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Varve microfabric record of seasonal sedimentation and bottom flow-modulated mud deposition in the coastal northern Baltic Sea

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ABSTRACT

Eutrophication-induced hypoxia has resulted in preservation of laminated sedimentary fabric in coastal areas of the northern Baltic Sea. These laminites offer a potential technique for dating recently deposited organic-rich muds, but their formation mechanisms have been inadequately understood. In this study, microfabric of the modern laminated sediments in the coastal Gulf of Finland and Archipelago Sea was investigated through X-radiography and scanning electron microscopy of samples embedded in epoxy resin. The sedimentary fabric comprises rhythmic biogenic and lithogenic lamina successions reflecting seasonal changes in the composition of accumulating material. The diatom-rich biogenic lamina succession is formed during the vernal phytoplankton bloom through rapid sedimentation of aggregates composed of intact diatom frustules and minor proportions of clay-rich lithic material that are enclosed in a sticky matrix of amorphous phytodetritus, analogous to the formation of the marine snow. Accumulation of the lithogenic lamina succession results from decline in primary production towards late summer, enhanced recycling of organic carbon due to grazing by zooplankton and intensified resuspension of lithic-rich terrigenous material concomitantly with increased cyclonic activity towards late autumn and winter. The inclusion of silt grains and isolated diatoms and faecal pellets in the lithogenic laminae attests to lateral transport and deposition from near-bottom flows, contradicting the generally accepted view that laminated sediments accumulate by suspension settling under quiescent conditions only. Accumulation rates inferred from ^{137}Cs dating are consistent with the biogenic–lithogenic lamina succession-couplet thickness, supporting the interpretation that the couplets reflect an annual cycle of deposition. The results indicate that these modern laminated sediments provide a high-resolution archive for assessing recent human-induced environmental changes as well as a robust tool for evaluating the lateral expansion of seafloor oxygen deficiency due to anthropogenic eutrophication in the area during the past decades.

1. Introduction

Annually laminated (varved) sediments deposited in lacustrine as well as in marine settings are a widely used, robust tool for assessing past environmental and climatic changes encompassing time-intervals of a few decades to several millennia (Renberg and Segerström, 1981; O'Sullivan, 1983; Saarnisto, 1986; Haltia-Hovi et al., 2007; Ojala et al., 2012). Laminated sediments are thought to form in low-energy environments through quiescent suspension settling under hypoxic to anoxic bottom water conditions and the absence of benthic macrofauna, occasionally reflecting seasonal changes in the deposition. Nevertheless, recent studies indicate that fine-grained laminated sediments are also deposited through migration of floccule ripples under more energetic conditions (Schieber et al., 2007; Macquaker et al., 2010a).

In the Baltic Sea, the formation mechanism and microfabric of sharply laminated intervals in muddy sediments of the deep central basins are relatively well understood (Burke et al., 2002; Virtasalo et al., 2011). These laminated intervals were deposited during times of lower hypoxic or anoxic bottom water conditions, caused by enhanced primary productivity and the restricted vertical mixing of oxygen due to a strong halocline, after the onset of the present brackish-water phase of the basin at 8100–7600 cal. BP (Virtasalo et al., 2007; Rößler et al., 2011). The deposition of laminated mud from brackish water has intermittently taken place also in sheltered coastal sub-basins above the halocline (Virtasalo et al., 2007; Virtasalo and Kotilainen, 2008). Since the 1950s, human-induced nutrient loading has led to eutrophication and the lateral expansion of laminated sediment accumulation in the coastal areas with restricted lateral water exchange (Persson and Jonsson, 2000; Kotilainen et al., 2007; Conley et al., 2011; Carstensen et al., 2014). Although these coastal laminated sediments are characterized by substantially greater and more variable lamina thickness than the laminated sediment intervals in the central deep basins of the Baltic Sea, the laminated or thinly-bedded structure was proposed to reflect

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an annual sedimentation cycle (Morris et al., 1988). However, findings by Virtasalo et al. (2014b) demonstrate that storm-triggered event deposition is an alternative mechanism for the formation of laminated or thinly-bedded sediments in the coastal areas of the Baltic Sea, underlining the need for further studies on the mechamism(s) of laminated sediment formation.

Laminated sediments of the Baltic Sea have been used as a chronological tool to assess recent changes in PCB and DDT sedimentation (Jonsson et al., 2000; Meili et al., 2000), heavy metal concentrations (Borg and Jonsson, 1996) as well as the lateral expansion and duration of anoxia (Persson and Jonsson, 2000; Kotilainen et al., 2007). Where laminated sediments reflect an annual sedimentation cycle, they provide a high-resolution tool for geochronology.

In this study, the microfabric of coastal laminated brackish-water muds of the Baltic Sea was inspected for the first time at intra-seasonal resolution. The sedimentation cycle observed in the lamina succession by means of X-radiography, optical microscopy and scanning electron microscopy was linked to sediment trap studies in the area. The results provide significant new insight into the formation mechanisms of laminated or thinly-bedded sediments that are widely used in studies of recent environmental change. In addition, our findings shed light on mud deposition and organic carbon burial in analogous ancient settings.

2. Regional setting and depositional history

The Baltic Sea, one of the largest brackish-water bodies in the world, is a shallow (mean depth 54 m) semi-enclosed basin on a continental shelf (Fig. 1). The sea is essentially non-tidal but irregular water level fluctuations of up to 1.3 m occur due to variations in wind and atmospheric pressure. The water body is characterized by strong salinity stratification, and a 10–20 m thick permanent halocline lies at a depth of 40–80 m, varying from basin to basin and preventing the oxygenation of the deep water (Leppäranta and Myrberg, 2009).

The water exchange with the North Sea commences through the Danish straits, and is mainly governed by the sea-level difference between the Kattegat and the Baltic Sea (Wulff et al., 1990). Salinity decreases from south to north as a result of the water exchange in the south and the large rivers in the north. The surface salinity ranges from ca. 8–10 PSU in the southern Baltic to 3–5 PSU in the Gulf of Finland and Gulf of Bothnia (Matthäus, 2006).

The deep water circulation in the Baltic Sea is hampered horizontally by the bottom topography and vertically by the halocline (Matthäus and Franck, 1992). The deep water of the central Baltic Sea is occasionally renewed by large inflows of higher salinity and oxygen-rich water from the North Sea, which replaces the old oxygen-depleted water of the deep basins (Leppäranta and Myrberg, 2009).

The sub-basins cored in this study are located in the coastal areas of the eastern Gulf of Finland and the Archipelago Sea (Fig. 1). These coastal areas are characterized by an expansive mosaic of islands with complex topography (Kaskela et al., 2012), and thus numerous small sub-basins with considerably different sedimentation conditions occur over short distances (Virtasalo et al., 2005b). Due to the shallow water and abundance of islands, water exchange between the archipelago and the open-sea is restricted (Mälkki et al., 1979). In the sheltered sub-basins, a strong thermocline prevents oxygen delivery to the bottom waters during summer, which occasionally results in at least seasonal oxygen depletion (e.g. Virtasalo et al., 2005a). As the permanent halocline is generally absent in coastal areas, mixing of the water column takes place in spring and autumn due to thermal convection (Leppäranta and Myrberg, 2009). The study area is annually ice-covered for 3–4.5 months (Seinä, 1994). The present glacio-isostatic uplift rate is 1–4 mm a^{-1}, increasing from east to west (Mäkinen and Saaranen, 1998).

The deglacial to present sediment fill of the Baltic Sea basin is a succession of ice-proximal tills and glacial outwash deposits, glaciolacustrine rhythmites, patchy debrites, postglacial lacustrine clays and brackish-water mud drifts (Virtasalo et al., 2007, 2014a). The final retreat of the Fennoscandian continental ice-sheet led to the formation of a large proglacial lake, the Baltic Ice Lake, in the southern Baltic Sea basin (e.g. Eronen, 1988; Björck, 1995) at approximately 16,000 cal. BP (Anjar et al., 2014). At the termination of the Younger Dryas at 11,700–11,600 cal. BP (Saarnisto and Saarinen, 2001), the Baltic Ice Lake drained to the Atlantic through south-central Sweden, leading to a catastrophic water level drop of ca. 25 m and establishment of the Yoldia Sea stage (e.g. Glückert, 1995; Andrén et al., 2002; Johnson et al., 2010). Roughly coinciding with the Baltic Ice Lake and Yoldia Sea stage, glaciolacustrine rhythmites (glacial varves) and scattered debrites were deposited (Virtasalo et al., 2007). At ca. 10,700 cal. BP the drainage threshold in south-central Sweden was uplifted above the Atlantic Ocean level and the Baltic Sea became ponded from the ocean, resulting in the formation of the Ancylus Lake (Andrén et al., 2000b; Brenner, 2005) and deposition of post-glacial lacustrine clays (Virtasalo et al., 2007). By 7600 cal. BP, the eustatic ocean-level rise exceeded the glacio-isostatic uplift rate, resulting in the ingression of saline Atlantic waters over the Danish straits and leading to the establishment of the brackish-water Litorina Sea, the direct precursor of the modern Baltic Sea (Andrén et al., 2000a,2000b; Virtasalo et al., 2007; Rößler et al., 2011). Since the ingression, wave and current controlled deposition of organic-rich brackish-water mud drifts with laminated intervals has prevailed (Virtasalo et al., 2007).

3. Materials and methods

3.1. Sediment coring and subsampling

The sediment cores MGGN-2013-13, MGGN-2013-14, MGGN-2013-15 and MGGN-2013-25 (abbreviated hereafter to G-13, G-14, G-15 and G-25, respectively) were collected onboard R/V Geomari in September 2013 (Table 1). The coring was conducted in collaboration with the Geological Survey of Finland alongside the ENPI CBC funded TOPCONS project. Geological maps that were produced within the TOPCONS project were used to determine the coring locations for the cores G-13, G-14 and G-15. The G-25 coring site was chosen based on a previous study that reported the occurrence of sharply laminated sediments in the Boistö sub-basin (Kotilainen et al., 2007).

Prior to coring, high-resolution acoustic data were collected with a sub-bottom profiling system (MD DSS Multi-Mode Sonar System; Meridata Finland Ltd, Lohja, Finland) operating in chirp and pinger modes at frequencies of 3.5–84 kHz and 28 kHz, respectively. The sub-bottom profiles were used to verify suitable coring locations. The sediment cores were retrieved with a GEMAX twin-barrel gravity corer, which is specifically designed for retrieving cores with undisturbed surfaces of soft sediments. The corer enables free water flow through the core tube, preventing the formation of hydraulic shock wave below the corer, thereby decreasing resuspension of surficial sediments as the corer approaches the seafloor (Blomqvist, 1991). In order to prevent disturbance in the fluffy sediment surface, the corer was lowered and lifted with a steady wire speed of ca. 1 m s^{-1}. In case the near-bottom water in the core tube was turbid or the sediment surface was uneven after lifting the corer on the deck, the core was considered disturbed and the coring procedure was repeated. One of the twin cores was split onboard for initial lithological description and the other was cut to 10 mm thick slices parallel to the laminations for ^{137}Cs dating. The slices were immediately placed into plastic bags and stored at 4–6 °C.

The cores G-13, G-14, G-15 and G-25 were sub-sampled with aluminium trays (Lamoureux, 1994). The trays (11 × 1 × 1.5 cm) were pushed into the cleaned and levelled sediment perpendicular to the laminations. Subsequently, the sediment-filled trays were extruded from the core with an aluminium jig and the excess sediment was removed parallel to the laminations. The sub-samples were wrapped in cling film and stored onboard at 4–6 °C.

The mini ice-finger core SJLI-048 (abbreviated hereafter to S-048) was retrieved on board R/V Aurelia in collaboration with the Archipelago