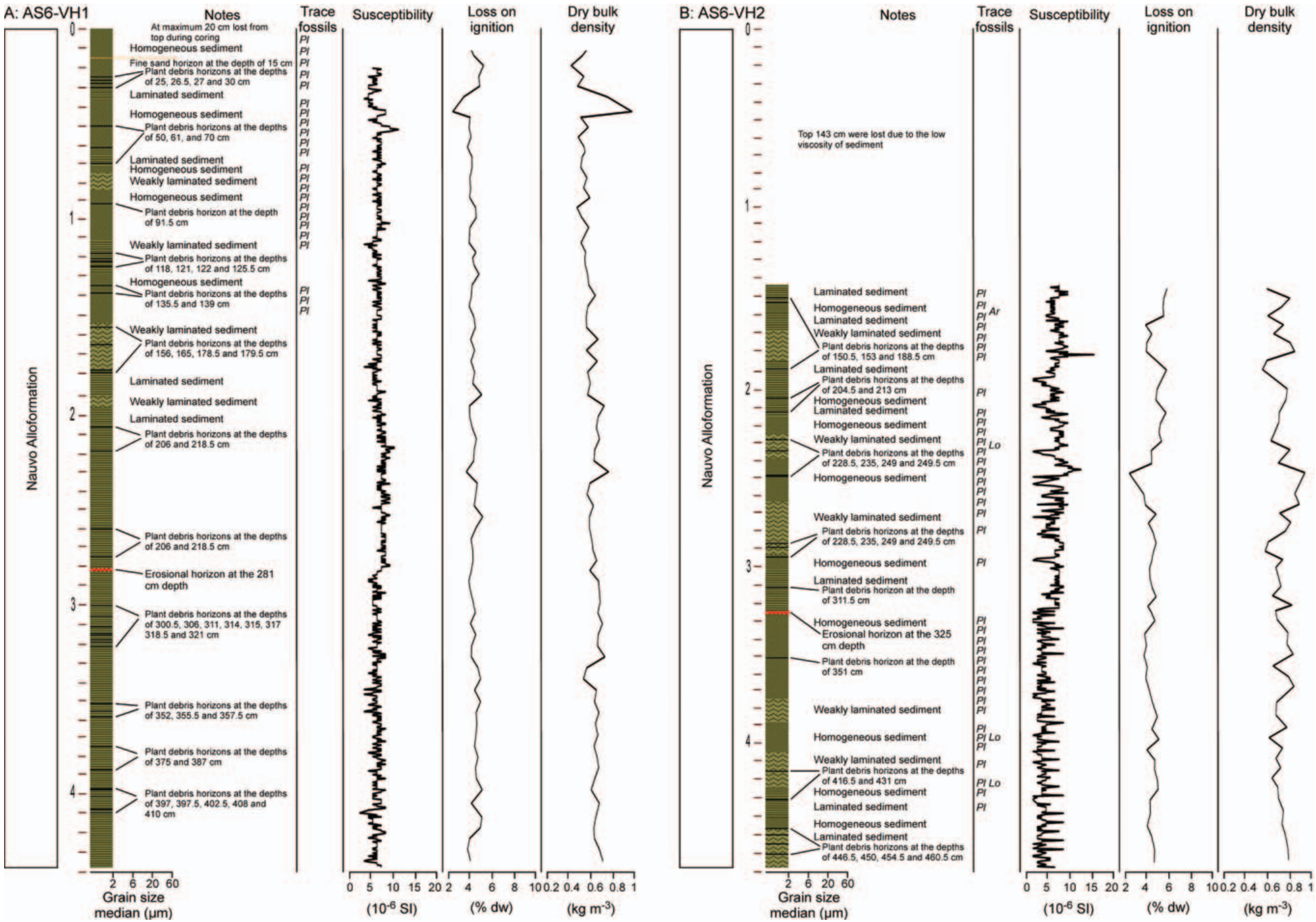

Fig. 8. Lithologic description of the cores AS6-VH1 (A) and AS6-VH2 (B) supplemented by trace fossils, susceptibility, loss on ignition and dry bulk density data. Trace fossils: Ar = *Arenicolites*, Pa = *Palaeophycus*, Pl = *Planolites*, Te = *Teichichnus*, Lo = *Lockeia*.

Table 4. Lithologic description of the Nauvo Alloformation deposits in the sediment cores.

AS2-VH2 (Stratotype)	**AS5-PC2**	**AS6-VH1**	**AS6-VH2**	**AS2-VH3**
Core depth (cm). Description.	Core depth (cm). Description.	Core depth (cm). Description.	Core depth (cm). Description.	Core depth (cm). Description.
27-0. Homogeneous greenish-grey (5Y4/1) mud. Black (N3) monosulphide mottling, pyrite concretions, plant debris. 45-27. Weakly laminated greenish-grey mud. Black mottling, pyrite concretions, plant debris. Gradual upper contact. 50-45. Homogeneous greenish-grey mud. Black mottling, pyrite concretions, plant debris. Sharp upper contact. 59-50. Weakly laminated greenish-grey mud. Black mottling, pyrite concretions, plant debris. Gradual upper contact. 65-59. Homogeneous greenish-grey mud. Black mottling, pyrite concretions, plant debris. Sharp upper contact. 247-65. Weakly laminated greenish-grey mud. Black mottling, pyrite concretions, plant debris. Gradual upper contact. Several horizons of allochtonous material. A 3 cm thick homogeneous silt layer at the base grades upward to mud.	Greenish-grey mud. Black mottling, pyrite concretions and plant debris. A 2 cm thick homogeneous fine sand to silt layer at the base grades upward to mud. Homogeneous to laminated intervals alternate as follows: 18-0. Weakly laminated. 51-18. Laminated. Sharp upper contact. 82-51. Homogeneous. Sharp upper contact. 112-82. Weakly laminated. Gradual upper contact. 159-112. Laminated. Sharp upper contact. 212-159. Weakly laminated. Sharp upper contact. 230-212. Homogeneous. Sharp upper contact. 250-230. Weakly laminated. Gradual upper contact. 306-250. Homogeneous. Sharp upper contact.	Greenish-grey mud. Black mottling, pyrite concretions and plant debris. Horizons of allochtonous material are frequent. The unit bottom is not reached. Homogeneous to laminated intervals alternate as follows: 33-0. Homogeneous. A fine sand horizon at 16 cm. 36-33. Laminated. Gradual upper contact. 66-36. Homogeneous. Sharp upper contact. 71-66. Laminated. Gradual upper contact. 75-71. Homogeneous. Sharp upper contact. 84-75. Weakly laminated. Gradual upper contact. 112-84. Homogeneous. Sharp upper contact. 129-112. Laminated. Gradual upper contact. 154-129. Homogeneous. Sharp upper contact. 178-154. Weakly laminated. Gradual upper contact. 190-178. Laminated. Sharp upper contact. 196-190. Weakly laminated. Sharp upper contact. 438-196. Laminated. Sharp upper contact.	Greenish-grey mud. Black mottling, pyrite concretions and plant debris. Horizons of allochtonous material are frequent. The unit bottom is not reached. Homogeneous to laminated intervals alternate as follows: 154-143. Laminated. 159-154. Homogeneous. Sharp upper contact. 169-159. Laminated. Gradual upper contact. 185-169. Weakly laminated. Sharp upper contact. 204-185. Laminated. Sharp upper contact. 209-204. Homogeneous. Sharp upper contact. 215-209. Laminated. Gradual upper contact. 225-215. Homogeneous. Sharp upper contact. 239-225. Weakly laminated. Gradual upper contact. 263-239. Homogeneous. Sharp upper contact. 294-263. Weakly laminated. Gradual upper contact. 302-294. Homogenous. Sharp upper contact. 326-302. Laminated. Gradual upper contact. 375-326. Homogeneous. Sharp upper contact. 389-375. Weakly laminated. Gradual upper contact. 406-389. Homogeneous. Sharp upper contact. 425-406. Weakly laminated. Gradual upper contact. 429-425. Homogeneous. Sharp upper contact. 441-429. Laminated. Gradual upper contact. 447-441. Homogeneous. Sharp upper contact. 468-447. Weakly laminated. Gradual upper contact.	85-0. Homogeneous greenish-grey mud. Black mottling, pyrite concretions, plant debris. A horizon of allochtonous material at 79 cm. A 2 cm thick homogeneous silt layer at the base grades upward to mud. Another 2 cm thick silt layer at 75 cm. **AS2-PC4** Core depth (cm). Description. 120-0. Homogeneous greenish-grey mud. Black mottling, pyrite concretions, plant debris. A 2 cm thick homogeneous fine sand layer at the base grades upward to mud. Another 1 cm thick fine sand layer at 115 cm. **AS3-PC1** Core depth (cm). Description. 33-0. Weakly laminated greenish-grey mud. Black mottling, pyrite concretions, plant debris. 265-33. Homogeneous greenish-grey mud. Black mottling, pyrite concretions, plant debris. Sharp upper contact. A 1 cm thick homogeneous silt layer at the base grades upward to mud. Another 1 cm thick silt layer at 253 cm. **MGTK-04-13** Core depth (cm). Description. 33-0. Homogeneous greenish-grey mud. Black mottling, plant debris. A 2 cm thick homogeneous silt layer at the base grades upward to mud.

as distinctively pyritized as in the Sandön Allomember. The biogenic structures become indistinct upward. The κ values are low (< 10 * 10^{-6} SI) and decrease upward. LOI values are high (5-15 % dw) and increase upward. DBD values are low (< 0.6 kg m^{-3}) and decrease upward.

CONCLUSIONS

A formal stratigraphic division is proposed for the Archipelago Sea Holocene succession. The proposed units are defined with an aim to make their identification and correlation as easy and unambiguous as possible. Regional mapping of these units will be facilitated by their distinctive expression in acoustic profiles. All the proposed units can be followed with acoustic surveys outside the Archipelago Sea toward the Gulf of Bothnia, the Baltic Proper and the western Gulf of Finland. The proposed division, thus, provides means for a more extensive correlation and understanding of how the units change laterally within the Archipelago Sea, as well as toward the neighbouring sea areas. The correlation with the sediments outside the Archipelago Sea should be done with caution, however. Future work is needed to resolve how far the proposed units can be traced in the neighbouring sea areas.

The rhythmic textural changes of the Dragsfjärd Alloformation are interpreted as glacial varves. They indicate deposition close to the subaqueous ice-margin, and reflect the seasonal character of the ice-sheet melting. The unit is bounded at the top by an erosional to non-depositional unconformity, which is most likely genetically related to the overlying Trollskär Allomember. The deformed and redeposited character of the Trollskär Allomember suggests that it was deposited under higher energy conditions than the sediments underlying it. The origin of the unit requires further study.

Possible explanations include: 1) an enormous surge from the melting ice-sheet and 2) erosion due to the extremely rapid regression that followed the deglaciation. The homogeneous primary structure of the Sandön Allomember indicates that its deposition was not affected by the seasonal ice-sheet dynamics. This reflects the ice-margin retreat from the area. The irregular distribution of the Nauvo Alloformation deposits indicates that currents have strongly affected their deposition. This reflects the shoaling of the sea area and the reworking of older sediments due to regression. Considering the cross-cutting reflectors, this unit can potentially be subdivided locally into allomembers.

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References

Björck, S. 1995: A review of the history of the Baltic Sea, 13.0–8.0 ka BP. *Quaternary International 27*, 19-40.

Edelman, N. 1949: Structural history of the eastern part of the Gullkrona Basin, SW-Finland. *Bulletin de la Commission géologique de Finlande 148*, 1-48.

Eyles, C.H., Eyles, N., Gostin, V.A. 1998: Facies and allostratigraphy of high-latitude, glacially influenced marine strata of the Early Permian southern Sydney Basin, Australia. *Sedimentology 45*, 121-162.

Gibbard, P.L. 1992: Formal stratigraphy in the Pleistocene of Finland. *Bulletin of the Geological Society of Finland 64*, 125-134.

Glückert, G. 1995: The Baltic Ice Lake in south Finland and its outlets. *Quaternary International 27*, 47-51.

Gripenberg, S. 1934: A study of the sediments of the North Baltic and adjoining seas. *Fennia 60*, 3, 1-231.

Häkkinen, A. 1990: *Saaristomeren vedenalaisten maa-ainesvarojen kartoitus Gullkronan selällä 1989*. Varsinais-Suomen seutukaavaliitto, Turku. 58 p. In Finnish.

Heino, A. 1973: Bottom deposits and sedimentation in northern Airisto in Southwestern Finland. Bulletin of the *Geological Society of Finland 45*, 131-142.

Hiscott, R.N., Aksu, A.E. 2002: Late Quaternary history of the Marmara Sea and Black Sea from high-resolution seismic and gravity-core studies. *Marine Geology 190*, 261-282

Hyvärinen, H. 1988: Definition of the Baltic stages. In Donner, J. & Raukas, A. (eds.): *Problems of the Baltic Sea history. Annales Academiae Scientiarum Fennicae A III 148*, 7–11.

Kotilainen, A. 1991: *Deglasiaatio ja sedimentaatio-olot Yoldiavaiheen aikana itäisellä Saaristomerellä*. Masters thesis, University of Helsinki. 112 p. In Finnish.

Mäkinen, J., Saaranen, V. 1998: Determination of postglacial land uplift from the three precise levellings in Finland. *Journal of Geodesy 72*, 516–529.

Miall, A.D. 1997: *The Geology of Stratigraphic Sequences*. Springer, Berlin. 433 p.

Murphy, M.A., Salvador, A. 1999: International stratigraphic guide - an abridged version. *Episodes 22*, 255-271.

North American Commission on Stratigraphic Nomenclature 2005: North American stratigraphic code. *American Association of Petroleum Geologists Bulletin 89*, 1547-1591.

Söderberg, P. 1988: Notes on the continuation of the Salpausselkä ice marginal zone in the northern Baltic Proper. *Geological Survey of Finland, Special Paper 6*, 69-72.

Salvador, A. 1994: *International Stratigraphic Guide*, 2nd edition. International Union of Geological Sciences, Trondheim, and The Geological Society of America, Boulder, Colorado. 214 p.

Sauramo, M. 1958: Die Geschichte der Ostsee. *Annales Academiae Scientiarum Fennicae A III 5*, 1-522. In German.

Walker, R.G. 1992: Facies, facies models and modern stratigraphic concepts. *In* Walker, R.G. & James, N.P. (eds.): *Facies Models - Response to Sea Level Change,* 1-14. Geological Association of Canada, St. John's, Newfoundland.

Winterhalter, B. 1972: On the geology of the Bothnian Sea, an epeiric sea that has undergone Pleistocene glaciation. *Geological Survey of Finland, Bulletin 258*, 1-66.

Winterhalter, B., Flodén, T., Ignatius, H., Axberg, S., Niemistö, L. 1981: Geology of the Baltic Sea. *In* Voipio, A. (ed.): *The Baltic Sea*, 1-121. Elsevier, Amsterdam.