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Relocation of soft mud deposits: An example from the Archipelago Sea, northern Baltic Sea

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ABSTRACT

Active sedimentation is one of the distinguishing characteristics of the Baltic Sea. This has led to the formation of fractally-distributed soft sediment deposits (muds) that can be up to several meters thick. In this study we examined, for the first time, stability of soft sediment deposits within a 3 km^2-sized sedimentary basin in the northern Baltic Sea (Eastern Archipelago Sea, Finland) using acoustic profiling (28 kHz and 3.5 kHz) and 200 kHz multibeam surveys, on three occasions from 2011 to 2013. Sub-bottom profile data and rasterized deposit thickness data revealed maximal annual thickness changes between −1.1 m erosion or +1.1 m deposition along primary survey lines, and skimming of up to 9% of the soft deposit area. The most notable finding was the significant instability of mud. When examined at local scale there was substantial and very localized erosion and deposition (apparent horizontal movement of unconsolidated mud 250–400 m per year) between 2012 and 2013. Maximum relocation of unconsolidated deposits was approximately 0.3 $km^3\ a^{-1}$ with 94% export to the exterior area (2011–2012), and was likely affected by abnormally high wave action in the northern Baltic Sea during the period of observation. The combination of acoustic and mathematical techniques is shown to be highly suited to examination of temporal variations in sub-bottom level environments.

1. Introduction

The Baltic Sea is a shallow, nearly enclosed basin that has been subjected to several Pleistocene glaciation events. The Baltic Sea differs from open ocean basins due to the lack of tidal currents and its much lower salinity, as well as its shallow bathymetry, the mean water depth being only 62 m. The Archipelago Sea, with an area of 8000 km^2 off the southwestern coast of Finland, consists of over 40,000 islands, inlets and open sea areas and forms the world's largest archipelago. The area is, like the Baltic Sea in general, further characterized by high primary production (photosynthetic growth of phytoplankton and production of organic molecules in the sea), shallowness (average depth of 23 m), highly variable bathymetry, the presence of diverse kinds of bottom materials (rock, till, clay, mud, etc.) and continuous land uplift, caused by post-glacial isostatic rebound. Local sediment erosion and deposition are affected by waves and water currents.

The oldest glacial varved deposits above the till formations were formed about 7000–10,000 years before present, after the latest glaciation. At the commencement of the Litorina Sea stage, sedimentation conditions changed rapidly because the ice sheet, which had previously been a sediment source, had disappeared. Sedimentation rates decreased and Litorina deposits are normally concentrated within deeps (Ignatius, 1958) where they form "basin fill" type deposits (Winterhalter, 1972). Although about 50–80% of the Baltic Sea is covered by postglacial Litorina sediments (e.g. Emelyanov and Kharin, 1988), areas where active sedimentation still continues are, however, quite limited (Ignatius and Niemistö, 1971). Based on echo sounding, the average linear rate of sedimentation in the Baltic Sea has been estimated at 0.1–2.0 mm a^{-1} (Ignatius, 1958), 0.2–4.3 mm a^{-1} (Kotilainen et al., 2000) and, based on radioactive tracers in the Gulf of Finland, at 1.5–4 mm a^{-1} (Mattila et al., 2006). In some isolated basins, linear sedimentation rates can be higher, such as in in Puck Bay (up to 4.5 mm a^{-1}; Szmytkiewicz and Zalewska, 2014), the Gdansk Basin (7 mm a^{-1}; Damrat et al., 2013) or up to 38.3 mm (surface layer; Mattila et al., 2006).

It is thought that wave induced water movements are eroding seafloor deposits at depths as great as 70 m (Kohonen and Winterhalter, 1999) in open sea areas and are strong enough to prevent recent sedimentation above 50 to 70 m (Winterhalter, 1972, 1976). Overall, water movement has a great influence on sediment transport (e.g. Van Straaten and Kuenen, 1957; Van Maren and Winterwerp, 2013). Thus it is natural that in some sheltered basins deep inside the archipelago, sediments can still accumulate in shallower areas in proximity to the shoreline. Areas with active sedimentation have often been

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classified as “recent” sedimentation areas. This “recent” sediment is much less consolidated than the underlying postglacial deposits. This layer is easy to identify, especially in areas where a clear erosion layer is present (e.g. Winterhalter, 1992). If the sedimentation has continued uninterrupted from the Litorina stage to the present, the boundary between the Litorina period deposits and “recent” sediments is often arbitrary and cannot be separated acoustically. Moreover, this boundary is not easily discerned in areas of gas-bearing sediments. Particularly under reducing conditions, Baltic Sea sediments release methane into the water column (Schmale et al., 2010). The methane gas bubbles are often concentrated in the upper sediment layers, cause strong reverberation of the acoustic pulse, preventing acoustic penetration deeper into the sediments (Siemes et al., 2010; von Deimling et al., 2013).

There have been very few studies of sediment mobility in the Baltic Sea. Tauber and Emeis (2005) reported detachment of freshly-accumulated 10 m sized patches of mud using SSS in the Baltic Sea. Virtasalo et al. (2014) have demonstrated from core samples that storm erosion takes place on average every 30 years in the easternmost Gulf of Finland. Those storm layers are normally <2 cm thick. In addition to wave base effects, currents affect the stability of soft deposits. According to Kuenen (1950) the deposited clay layers need a current velocity of 1–2 ms^{-1} velocity for erosion to occur. The nearest study (Rasmus et al., 2015) from the Gulf of Finland reported average near-bottom currents of 5.5 cm s^{-1}. Therefore we can infer that wave base effects can be sufficient for detaching sediment particles and that currents will be capable of transporting them.

Acoustic methods have been widely used in various marine geological surveys, e.g. exploring the structures of bedrock and sedimentary deposits, or to provide a general view of the Quaternary sediments and how they are reflected in acoustic profiles (e.g. Nuorteva, 1988). These techniques rely on the use of echo sounding, seismic surveys or multibeam sounders operating at several frequency regimes and angles. Nowadays, habitat mapping relies mostly on the use of side scan sonar (SSS; e.g. Davis et al., 2002; Degraer et al., 2008; Isachenko et al., 2014), or multibeam echo sounding (MBES; Brown and Blondel, 2009; McGonicle et al., 2009; Micallef et al., 2012; Tang et al., 2015; Zhi et al., 2014; Alevizos et al., 2015; the Finnish Inventory Program for the Underwater Marine Environment), in spite of the many inherent restrictions of both SSS and MBES as well as the multibeam technique (Brown et al., 2011). Brissette and Clarke (1999) carried out a comprehensive evaluation and comparison of both systems. Acoustic methods have been used also to determine the annual average sedimentation (e.g. Yutsis et al., 2014).

Automated methods for classification of sediments have been attempted in the past. These methods rely on objective classification algorithms, but only a few studies have been published in which different automated seabed mapping systems are compared (e.g. Che Hasan et al., 2012). Diesing et al. (2014) compared different methods of manual interpretation to object-based image analysis and geostatistics. Ground-truthing is often required to reliably couple the signal to real properties of the sediment and to facilitate the machine learning approach. Experimental studies from Clyde Sea (Ireland) and from the Southern Baltic have shown that with high-resolution seismic reflection data, only limited ground truth information is needed to produce quantitative information on the spatial distribution of seafloor sediment physical properties (Davis et al., 2002). Overall, there is still lack of fit-for-purpose seabed maps, and the overall thematic classification accuracy of most common seafloor surficial deposits classes varies between 67 and 76% (Diesing et al., 2014).

We hypothesized, that the upper fluffy layers of mud are unstable in the study area. In the present study we have examined, for the first time in the Baltic Sea region, a) the applicability of a combination of acoustic methods and data processing to seabed stability surveys and b) determined the temporal stability of the recent marine mud deposits in the survey area. A confined area to the northwest of the town of Hanko, on the southwest coast of Finland, was chosen for the survey.

2. Description of the study area

The survey area is located (central point ca. 59° 54.60′ N, 22° 48.00′ E) in the eastern part of the Archipelago Sea, approximately 14 km northwest of the town of Hanko, Finland (Fig. 1). Water depth over the surveyed seafloor is between 9.3 and 44.4 m. The area is bordered by three local shipping routes so that the northwest and southeast tips of survey area are about 350 and 100 m off of the route lines respectively. The study area is annually ice-covered for 3–5 months during the northern winter period. There is no water column stratification in the investigated area, because the permanent halocline is generally absent in coastal areas. The surface salinity in the Archipelago Sea ranges between 2 and 5 PSU. The present glacio-isostatic uplift rate is 3–4 mm a^{-1}. The seafloor deposits in the area consist of a mosaic of mud, postglacial clays and outcrops of crystalline bedrock. The thickness of Quaternary (post glacial) deposits over the basement typically varies between 0 and ca. 12 m (unpublished data). Nuorteva (1994) reported the latest published data on average sedimentation rates (1–8 mm a^{-1}) based on postglacial (7000 years) deposit thickness (maximum 62 m) for the area (close to Hanko). No data regarding the characteristics (e.g. sedimentation rate) of the uppermost layer have been published.

3. Material and methods

3.1. Platform and acquisition of acoustic data

The study was conducted during three cruises of r/v ‘Geomari’ (Geological Survey of Finland) in August 2011, June 2012 and August 2013 (Fig. 1). The survey campaigns were conducted in calm conditions during a single day each year. Vertical profiles were gathered with an Odom Mk III (Teledyne Odom Hydrographic) echo sounder with two different transducers (Massa Products Corporation, MA, USA), operating at 28 and 3.5 kHz frequencies with a survey speed of 4–5 knots. Both transducers were triggered simultaneously to avoid interferences and constant settings were saved for use during the surveys each year. Raw data were saved in one datafile with iXSea software (iXBlue SAS, France). An Atlas Fansweep 20 (180/210 kHz, Teledyne Atlas Hydrographic) interferometric multibeam system was used simultaneously to obtain bathymetry and SSS sounding data from the seafloor. These survey results were used as auxiliary data for the echo sounding data.

The 28, 3.5 and 200 kHz sound sources facilitated depth resolutions better than 10, 20 and 5 cm, respectively. Data from the 28 kHz sound source generated the primary material for post-processing and analysis. Speed of sound was measured during each survey using a Navitronic SVP15 (Teledyne Reson A/S, Denmark) sound velocity probe. Survey lines were 2.5–4.2 km long with a 100 m perpendicular separation. In total seven lines were examined in 2011 and 10 lines in 2012 and 2013, so that the whole studied area covered 2.926 km^2 with a total length of analyzed echo profiles of 85.340 km.

3.2. Wave height data

Monthly open-access data on average maximum wave heights in the northern Baltic Proper (most proximal location to the survey area) for 2011–2013 and long-term average data for 1996–2013 were obtained from the Finnish meteorological Institute (FMI) (Pettersson et al., 2012, 2013). The distance between the wave height buoy and the study area is about 70 km.

3.3. Interpretation and handling of acoustic data

3.3.1. Multibeam data

The MBES data were processed using the Hypack Hydrographic Survey Software (Hypack Inc., USA) and CARIS HIPS and SIPS software (CARIS, New Brunswick, Canada), where they were corrected for sea level (tidal) variations and sound speed and merged together to create