Estuarine, Coastal and Shelf Science 195 (2017) 51–59

Contents lists available at ScienceDirect

Estuarine, Coastal and Shelf Science

journal homepage: www.elsevier.com/locate/ecss

Grain-size of varved clays from the north-eastern Baltic Ice Lake: Insight to the sedimentary environment

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A R T I C L E I N F O

Article history:
Received 27 January 2016
Received in revised form
1 July 2016
Accepted 11 August 2016
Available online 13 August 2016

Keywords:
Varves
Glacial deposits
Sediment texture
Grain size
Baltic Ice Lake
Baltic Sea, Pärnu Bay

A B S T R A C T

Besides providing high resolution chronological information, varved sediments also are excellent environmental archives. We examined the grain size distribution of varved glaciolacustrine sediments as a proxy for estimation of the water depth and the duration of winter – a period with diminished sediment input from the melting glacier and restricted water circulation due to ice cover. The particle size at the top of the winter layer is assumed to reflect the time available for a particle to settle from the top of water column during the winter before water mixing and new sediment input in spring. Glacial varves from Pärnu Bay in SW Estonia, where a local varve chronology of 584 years was established previously is examined as a case study. X-ray absorption granulometer was used to determine the grain size distribution within 10 varves with 2–14 samples collected from each varve. The coarsest particle size found on top of the winter layer is calculated for each varve from measured grain size distributions using a novel methodology and compared to the reconstructed water depth of the Baltic Ice Lake to constrain the likely duration of the winter. A high variability of the constrained winter length with an average close to the duration of a calendar year was found. It is concluded that the coarsest particles on top of the winter layer have settled from intermediate depths due to water stratification, or less likely the actual water level was lower than reconstructed. We conclude that the methodology can be used to constrain environmental parameters in glacial lakes where varved sediments are formed.

1. Introduction

Varved clays formed in glaciolacustrine lakes are an excellent environmental archive of the chronology of the deglaciation (De Geer, 1912). Yet relatively little research is done to extract useful proxy data from grain size of sediments formed in this environment although the sediment grain size in arctic and boreal lakes has attained noticeable attention (Cockburn and Lamoureux, 2008; Cuven et al., 2010; Francus, 2002; Francus et al., 2008; Lapointe et al., 2012). It is found that the climate signal recorded by clastic varved sediments may be less straightforward than initially thought.

Various aspects of proglacial lacustrine sedimentary environment and varve formation are presented in numerous publications since the pioneer works of De Geer (1912) and the comprehensive overviews by Ashley (1975, 2002; Ashley et al., 1985) as well as recent developments mapping the controls on annual sediment accumulation through sediment traps and cross correlation with hydroclimatic data (Cockburn and Lamoureux, 2008; Francus et al., 2008; Glur et al., 2014; Hanson et al., 2012; Lamoureux and Gilbert, 2004; Leemann and Niessen, 1994; Ojala et al., 2013; Tomkins and Lamoureux, 2005).

We start the investigation with a basic assumption that during the melting season (summer) there is continuous input of the sediments in the glacial lake and during the autumn overturn a homogenous vertical distribution of suspended sediment is produced. During the winter the lake is completely covered by lake ice and there is neither sediment input nor water mixing. It is well established, that the Baltic Ice Lake was a freshwater body as its level was significantly above the global ocean level (Andrén et al., 2011). Freshwater lakes, even the very largest ones (Schertzer et al., 1987; Kirillin et al., 2012), in the temperate climate have a characteristic thermal stratification in summer followed by autumn overturn. During the winter, under the ice cover, little water mixing is expected (Kirillin et al., 2012) and factors usually playing

Abbreviations: TGS, terminal grain size; BIL, Baltic Ice Lake.

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http://dx.doi.org/10.1016/j.ecss.2016.08.009
0272-7714/

secondary role can become important. Particularly in the case of glacial lake the gradual settling of suspended sediments will produce density stratification hindering vertical water movement.

By making the assumptions we do neglect that there might be significant water circulation during the winter induced by the nearby ice-contact deep water margin of the lake (Roehl, 2003; Warren and Kirkbride, 1998). Mixing can take place due to poorly explored phenomena of internal waves and inertial currents in the ice-covered lakes (Kirillin et al., 2012).

The varves observed at the Pärnu bay region (Hang et al., 2007) are the classical bi-modal varves with coarse grained summer lamina and fine grained winter lamina. Sturm (1979) suggested that these couplets are formed as a result of pulse of sediment input during period of water stratification depositing the coarse grained lamina followed by overturn of the water column and deposition of clay-rich lamina. Sturm (1979) suggested that there is no grading in the fine grained lamina, however we suspect that this is not the case – there is normal grading, that can be detected by sophisticated grain size analysis.

We define a concept of **Terminal grain size** (**TGS**) as the largest particle size settled at the very end of the winter just before the input of new sediment pulse at the onset of the melting season. The TGS particles would have settled from the very top of the water column during the winter period. If the above assumptions are valid the TGS is directly controlled by the water depth and the duration of the period when there is no water mixing and no sediment input. In such a situation the TGS can be a useful proxy for paleolimnological reconstructions.

The terminal settling velocity can be calculated by the Stokes' law describing drag force on rigid spherical objects settling in a viscous fluid. The settling speed is a function of particle size and density and the density and viscosity of the water. The viscosity dependence on the temperature is the major source of uncertainty: the estimated winter length would vary by around 15% assuming the realistic water temperature during the winter of 0 °C or 5 °C for the same TGS. Other factors, like water density variations and pressure and salinity effects in the freshwater lake are assumed to be of secondary importance.

The Stokes law describes the settling of a spherical particle while the clay-size particles are more likely to be tabular. The settling speeds for spherical and tabular particles of identical mass will be different. We avoid this limitation by using a sedimentation based grain size analysis method: the measured particle size is expressed as a velocity-equivalent spherical diameter. This method was recommended for the sedimentology-related grain size investigations (McCave et al., 2006). Another problem with the Stokes law is the interactions between suspended particles that can include flocculation and settling speed interferences. The studied environment is a freshwater proglacial lake, thus we do not expect to have any clay particle flocculation to take place and the concentration of particles in the suspension was small enough to limit interference between thinking particles.

The aim of this research is to investigate if the grain size distribution within individual varves accumulated in the Baltic Ice Lake can be related to the water depth and length of the winter. We define winter as the season when sediment input into the lake is negligible and the water circulation is hindered by the ice cover.

2. Material and methods

The retreating Late Weichselian ice margin in Estonian territory between 14.7 and 12.7 ka BP was bordered by extensive proglacial bodies of water as evidenced by wide distribution of varved clays. The ice margin stagnation at the Pandivere-Neva line (Fig. 1) at about 14.0–13.8 ka BP is correlated to the highest shorelines of the Baltic Ice Lake (BIL) A1 stage (Hang et al., 2014; Vassiljev and Saarse, 2013). The following A2 stage of BIL is correlated to the ice stagnation at the Palivere line and its age is about 13.5–13.2 ka BP correlated to the shorelines of the BIL stage A2 (Vassiljev and Saarse, 2013). Due to isostatic uplift of the earth crust as the ice sheet was retreating BIL water depth in SW Estonia was decreasing from the initial around 80 m to 20–40 m when the ice margin stood at first line of the Salpausselkä end-formations (12.3–12.1 ka BP) in southern Finland (Rosentau et al., 2009).

The study site is the Pärnu varved clay basin, located in the SW Estonia, where the Baltic Ice Lake varves were deposited in ice-proximal conditions (Hang and Kohv, 2013). The thickness of the clay can reach up to 30 m, although around 10 m is the average. The clay is characterised by distinct lamination with visually distinguishable seasonal layers. Ripple marks, erosional features and synsedimentary disturbances are rare (Hang et al., 2007).

The local chronology spans 584 years (Hang and Kohv, 2013). It is built up by a set of 26 cross-correlated, largely contemporaneous sections scattered in an area of around 400 km^2. Varve correlation made directly on sediment cores provided a plausible correlation. We estimate an error in this chronology in the range of ±5% as constrained from repeated varve counts. The error always occurred in the upper varve series with thin clayey varves lacking distinct structural characteristics. This upper varve series is not considered in this study.

2.1. Samples

In this study, the sediment core was acquired by 1 m long Russian type peat corer with 7 cm diameter. The seasonal layers were identified visually. The winter-summer transition is always sharp and easy to identify while summer-winter transition within an individual varve is commonly gradual. The core surface was cleaned in the lab and series of bulk samples for the grain size analysis were cut out of the sediment by a knife in 0.5–1.0 cm thick slices with wet weight of 3.5–8.9 g. Two to 14 samples were taken from each examined varve. Care was taken to include the very top of the winter layer in the respective subsample by grabbing a little of the summer layer of the above varve. As explained below the TGS will be estimated from the mass ratios between size classes rather than directly measured. The TGS is within the finest size class that is relatively underrepresented in the sample from the top of winter layer compared to other samples. Thus contamination with overlaying summer sediments does not preclude the identification of the underrepresented size classes.

Four thick proximal varves (Y86, Y87, Y96 and Y97; the number indicates the local varve year in Pärnu chronology) and six distal varves (Y151, Y152, Y153, Y154, Y155 and Y157) were sampled (Fig. 2). Varves Y86 and Y87 fall within an interval of abundant ice-rafted debris found both in summer and winter laminae and deposition of massive diamicton in some parts of the basin (Hang and Kohv, 2013). The Y96 varve of extraordinary thickness marks the colour change in the sequence and the end of interval with ice-rafted debris. This change is interpreted as an initiation of ice retreat from Pandivere-Neva line (Hang and Kohv, 2013).

2.2. Grain size analysis

For the grain size analysis, samples were immersed in the 70 ml 0.4% sodium hexametaphosphate solution for de-flocculation for at least a day. To achieve full de-flocculating 30 s of ultrasonication prior to the analysis was used.

The samples were analysed with a SediGraph III X-ray absorption granulometer for the grain size range from 50 to 0.3 μm subdivided into 91 individual size-classes. Actual settling speed of